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International Energy Agency

Iron and Steel Technology Roadmap

Towards more sustainable steelmaking

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Abstract

Steel is vital to modern economies and so over the coming decades global demand for steel is expected to grow to meet rising social and economic welfare needs. Meeting this demand presents challenges for the iron and steel sector as it seeks to plot a more sustainable pathway while remaining competitive. The sector is currently responsible for about 8% of global final energy demand and 7% of energy sector CO_2 emissions (including process emissions). However, through innovation, low-carbon technology deployment and resource efficiency, iron and steel producers have a major opportunity to reduce energy consumption and greenhouse gas emissions, develop more sustainable products and enhance their competitiveness.

This report explores the technologies and strategies necessary for the iron and steel sector to pursue a pathway compatible with the IEA's broader vision of a more sustainable energy sector. Considering both the challenges and the opportunities, it analyses the key technologies and processes that would enable substantial CO_2 emission reductions in the sector. It also assesses the potential for resource efficiency, including increased reuse, recycling and demand reduction. Realising this more sustainable trajectory will require co-ordinated efforts from key stakeholders, including steel producers, governments, financial partners and the research community. As such, the publication concludes with an outline of priority actions, policies and milestones for these stakeholders to accelerate progress towards zero emissions from the iron and steel sector.

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[1] The IEA Clean Energy Transitions Programme (CETP) leverages the IEA's unique energy expertise across all fuels and technologies to accelerate global clean-energy transitions, particularly in major emerging economies. CETP activities include collaborative analytical work, technical co-operation, training and capacity building and strategic dialogues. Further details can be found at: https://www.iea.org/areas-of-work/programmes-and-partnerships/clean-energy-transitions-programme.

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Executive summary

Steel needs energy and the energy system needs steel

Steel is deeply engrained in our society. The construction of homes, schools, hospitals, bridges, cars and trucks – to name just a few examples – rely heavily on steel. Steel will also be an integral ingredient for the energy transition, with solar panels, wind turbines, dams and electric vehicles all depending on it to varying degrees. Since 1970 global demand for steel has increased more than threefold and continues to rise as economies grow, urbanise, consume more goods and build up their infrastructure.

Among heavy industries, the iron and steel sector ranks first when it comes to CO_2 emissions, and second when it comes energy consumption. The iron and steel sector directly accounts for 2.6 gigatonnes of carbon dioxide (Gt CO_2) emissions annually, 7% of the global total from the energy system and more than the emissions from all road freight.[1] The steel sector is currently the largest industrial consumer of coal, which provides around 75% of its energy demand. Coal is used to generate heat and to make coke, which is instrumental in the chemical reactions necessary to produce steel from iron ore.

Sustaining projected demand growth while reducing emissions poses immense challenges

Global demand for steel is projected to increase by more than a third through to 2050. The Covid-19 crisis has sent shockwaves through global supply chains, leading to an estimated 5% decline in global crude steel output in 2020 relative to 2019. The People's Republic of China ("China") bucks the global trend, with its production estimated to increase in 2020, based on strong levels of output in the first half of the year. After a global slump in the near term, the steel industry returns to a robust growth trajectory in our baseline projections. Without targeted measures to reduce demand for steel where possible, and an overhaul of the current production fleet, CO_2 emissions are projected to continue rising, despite a higher share of less energy-intensive secondary production, to 2.7 Gt CO_2 per year by 2050 – 7% higher than today.

[1] Energy system CO_2 emissions include both those from the combustion of fossil fuels and industrial process emissions, totalling 36 Gt CO_2/yr in 2019. When including indirect emissions from the power sector and the combustion of steel off-gases (a further 1.1 Gt CO_2/yr), the share of energy system CO_2 emissions attributable to the iron and steel sector rises to 10%.

Steel is one of the most highly recycled materials in use today. While iron ore is the source of around 70% of the metallic raw material inputs to steelmaking globally, the rest is supplied in the form of recycled steel scrap. Steel production from scrap requires around one-eighth of the energy of that produced from iron ore – mainly in the form of electricity, rather than coal for production from iron ore. This benefit results in high recycling rates (around 80-90% globally). However, scrap cannot fulfil the sector's raw material input requirements alone because steel production today is higher than when the products that are currently being recycled were produced. This means that recycling alone cannot be relied upon to reduce emissions from the sector to the extent needed to meet climate goals.

Existing infrastructure cannot be ignored if energy and climate goals are to be achieved. Global crude steel production capacity has more than doubled over the past two decades; three-quarters of the growth took place in China and around 85% of total capacity today is located in emerging economies. This rapid growth has resulted in a young global blast furnace fleet of around 13 years of age on average,[2] which is less than a third of the typical lifetime of these plants. If operated until the end of their typical lifetime under current conditions, these and other assets in the steel industry could lead to around 65 Gt CO_2 of cumulative emissions. This would exhaust most of the CO_2 budget compatible with a sustainable transition for the sector, leaving no room to manoeuvre for the capacity additions that will be required over the coming decades.

More efficient use of energy and materials can help, but will not be sufficient

To meet global energy and climate goals, emissions from the steel industry must fall by at least 50% by 2050, with continuing declines towards zero emissions being pursued thereafter. The IEA Sustainable Development Scenario sets out an ambitious pathway to net-zero emissions for the energy system by 2070. While more efficient use of materials helps to lower overall levels of demand relative to our baseline projections, the average direct CO_2 emission intensity of steel production must decline by 60% by 2050, to 0.6 tonnes of CO_2 per tonne of crude steel (t CO_2/t), relative to today's levels (1.4 t CO_2/t).

More efficient use of steel lightens the load on the required shift in process technology. Pursuing a suite of material efficiency measures along supply chains reduces global steel demand by around a fifth in 2050, relative to baseline projections. Savings stem from measures undertaken within the sector and its supply

[2] This estimate takes account of the last date of major refurbishment. The figure since initial installation is around 24 years.

chain (e.g. improving manufacturing yields) and those downstream of the sector (e.g. extending building lifetime), with the latter category contributing the majority of the material savings. Material efficiency strategies contribute 40% of the cumulative emissions reductions in the Sustainable Development Scenario.[3]

Energy performance improvements to existing equipment are important, but by themselves not sufficient for a long-term transition. The energy intensity of state-of-the-art blast furnaces is already approaching the practical minimum energy requirement. For inefficient equipment the gap between current energy performance and best practice can be much larger, but with energy making up a significant proportion of production costs, there is already an incentive to replace the least efficient process units. Improvements in operational efficiency, including enhanced process control and predictive maintenance strategies, together with the implementation of best available technologies contribute around 20% of cumulative emissions savings in the Sustainable Development Scenario.

A revolution in innovation and enabling infrastructure

New steelmaking processes are critical, but there is no one right answer. Hydrogen, carbon capture, use and storage (CCUS), bioenergy and direct electrification all constitute avenues for achieving deep emission reductions in steelmaking, with multiple new process designs being explored today. Energy prices, technology costs, the availability of raw materials and the regional policy landscape are all factors that shape the technology portfolio in the Sustainable Development Scenario. Access to low-cost renewable electricity (USD 20-30 per megawatt hour) in several countries provides a competitive advantage to the hydrogen-based direct reduced iron (DRI) route, which reaches just under 15% of primary steel production globally by 2050. Innovative smelting reduction, gas-based DRI and various innovative blast furnace concepts, all equipped with CCUS, prevail in areas where the local policy context is favourable and cheap fossil fuels are abundant. Hydrogen and CCUS together account for around one-quarter of the cumulative emission reductions in the Sustainable Development Scenario.

New technology must be deployed at a blistering pace, with new infrastructure to boot. While a smooth transition to larger shares of scrap-based production is possible as economies start to mature and scrap availability increases (e.g. China), a rapid roll-out of technologies that are currently at early stages of development will need to accompany this shift. In the Sustainable Development Scenario the deployment of one hydrogen-based DRI plant per month is required globally following market

[3] Cumulative emission savings are stated for the period 2019-50, and are relative to the baseline scenario.

introduction of the technology. This raises electricity demand by 720 terawatt hours by 2050, equivalent to 60% of the sector's total electricity consumption today. The concurrent deployment of CCUS-equipped plants requires around 0.4 Gt CO_2 capture globally in 2050, equivalent to the deployment of a large CCUS installation (1 million tonnes CO_2 capture per year) every 2-3 weeks from 2030.

Deep emission reductions are not achievable without innovation in technologies for near-zero emissions steelmaking. Of the cumulative emission reductions to 2050 in the Sustainable Development Scenario, 30% stem from steelmaking technologies that are at demonstration or prototype stages today. The rapid deployment of facilities utilising CCUS and low-carbon hydrogen in the Sustainable Development Scenario will not materialise without continued efforts to spur these technologies through the innovation pipeline. Our Faster Innovation Case explores the technology implications of bringing forward to 2050 the date at which net-zero emissions for the energy system is reached. In the Faster Innovation Case nearly three-quarters of the annual emission savings in 2050 stem from currently pre-commercial technologies, relative to around 40% in the Sustainable Development Scenario.

India takes centre stage

By 2050 almost one-fifth of the steel produced globally is expected to come from India, compared to around 5% today. India is already the world's second-largest steel-producing country and is expected to increase its annual production volumes by 2050 by an amount equivalent to twice that of the European Union's total production in 2019. The Covid-19 crisis is hitting the country's steel industry hard, but the underlying factors that point to growth in the future – a population whose number and prosperity are growing, a proven commitment to economic reforms that improve competitiveness and a supportive policy environment – still persist.

A diverse technology portfolio emerges in India to tackle an array of challenges. India's existing production fleet can be characterised as relatively young, energy-intensive and growing at a faster pace than domestic scrap availability. Furthermore, the country has vast renewable resources and long-held experience in DRI production. These factors lead to multiple options being pursued in the Indian steelmaking context. In the Sustainable Development Scenario innovative CCUS-equipped blast furnace concepts are retrofitted to efficient new blast furnaces that are installed during a period in which few low-carbon alternatives are available. By 2050 this technology family accounts for around 7% of steel production from iron ore. The hydrogen-based DRI route accounts for a further 22%, taking advantage of India's access to low-cost solar PV electricity in particular. The innovative smelting reduction process with CCUS, which negates the need to use coking coal – a resource that is in short supply in India – accounts for a further 26%.

Governments need to help accelerate the transition

A sustainable transition for the iron and steel sector will not come about on its own; governments will play a central role. Policy portfolios will be diverse, but the following recommendations serve as a starting point for those seeking to effect change and accelerate the transition:

- Establish a long-term and increasing signal for CO_2 emission reductions.
- Manage existing assets and near-term investment.
- Create a market for near-zero emissions steel.
- Support the demonstration of near-zero emission steelmaking technologies.
- Accelerate material efficiency.
- Increase international co-operation and ensure a level global playing field.
- Develop supporting infrastructure for near-zero emission technologies.
- Track progress and improve data collection.

The projection horizon of this technology roadmap extends to 2050, but governments and decision makers should have 2030 firmly in mind as the critical window to accelerate the transition. Tangible and measurable target-setting in three short-term priority areas can begin today:

1. **Technology performance and material efficiency.** To ease the burden of deploying innovative technology and enabling infrastructure later on, opportunities must be seized immediately to make more efficient use of energy and materials through a suite of readily-available best available technologies and measures.
2. **Existing assets and new infrastructure.** A plan must be put in place to deal with existing assets that acknowledges the decline in the CO_2 intensity of production required just one investment cycle away. At the same time, a co-ordinated push on new hydrogen and CO_2 transport and storage infrastructure is needed to pave the way for deploying innovative technology.
3. **R&D and demonstration.** Pilot and demonstration projects for innovative near-zero emission technologies over the next decade must be consistent with deployment ambitions post-2030.

The ensuing economic crisis in the wake of the Covid-19 pandemic presents both challenges and opportunities in this regard, but these critical interim milestones are prerequisites for a sustainable transition.

Chapter 1. Steelmaking today

HIGHLIGHTS

- Steel production is highly energy- and emissions-intensive, accounting for around 8% of global energy demand and 7% (2.6 Gt CO2) of total emissions from the energy system. This is more than the amount generated by all road freight today. Its large contribution stems largely from the sector's high reliance on coal, which supplies 74% of its energy inputs.

- Steel is an indispensable material in modern society. Buildings and infrastructure are a key source of demand, but steel is also a critical ingredient for several modes of transport (e.g. cars, trucks, ships and rail), household products (e.g. utensils, appliances and furniture) and many other items besides. It also plays a vital role in the global economy, with over USD 2.5 trillion in revenue and employing around 6 million people globally.

- Steel is a highly traded commodity and is often in the spotlight of trade negotiations. The People's Republic of China accounts for more than half of global steel production today and – despite high domestic demand – it is also the largest exporter, followed by Korea, Japan and the Russian Federation. The steel industry is highly competitive and fragmented. The top 10 producers account for just 25% of global production, which is low compared with other sectors, such as aluminium.

- Steelmaking has two main metallic inputs: iron ore and recycled steel scrap. Around 70% of the total metallic input to steel production globally is derived from iron ore, with scrap making up the rest. Primary steel production refers to operations where iron ore is the main input, but scrap typically accounts for up to 15-25% of the metallic input in primary production. The blast furnace is the major piece of equipment used for primary steelmaking, with this route accounting for 90% of production from iron ore. Secondary (or scrap-based) production is carried out in electric furnaces and is around one-eighth as energy-intensive as production from iron ore, using electricity – as opposed to coal – as the main energy input.

- Energy and raw materials account for 60-80% of steel production costs combined. Energy efficiency improvements in recent decades have led to modest reductions in energy consumption and emissions, but each tonne of steel produced today still results in 1.4 t CO_2 of direct emissions on average.

- Global steel production capacity is relatively young, with blast furnaces only around 13 years old on average, counting the last major refurbishment, relative to a typical lifetime of 40 years. Strategies to deal with existing assets are integral to realising a sustainable transition for the sector.

Steel and society

At around 1.9 billion tonnes of production per year, steel is the third most abundant man-made bulk material on earth, after cement and timber. Its use is ubiquitous, with the material serving as a key input to the buildings, infrastructure, transport, machinery and consumer goods sectors. While other materials provide alternatives to steel in several applications, its high strength, recyclability and durability, the ease with which it can be used to manufacture goods, and its relatively low cost make its wholesale substitution unlikely in the foreseeable future.

The iron and steel sector[1] directly employs around 6 million people and generates around USD 2.5 trillion in revenue globally (World Steel Association, 2019a). The steel industry[2] forms the lifeblood of many local economies, but at the same time steel is one of the most widely traded commodities in the world, with producers competing in an international market. The industry has faced a number of economic headwinds in recent years, including overcapacity, trade tensions and low margins for producers. All of these are likely to be exacerbated in the coming months and years as the economic consequences of the Covid-19 coronavirus pandemic come to pass. The dynamics of the steel industry and our global economic system are therefore thoroughly intertwined.

Steel needs energy and the energy system needs steel. Iron and steel production is a highly energy-intensive industrial activity, with the sector accounting for 20% of industrial final energy consumption[3] and around 8% of total final energy consumption. Steel demand is projected to grow in net terms even as the stock of steel in advanced economies saturates, to support a growing population and rising levels of economic welfare, particularly in emerging economies. Steel is also a critical input for the clean energy transition. The generation and use of electricity depend in part on the ferromagnetic properties of steel and its alloys. Steel is a key input material for wind turbines, transmission and distribution infrastructure, hydropower and nuclear power plants, among other critical energy sector assets.

While being a facilitator of the clean energy transition, steel is also a large contributor to the current challenge we face in meeting our climate goals: direct CO_2 emissions

[1] The "iron and steel sector" corresponds to the IEA Energy Balances "iron and steel" sub-sector's final energy consumption in addition to energy use in blast furnaces and coke ovens in the transformation sector. These categories correspond to classes 2410 and 2431 of the United Nations International Standard Industrial Classification (ISIC) of all economic activities.

[2] The terms "iron and steel sector" and "steel industry" are used in this publication interchangeably.

[3] Throughout, industrial energy use refers to the IEA Energy Balance boundaries of total final consumption by industry, non-energy use for chemical feedstocks, and energy consumed in the transformation sector by blast furnaces and coke ovens.

from the sector are around 2.6 gigatonnes of carbon dioxide (Gt CO_2) per year, or around a quarter of industrial CO_2 emissions, owing to its large dependence on coal and coke as fuels and reduction agents.[4] This is equivalent to about 7% of total emissions from the energy system, when including industrial process emissions. A further 1.1 Gt CO_2 of emissions are attributable to the use of its off-gases,[5] along with other fuels, to generate the electricity and imported heat it consumes.

It is hard to imagine the modern built environment without steel. Consider your immediate surroundings – the building you are in, the mode of transport you used to get there, the utensils, appliances and furniture you are using to provide you and those around you with sustenance, hygiene and comfort – it is likely that at least one of these components of modern life relies heavily on steel. For those regions of the world where these material services are in short supply, steel demand is set to grow. Beyond the essential, many of the defining artefacts of modern civilisation are constructed from steel, or its base metal, iron: the Eiffel Tower, the Golden Gate Bridge, the London Eye and the countless skyscrapers that form the iconic skylines of the world's major cities. Steel is ubiquitous.

While steel plays a prominent role in the foreground of our daily lives, it also plays a role that is perhaps even more important behind the scenes. Our water and sanitation infrastructure is highly dependent on steel, as is the energy system. From oil and gas drilling platforms and transmission equipment to the foundations and generators in wind turbines and dams, both dominant and emerging energy technologies would be nowhere without steel. Understanding steel and its role in society is a good starting point for examining any possible future of the steel industry. This sub-section provides an overview of the attributes and origins of steel as a material, and the common ways in which it is produced today.

An indispensable alloy

"Iron" denotes the chemical element in its pure form, but also carbon-saturated intermediate (e.g. "pig iron") and final (e.g. "cast iron") products in the iron and steel sector. "Steel" denotes an alloy of iron and carbon, of which "carbon steel" is the simplest and most common variety. Many other elements are added to form more complex steel alloys, augmenting or diminishing certain physical properties for a

[4] Throughout, "direct industrial emissions" or just "industrial emissions" refers to CO_2 emissions from fossil fuel combustion within the "industrial energy use" boundary described above, along with CO_2 emissions from industrial processes within these sub-sectors. Emissions from non-renewable waste, indirect emissions from electricity generation and process emissions from fuel transformation are not included within this definition. See Box 1.3 for a detailed explanation of the energy and emissions boundaries used in this analysis.

[5] "Off-gases" refers collectively to blast furnace gas, coke oven gas and other energy-containing gases that arise from various processes within the steel industry.

given application. Chromium or nickel are added to form "stainless steel", known for its ability to withstand corrosion, commonly being used for kitchenware. Molybdenum, vanadium, manganese, tungsten and titanium are further examples of alloying elements used to garner or enhance a variety of desirable properties. There are around 3 500 different grades of steel in use today, many of which have been developed in the past 20 years (World Steel Association, 2018a).

Small adjustments to the amount of carbon contained in steel can have a marked impact on its properties. While steel can contain up to around 2% carbon by weight, this is quite rare, with the majority of carbon steels containing less than 0.25% carbon. Raising the carbon content of steel has the impact of increasing its hardness (this can be thought of as the ability to scratch it), but also its brittleness (this can be thought of as the tendency for the material to fracture, rather than bend, when under stress). High-carbon steels are typically used for applications where resistance to abrasion is required – an important example is the steel used to make tools. The property of steel that is more commonly sought is ductility – the opposite property of brittleness. The ability of steel to deform both elastically (whereby the original shape is returned to instantaneously) and plastically (whereby the shape is permanently altered), without breaking, makes it the natural choice for many structural applications, such as beams and columns for buildings, and chassis for vehicles.

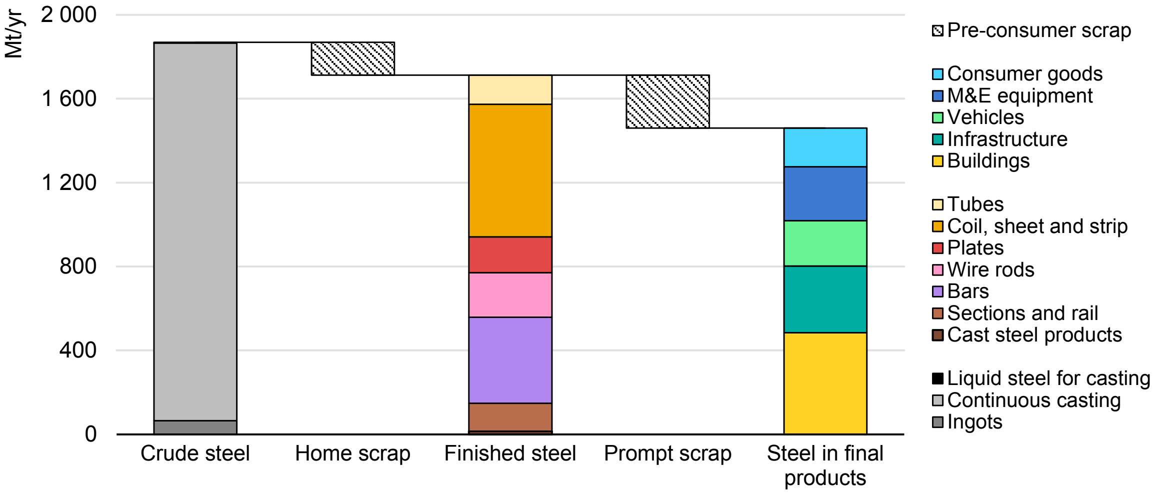
While steel is used as the primary material in many applications, it is also paired with a wide variety of other "partner" materials and coatings. Reinforced concrete is an important example in the buildings and infrastructure demand segments. Steel has high tensile (pulling) strength. Concrete has low tensile strength, but relatively high compressive (pushing) strength. Concrete reinforced with steel, either in a prefabricated element, or cast in situ on a building site, is a ubiquitous composite engineering material used for foundations, floor slabs and shear walls. One potential weakness of steel as a material is its tendency to corrode, particularly in the presence of moisture and oxygen. To avoid this, steel can be coated with protective paint or bathed in molten zinc (a process called galvanising) so that it can be used in applications where exposure is unavoidable, such as the hulls of ships or the shafts of wind turbines. Steel also loses its strength when heated to very high temperatures. In structural applications steel can be coated with a protective layer of another material (such as plasterboard or intumescent paint), or oversized to allow for a degree of lost strength in a fire.

By and large, people do not want steel *per se;* they want the material services steel as a material provides. Steel has a very high strength-to-weight ratio, and a relatively low cost compared to other bulk materials with comparable properties. In the period since 2018, steel prices have been approximately in the range of USD 550-800 per tonne, compared with USD 1 700-2 000 per tonne for aluminium, and USD 5 500-7 000 per tonne for copper. "Strength" has various engineering measures, and it is impossible to simplify the material selection process for a given application or specification down to a single number. Nonetheless, one can observe that steel is often the winner when it comes to choosing a material where strength, weight and cost are the key design criteria, especially in the automotive and construction sectors.

There are notable exceptions though. The availability of large volumes of plastic, particularly since the middle of the 20th century, has led to the displacement of steel used in the packaging sector, and plastics are increasingly substituting steel in certain components of buildings (e.g. pipes and fittings) and cars (e.g. bumpers and external body panels). Because plastic can be extruded and moulded into complex geometries, a smaller amount can be used for certain applications, and it is highly resistant to corrosion and degradation. Composites, such as glass and carbon fibre-reinforced resins, are increasingly the materials of choice where weight reductions are critical, and ductility and cost are less of a concern. Aluminium has long been the material of choice for aircraft – and increasingly many high-performance vehicles – for the same reasons. Timber, for low-rise buildings especially, continues to be the material of choice in many regions where it is available at low cost and local environmental conditions permit, whereas steel and concrete are dominant in high-rise and commercial buildings.

For steel to be so widely used and versatile as a material, it has to be produced in a variety of forms (Figure 1.1). "Crude steel" is the name given to steel in its first solid form, when it is cast after leaving the final furnace in a given production process. While it is possible for steel to be cast directly into its final shape, this process is only used for specialised products that would be technically challenging or more costly to fabricate from off-the-shelf steel products. Liquid steel is most commonly continuously cast into slabs (flat, thick panels), billets (long rectangular beams, up to 155 millimetres [mm] by 155 mm), and blooms (long rectangular beams, greater than 155 mm by 155 mm). Much less commonly, liquid steel is cast into ingots, which are later rolled into semi-finished or finished products. These semi-finished products may be transported to other sites for further processing, or converted to finished steel products in processing plants, often in a separate facility or company. Conversion to finished products can involve various processes such as rolling, forming, pressing, cutting and bending, with some finished products requiring more steps than others (for example, successive rounds of rolling – hot and cold – and coating). Key finished products include coil, sheets, strips, wire, bars, rods, tubes, pipes, rail and plated/coated versions of each of these products.

Figure 1.1 Global steel production by product and demand segment in 2019



Notes: Mt = megatonne. Total crude steel quantity is from World Steel Association (2020b). Shares of crude steel products are an estimate based on reported 2017 values from World Steel Association (2018a). Continuous casting is continuously cast semi-finished products, which include billets, blooms and slabs. Finished steel and end-use steel are IEA estimates, which draw on data from Cullen, Allwood and Bambach (2012), Pauliuk and Müller (2013) and World Steel Association (2018a). "M&E equipment" includes mechanical and electrical equipment. "Consumer goods" includes metals goods, appliances and packaging.

Buildings and infrastructure account for around half of total steel demand, which is brought to market in many different forms for its final processing and assembling.

Steel and the global economy

Steel is one of the most widely traded commodities in the world, and it forms the lifeblood of many local economies. Steel production is a multi-trillion-dollar industry and employs millions of people across the globe. The Covid-19 pandemic (Box 1.1) threatens to interrupt the sector's strong growth trajectory over the past two decades, but other structural issues, including overcapacity, trade tensions and low margins were already hampering progress. The dynamics of the steel industry and our global economic system are thoroughly intertwined.

Box 1.1 Uncertainty in the short-term outlook for the steel sector: Covid-19

A multitude of factors contribute to uncertainty in the global outlook for the steel industry, affecting forecasters' ability to anticipate prices, future levels of demand, employment and many other aspects. Many of these factors are persistent, such as uncertainty about the future rate of growth in the global economy, or the levels of consumer demand in a given downstream market. But the current levels of uncertainty for the short-term outlook for the sector, like all other sectors of the economy, may well be unprecedented, largely relating to the unknown future impacts of the Covid-19 coronavirus pandemic.

The first outbreak of the Covid-19 disease stemming from the most recently discovered strain of coronavirus was registered in Wuhan, the People's Republic of China ("China"), in December 2019 (WHO, 2020). The outbreak triggered a series of confinement procedures in the country, and several downstream industries (construction, automotive etc.) have seen reductions in output. However, China's crude steel output has remained robust, with a 2.2% year-on-year increase to 503 Mt per year in the first half of 2020 (World Steel Association, 2020a). Stagnating and declining demand levels in its domestic and export markets indicate a significant accumulation of inventory during this period of strong production growth.

In production centres elsewhere the virus has had a much more profound impact on production levels. In the first half of 2020 steel production in Europe declined by 13% relative to the same period in 2019, by 17% in North America and 24% in India. Some of these regions are likely to experience a permanent reduction in output, as they did in the wake of the global financial crisis when individual plants become no longer viable. Stimulus packages being announced across the world, and which sectors they target, will be critical in determining the impact of the disease on steel demand by year end 2020.

The longer-term impacts of the virus outbreak are even more uncertain. The way that other countries besides China respond to the outbreak, in terms of the duration and extent of confinement policies, and the level to which demand in various economies is restored – including the extent to which stimulus packages are aimed at infrastructure and other steel-intensive sectors – are the key determining factors that will affect the steel industry's outlook in the coming years.

A number of macroeconomic factors influence the global and regional dynamics of steel production. Among the most important are economic development, trade and competitiveness, all of which are interlinked. Steel is used in a number of sectors that are closely tied to overall economic activity – the steel industry is both a reflection of, and contributor to, global economic growth. When the global economy is buoyant, people buy houses and cars, governments build more infrastructure and the private sector invests in commercial buildings and machinery. While the regional dynamics are more nuanced, the relationship between steel demand and economic activity at the global level are closely related.

Steel is produced all over the world and around 25% of its annual production volume is traded between nations each year (World Steel Association, 2020b). Because steel is a key input material for several high-value and strategic industries (e.g. automotive, defence), it is often in the spotlight during trade negotiations. Along with aluminium, steel has been at the centre of recent trade negotiations between the United States and China, with tariffs of 25% being placed on imports to the United States (White House, 2018). In a matter separate from trade negotiations, the European Union has also put in place anti-dumping measures in the form of import tariffs of up to 66% on certain products, specifically targeting Chinese producers (Bloomberg, 2019).

In part because of the global market for steel, and the great extent to which it is traded, the steel industry is highly competitive (Box 1.2). As with many bulk commodity businesses, in the absence of monopolies, margins tend to be low. Net pre-tax margins tend to be in the range of 5-10% in good years, and negative in bad ones. The most recent five-year period can be characterised as one of low prices and low margins, in part explained by overcapacity. China accounts for around half of the world's steel production capacity. Despite China's efforts to close down outdated and inefficient iron and steelmaking capacity by tens of millions of tonnes in recent years, including the closure of dozens of illegal induction furnaces, new investments are still underway. Hence the world remains in a position whereby the potential output of the global production fleet outstrips demand by almost 25% (OECD Steel Committee, 2019a, 2019b).

The steel industry employs around 6 million people worldwide and is the source of an estimated further 43 million additional jobs in other sectors (World Steel Association, 2018a). Assuming a global labour pool of 3 billion people, the industry indirectly accounts for more than one in every hundred jobs across all sectors of the global economy. At the local level, the steel industry is often a principal source of employment and community pride in towns and cities where steel plants are located. Plant closures make headlines, whether it be in China or the United Kingdom, mainly because of employment concerns, rather than those associated with the profitability of specific firms.

Box 1.2 The competitive landscape faced by steel producers

The competitiveness of the global steel industry has come a long way since the titanic monopolies of the 20th century. At its zenith, Andrew Carnegie's United States Steel Corporation, which he sold to J. P. Morgan in 1901, making him one of the richest people to have ever lived, controlled around 60% of steel production in the United States (Boselovic, 2001). August Thyssen-Hütte AG, Krupp (Germany), Nippon Steel (Japan), British Steel Corporation (United Kingdom) and Usinor (France) at various points in the 20th century controlled upwards of 30% of their national output capacities. While several national champions (such as Nucor, Nippon Steel, POSCO and thyssenkrupp) hold similar shares today, steel is now the archetypical global marketplace, making national market shares less relevant.

Top steel producers and estimated market share in 2019

Rank	Company	HQ	2019 output (Mt)	Share of global output (%)
1	ArcelorMittal	Luxembourg	97.3	5.2%
2	China Baowu Group	China	95.5	5.1%
3	Nippon Steel Corporation	Japan	51.68	2.8%
4	HBIS Group	China	46.6	2.5%
5	POSCO	Korea	43.1	2.3%
6	Shagang Group	China	41.1	2.2%
7	Ansteel	China	39.2	2.1%
8	Jianlong Group	China	31.2	1.7%
9	Tata Steel Group	India	30.2	1.6%
10	Shougang Group	China	29.3	1.6%
Top 10	-	-	505	27%
Top 25	-	-	785	42%
Top 50	-	-	1 049	56%
Total	-	-	1 869	100%

Source: World Steel Association (2020c), *Top Steelmakers in 2019*.

The degree of consolidation in a given marketplace cannot be seen as the only measure of competitiveness, but it is an important indicator. In 2019 the World Steel Association recorded 104 steel producers with an output of more than 3 Mt per year (0.2% of global production). The top 10 companies account for just over a quarter of global output, with the top 25 and top 50 accounting for 42% and 56% respectively. This reflects a highly competitive marketplace, especially given the extent to which steel is traded. While the degree of consolidation in the industry has not changed much over the past half-century, gone are the days when a regional producer can expect to have unfettered access to a regional marketplace – contracts with international players can be signed in minutes.

It is difficult to compare the degree of consolidation of one market with respect to another because of different definitions of output and market sizes. Few industries produce a single physical output (albeit with differing grades and product types) that is as directly comparable between market participants as the steel industry. However, two familiar markets provide some contrasting context. The output of the top ten aluminium producers accounts for about half of global primary aluminium production (Rusal, 2019). In the energy sector, seven major international oil companies account for around 15% of global oil production, but Saudi Aramco, the world's largest producer, accounts for almost 10% on its own (Umar, 2019). By the standards of these industries and also those of many of its upstream suppliers and downstream markets, the iron and steel sector can be seen to be much less consolidated.

Steel production fundamentals

The first iron and steel artefacts are thought to date back more than 5 000 years, but it was not until the industrial revolution gathered pace in the 18th and 19th centuries that steel was able to be produced at a reasonable cost and on a large scale. Henry Bessemer patented the first cost-effective industrial steelmaking process in England in 1855, with Charles Hall doing so for aluminium in Ohio in 1886. Since its inception, nearly every part of the process of steelmaking has undergone significant technological advance, with the primary aim being to reduce yield losses and energy consumption, thereby making the process more efficient and cheaper to operate. Despite this evolution, many of the process fundamentals remain relevant today.

The primary factors in determining the cost of producing steel are the production route and the costs of the main input materials (iron ore, scrap and energy). The cost of producing steel, the size of domestic or nearby markets and government policy (including environmental policies and industrial strategy) are in turn the key determinants of the regional distribution of steel production around the globe. This section provides an overview of the main production pathways, an overview of the main cost considerations and a detailed look at where steel is produced and consumed today.

Main production pathways

The principal inputs to steelmaking today are iron ore, energy (mainly coal, natural gas and electricity), limestone and steel scrap. Iron ore and scrap are used to provide the metallic charge, with scrap having a significantly higher metallic concentration (>95%) than iron ore (typically in the range of 50-70%). Metallic input of 1.05-1.2 tonnes is required per tonne of steel. Energy inputs are used to provide heat to melt the metallic input, and in the case of iron ore, to chemically reduce it (remove oxygen) from its naturally occurring states found in the earth's crust.[6] "Primary" steel production refers to that which uses iron ore as its main source of metallic input, whereas "secondary" production is that based on scrap (Figure 1.2). However, in many instances this distinction can become less clear-cut, as scrap is often used in primary production, and iron is commonly used in electric furnaces, which are the typical unit for secondary production. Consequently, when describing the situation

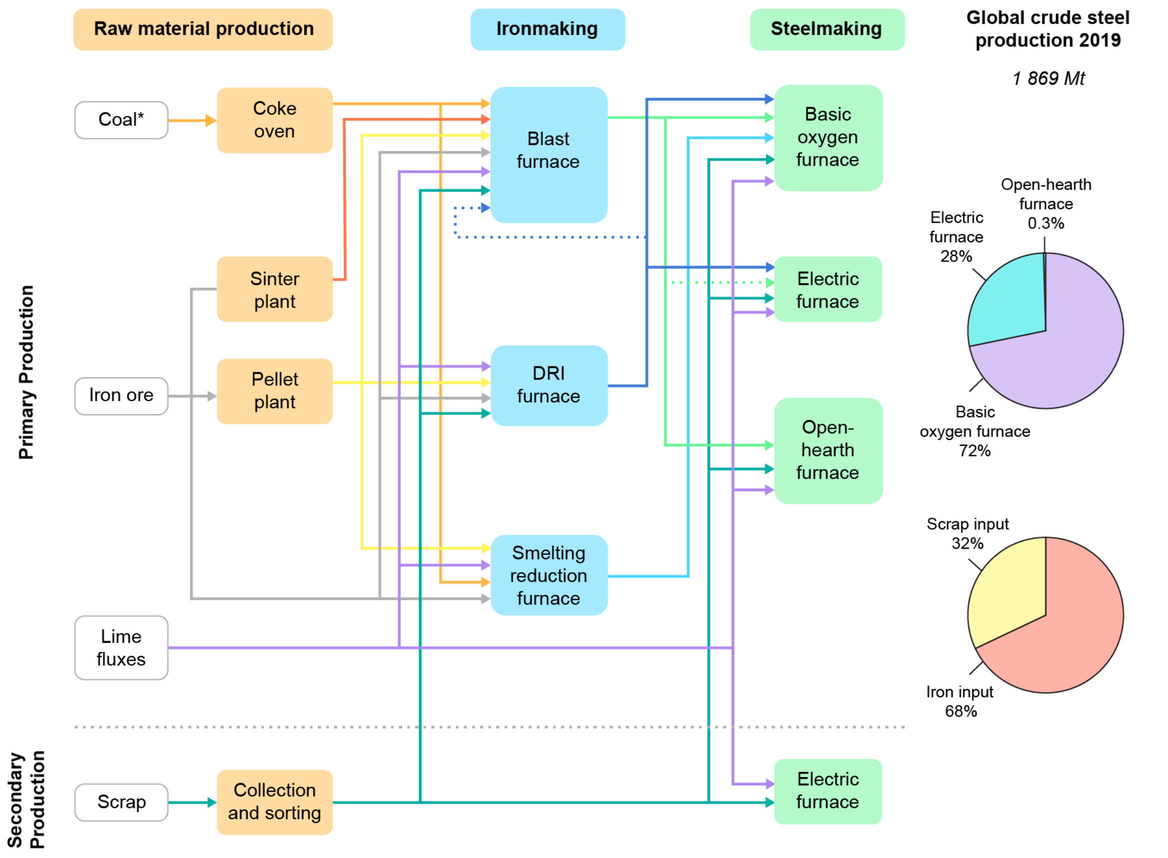
[6] Key iron ore constituents include: magnetite, Fe_3O_4, 72.4% iron content; haematite, Fe_2O_3, 69.9% iron content; goethite, $FeO(OH)$, 62.9% iron content; limonite, $FeO(OH)\cdot n(H_2O)$, 55% iron content; siderite, $FeCO_3$, 48.2% iron content.

in a given region or portfolio, it is instructive to quote the share of scrap in total metallic inputs alongside the shares of primary and secondary production.

Carbon monoxide and hydrogen are the reducing agents that help cleave the oxygen from these iron ore molecules. Virtually all of the carbon monoxide and hydrogen used to reduce iron ore today are generated from fossil fuel energy inputs, mainly coal and its derivative coke (and to a much lesser extent natural gas). Lime fluxes, such as limestone and dolomite, are used at various stages of the steelmaking process to help remove impurities such as sulphur, phosphorus and silica. The production and use of lime fluxes leads to industrial process CO_2 emissions, and when chemically combined with the non-iron content of the iron ore they form a steelmaking co-product called slag.

The production of 1 tonne of steel results in around 400 kilogrammes (kg) of slag, around 125 kg of which stems from the basic oxygen furnace and the rest from the blast furnace (World Steel Association, 2018b). Slag is also produced in electric furnaces fed by scrap, but at around half the rate and with a different chemical composition. Unless slag can be put to use elsewhere, it has to be stored or disposed of, but this is costly and can create a safety hazard. Fortunately, iron- and steelmaking slags can be used as substitutes for virgin materials in several industrial applications, including the fertiliser, construction and bulk material industries. Blast furnace slag in particular forms a vital input to the cement industry, where it can be used as a substitute for clinker (the active ingredient in cement, and its most emissions-intensive component) (IEA, 2018). Slag and other clinker substitutes are typically used to form shares of up to 40-50% by weight in the final cement product, leading to a near-halving in the emission intensity of production in the cement sector. Because the availability of slag is limited, the share of slag used in cement production globally is much lower.

Figure 1.2 Main steel production pathways and material flows in 2019



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

Notes: DRI = direct reduced iron, EAF = electric arc furnace. In some regions (particularly the United States), the DRI-EAF route has a high ratio of scrap to DRI inputs, but is still categorised as primary production in this publication. Iron ore includes concentrate, lump and fines. Electric furnace includes both EAFs and induction furnaces. DRI input into blast furnace and blast furnace input into EAFs are less common (dashed lines).

Source: Crude steel production quantities based on World Steel Association (2020b), *World Steel in Figures 2020*.

More than 80% of crude steel is produced via primary routes using mostly iron ore along with some scrap. The remainder is produced via recycled scrap.

The primary production of crude steel has three key phases: raw material preparation, ironmaking and steelmaking (Figure 1.2). After mining and beneficiation, the iron ore inputs need to be processed before they are used in the ironmaking step. Unprocessed iron ore is found in a mixture of fines and lumps, with highly concentrated forms of the latter being rarer and typically more expensive, as it can be directly used without further processing. Iron ore fines need to be agglomerated, either by producing sinter or pellets. Agglomeration processes use heat and pressure to form nodules (sinter) and pebble-sized particles (pellets), which when stacked in a furnace allow gases to flow through and around them. Depending on the iron content of the ore and the pellet or sinter quality, these processes consume varying quantities of coal, coke, natural gas and electricity, but typically in the range of 1-3 gigajoule (GJ) per tonne of pellets or sinter. The quality of raw materials used has a significant impact on the energy and emission intensities of the subsequent process of steelmaking.

Coke is another input that requires an intermediate step of transformation. Coking coal (a specific grade of hard coal with elevated carbon content) is heated to around 1 100°C in a coke oven in the absence of air to remove its volatile components, resulting in coke, a mostly carbon-based substance with high compressive strength. Scrap also requires some degree of preparation before it is used in steelmaking (and less commonly in ironmaking), depending on where it was sourced (see Box 2.2). Post-consumer scrap (as opposed to that generated in mostly pure forms within a production site or manufacturing operation) must be separated from other materials, which is typically done with the help of magnets. Copper is a persistent contaminant. It can be difficult to separate from steel at a reasonable cost, as it is often wrapped tightly around steel in several end-use applications (e.g. alternators, generators, motors). Improved scrap sorting and better separation techniques to reduce contamination by trace metals like copper will be important to ensure the majority of steel grades can be produced via the secondary route. This may increase sorting costs (Daehn, Serrenho and Allwood, 2017).

Whereas many – comparatively small – steel plants around the world exclusively employ the secondary route for production (i.e. purely scrap-based), primary production facilities can use up to around 15-25% scrap alongside iron ore. While iron ore is mined all over the world (it is one of the most abundant elements on earth), scrap availability is limited by the rate at which steel products reach the end of their life and the effectiveness of scrap collection and sorting systems. Around 700 Mt per year of scrap is consumed each year for steel production (compared with a total crude steel production volume of 1 869 Mt per year), with comparable amounts of scrap used in the primary and secondary routes.

Once scrap is collected and sorted, the secondary production route mainly requires electricity to melt the steel in an electric furnace, often along with a small amount of natural gas or coal to form a protective slag foam. Highly conductive graphite electrodes are also consumed during the process of heating the scrap metal to temperatures of up to 1 800°C. Electric arc furnaces (EAFs) are the most commonly used furnace for scrap-based production, but typically less energy-efficient induction furnaces are also used, particularly in India and China. Producing one tonne of steel via the scrap-based route requires around 2 GJ of final energy per tonne of crude steel.

The primary production pathway is more complex than the secondary route, comprising multiple different process arrangements. The most common primary production pathway is the blast furnace-basic oxygen furnace (BF-BOF) route, which accounts for around 70% of global steel production and around 90% of primary production. Coke and iron ore are both fed into the blast furnace from the top; simultaneously, hot air and pulverised coal or natural gas (and in an experimental site in Germany also hydrogen) are injected through pipes in the side of the lower part of the furnace called *tuyeres*. This results in a counter-cyclical process of descending iron ore met by rising reducing gases. Producing one tonne of liquid steel via the BF-BOF route requires around 15 GJ of final energy input (see Box 1.3 for an explanation of the analytical boundaries used in this analysis). Lime fluxes and other additives are also used in the blast furnace in varying quantities to control the level of impurities and the temperature. The blast furnace produces molten iron ("hot metal") at temperatures up to 1 400-1 500°C. The hot metal is then fed to the BOF, often in conjunction with some scrap, where oxygen is injected to lower the carbon content from approximately 4-5% to the required level of carbon for the steel grade produced (typically around 0.25%).

The other main method of primary steel production is the direct reduced iron-electric arc furnace (DRI-EAF) route. The principal differences between this route and the BF-BOF route are:

- The type of iron ore that is typically used – high-quality DRI pellets are used in the DRI-EAF route, whereas the BF-BOF route has the flexibility to use iron ore with more impurities, and a combination of pellets, fines, sinter and lump ore.
- The state of the material when it is reduced – the iron ore is reduced in a solid state in the DRI furnace (as opposed to the liquid phase in the blast furnace), before being melted in the EAF, often in conjunction with some scrap.
- The main reduction agents – they are carbon and carbon monoxide in the BF-BOF route, while hydrogen and carbon monoxide play more balanced roles in the DRI-EAF pathway.
- The balance of energy inputs – DRI-EAF facilities today mainly use natural gas to generate the reducing syngas (carbon monoxide and hydrogen), but can also use coal, while BF-BOF producers mainly use coke and coal, with natural gas injection being less common.
- The final energy requirement – producing one tonne of steel via the DRI-EAF route requires between 18 GJ and 30 GJ of final energy, with natural gas-based production generally being more efficient than coal-based gasification arrangements, while BF-BOF requires around 15 GJ of final energy.

The main BF-BOF and EAF (both DRI-EAF and scrap-based EAF) routes combined account for 95% of global steel production. Three other process units are also in use today, but see very limited penetration. Smelting reduction is an alternative class of processes for ironmaking that facilitates the use of iron ore fines directly (rather than agglomerated pellets and sinter) and avoids the use of a coke oven or coking coal. Several designs are currently commercially available or under development, but the process is yet to see widespread adoption within the industry. The open-hearth furnace is an outdated alternative to the BOF, and has largely been phased out given its inferior energy performance. Production of steel using induction furnaces has been increasing in recent years, despite the closure of illegal units in China (OECD Steel Committee, 2020). Those furnaces are generally smaller than electric arc furnaces, often used to produce special alloys.

Cost considerations

The cost of producing steel is highly dependent on the cost of the main inputs to the production processes, particularly the cost of iron ore, scrap and energy inputs. Using the simplified levelised cost metric as a proxy for the cost of producing one tonne of steel, these raw material and energy inputs typically account for 60-80% of the total (Figure 1.3). The annualised cost of capital expenditure (CAPEX) and the fixed operational expenditure (OPEX)[7] account for the remainder.

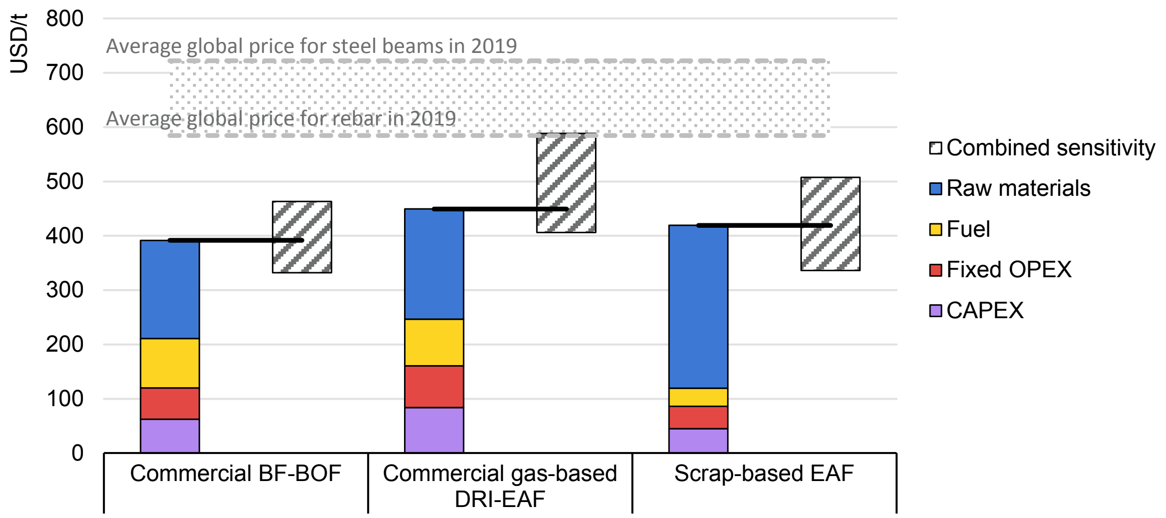
The prices of the main metallic raw material inputs – iron ore and scrap – strongly influence the final production cost of crude steel. Scrap tends to be more expensive than iron ore, reflecting the lower conversion cost (excluding input materials) to produce steel. Iron ore prices are governed by a more straightforward set of supply and demand dynamics. The cost of producing iron ore, which is mined on a large scale in Australia, Brazil, the Russian Federation (“Russia”), China and India, is primarily dictated by its iron concentration, local labour costs and capital costs. The demand for iron ore is dictated by the demand for steel, and when the supply of iron ore is high relative to the level of demand of steel, iron ore prices tend to be lower, and vice versa. Prices of iron ore fines in 2019 averaged around USD 90 per tonne, whereas just 4-5 years earlier they were around half this level (Index Mundi, 2020). Like steel, iron ore is also widely traded.

As discussed in the previous section, scrap availability is finite and predetermined, but there is still a cost curve associated with its collection, sorting and ultimate provision. Two key dynamics govern this cost curve. At higher absolute scrap prices, more scrap becomes available as higher separation and sorting rates become economic. A study of the US market suggests a step change in the elasticity of scrap supply once prices

[7] The fixed OPEX boundary used in this analysis includes maintenance, replacement parts and the associated engineering, procurement and construction. Variable OPEX, such as the labour required for operating the plant, is not included. Energy costs are accounted for separately.

exceed the historically high value of USD 250-300, with considerably more scrap becoming available, reflecting the additional incentive required to motivate higher recovery rates (McKinsey, 2017). The price at which this incentive has an impact will vary across regions depending on overall availability, labour costs etc. In tandem, the price of scrap relative to that of iron ore also governs its demand level. Scrap demand is higher when its price relative to the cost of iron ore is low.

Figure 1.3 Simplified levelised cost of steel production via major commercial routes



Notes: Annualised CAPEX: USD 52-94/tonne (t) crude steel for BF-BOF, USD 53-136/t crude steel for DRI-EAF, USD 34-58/t crude steel for scrap-based EAF. CAPEX includes engineering, procurement and construction costs. 8% discount rate, 25-year lifetime and a 90% capacity factor are used for all equipment. OPEX: USD 48-87/t crude steel for BF-BOF, USD 48-125/t crude steel for DRI-EAF, USD 31-54/t crude steel for scrap-based EAF. Energy prices: Natural gas = USD 2-10/million British thermal units, thermal coal = USD 35-80/tonne of coal equivalent (tce), coking coal = USD 75-155/tce, and electricity = USD 30-90/megawatt hour (MWh). Scrap = USD 200-300/t. Iron ore = USD 60-100/t.
Source: World Steel Prices (2020), *2019 Beams and Rebar Prices*.

The cost of producing steel is highly sensitive to raw material and energy costs, which typically account for 60-80% of the cost of production.

The primary production pathways (BF-BOF and DRI-EAF) consume around eight times as much final energy as the secondary route, so are much more sensitive to energy prices. While the primary production routes consume large amounts of coal and natural gas (and electricity and heat generated from their off-gases), the scrap-based EAF pathway mainly uses electricity imported from the grid. Electricity and natural gas prices are subject to much wider regional variation, hence the larger contribution of energy to overall cost sensitivity in the DRI-EAF and scrap-based EAF routes.

CAPEX and fixed OPEX tend to be fairly consistent across countries when only considering production equipment. For a given production route, there is little variation in the individual pieces of equipment available in each region, with each producer tailoring the size and arrangement of the steel mill to suit local circumstances (e.g. grades of steel required, land availability). However, when considering engineering, procurement and construction costs, as well as ongoing variable OPEX (e.g. plant operators), there is significant variation between regions.

Regional supply and demand

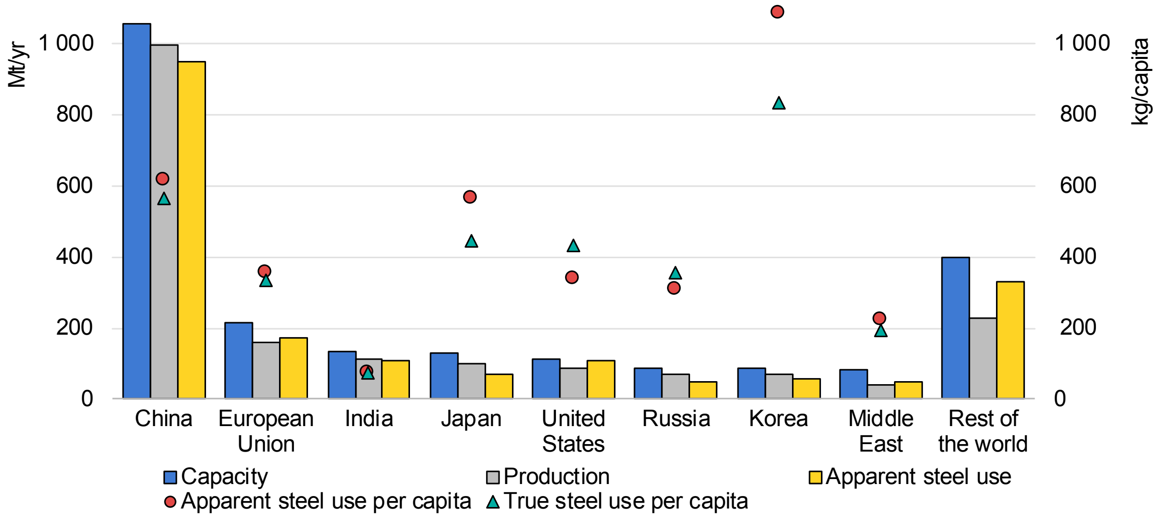
Increases in global economic activity or gross domestic product (GDP) go hand in hand with increases in global steel demand. Since the millennium global GDP and steel demand have both roughly doubled.[8] However, this relationship does not hold at the regional level. In 2015 steel demand decreased by 5% in China, despite robust economic growth of 7%. In the United States steel demand has hitherto failed to eclipse its 1973 peak of 150 Mt, despite the economy expanding more than threefold since then. The correlation between GDP and steel demand is rather complex, impacted by factors including industrial structure, level of economic development, level of investment in a given period (including government stimulus projects) and cycles of infrastructure renewal.

More robust regional trends can be seen when examining "stocks" of steel products in society, that is, steel stored in goods, buildings and infrastructure. While countries are in the early stages of development, their steel demand tends to rise rapidly to meet evolving infrastructure needs and growing consumer demand. Annual demand may rise and fall, but during this development phase the stock of steel in society tends to increase markedly until it reaches a level of 8-16 tonnes per capita (Pauliuk and Müller, 2013). At this level, the stock of steel in advanced economies tends to saturate, with future steel demand being required only to maintain and replace the existing stock, and perhaps to a lesser extent to meet needs for new technologies (e.g. wind turbines).

Conversely, when economic growth slows or declines, the demand for steel tends to follow the same trend. During the 2008 financial crisis global economic growth contracted, falling to 2.9% GDP growth in 2008 and a 0.4% decline in 2009 compared to robust average growth of 5.0% in the previous five years. Global steel demand fell by 8% in 2009, although it recovered quite quickly with 15% growth in 2010, returning demand to a level higher than that of 2008. Following a period of relatively flat demand from 2014 to 2016, steel demand saw robust growth of 3-7% during the years 2017-19. This prevailing economic context, together with the impacts of the recent Covid-19 pandemic, has made for a turbulent few years and an uncertain short-term outlook for the industry (Box 1.1).

[8] Steel demand values in this sub-section "Regional supply and demand" refer to apparent steel use, on a crude steel basis.

Figure 1.4 Regional crude steel production and demand in 2019*



*Data on capacity, production, and apparent steel use are provided for 2019. Data on apparent steel use per capita and true steel use per capita are provided for 2018, for comparability purposes since data on true steel use are not yet available for 2019. India and Middle East true steel use per capita are estimates based on 2017 data as disaggregated 2018 data for these individual regions are not available.

Notes: All data are shown in terms of crude steel equivalent. Apparent use includes trade of intermediate steel (semi-finished and finished steel products), while true steel use also includes indirect trade of steel-containing goods. For further discussion of regional variation in steel demand and production, please see the Chapter 2 section "The outlook for demand and production".

Sources: World Steel Association (2020b), *World Steel in Figures 2020*; World Steel Association (2019b), *Steel Statistical Yearbook 2019*; OECD Steel Committee (2019b), *OECD Steelmaking Capacity Database*.

In 2019 China accounted for about half of steel production and consumption. Other leading producers include the European Union, India, the United States and Japan.

China is currently the largest steel producer, accounting for more than half of global production in 2019, followed by the European Union (9%),[9] India (6%), Japan (5%), the United States (5%), Russia (4%) and Korea (4%) (Figure 1.4). Today's regional distribution of production looks considerably different from 20 to 30 years ago. In 1990 global steel production was only 41% of the current level (770 Mt in 1990 compared to 1 869 Mt in 2019), with the top producers being today's members of the European Union (26% of global production), the Union of Soviet Socialist Republics (20%), Japan (14%), the United States (12%) and China (9%). In the following decade global production grew 10% to reach 850 Mt in 2000, with the European Union remaining the top producer (25%), followed by China (17%), Japan (14%), the United States (13%), Russia (8%) and Korea (6%). Since 2000 global steel production

[9] Figures for the European Union in this publication include the United Kingdom, which left the union on 31 January 2020.

has grown by 120%, driven in large part by soaring production levels in China as a result of rapid domestic economic development and industrialisation.

While in many cases a country's production level aligns relatively closely with its levels of domestic demand, steel is a highly traded commodity, with one country's surplus production serving another's need to import. Given the diversity of steel grades produced and needed, it can also be the case that a country has both a high export and import share for steel production and demand, respectively. Since steel is traded both as an intermediate product (e.g. steel plate) and embedded in steel-containing end-use goods (e.g. vehicles), demand and end-use quantities can be calculated in various ways. "Apparent steel use" is equivalent to crude steel production plus imports less exports of both crude steel and intermediate steel products (i.e. semi-finished and finished steel products). Apparent steel use therefore represents steel use by next-tier manufacturers, such as vehicle makers, fabricators and construction companies, some of whose products may be destined for export.

"True steel use" incorporates to some degree the indirect trade of steel in steel-containing products, thus aiming to represent steel use by final consumers (World Steel Association, 2012). Estimating true steel use is challenging, given that it requires an estimation of steel contained in a multitude of end-use products, including items as diverse as household appliances and industrial equipment. It may thus be imprecise. Nonetheless, this measure can help provide a better representation of actual steel use by final consumers rather than the quantity demanded by intermediate industries.

In 2019, 25% of global steel production was traded as intermediate steel products (finished and semi-finished steel products), with the remainder being used by next-tier manufacturers in the country in which it was produced (World Steel Association, 2020b). After steel is used in a variety of manufacturing sectors and processes, another round of steel trade takes place. Figures for the trade in volumes of steel contained in goods are much more uncertain; the most recent estimate for 2018 suggests that 22% of this steel is exported. The remaining 78% of the steel contained in goods is used in the countries where the goods are produced.

China, as the leading global producer, has been a net steel exporter in recent years. However, much of its production is used domestically – around 95% of production in 2018 was used by next-tier manufacturers, that is domestic manufacturers and in construction (apparent steel use), and about 85% of steel was used domestically by final consumers (true steel use) (Table 1.1). Other net exporters include Russia, Japan, Korea, and India, while net importers include the Middle East, the United States and the European Union.[10] Many countries with smaller steel industries are net importers from the major exporting countries. Some small producers are net exporters, but export relatively small quantities compared with global trade volumes.

Table 1.1 Steel trade by major steel producers and users (2018)

Country	Net exporter or importer	Net exports as % of production		Net imports as % of use	
		Apparent steel use basis	*True steel use basis*	*Apparent steel use basis*	*True steel use basis*
China	Exporter	5%	14%	-	-
India	Exporter	4%	5%		
Japan	Exporter	32%	46%		
Korea	Exporter	23%	41%	-	-
Russia	Exporter	38%	29%	-	-
European Union	Importer	-	-	9%	3%
Middle East	Importer	-	-	26%	16%
United States	Importer	-	-	23%	44%

Notes: "Apparent steel use" and "True steel use" are considered in terms of crude steel equivalent. 2018 data are used for comparability, as 2019 data for true use are not yet available. India and Middle East true steel use are estimates based on 2017 data as disaggregated 2018 data for these individual regions are not yet available.

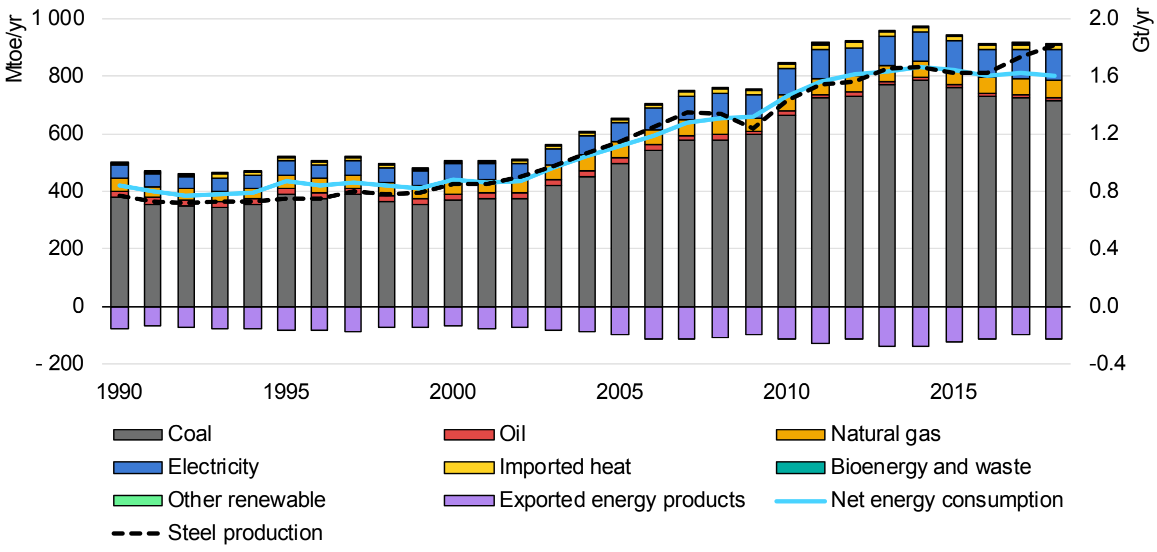
Source: World Steel Association (2020b), World Steel in Figures 2020; World Steel Association (2019b), Steel Statistical Yearbook 2019.

Steel and the environment

The iron and steel sector is highly energy- and emissions-intensive, accounting for 8% of global final energy use and 7% of global direct energy-related CO_2 emissions (including industrial process emissions). Iron and steel production is highly reliant on coal or natural gas for iron ore-based production, which is considerably more energy- and emissions-intensive than pure scrap-based production, which uses mostly electricity for its energy input. Over the past three decades, the sector's total energy consumption has doubled (Figure 1.5). Production grew at a somewhat higher rate of 2.4 times during the same period, indicating that energy efficiency improvements have led to a modest reduction in the energy intensity of steel production.

[10] In this publication, the Middle East region includes the following countries: Bahrain, Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen.

Figure 1.5 Final energy consumption in the steel industry



Notes: Gt = gigatonne; Mtoe = million tonnes of oil equivalent. "Exported energy products" refers to energy products that are produced but not used directly in the iron and steel sector (including coke ovens and blast furnaces). Key examples of these exported energy products are steel off-gases (coke oven gas, blast furnace gases) and coke, and are shown as negative values in the figure. "Net energy consumption" is the sum of the gross energy input to the sector (the positive values in the figure) and these negative exported quantities. Net energy consumption is the default definition of sectoral energy consumption used in this publication, and is referred to simply as "energy consumption" elsewhere for brevity.

Source: IEA analysis based on IEA (2020a), *World Energy Balances*, and multiple editions of the World Steel Association *Steel Statistical Yearbook*.

Energy demand in the iron and steel sector has nearly doubled over the past three decades, with most of the growth owing to China's post-millennium surge in output.

It will be important to decouple CO_2 emissions from steel production in the years to come for the sector to play its part in achieving global climate goals. Steel plant installations have long lifetimes, typically with 25-year investment cycles and 40-year typical average lifetimes. As such, capacity built in the past 2-3 decades could already imply considerable emissions for the sector in the medium term. The average age of ironmaking capacity is only around 13 years globally. Engaging a variety of strategies to address the sector's existing stock of assets will be critical to putting the industry on a more sustainable emissions pathway. Strategies include early retirements, underutilisation, retrofitting and fuel switching. This must also be done parallel to addressing the various challenges associated with meeting future steel demand, which are explored in Chapter 2.

An energy- and CO_2 emissions-intensive sector

The iron and steel sector accounted for 845 Mtoe of energy consumption[11] globally in 2019, representing 20% of industrial energy use and 8% of total final energy use. It is the second-largest industrial energy consumer, after the chemical sector (which uses a vast amount of oil, gas and coal as feedstock). The main energy input is coal, accounting for almost three-quarters of the sector's energy use. Much of the coal consumed is coking coal used to produce coke for blast furnaces as a chemical reduction agent and for its physical properties, although other coal grades are also used, mainly to provide heat. Coking coal alone accounted for about 16% (872 million tonnes of coal equivalent [Mtce]) of global coal demand (5 530 Mtce) in 2019, with the steel sector accounting for almost all of its use, constituting a major demand sector of the coal industry.

Electricity and natural gas account for most of the remaining energy demand in the iron and steel sector, in almost equal measure. The steel industry accounted for 2.5% (90 billion cubic metres [bcm]) of global gas demand and 5.5% (1 230 terawatt hours [TWh]) of global electricity demand in 2019. Both of these energy carriers are used for a wide range of processes, including finishing processes such as rolling, with a considerable proportion of the electricity used to power EAFs and induction furnaces, and much of the natural gas used in DRI and natural-gas injection BF-BOF production.

BF-BOF production results in co-product gases – including coke oven gas, blast furnace gas and basic oxygen furnace gas – consisting of a mixture of nitrogen, carbon dioxide, carbon monoxide, hydrogen, methane and other gases. These off-gases contain sufficient energy content for use in other processes: around 6 GJ per tonne of crude steel produced. A share of these off-gases may be used on site for ancillary processes such as heating furnaces in rolling mills or preheating air for blast furnaces. The remainder can be used for on- or off-site power and steam generation, which is often used for internal steel plant energy needs both in steelmaking and downstream processes. Some steel companies are also exploring the use of off-gases as inputs to chemical and fuel production via carbon capture and use (CCU) installations. Coke oven gas, owing to its high hydrogen content, is already used as a feedstock to produce methanol in China.

Globally the sector accounted for 2.6 Gt of direct CO_2 emissions in 2019, representing about one-quarter of industrial CO_2 emissions and 7% of total energy sector emissions (including process emissions). Of the steel sector's direct CO_2 emissions, around 0.3 Gt are process emissions arising from the use of lime fluxes and from ferroalloy production. An additional 1.1 Gt CO_2 of indirect emissions are emitted through the use

[11] See the notes below Figure 1.5 for an explanation of how energy consumption is accounted for in this publication.

of steel off-gases, along with other energy inputs, to generate the electricity and imported heat consumed by the steel sector. Direct CO_2 emissions from the iron and steel sector more than doubled between 2000 and 2019, driven by high production growth, particularly in China. With production expected to continue growing in the future, albeit at a considerably slower rate than in the past two decades, reducing the CO_2 intensity of steel production will be critical to limiting the sector's contribution to anthropogenic climate change.

Largely owing to its reliance on coal, steel production is currently highly emissions-intensive. Producing a tonne of crude steel results in, on average, 1.4 t of direct CO_2 emissions and 0.6 t of indirect CO_2 emissions on a sectoral basis (see Box 1.3 for discussion of these categories of emissions).[12] Focusing on crude steel production prior to finishing processes, the BF-BOF route – which accounted for 71% of production in 2019 – is highly emissions-intensive. Producing a tonne of crude steel via the BF-BOF route with coal injection directly emits around 1.2 t CO_2. In addition, it results in an average of 1.0 t CO_2 in indirect emissions from electricity and imported heat generation. About 90% of BF-BOF production relies on coal injection, with the remaining share relying on injection of other fuels such as gas or charcoal, which results in a somewhat lower direct emission intensity. The considerable indirect emissions from the BF-BOF route results in part from use of steel off-gases for a large proportion of heat and electricity, and also from imported generation, which generally takes place on site, and also from imported electricity and heat. The energy content of steel off-gases relative to their carbon content is variable and generally quite low owing to a substantial non-combustible CO_2 content (~25%), meaning they are emissions-intensive when combusted (up to about 2.5 times the emission intensity of coal).

The other main primary route, DRI-EAF, can achieve somewhat lower emission intensities. This is largely due to 70% of DRI-EAF production relying on natural gas rather than coal. A tonne of crude steel produced by natural gas-based DRI-EAF results in 1.0 t CO_2 in direct emissions. At the current global average CO_2 intensity of electricity generation – 538 grammes of CO_2 per kilowatt hour – the route results in 0.4 t CO_2/t in indirect emissions from electricity generation (the DRI-EAF route does not produce off-gases with sufficient energy content for use in electricity or heat generation). The coal-based DRI-EAF route produces almost three times more direct emissions and a similar quantity of indirect emissions as its gas-based DRI-EAF counterpart.

[12] Throughout the publication, "sectoral" energy and emission intensities are calculated by dividing the sector's total energy use and emissions by total crude steel production; thus finishing and other ancillary processes are included. However, when energy and emission intensities are presented for particular process routes (BF-BOF, DRI-EAF, scrap-based EAF, etc.), finishing processes are not included. See Box 1.3 for further details on the boundaries used for energy consumption and emissions in this analysis.

Conversely, scrap-based EAF production relies primarily on electricity and has a much lower emission intensity. The route results in only about 0.04 t CO_2/t of crude steel produced on a direct emissions basis, as a result of a small amount of coal or gas use and from the production and use of lime fluxes. Based on the current global average CO_2 intensity of electricity generation, the scrap-based EAF route results in an additional 0.3 t CO_2/t in indirect emissions.

Some installations have already achieved emission intensities considerably lower than the typical values just mentioned. These can be achieved through measures such as maximising operational energy efficiency and by employing best available technologies. While a good first step, these incremental improvements will be insufficient to drive deep emission reductions – step changes in production methods will be needed, as explored in Chapter 2.

Box 1.3 Analytical boundaries: Energy consumption and CO_2 emissions

Stakeholder groups in the steel industry adopt a range of approaches to energy and emissions accounting. Multiple approaches can be valid, but it is important to communicate how the quantitative results in this technology roadmap relate to the conventions adopted elsewhere, and specifically those of the World Steel Association (worldsteel), the global industry association and a central body for dissemination of information within the sector. The ISO 14404 family of standards and the European Commission's BREF on the iron and steel sector are also important reference documents (ISO, 2020; European Commission, 2020).

Broadly speaking, the IEA and worldsteel values are the same once adjusted for the treatment of electricity generation. Whereas the IEA accounts for electricity consumption in final energy terms and emissions from electricity generation as indirect emissions, worldsteel accounts for it in primary energy terms and attributes these emissions directly to the iron and steel sector.

Sectoral boundary for energy accounting

The sectoral designations for energy accounting adopted in this technology roadmap follow those of the IEA World Energy Balances dataset, which comprises an annual computation of all major energy flows in the energy system based on statistics submitted by countries across the world (IEA, 2020a). The energy used in blast furnaces and coke ovens (accounted for separately in the IEA dataset), and within final consumption in the iron and steel industry sub-sector, are merged to form the sectoral boundary for energy accounting in this technology roadmap.

The accounting of fuel used to generate heat and electricity also follows the convention adhered to in the IEA World Energy Balances, which may be unfamiliar to readers. Fuel consumed to produce heat on site, including within a core process unit (e.g. a blast furnace) or in a dedicated heat or co-generation plant, is directly accounted for as fuel consumption (e.g. natural gas or coal) within the iron and steel sector final energy consumption boundary. Fuel used to generate heat that is sold is accounted for in the fuel transformation sector, and is therefore not included within the iron and steel sector boundary. This energy use is directly accounted for as imported heat within the iron and steel sector boundary, and is a small share of the sector's total energy consumption.

Fuel used to generate electricity, whether on site (e.g. an autoproducer power plant utilising steel off-gases) or in a dedicated utility (e.g. a main activity producer coal power plant in the power sector), is accounted for in the fuel transformation sector – outside the iron and steel sectoral boundary. This energy use is recorded as electricity consumption within the sector boundary. Co-generation plants also follow this convention, with the fuel inputs split between the iron and steel and fuel transformation sectors in proportion to the shares of heat and electricity generated by the unit. For example, if an iron and steel sector co-generation unit produces heat and electricity in a ratio of 1:2, one-third of its fuel inputs would be accounted for directly as fuel consumption within the iron and steel sector boundary, and two-thirds within the fuel transformation sector.

This energy accounting methodology results in an average energy intensity of crude steel of 19 GJ/t in 2019. The IEA states all energy intensities in final energy terms, whereas worldsteel accounts for electricity consumption in primary energy terms, using a conversion factor of 9.8 GJ of fuel per MWh of electricity (equivalent to a 37% conversion efficiency). This results in a higher value of sectoral energy intensity using the worldsteel methodology (around 20 GJ/t in 2017) (World Steel Association, 2019a). Using the IEA accounting methodology, the total energy consumption of the sector is 845 Mtoe in 2019, whereas the value arrived at using the worldsteel methodology would be around 1 030 Mtoe. Accounting for this difference in the treatment of electricity (final vs primary), the values are broadly comparable.

Sectoral boundary for CO_2 emissions accounting

There are three categories of CO_2 emissions attributed to the iron and steel sector in this technology roadmap: energy-related emissions, process emissions and indirect emissions. The first two categories are both considered to be direct emissions and are the focus of the analyses presented in this technology roadmap. Indirect emissions are those attributable to electricity generation, whether on site or imported from the electricity grid, as well as the small amount of imported heat. These indirect emissions are presented as a complement to the direct emissions in specific instances, and are not a core analytical component of the technology roadmap analysis, to avoid implicit double counting of emissions from power generation presented in other IEA publications.

Direct energy-related emissions are the CO_2 emissions generated from fuel combustion in the iron and steel sector corresponding to the energy accounting definitions outlined above. This includes the consumption and transformation of energy in coke ovens and blast furnaces.[13] The consumption of electricity, imported heat and bioenergy do not lead to any direct energy-related emissions.

Process emissions include those arising from the use of lime fluxes and from ferroalloy production. Lime fluxes such as limestone and dolomite are introduced directly into steelmaking processes to remove impurities, or after being converted to quicklime. All CO_2 emissions associated with the use of lime fluxes are included within the sectoral boundary, whether or not conversion to quicklime takes place on site or elsewhere before purchase. Process emissions from ferroalloy production include further emissions from the use of lime fluxes, together with those from the consumption of carbon-containing electrodes and the calcination of carbonates present in various ores. A small amount of process emissions is also generated during the consumption of graphite anodes in EAFs.

Indirect emissions are those attributable to electricity generation, whether the electricity is produced on site (autoproducers) or imported from the grid (main activity producers), as well as imported heat. In the sectoral emissions accounting in this technology roadmap, the CO_2 intensity of electricity is calculated on a regional basis for imports from the grid, depending on the power generation technology mix. For electricity generated on site from steel off-gases, the emissions factors for the relevant gases (coke oven gas, blast furnace gas etc.) are used. Where co-generation plants are used, the emissions associated with burning the fuel are categorised as direct energy-related emissions for the proportion attributable to heat, and indirect emissions for the proportion attributable to electricity. As is the case for energy, the fuel inputs are allocated between these categories based on the proportions of heat and electricity generated, in energy terms.

This CO_2 emissions accounting methodology results in an average sectoral direct emission intensity of crude steel of 1.4 t CO_2/t, and a direct + indirect emission intensity of 2.0 t CO_2/t in 2019. The latter compares favourably with the worldsteel figure of 1.9 t CO_2/t in 2018, which includes the IEA's category of indirect emissions (scope 1, 1.1, 2 and 3 emissions in the worldsteel nomenclature) (World Steel

[13] This accounting of energy-related emissions differs from that of "CO_2 emissions from fuel combustion" in the IEA *World CO_2 Emissions* dataset, where emissions arising from the transformation of fuels in coke ovens and blast furnaces are not included, following the IPCC designation of energy transformation processes as process CO_2 emissions (IEA, 2020b).

Association, 2020d). No adjustments or additions are made to the IEA figures for "scope 3" emissions, whereas worldsteel includes further quantities of emissions or emissions credits related to the procurement or delivery of raw materials and co-products. These adjustments tend to be small.

Energy and emission intensities of main production routes

When quoting emissions associated with a specific production route, this technology roadmap uses a "crude steel boundary", as depicted in Figure 1.2. This boundary includes agglomeration and coke production, ironmaking and steelmaking, and casting. It excludes other semi-finishing and finishing processes, the use of which differs according to the specific finished steel product being produced.

There are three main production routes for which energy and emission intensities are provided by the IEA and worldsteel: the BF-BOF route, the scrap-based EAF route and the natural gas-based DRI-EAF route. The IEA's reference values for these routes are based on worldsteel energy data, adjusted for differences in accounting boundaries, particularly with respect to electricity. The IEA states all energy intensities in final energy terms, whereas worldsteel accounts for electricity consumption in primary energy terms, using a conversion factor of 9.8 GJ of fuel per MWh of electricity (equivalent to a 37% conversion efficiency). This means that processes that consume electricity will appear more energy intensive when quoted using the worldsteel analytical boundary, relative to the one used by the IEA.

Energy intensities of main production routes

Methodology	BF-BOF	Scrap-based EAF	Natural gas-based DRI-EAF
IEA	21.4 GJ/t	2.1 GJ/t	17.1 GJ/t
worldsteel	22.7 GJ/t	5.2 GJ/t	21.8 GJ/t

Note: worldsteel reference values are adjusted to match the IEA "crude steel boundary" described above. Differences between the IEA and worldsteel values shown here are mainly attributable to the treatment of electricity.

The IEA's values for emission intensities of the main production routes are calculated according to the sectoral emission boundaries described above. The direct emission intensities presented in the table below correspond to the final energy consumption quantities in the table above, using the IEA calorific and carbon content values for each fuel (IEA, 2020b). The indirect emission intensities for these main production routes are calculated here using a global average CO_2 intensity of power generation for electricity imported from the grid, similar to the methodology used by worldsteel, to aid comparison. The emissions associated with burning steel off-gases on-site (relevant to the BF-BOF route only) are calculated using the relevant emissions factors for coke oven gas and blast furnace gas. The direct emission intensities are the analytical focus of this technology roadmap, but once adjusted for the inclusion of indirect emissions, it can be seen that the IEA direct + indirect emission intensities compare favourably those of worldsteel.

CO_2 emission intensities of main production routes

Methodology	BF-BOF	Scrap-based EAF	Natural gas-based DRI-EAF
IEA (direct)	1.2 t CO_2/t	0.04 t CO_2/t	1.0 t CO_2/t
IEA (direct + indirect)	2.2 t CO_2/t	0.3 t CO_2/t	1.4 t CO_2/t
worldsteel	2.2 t CO_2/t	0.3 t CO_2/t	1.4 t CO_2/t

Note: worldsteel reference values are adjusted to match the IEA "crude steel boundary" described above.

Non-CO_2 environmental impacts

While this technology roadmap focuses on CO_2 emissions, it is also important to address the iron and steel sector's other environmental considerations, including its contribution to air pollution, soil contamination and water use.

Outdoor air pollution is linked to 2.9 million premature deaths globally each year. The industry sector, of which the steel industry is a part, accounts for around 45% of sulphur oxides (SO_x), and about 25% of each of nitrous oxides (NO_x) and dust/particulate matter ($PM_{2.5}$) (IEA, 2019; World Steel Association, 2019c). In the steel sector, stack emissions from point sources are most commonly regulated by emission limit values specified in environmental operating permits, and they are kept under regulated limits through measures such as removing contaminants prior to processing, yield optimisation, combustion control, technologies that remove pollutants from flue gases such as scrubbers, and monitoring and maintenance regimes.

Diffuse and fugitive emissions in the steel sector result from non-point sources, including material handling, stockpiling and transport, and escapes from valves and evaporation of solvents. Stockpile emissions are controlled for example through stockpile design and watering, storage enclosures, and monitoring, while maintenance and monitoring are critical to limiting fugitive emissions. Continued efforts to monitor and reduce air pollutants are important, particularly diffuse dust that is more challenging to control. Increased control is particularly needed in highly industrialised areas where the combined emissions of multiple sources, including industry, transport and household heating, lead to poor local air quality.

In China, for example, air pollution remains a major concern and the steel industry has become the largest industrial source of air pollutants after major restrictions on coal plants began to be enforced in 2014 (South China Morning Post, 2019). In the past couple of years the government has enforced increasing controls on industry in an effort to reduce smog, including production restrictions on smog days. Steel mills can be exempt from these production restrictions only if they meet stringent emissions limits. New ultra-low emission standards are gradually being introduced, starting with the most heavily polluted provinces and expanding further to the majority of plants in the coming years (Reuters, 2019; South China Morning Post, 2019).

In addition to air pollutants, the steelmaking process can concentrate or lead to the release of naturally occurring heavy metals in raw materials – especially from contaminated scrap and coal – that can accumulate in and contaminate soil. Heavy metals can be released into the air from flue gases, raw material stockpiles and slag heaps (consisting of slags that are not reprocessed and instead stored long-term at steel sites), typically attached to dust particles. They are then deposited on soils surrounding the plant. Various studies have found at least some degree of elevated heavy metal concentrations surrounding steel mills (Yang et al., 2018; Khudhur, Khudhur and Ahmed, 2018; Qing, Yuton and Shenggao, 2015; Namuhani and Cyrus, 2015). While in many cases heavy metal concentrations may not exceed limits set by soil standards or exposure risk thresholds, it is nonetheless important to monitor contamination and implement reduction measures, and to ensure proper site remediation following plant retirements.

Furthermore, the steel industry requires substantial quantities of water for various processes including cooling, descaling and dust scrubbing (World Steel Association, 2015). This includes using untreated sea water for cooling that does not require contact with equipment and materials, and fresh water for processes that do require contact with equipment and materials. All water apart from that used once for cooling is treated on-site before discharge. On average, an intake of about 28 cubic metres (m^3) of water is needed to produce a tonne of steel, which includes sea water for once-through cooling, although there is considerable variability between plants. About 90% of that water is normally returned to its source, as clean as or cleaner than when extracted and at the same or similar temperature, with the remainder lost due to evaporation or in waste products such as sludge. The difference between water removed from source and water returned is known as water consumption. Water consumption is generally much lower than water intake, with typical water consumption falling in the range of 1-4 m^3 per tonne of steel.

Local water availability affects the extent to which water intake and water consumption may be of concern. Water used in cascades or water reuse within a plant can be effective ways to reduce water intake, but must be considered in light of increased energy requirements for water cooling and desalination, production of by-product salts during desalination that need to be landfilled, and the potential for increased water evaporation from recirculation. Water consumption can be reduced through measures to reduce evaporation and prevent leaks. Given the considerable variability in local circumstances, such as differences in the extent to which water is abundantly available or scarce, water management is best regulated by local and regional authorities. The International Organization for Standardization has developed a standard (ISO 14046:2014) than can help evaluate and improve the water footprint of industrial operations based on local conditions.

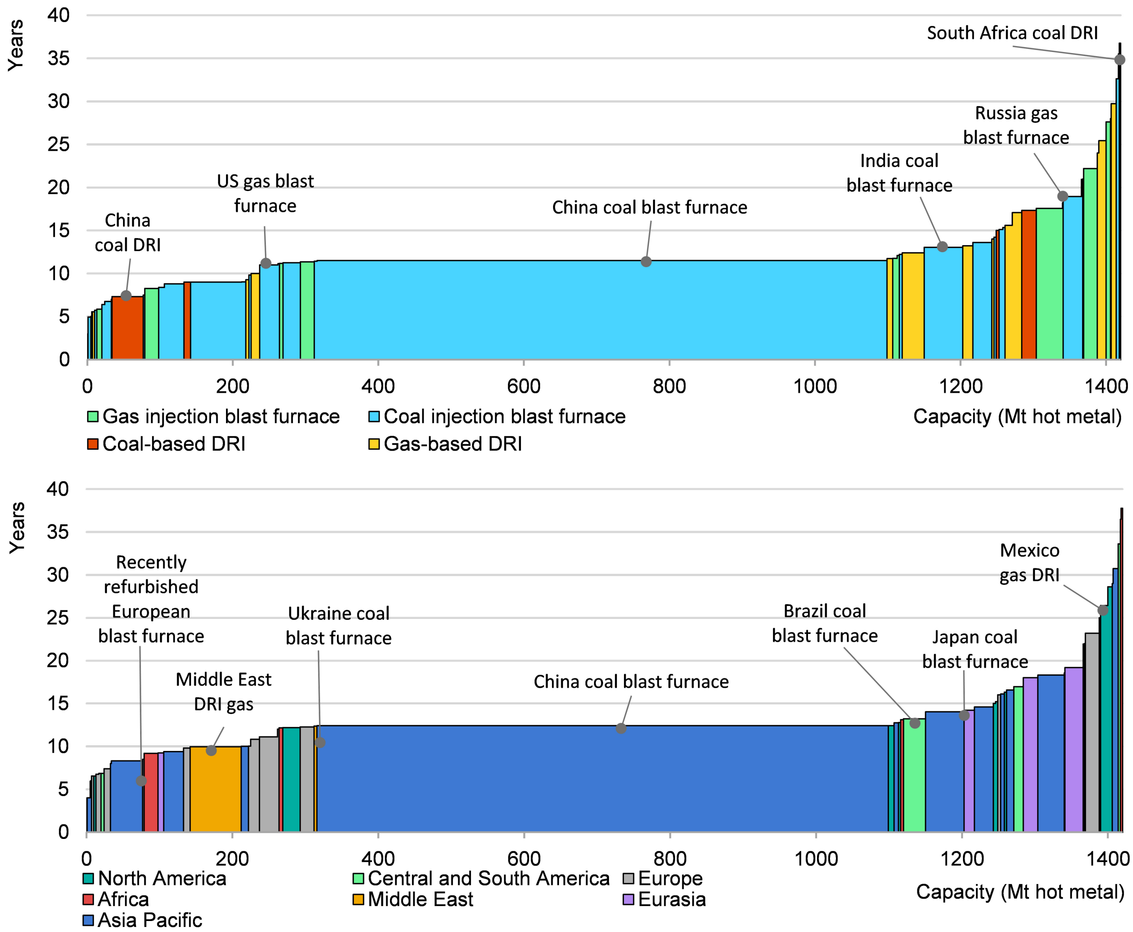
What will happen to today's CO_2 emissions from the steel industry tomorrow?

The steel industry's infrastructure is like a container ship – it has inertia and is slow to change direction. While producers are constantly responding to price fluctuations and changes to their order books, short of major disruption to the economy (Box 1.1), the behaviour of the system tends to maintain fairly stable trends (Figure 1.5). Understanding the status quo of the main pieces of equipment that comprise the steel industry's infrastructure is critical to assessing the underlying momentum in the system (Figure 1.6). Existing infrastructure certainly presents challenges for reducing emissions, but there are also technology opportunities to be seized.

The amount and type of energy that the steel industry uses at any given moment is the consequence of past investments in steel sector assets, as well as historic consumption of steel-containing goods. It is not possible to predict accurately the future energy consumption and subsequent emissions of these assets, as there is scope for adjusting both the quantities and types of energy carriers that they will consume, the material inputs to the processes, and how long they actually remain in operation. In the end, decisions about whether to cease, continue or extend the operation of a given piece of equipment will be based predominantly on its operational cost relative to existing or emerging alternatives, and/or the ability to obtain a sufficient return in a given economic and regulatory context. However, examining the likely trajectories of various emission streams is a useful starting point to examine our room to manoeuvre in the coming decades.

When considering direct CO_2 emissions from the iron and steel sector (Box 1.3), blast furnaces and DRI furnaces are the principal emitting assets in the industry. They are also among the longest-lived and most capital-intensive assets within a steel mill, and they tend to be the installations around which investment decisions for the plant as a whole are centred. The average lifetime of these assets is typically around 40 years, although there are several examples – of blast furnaces in particular – where installations are operated for several decades longer than this, with a number of rounds of refurbishment.

Figure 1.6 Geographic distribution and average age of main assets in the iron and steel sector by production route and region



Sources: Estimates informed by Steel Institute (2018), *Steel Institute VDEh PLANTFACTS database*, and OECD Steel Committee (2019a), *Latest Developments in Steelmaking Capacity*.

Around 50% of the existing stock of ironmaking equipment is based in China, with India contributing a further 5%.

Typical plant lifetimes only tell part of the story. Roughly every 25 years after commissioning a plant, producers will face an investment decision on its main assets.[14] After each 25-year period of near-continuous operation, a blast furnace will need to have its internal refractory lining replaced. During operation this lining is subjected to temperatures in excess of 1 400-1 500°C and corrosive compounds present in the slag and molten iron, which eventually cause it to degrade. The initial installation cost of a blast furnace is around USD 200-300 million per million tonnes

[14] The range associated with this estimate is 15-30 years.

of capacity,[15] and the relining cost is typically around half of this figure. This significant level of additional investment to renew the life of the furnace must be considered in the context of several competing outlets for capital expenditure, including greenfield investments in a new location.

Assuming a typical lifetime of 40 years, alongside an interim investment cycle of 25 years, it is possible to assemble the regional average age profile of the existing fleet of blast furnaces and DRI furnaces (Figure 1.6).[16] The weighted global average age of these regional figures is about 13 years for blast furnaces and 14 years for DRI furnaces. Coal injection blast furnaces tend to be a little younger at 13 years, whereas gas injection installations stand at around 16 years. For coal- and gas-based DRI furnaces, the figures are 13 years and 14 years respectively. Underlying these global figures is considerable regional differentiation.

China accounts for over 50% of all ironmaking capacity (both DRI and blast furnace). Its relatively young blast furnace fleet (around 12 years on average) is the main factor explaining the youth of the global fleet overall. Its coal-based DRI furnaces are younger still, at just 8 years on average. The range of ages of individual plants within the country will vary considerably, but China's growth in steel output over the past 20 years (more than eightfold) shows the relatively short timeframe over which most of these installations have been added.

On either side of the giant share of Chinese capacity in the middle of the age profile curve is significant variation in average age across the other regions. At either extreme are some of the recently refurbished European blast furnaces (less than 10 years) and coal-based DRI furnaces in South Africa (around 35 years). The other major producing regions at the younger end of the spectrum are the United States (gas injection blast furnaces around 12 years) and the Middle East (gas-based DRI furnaces around 10 years). At the older end are Russian gas injection blast furnaces (around 20 years) and Mexico's gas-based DRI fleet (around 25 years). India and Japan's coal blast furnaces are similar in average age to China's at 15 years and 14 years respectively.

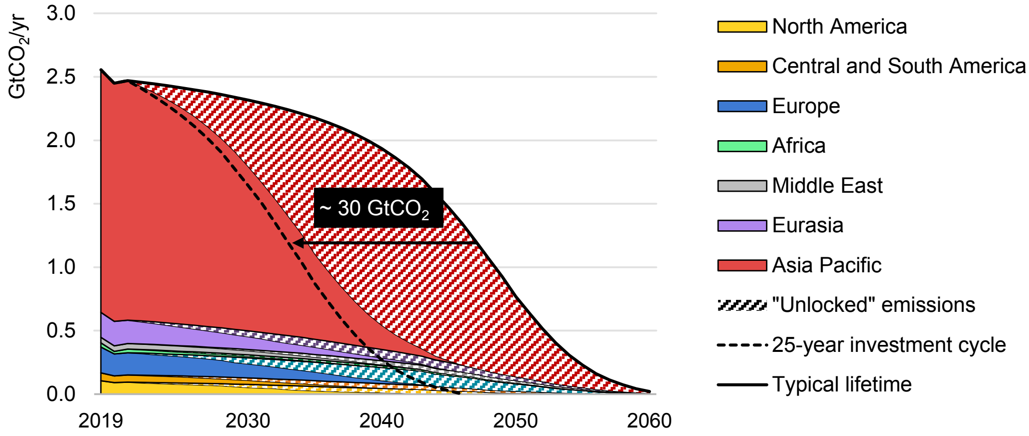
The age profiles and typical lifetimes of these larger assets are a good guide to the rate at which the existing stock of equipment in the iron and steel sector will be decommissioned. Without any further investment in new capacity, emissions from the steel industry would decline, but not as fast as one might think. If operated under

[15] This refers to the blast furnace only, including engineering, procurement and construction costs. The CAPEX for all equipment required to provide 1 Mt of annual capacity (including agglomeration, coke ovens etc.) is around USD 1-1.5 billion.

[16] These estimates incorporate plant-level information on the years when individual plants last underwent major refurbishment, irrespective of the 25-year investment cycle estimate.

the conditions typically observed in recent years, existing steel industry infrastructure could lead to roughly 65 Gt CO_2 of cumulative emissions between now and 2060 (Figure 1.7).

Figure 1.7 Emissions from existing steel industry infrastructure under different lifetime assumptions



Sources: Estimates informed by Steel Institute (2018), *Steel Institute VDEh PLANTFACTS database*, and OECD Steel Committee (2019a), *Latest Developments in Steelmaking Capacity*.

Intervening at the end of the next 25-year investment cycle could "unlock" roughly 30 Gt CO_2, or around 50% of projected emissions from existing equipment in the steel industry.

To the extent that much of the existing capital stock will still be in operation decades into the future, the associated CO_2 emissions are often considered to be "locked-in". However, these emissions are by no means destined to take place, and there are several strategies and technologies that can be deployed to varying extents to help "unlock" emissions from existing infrastructure:

- **Early retirement or interim underutilisation of assets,** either because of a change in policy or market conditions that makes them uneconomic or because of laws and regulations that force early closure or partial operation.
- **Refurbishment and retrofitting**, such as enhanced process integration to boost energy efficiency, or the application of emission-reduction technologies such as replacing natural gas by hydrogen or applying carbon capture, use and storage (CCUS).
- **A change in material inputs**, for example a higher share of scrap use in various process units, or higher-quality iron ore, although both of these options are limited by availability.

- **Fuel switching and incremental blending**, sometimes combined with some degree of retrofit, to allow assets to use less-carbon-intensive or recovered fuels.

In addition to the nuances at the sub-sector level, the scope for unlocking emissions varies greatly across regions, according to the age of the different types of infrastructure. In the regions where industrial capacity is generally older, there is much more potential for early retirement, as the economic losses involved would be significantly lower. In the countries with younger assets, greater emphasis is likely to be placed on retrofitting with more energy-efficient and less carbon-intensive technologies, where it is economic to do so.

Beyond applying the mitigation strategies above, existing production facilities can be used to bridge the gap to breakthrough technologies. This is especially important for the sustainable transition of the steel sector, where readily available alternatives for dramatic reductions in emission intensity are not commercially available today. Strategically timed investment to partially renew existing infrastructure – or a decision to forgo investment – can form an important strategy to avoid a new investment cycle occurring just at the wrong time. By eliminating the seemingly small period of 15 years between the 25-year investment point and the typical 40-year plant lifetime, operators can have a big impact on future emissions from the iron and steel sector: around a 30 Gt CO_2 reduction in cumulative emissions from these assets, or approximately 50% (Figure 1.7).

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Chapter 2. The future of steelmaking

HIGHLIGHTS

- For the steel industry to follow a trajectory compatible with the goals of the Paris Agreement, its direct CO_2 emissions must fall by more than 50% by 2050 relative to today. Our Sustainable Development Scenario outlines a pathway compatible with achieving these goals, which requires a reduction in the direct emission intensity of crude steel production of 58% over this period.

- Steel production grows from around 1.9 Gt in 2019 to over 2.5 Gt in 2050 in the Stated Policies Scenario, driven by rising demand in emerging economies. The dominance of the People's Republic of China in global production declines from just over 50% today to 35% in 2050, as India's production more than triples to cater for booming domestic demand.

- Material efficiency strategies can help reduce growth in global demand for steel while delivering the same material services. In the Sustainable Development Scenario, steel demand is 19% lower than in the Stated Policies Scenario in 2050.

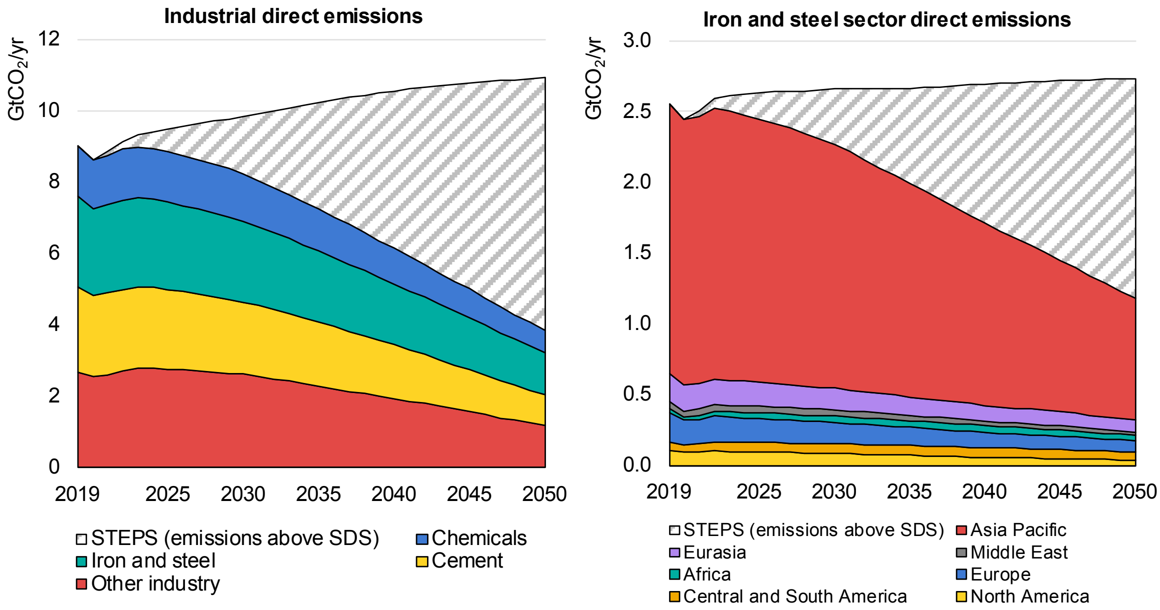
- Technology performance improvements and material efficiency deliver 90% of the emission reductions under the Sustainable Development Scenario in 2030, whereas in the longer term, innovative technologies that integrate various CCUS and hydrogen technologies are required for further emission reductions. By 2050 around 400 Mt CO_2 is captured annually, and 16 Mt of hydrogen is used.

- Energy consumption for steel production decreases by 14% by 2050 in the Sustainable Development Scenario relative to today and the proportions of various fuels change radically. Coal use declines by 40% by 2050, while electricity consumption doubles. 30% of this electricity (or around 700 TWh) is used for electrolytic hydrogen generation in 2050, requiring around 165 GW of electrolyser capacity.

- Innovation plays a critical role in the Sustainable Development Scenario, with technologies that are pre-commercial today contributing around 30% of cumulative emission reductions, and accounting for around a quarter of primary steel production in 2050. The regional deployment of individual technologies depends on local energy costs, the regulatory context and the existing portfolio of assets.

There are many possible futures for the steel industry, and to forecast a specific one for the time horizon we are examining in this publication (2019-50) would no doubt be futile. Scenario analysis offers a constructive way to deal with the high degree of uncertainty associated with making predictions about the future. Quantifying the likely future outcomes of baseline assumptions can help identify the policy interventions that may be needed for a desirable future.

Figure 2.1 The contribution of the iron and steel sector to direct industrial CO_2 emissions by scenario



Notes: Gt CO_2/yr = gigatonnes carbon dioxide per year. STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario. "Other industry" includes emissions from the remainder of industry total final consumption in the IEA Energy Balances, including for example aluminium, pulp and paper, food and beverage, machinery, mining and textiles.

In the Sustainable Development Scenario, the iron and steel sector accounts for a similar share (25-30%) of direct industrial emissions throughout the projection horizon, while reducing its absolute direct emissions by 54% by 2050.

The purpose of this chapter is to explore two contrasting future scenarios for the steel industry (Box 2.1). The first is the **Stated Policies Scenario** constructed by projecting forward its current trajectory, shaped by existing and announced policies. The second is the **Sustainable Development Scenario** constructed by stipulating a more sustainable end point and examining the pathway by which it might be realised. These scenarios are not intended to be predictions nor the only possible paths, but rather as illustrations of two possible directions for the steel sector.

These scenarios are used in this chapter to shed light on the energy and emissions implications of the steel industry's current heading, one in which emissions rise by

7% by 2050 relative to 2019 – the Stated Policies Scenario (Figure 2.1). In the alternative, the Sustainable Development Scenario, we present a more sustainable future for the steel industry, in which global absolute direct emissions fall by 54% between 2019 and 2050, while production levels moderately rise. This latter pathway for the steel industry is compatible with the temperature goals of the Paris Agreement in that it forms part of a wider system scenario. This is a scenario in which the energy system as a whole reaches net-zero CO_2 emissions globally by 2070.

Under the Sustainable Development Scenario emissions from the iron and steel industry are reduced by 90% by 2070. Similar to other heavy industry sectors – cement and chemical production – the direct emission intensity of output (in this case, crude steel production) falls by almost 60% between 2019 and 2050, and by 90% by 2070. This is in contrast to the power sector, for instance, which sees a reduction of 95% in the CO_2 intensity of the electricity it produces by 2050, and reaches net-negative emissions by 2070. Such difference reflects their levels of readiness for change – that is, the maturity and scalability of near-zero emissions technologies in each sector.

Box 2.1 Scenario definitions and the broader energy system context

The *Energy Technology Perspectives (ETP)* series has been informing the global energy and environment debate since 2006. Meeting the shared policy goals of energy security, economic development and environmental sustainability requires energy technology development and innovation. *ETP 2020* sets out where key technologies stand today, the potential for wider deployment to meet energy policy goals, the opportunities for and barriers to developing selected new technologies in the coming decades, and what policy makers and other stakeholders need to do to accelerate the development and deployment of the cleanest possible technologies.

ETP 2020 presents the same two scenarios explored in this technology roadmap to describe possible energy technology pathways over the next half century:

- **The Stated Policies Scenario** takes into account countries' energy- and climate-related policy commitments, including nationally determined contributions under the Paris Agreement, to provide a baseline against which we assess the additional policy actions and measures needed to achieve the Sustainable Development Scenario.
- **The Sustainable Development Scenario** sets out the major changes that would be required to reach the main energy-related goals of the United Nations Sustainable Development Agenda, including an early peak and subsequent rapid reduction in emissions, in line with the Paris Agreement, universal access to

modern energy by 2030 and a dramatic reduction in energy-related air pollution. The trajectory for emissions in the Sustainable Development Scenario is consistent with reaching global "net-zero" CO_2 emissions for the energy system as a whole by around 2070.

The trajectories of these two scenarios are also broadly the same as those explored in the other IEA flagship modelling publication, the *World Energy Outlook (WEO)*.

Neither scenario should be considered as predictions or forecasts, but rather as analyses of the impacts and trade-offs of different technology choices and policy targets. This is a quantitative approach to support decision making in the energy arena and provide strategic guidance on technology choices for governments and other stakeholders.

In addition to the two scenarios, *ETP 2020* presents the **Faster Innovation Case**, which explores the implications of bringing forward the date at which net-zero emissions is reached to 2050. It is not designed to be an ideal pathway to net-zero emission by 2050 – such a pathway is likely to require fundamental changes to current behaviour and lifestyles. Rather, it is designed to explore how much development cycles would need to be compressed and technology diffusion rates would need to be increased, relative to the Sustainable Development Scenario.

ETP 2020 provides the wider energy system context for the analytical work in this technology roadmap. This includes energy price signals, constraints on certain resources used elsewhere in the energy system and sub-sector interactions, such as the use of coke oven gas as chemical feedstock or slag from iron and steelmaking in the cement industry. Chapter 4 of *ETP 2020* presents further details on the scenario analysis for the iron and steel sector in the longer term, out to 2070.

The outlook for demand and production

As discussed in Chapter 1, steel is an indispensable material for virtually all aspects of the built environment. With no perfect substitutes currently on the horizon, the underlying demand for steel is expected to remain robust in both scenarios we examine. However, a more ambitious adoption of material efficiency strategies in the Sustainable Development Scenario paves the way for significant reductions in global demand for steel, relative to the Stated Policies Scenario, forming one of the principal levers for emission reductions throughout the projection horizon.

Two critical dynamics underpin the regional distribution of production capacity to satisfy future demand for steel in our scenarios. Firstly, advanced economies, such as those of the United States, the European Union, Japan and Korea, see stagnating or gently declining shares of global steel production, despite preserving similar levels of absolute output. Overall, advanced economies account for about 25% of production in 2019, declining slightly to around 20% by 2050. The second dynamic is the growth that takes place in many emerging economies, particularly India (see Chapter 3 for a detailed look at the outlook for India). This compensates for the decline in output from the People's Republic of China ("China"), which is in the process of shifting its industrial structure towards less energy-intensive activities after having satisfied a certain level of infrastructure and housing development. China's share of global production declines from around 53% in 2019, to 35% in 2050. Contrastingly, India's output share surges, from 6% in 2019, to 17% by 2050, reflecting its need for materials like steel to support its economic development.

Demand outlook and the impact of material efficiency

Demand for steel is expected to continue rising in the future, as demand for goods and services increases with economic and population growth. As mentioned in Chapter 1, societies do not demand steel *per se*, but rather the services that the steel material provides. Because there are few cost-competitive sustainable substitutes for steel for many end-use applications, economies tend to continue to demand steel at all stages of their economic development. At the early stages, countries typically require large amounts of steel to build up their infrastructure. As the in-use stock of steel accumulates in buildings, vehicles and many other steel-containing goods, the demand shifts to serve the maintenance of this installed inventory of steel products, or in-use stock, rather than increase its volume.

In the Stated Policies Scenario global end-use demand for steel reaches 2.1 gigatonnes (Gt) by 2050, a nearly 40% increase from the 1.5 Gt of end-use demand in 2019.[1] This end-use demand growth is driven in particular by emerging economies, which are still building up their in-use stock of steel towards levels seen in advanced economies today. Global iron and steel in-use stock per capita was estimated in 2019 at 4.2 tonnes per capita (t/capita) and is expected to rise to nearly 6.5 t/capita by 2050 in the Stated Policies Scenario, during which time the global population grows from 7.7 billion to 9.7 billion and global gross domestic product (GDP) grows by 2.5 times.

Underlying the global steel demand trend is a saturation of demand in advanced economies, with in-use stock per capita remaining relatively constant at around 10-15 t/capita on average in, for example, the United States and many European countries. Meanwhile, in-use stocks grow considerably in emerging economies,

[1] "End-use demand" refers to the quantity of steel that makes its way into end-use products, excluding the quantities that become scrap during semi-manufacturing and manufacturing (home scrap and prompt scrap). As such, total end-use demand is lower than total production.

which today have considerably smaller stocks, some less than 0.5 t/capita, for example in several sub-Saharan African countries. Per-capita in-use stocks are expected to continue to rise after 2050, reaching saturation in most regions by the end of the century at a global average of nearly 10 t/capita.

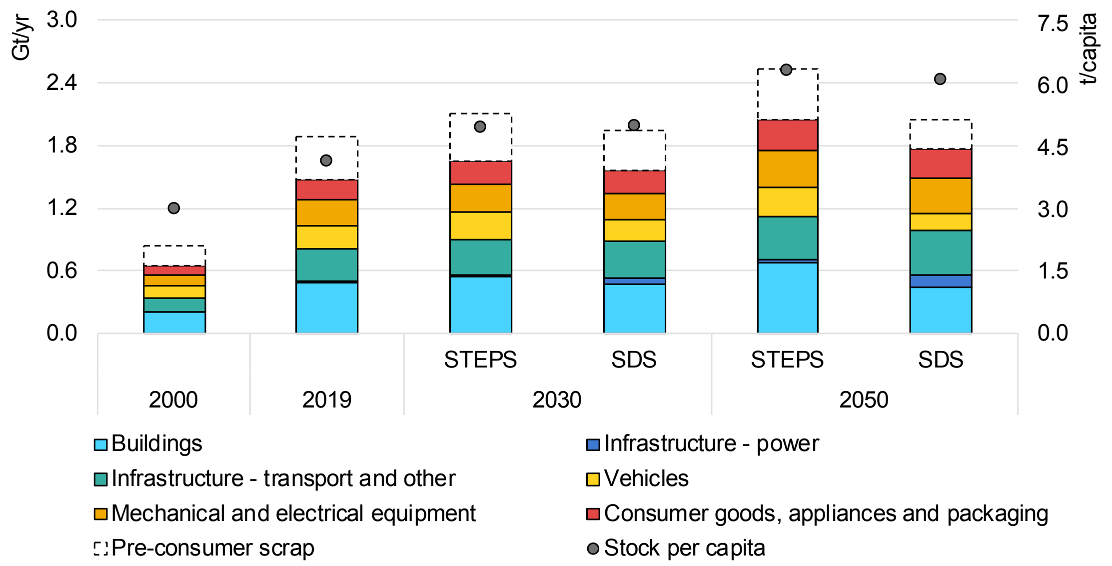
Large variability is observed in steel demand per capita, when calculated on an apparent use basis – that is, steel production plus imports less exports of finished products. Apparent use represents demand by the next tier of manufacturing processes, such as fabricators and the automotive industry, the products of which are often destined for export. The result is that some countries may appear to have unusually high demand per capita if they are large exporters of steel-containing goods. For example, Korea's annual apparent use is more than 1 t/capita – compared to a global average of 0.25 t/capita and around 0.35 t/capita in the European Union – due to its large shipbuilding industry. However, when looking at iron and steel demand from the perspective of end-use products, or true steel use, advanced economies saturate at much more consistent levels, with some variability due to factors such as population density. It is projected that emerging economies will eventually reach these same levels on a true steel use basis.

Demand for steel can be broadly divided into four end uses: construction, vehicles, machinery and consumer goods. The largest share of demand tends to be from the construction sector, which includes buildings and infrastructure such as bridges, power plants, pipelines and sanitation systems. Construction normally accounts for about half of total end-use demand, but nearly 70% of steel in-use stock, given that buildings and infrastructure tend to have the longest lifetimes. These range from 25-35 years for some power infrastructure and commercial buildings, up to 75-100 years or even longer for some infrastructure assets and residential buildings.

In recent decades, vehicles – including cars, trucks and ships – have accounted for about 15% of end-use demand and 10% of the global in-use stock, given their shorter lifetimes, which average 15-20 years for cars and trucks, and closer to 30 years for ships. Machinery, including mechanical and electrical equipment, has accounted for about 20% of end-use demand and 15% of global in-use stock, with lifetimes of 20-30 years. The remaining share of demand comes from consumer goods, which include metal goods, domestic appliances and food packaging. This segment normally accounts for almost 15% of end-use demand and 5% of the global in-use stock, with short lifetimes of about 10-12 years for goods and appliances, and less than a year for most packaging applications. These general patterns in demand share by segment may differ at particular points in time, such as in 2020 when the Covid-19 crisis has had varying impacts on different aspects of demand in different countries.

At the country level the pattern of end-use demand shares is partly influenced by the level of economic development. At lower levels of GDP, a somewhat higher share of demand tends to be for construction and machinery, in order to build up in-use stocks of steel. At higher levels of GDP, demand for construction and machinery tends to be more for maintenance, resulting in lower demand levels, and an increased share of demand is for vehicles and consumer goods, driven by their shorter lifetimes and the fact that these segments include many discretionary purchases that are more common at higher levels of income. Despite this slight divergence in regional trends, the resulting impact on the shares of each demand segment at the global level is not that noticeable in our projections. The shares of these four broader segments remain relatively similar through to 2050 under the Stated Policies Scenario to their levels today (Figure 2.2).

Figure 2.2 Global end-use steel demand and in-use steel stock by scenario



Note: STEPS = Stated Policies Scenario, SDS = Sustainable Development Scenario.
Source: IEA analysis informed in part by Pauliuk, Wang and Muller (2013), Cullen, Allwood and Bambach (2012) and Gibon et al. (2017).

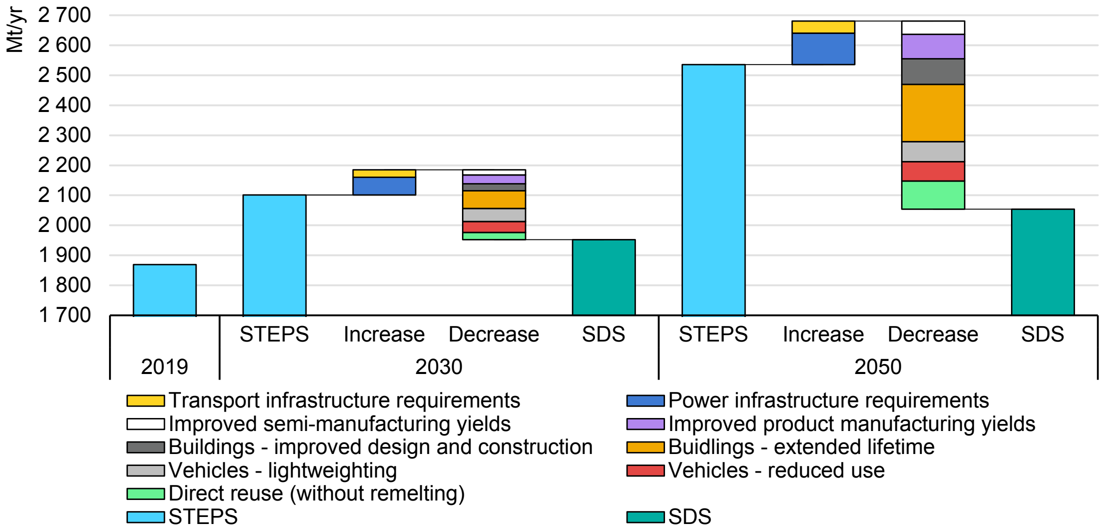
In the Sustainable Development Scenario material efficiency strategies can help reduce growth in global demand for steel while delivering the same services, such that demand is nearly 20% lower in 2050 compared to the Stated Policies Scenario.

Growth in demand for steel is reduced in the Sustainable Development Scenario, with production reaching a level in 2050 that is nearly 20% lower than the Stated Policies Scenario, and only 10% higher than in 2019. This reduction is driven by a variety of material efficiency strategies and shifts in demand, involving various sectors and actors at different stages along the steel value chain (Figure 2.3). Global steel in-use stocks, nonetheless, reach levels similar to the Stated Policies Scenario in 2050 (only

4% lower), reflecting the combined impact of several demand reduction strategies: longer lifetimes reduce demand considerably by holding steel in-use stocks for longer, direct reuse returns steel back to in-use stocks, and improved yields do not reduce in-use stocks because scrap generation does not contribute to in-use stocks in the first place.

Steel used to build clean energy infrastructure drives up demand in particular end-use segments, with demand from the power sector in 2050 about three times higher than under the Stated Policies Scenario and rail infrastructure about one-third higher. However, these segments account for a relatively small share of total end-use steel demand to begin with (currently about 1% and 3%, respectively). These increases (equivalent to a combined 5% increase in demand in 2050 relative to the Stated Policies Scenario) are therefore far outweighed by the combined impact of demand reduction from material efficiency.

Figure 2.3 The contribution of material efficiency strategies to reductions in global steel demand



Notes: STEPS = Stated Policies Scenario, SDS = Sustainable Development Scenario. "Demand" here equates to global crude steel production rather than end-use demand alone, in order to include the impact of reducing pre-consumer scrap on required production levels.

Extending the lifetime of buildings accounts for about one-third of steel demand reduction in the Sustainable Development Scenario in 2050, with substantial reductions also coming from strategies such as improved manufacturing yields, reduced vehicle use, improved building design, and reuse.

A considerable proportion of the demand reduction occurs by improving yields, that is, reducing scrap generation during manufacturing. About 7% of the cumulative reduction in steel demand to 2050 in the Sustainable Development Scenario, relative to the Stated Policies Scenario (or a 1.5% reduction in demand in 2050), result from improved yields during semi-manufacturing, the process in which crude steel is converted into steel products like bars, sheets and coils. Another 13% of the cumulative reductions (or a 2.5% reduction in demand in 2050) occur during product manufacturing, when steel products are converted to end-use goods. Some manufacturing processes currently generate considerable scrap, such as cutting body panels for vehicles from metal sheets, which can result in up to 30% scrap generation. These yield losses can be reduced through improved manufacturing techniques, in some cases aided by digitalisation (e.g. through additive manufacturing that forms complex shapes with minimal material losses).

The largest proportion of steel demand reductions comes from changes in the design and use of end-use products, aspects that are outside the direct control of the steel industry. Steel demand for buildings can be reduced with improved design and construction practices, which account for 13% of cumulative reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario (or a 2.5% reduction in demand in 2050). This includes:

- Reducing over-specification of structural steel.
- Section and profile optimisation that better tailors components to their required functionality.
- Innovative modular building designs that require less material.
- The use of higher-strength steel to facilitate using smaller members and sections.
- Increased use of pre-tensioned and precast reinforced concrete, which takes advantage of the complementary properties of both materials.

The single largest contributor to demand reduction is extending the lifetime of buildings, accounting for 32% of cumulative reductions (or a 6% reduction in demand in 2050). Many buildings are currently demolished before the end of their technical lifetime, in particular commercial buildings that are often only used for 30 to 40 years compared to a technical lifetime of 75 years or more. Taking the opportunity to refurbish and repurpose these buildings leads to a considerable reduction in material demand, as steel is held in steel in-use stocks for longer periods of time. Many such retrofits are linked to energy efficiency, which opens the opportunity for broader retrofits and provides an incentive to use the building for longer to recoup the energy efficiency investment. The repurposing of buildings can be aided by modular design and other design considerations for future retrofitting, as well as aligning policy incentives to favour retrofits over demolition.

In the vehicle supply chain, lightweighting is pursued to improve fuel economy, including to allow a longer driving range with smaller batteries in the case of electric vehicles. Steel demand is reduced through a combination of better tailoring parts to their function, increased use of high-strength steel that enables using less steel for the same function, and substitution by other lighter materials such as aluminium, plastics and, to a lesser degree, advanced materials like carbon fibre-reinforced polymers, to the extent that such substitution reduces lifecycle emissions. Lightweighting in cars and trucks combined contributes 11% of the cumulative demand reductions in steel demand in the Sustainable Development Scenario (or a 2% reduction in demand in 2050).

Reductions in vehicle sales driven by changes in transport activity account for an additional 10% of cumulative reductions (or a 2% reduction in demand in 2050). In the Sustainable Development Scenario the number of vehicles is reduced through:

- Modal shift, in which travel moves increasingly away from private vehicles and towards public transport, cycling and shared mobility options.
- Improvements in the efficiency of freight transport networks.
- A reduction in total travel from urban densification, increased teleworking and reduced discretionary travel.

What happens to steel in the end-of-life phase is also an important aspect of material efficiency. When retrofitting or refurbishing an entire product or building is not possible, steel components can in some instances be recovered for direct reuse – that is, used again without remelting. Although reuse rates for steel components are currently low, considerable potential exists in certain applications, such as reusing steel beams and other building components, and using steel from ship plates and pipelines for other applications (Cooper and Allwood, 2012). This approach will require adequate documentation and labelling of materials to ensure quality control. In the Sustainable Development Scenario direct reuse accounts for 15% of the cumulative reductions in demand for crude steel relative to the Stated Policies Scenario (or a 3% reduction in demand in 2050).[2]

When direct reuse is not possible due to technical constraints, such as degradation of the material or incompatibility of the product, steel can be recycled and used as an input into secondary (and primary) production processes. While recycling does not reduce total steel demand, scrap-based production is considerably less energy and emission intensive than ore-based production. Steel recycling rates are currently quite high, with approximately 85% of end-of-life steel collected for recycling on average globally. Yet the recycling rate is quite variable depending on the end use – at the higher end, vehicles, industrial equipment, structural steel and appliances have recycling rates of 95% or higher, while packaging and reinforcing steel (rebar) are at

[2] Note that direct reuse here excludes reuse of whole steel building structures through repurposing, which are instead included in building lifetime extension.

the lower end, with recycling rates of only 50-60% on average globally, although with higher rates of more than 80% for packaging in some regions such as the European Union (APEAL, 2020; ArcelorMittal, 2020).

In the Sustainable Development Scenario, efforts are made to increase scrap collection rates, particularly for those end uses and regions seeing lower levels today, although some steel is likely to remain difficult to recover (for example, underground pipes and rebar in obsolete foundations). By 2050 the overall collection rate increases to about 88% in the Stated Policies Scenario, and just over 90% in the Sustainable Development Scenario.

Beyond collection rates, scrap availability for use in secondary production is inextricably linked to steel demand and material efficiency. Scrap becomes available at multiple stages in the steel value chain (Box 2.2). This scrap is used in secondary production routes, in both electric arc furnaces and induction furnaces, and is also often combined with iron ore at scrap rates typically up to about 15-25% in primary production routes, including foundries producing cast iron. In 2019 it is estimated that approximately 865 megatonne (Mt) of iron and steel scrap were available for use globally, comprised of about 20% home scrap (165 Mt), 30% prompt scrap (255 Mt) and 50% end-of-life scrap (445 Mt). Of this, about 8% (70 Mt) was used in cast iron foundries via a combination of internal recirculation and additional end-of-life scrap. This left just under 800 Mt of scrap available for steel production.

Box 2.2 Scrap types and availability

The name "scrap" may suggest that this is a waste product – something to be discarded – but quite the contrary, it is a vital industrial material flow. Steel scrap is produced throughout the steel supply chain and is recycled within the industry. Steel is one of the most recycled materials globally, with an average collection rate of around 85% currently.

Scrap steel is used in the steel industry in both primary and secondary steelmaking, with the advantage that its chemical composition is very close to that (if not identical) to the desired product. This means that there is a significant benefit when it comes to energy consumption, wherever it is used in the production process. Scrap is typically categorised in three ways:

Home scrap: also known as return scrap, internal scrap or semi-manufacturing scrap, this material is generated due to the imperfect yields of steelmaking, rolling and finishing processes within a site. This scrap does not usually leave the steel mill and most is recycled immediately. It is generated in proportion to current levels of steel production.

Prompt scrap: also known as new scrap, industrial scrap or manufacturing scrap, this material is generated during the manufacture of steel products by first-tier customers, and is generally of high quality and near zero contamination. Most of this scrap is recycled within a year and is generated in proportion to current levels of steel production.

End-of-life scrap: also known as old scrap, obsolete scrap or post-consumer scrap, this material is generated at the end of a steel-containing product's lifetime, which can be anything from less than a year to more than a century. Recycling of this form of scrap depends on the collection and sorting practices of the jurisdiction in which the steel product is finally used, and the volumes available depend on historical production volumes and patterns of use.

From a material efficiency standpoint, use of end-of-life scrap is desirable when life extension or direct reuse is not possible, and thus collection of end-of-life scrap should be maximised. Meanwhile, home scrap and prompt scrap represent steel that has not been used, and thus their generation should be avoided as much as possible, given that remelting adds energy use and emissions to the steel production process. Nonetheless, where home and prompt scrap cannot be avoided, their collection and use in secondary production still results in energy and emission savings relative to primary production.

While scrap can make an important contribution to production, it has historically only met a proportion of steel demand, accounting for about one-third of total metallic inputs to steel production globally in 2019, the remainder of inputs being ore. This is due to consistent historical growth in steel demand and the lifetime lag between products coming into service and when they become available for recycling – so, lower inputs in previous decades cannot meet the higher demand requirements of subsequent decades. While scrap is often used in the region where it is generated, it has significant monetary value and is therefore traded internationally to some degree. This facilitates higher usage globally, allowing regions with abundant scrap to export it to those that are short of it.

In the coming decades total scrap availability is expected to increase considerably, driven primarily by the release back into the system of steel stock (end-of-life scrap) that has built up in past decades. Meanwhile, efforts to improve yields will lead to little growth or even a decline in home and prompt scrap. In the Stated Policies Scenario, total iron and steel scrap availability increases by about 70% to reach 1 480 Mt in 2050 (of which 1 400 Mt is available for steel production as opposed to iron foundries). Despite this significant growth, scrap still only accounts for about 45% of inputs into the 2 535 Mt of steel produced in that year, again due to demand growth and the lag in steel stock turnover. The share of home scrap out of total scrap available falls to 12% in 2050 as a result of internal efficiency improvements (from 20% in 2019) and prompt scrap falls to 22% (from 30% in 2019), driven by improvements in semi-manufacturing and manufacturing yields. Excluding scrap generated in foundries and from cast iron, this is equivalent to 19% of crude steel production not immediately making it into a product in 2050 (i.e. ending up as home or prompt scrap), compared to 22% in 2019. Meanwhile, the share of end-of-life scrap increases to 67% (from 50% in 2019), as steel stocks built up over the previous decades reach end-of-life.

Material efficiency measures in the Sustainable Development Scenario lead to further changes in scrap availability. While improved collection rates lead to a small increase in scrap availability, most material efficiency measures reduce the availability of scrap:

- Improved manufacturing yields further reduce home and prompt scrap generation.
- Lower levels of overall demand reduce total throughput and thus scrap becoming available at all three stages.
- Lifetime extension holds steel in in-use stocks for longer and thus reduces end-of-life scrap.
- Direct reuse diverts scrap from recycling.

The result is that in the Sustainable Development Scenario the availability of iron and steel scrap increases from current levels by a more modest 43% to reach 1 240 Mt in 2050 (of which 1 160 Mt is available for steel production as opposed to iron foundries), comprised of 10% home scrap, 16% prompt scrap and 74% end-of-life scrap. Excluding scrap generated in foundries and from cast iron, this is equivalent to now only 14% of crude steel production not immediately making it into a product in 2050 (i.e. ending up as home or prompt scrap).

While these material efficiency measures reduce the potential for secondary production, they also reduce total steel demand and therefore lead to greater energy and emission savings – it is less emission intensive to avoid producing a tonne of steel altogether than to produce it and later have it available as scrap for secondary production. Despite lower absolute scrap availability, scrap accounts for a similar share of metallic inputs to total production in 2050 – 45% – in the Sustainable Development Scenario as in the Stated Policies Scenario, given lower total demand.

When considering the potential for scrap use, it should be noted that end-of-life scrap may contain contaminants – including trace metals, such as copper, tin and nickel, which are used in tandem with steel in products – or may have degraded over the course of its lifetime, which could lead to lower quality of secondary steel.

Contamination can generally be well-managed through operational techniques, such as separating non-ferrous metals from scrap, or by diluting with ore-based steel. Designing products with cost-effective end-of-life material separation in mind, more careful demolition and dismantling techniques, and improved scrap sorting and separation will be important to reduce contamination, and policy will be needed to help incentivise these measures. This will ensure that the majority of steel grades can be produced via the secondary route and secure the long-term continued recyclability of steel by limiting lower-quality steel from entering circulation.

A final aspect to note is that the steel industry can be a contributor to material efficiency in the cement sector, through the provision of slag. Slag is a co-product of ironmaking and steelmaking, consisting of iron ore and impurities (a mixture of silica and oxides) removed from raw materials in the blast furnace and hot metal (liquid iron) during processing in the basic oxygen furnace (BOF) converter. Slag is generated at a rate of around 400 kilogrammes (kg) per tonne of crude steel produced via the blast furnace-basic oxygen furnace (BF-BOF) route.

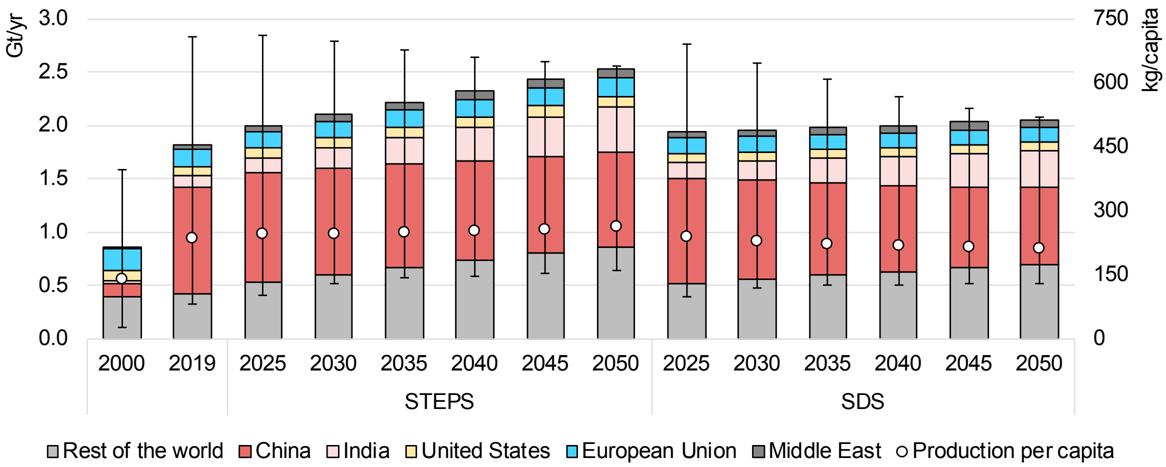
Several types of slag are marketed for use in various applications, including concretes, roofing, railway ballast, insulation, tiles, bricks and road construction (World Steel Association, 2018). Granulated blast furnace slag, in particular, has chemical properties that enable it to substitute for a proportion of clinker in blended cements. Since clinker is the most emissions-intensive component in cement manufacturing, use of slag reduces the emission intensity of cement production significantly. Slag can constitute 30-70% of the mass of cement, leading to large emission reductions per tonne of cement (ECRA, 2017). However, its absolute quantity available is limited by total BF-BOF steel production, and this quantity is quite small relative to total cement production: about 550 Mt of slag was produced in 2019 relative to over 4 000 Mt of cement production. Furthermore, slag production is set to decline in the Sustainable Development Scenario as the BF-BOF route decreases its share of total production, with only 370 Mt of slag produced in 2050.

Production projections

Steel is a highly traded commodity. Therefore regional production does not always directly correspond to regional patterns of demand for steel-containing end-use products, nor demand for steel for manufacturing. Nonetheless, changing demand patterns are expected to lead to some shifts in the regional distribution of global steel production in the future. National industrial policies also have an influence. While it is impossible to predict with certainty which regions will produce what share of global demand in the long term, the present scenarios provide a possible projection of future distribution of production.

Currently China accounts for over half of global steel production (Figure 2.4). This large share results from particularly high growth in production between 2000 and 2013, during which China's steel output increased more than sixfold. Meanwhile, the output of a number of other leading producers, such as the United States and Japan, remained relatively constant. Such major growth in Chinese steel production took place during a period of very rapid economic development and industrialisation. Increasing manufacturing capacity and infrastructure build-up required large volumes of steel inputs. The rapid build-up of steel production capacity in China has led to excess capacity globally, which is depressing global steel prices. In recent years the Chinese government has therefore implemented measures to curb overcapacity. We expect production in China to gradually begin declining as domestic demand ebbs in the coming years, driven by structural changes in the economy that the Chinese government is implementing. In both the Stated Policies Scenario and the Sustainable Development Scenario, China's steel production falls and accounts for around a third of global production by 2050.

Figure 2.4 Regional steel production and production per capita by scenario



Notes: STEPS = Stated Policies Scenario, SDS = Sustainable Development Scenario. Production per capita: dot represents the global average; the range represents the spread of regional values.

Steel production in advanced economies remains relatively stable through 2050 while declining markedly in China, the single largest driver of past global growth. India drives world production growth to 2050 as output rises by three- to fourfold by 2050 in both scenarios.

Following China, the leading steel producers in 2019 included the European Union (9% of global production), India (6%), Japan (5%), the United States (5%), Korea (4%) and the Russian Federation ("Russia") (4%). Considerable growth in steel production in India is expected in the coming years, driven by economic development and the government's stated intention to build up the nation's steel industry. This growth would be in line with its ambitions under the "Make in India" initiative to transform the nation into a global manufacturing hub (Chapter 3). India's production increases nearly fourfold by 2050 in the Stated Policies Scenario, and threefold in the Sustainable Development Scenario. This brings India's production in both scenarios to 17% of global production, significantly reducing the dominance of China. Thus, India's pathway is a critical component of any sustainable transition in the steel sector.

In other economies, while production changes in the future may be less marked in terms of global production, they can be domestically significant nonetheless. Production in the Middle East is expected to more than double by 2050 relative to 2019 in the Stated Policies Scenario, with the region accounting for almost 4% of global production in 2050. This is driven in part by the availability of inexpensive natural gas, which facilitates direct reduced iron production, as well as a growing number of large infrastructure developments. In many emerging economies in Latin America, Africa and other parts of Asia that currently have very small steel industries, output is expected to increase by anywhere between twofold and above fourfold in the Stated Policies Scenario (although given the low starting levels, this increase still represents a small percentage of global demand). Meanwhile, advanced economies are not expected to make large additions to steel capacity over the coming years, and thus production in markets such as Japan, Korea, the United States, Europe and Russia is expected to remain relatively constant in the Stated Policies Scenario. In both emerging and advanced economies, the production trajectory in the Sustainable Development Scenario is reduced relative to the Stated Policies Scenario through material efficiency, as discussed above.

Technology pathways towards zero emissions

As discussed in Chapter 1, steel is both a contributor to and a key enabler of mitigating CO_2 emissions from the energy system. It is also one of the most energy- and emissions-intensive bulk materials produced globally. Therefore the iron and steel sector must undertake significant steps to transform its production processes if it is to contribute to a sustainable transition of the energy system. The high reliance on coal in current primary steel production, long-lived capital assets and the sector's exposure to international trade and competitiveness make this transition towards near-zero emissions challenging. It is for these reasons that the sector is sometimes referred to as among those that are "hard to abate". This section examines the main technologies and strategies available to put the iron and steel sector on a pathway towards zero emissions in the latter half of this century. Box 2.3 provides an overview of the technology modelling conducted for this analysis.

Box 2.3 Technology modelling methodology

The iron and steel model is one of a group of five that the IEA uses to examine energy-intensive sub-sectors. The other four are cement, chemicals and petrochemicals, pulp and paper, and aluminium. The models interact with other models in the IEA via price signals (e.g. for fuels), availability of resources (e.g. biomass) and user constraints (e.g. CO_2 emission trajectories and the availability of CO_2 storage). The 2020 edition of *Energy Technology Perspectives* describes the wider energy system context for this technology roadmap and contains a more detailed description of the full ETP Model.[3]

The industry modelling architecture used for this publication consists of four main components: activity modelling (production and demand), stock modelling (stocks or inventory of steel in society and the potential for material efficiency), capacity modelling (examining the existing stock of production equipment) and technology modelling (the selection of technologies used to meet the required production levels). This industry modelling architecture sits within a broader energy system modelling architecture for the whole energy system, with various cost signals and constraints being taken from other sub-sector model results. The aim of the modelling is to present energy, emissions and investment implications of least-cost technology pathways for a given scenario definition.

The technology modelling is the heart of the model, with the other models creating intermediate results with which to inform its inputs and constraints. The technology model is implemented in the TIMES (The Integrated MARKAL-EFOM System) model generator, using 40 model regions to obtain global coverage. The iron and steel sub-sector model selects from a range of iron- and steelmaking technologies with a technology readiness level (TRL) of 5 and above (for discussion of the IEA TRL scale, see Box 2.5). The technology choice is performed in annual time steps, based on constrained optimisation that aims to minimise system cost while satisfying demand for crude steel. System cost includes capital expenditure (CAPEX) and fixed operating expenditure (OPEX), along with energy and feedstock costs where relevant. Cost and energy parameters for technologies at an early stage of development are obtained in consultation with industry experts.

Steel demand and production projections are based on country-level macro-economic data and historical production levels, informed by regional saturation levels from the modelling of steel stocks in society, and also bottom-up signals from other IEA end-use sector models (e.g. the transport and buildings sector models).

[3] Please see *ETP 2020* for information about the full modelling context (https://www.iea.org/reports/energy-technology-perspectives-2020/). More detailed documentation of the full ETP Model is found in the *ETP 2020* annex (https://www.iea.org/reports/energy-technology-perspectives-2020/etp-model).

The technology model must satisfy these production levels while conforming to various scenario-specific constraints, such as limits on the availability of scrap and certain energy carriers, as well as constraints on CO_2 emissions and other constraints to reflect the regional political economy and other circumstances. Scrap availability and the subsequent share of secondary production is based on a signal from the stock model.

The capacity model provides a signal of the existing capacity of steelmaking production facilities, along with a projection of their phase-out rate over time. The capacity model takes account of the regional variation of specific technology types, as well as the timeframe since the installation or last major refurbishment of each individual plant, to provide region-specific phase-out rates for existing facilities.

Energy consumption and CO_2 emissions

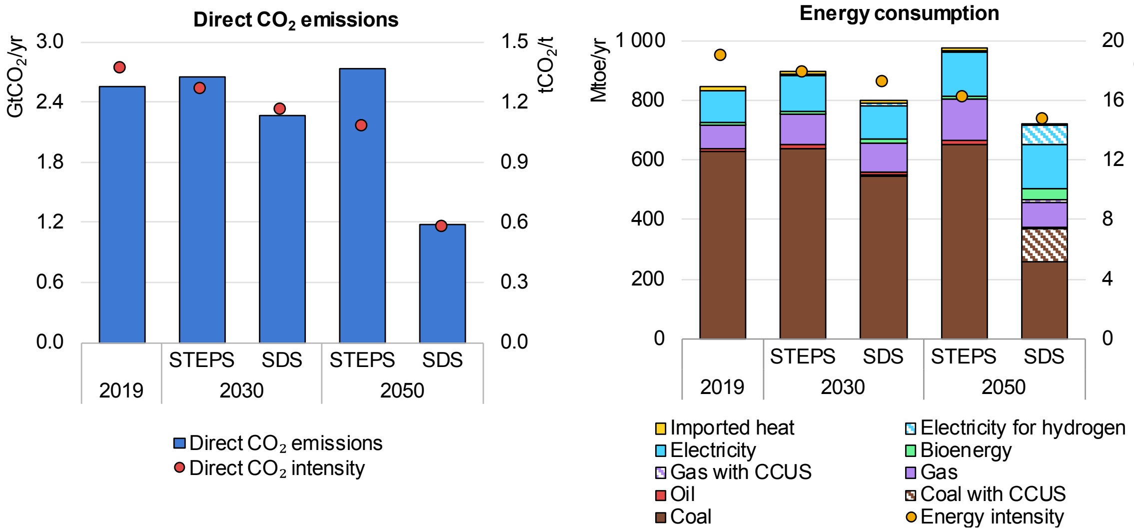
The iron and steel sector is a highly energy-intensive industry, with coal accounting for about 75% of its energy inputs today. In 2019 the sector's consumption of coal stood at around 900 million tonnes of coal equivalent (Mtce) (26.2 exajoules [EJ]), or around 15% of global primary demand for coal. The majority of the coal is consumed in the blast furnace, a large proportion of which is transformed from coal to coke in the coke oven beforehand. In some regions, depending on the availability of alternative energy inputs, blast furnaces also use natural gas, oil products, waste or charcoal, as well as recirculated off-gases, but the shares of these energy inputs are usually small in the overall energy intake. After coal, electricity provides the next largest energy input, with around 1 230 terawatt hour (TWh) (4.4 EJ) consumed overall in 2019, of which about 25% is used by the electric furnaces for converting iron, direct reduced iron (DRI) and scrap into steel. Much of the remainder is used in semi-finishing and finishing processes. In addition, around 90 billion cubic metres (bcm) (3.4 EJ) per year of natural gas is consumed, mainly to generate heat and reducing gases (which includes 5 Mt of hydrogen derived from the natural gas) in DRI furnaces, accounting for 10% of the sector's total energy demand.

Over the past two decades the energy intensity of steel production has reduced slightly according to IEA energy statistics. But these relatively small energy intensity declines have been far outweighed by increases in output. On average for the sector as a whole, around 19 gigajoule (GJ) (0.45 tonnes of oil equivalent) of final energy is required per tonne of crude steel (including finishing processes, ferroalloy production and other ancillary processes – see Box 1.3 for an overview of the analytical boundaries used in this analysis). The energy intensity of production is heavily influenced by the proportions of scrap and iron ore being used, with primary production being around eight times more energy-intensive than that based on scrap alone (on a final energy basis). Other factors, such as the quality of iron ore, also affect the energy intensity. The global dominance of primary production routes that rely mostly on iron ore inputs – these routes account for around 80% of production – means that the sector is highly reliant on fossil fuels. As a result the sector emits around 2.6 Gt of direct CO_2 emissions annually, which is close to 30% of the current total of direct industrial emissions (see Box 2.4 for a discussion of indirect steel sector CO_2 emissions).[4]

In the Stated Policies Scenario, sectoral energy consumption is projected to moderately rise through to 2050, as demand for output rises while energy intensity gently declines (Figure 2.5). Coal demand remains relatively stable, whereas gas and electricity consumption rise to 155 bcm (70% increase) and around 1 740 TWh (40% increase) by 2050, respectively. This is a result of multiple factors. First, increased scrap availability (due to existing steel stock coming to the end of its lifetime and increased collection rates) enables a boost in secondary production, with the scrap share of total metallic inputs increasing from 32% to 45%. Second, production via the BF-BOF route declines, particularly in advanced economies, and is counterbalanced by increased gas-based DRI-EAF production in regions with advantageous access to gas (see section "Different regional contexts, different technology portfolios" for regional projections of different iron- and steelmaking routes).

[4] Note that in World Steel Association statistics, production is reported in terms of the share of oxygen blown converters (BOFs) and electric furnaces (EFs). In this publication, to arrive at the primary share, the portion of EF production using DRI is added to the BOF share, leading to a higher share of primary production compared to the share of BOF production alone. Secondary production here is defined as production in EFs, including electric arc furnaces (EAFs) and induction furnaces, for which scrap accounts for all (or almost all) of the metallic input.

Figure 2.5 Direct CO_2 emissions and energy consumption in the iron and steel sector by scenario



Notes: STEPS = Stated Policies Scenario, SDS = Sustainable Development Scenario. The CO_2 and energy intensities are stated on a sectoral basis (including finishing processes, ferroalloy production and other ancillary processes). See Box 1.3 in Chapter 1 for a detailed explanation of the analytical boundaries used in this analysis.

By 2050 the direct CO_2 emission intensity of steel production is almost 50% lower in the Sustainable Development Scenario relative to the Stated Policies Scenario, while the energy intensity difference is only about 10%.

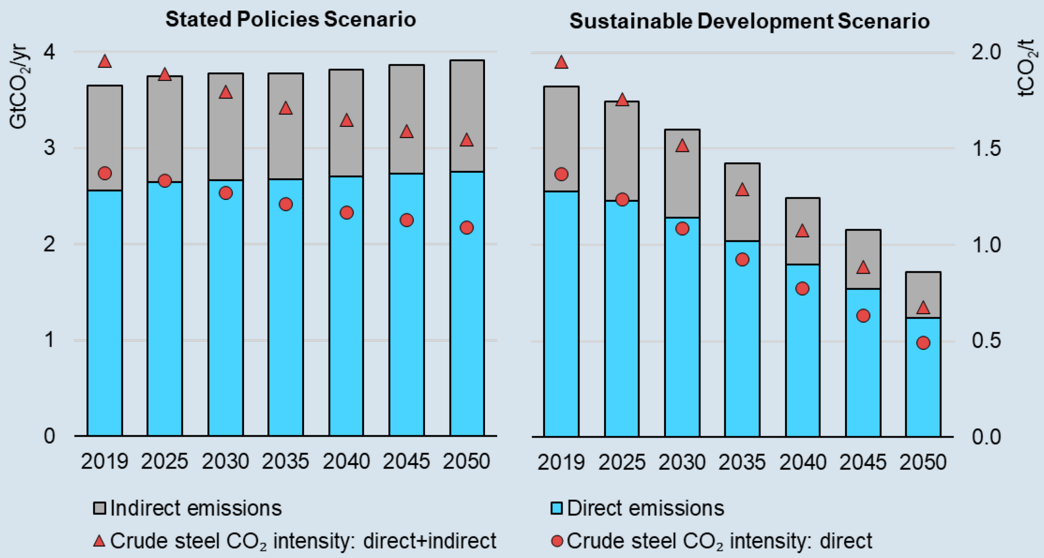
The 16% growth in total energy consumption, along with the previously mentioned shifts in fuel shares, translates into a 7% direct CO_2 emissions increase by 2050, relative to 2019. However, due to the increasing share of scrap-based production as well as process technology performance improvements, the average sectoral energy and direct CO_2 emission intensities of crude steel are both moderately reduced, to 16 gigajoules per tonne (GJ/t) and 1.1 tonnes of carbon dioxide per tonne (t CO_2/t) of crude steel, respectively (compared to 19 GJ/t and 1.4 t CO_2/t, in 2019).

Box 2.4 How are indirect emissions tackled?

The emissions footprint of the iron and steel sector, including both direct and indirect CO_2 emissions, was approximately 3.7 Gt CO_2 in 2019, around 1.1 Gt CO_2 higher than its direct emissions footprint alone. To maintain consistency with the sectoral definitions and accounting boundaries used in IEA publications, and to avoid double counting at the total energy system level, the results of our scenario analyses are presented on a direct emissions basis. However, the accounting methodology used by the steel industry typically considers these indirect emissions to be within its direct accounting boundary, as discussed in Chapter 1 (Box 1.3).

The way in which the steel industry derives a substantial proportion of the electricity and heat it uses to fuel its processes is unique: off-gases from coke ovens and blast furnaces are used in on-site electricity, heat and co-generation plants. Electricity and heat generated from these off-gases can be quite emissions-intensive: typically around 280 grammes of carbon dioxide per kilowatt hour (gCO_2/kWh) of electricity produced from coke oven gas and 1 640 gCO_2/kWh produced from blast furnace gas (the latter currently accounts for about 80% of off-gases produced). This compares to around 800 gCO_2/kWh produced from coal in a supercritical steam turbine plant and around 350 gCO_2/kWh produced from natural gas in a combined-cycle gas turbine plant.

Direct and indirect CO_2 emissions and intensities of crude steel production



In the Stated Policies Scenario the BF-BOF route remains the dominant pathway for producing steel, with around 250 Mtoe of off-gases being generated in 2050. About 60% of these off-gases are used to fulfil on-site heat requirements (their emissions are considered direct emissions) and the remainder is used to produced power for the steel sector (their emissions are considered indirect emissions). Global direct emissions are 2.7 Gt CO_2 in 2050, but when adding indirect emissions the figure rises by over 40% to 3.9 Gt CO_2. This means that the steel industry's contribution to global energy sector emissions is projected to be around 7% on a direct emissions basis in 2050, and 10% when including indirect emissions – very similar shares as today.

In the Sustainable Development Scenario the technology portfolio undergoes a radical shift, with widespread deployment of production pathways that either manage the carbon contained in these gases once it is generated (e.g. by deploying carbon capture, use and storage [CCUS]), or avoid the generation of off-gases in the first place (e.g. switching to hydrogen-based production). By 2050 the total generation of off-gases is 130 Mtoe, about 50% lower than in the Stated Policies Scenario, and 40% lower than in 2019. This implies greater use of on-site generation using other fuels (e.g. natural gas or bioenergy), increased supply through dedicated renewable power or greater reliance on imported grid electricity. In the Sustainable Development Scenario the electricity supply (excluding that supplied by off-gases) decarbonises by over 95%, from 540 gCO_2/kWh on average in 2019 to 18 gCO_2/kWh in 2050[5].

The change in emission intensity in each scenario is marked. From a direct emission intensity of 1.4 t CO_2/t in 2019 (2.0 t CO_2/t including indirect emissions), it declines to 1.1 t CO_2/t in the Stated Policies Scenario by 2050 (1.5 t CO_2/t including indirect emissions). This reduction is due to a higher proportion of scrap as a share of total metallic inputs. In the Sustainable Development Scenario the decline is much steeper, reaching 0.6 t CO_2/t by 2050 (0.8 t CO_2/t including indirect emissions).

In contrast to the moderate increase in total energy consumption and consequent emissions in the Stated Policies Scenarios, marked declines in both occur in the Sustainable Development Scenario. In 2050 energy demand for steel is 121 Mtoe lower (14% lower) than in 2019. Total coal consumption is reduced by 40% from today, in large part due to the decline in the use of the BF-BOF route, resulting from a combination of increased secondary production and primary production shifting increasingly towards other innovative low-emission routes. However, electricity consumption doubles, amounting to 2 470 TWh in 2050 (including electricity required for electrolytic hydrogen production).

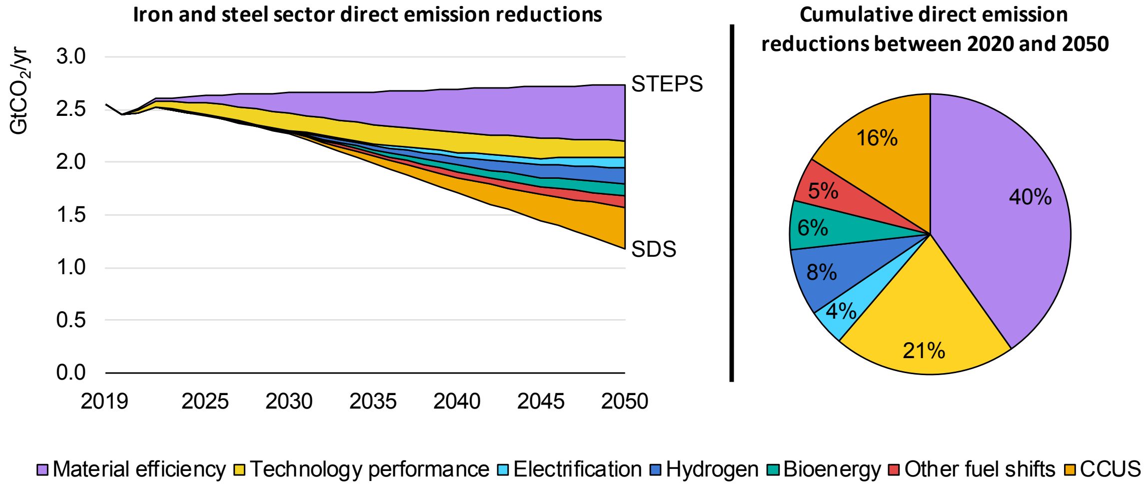
The scrap share of total metallic inputs to steel production in the Sustainable Development Scenario increases to 45% in 2050, the same as in the Stated Policies Scenario. This increase in secondary production contributes to reducing the energy intensity of steel production, as do improvements in technology performance and shifts to innovative primary production routes. As a result, the average sectoral energy intensity of steel production is 12 GJ/t in 2050 in the Sustainable Development Scenario, around one-third lower compared to today. As a result of this lower energy intensity of steel production, plus even more importantly a strong shift to technologies that specifically target reductions in emission intensity, direct CO_2 emissions fall by 2050 to less than half of their starting value in 2019 (1.2 Gt CO_2 in 2050). This is achieved via a 66% reduction in the average sectoral direct CO_2 intensity of crude steel production between 2019 and 2050, to 0.5 t CO_2 per tonne of crude steel (the reduction in CO_2 intensity is slightly greater than the total CO_2 emissions reduction due to somewhat increased production).

[5] In this report, average emission intensities are used to calculate indirect emissions for imported electricity and heat on a final consumption basis, after accounting for transmission and distribution losses. These final consumption values are higher than those calculated at the 'plant gate' of the power, heat or CHP plant.

A portfolio of mitigation options

Like the wider energy system, the iron and steel sector cannot rely on one technology or mitigation lever alone to make progress on its climate goals – it must pull on all levers that can make a difference for its transition to zero emissions to take place as quickly as possible. However, the relative importance of different mitigation options evolves over time. In the short term, the largest role is played by technology performance improvements within conventional routes and demand reduction through material efficiency, together delivering 90% of the annual sectoral emission reductions in 2030 in the Sustainable Development Scenario. In the medium to long term, CCUS and fuel shifts – away from coal towards natural gas, hydrogen and bioenergy – play a larger role. When examining emission reductions cumulatively during 2020-50, the largest roles are played by material efficiency, technology performance improvements and CCUS (40%, 21% and 16%, respectively, relative to the Stated Policies Scenario) (Figure 2.6).

Figure 2.6 Iron and steel sector direct CO_2 emission reductions in the Sustainable Development Scenario by mitigation strategy



Note: STEPS = Stated Policies Scenario, SDS = Sustainable Development Scenario. Emission reductions are measured relative to the Stated Policies Scenario; as such, the proportion of improvements relative to today that occurs in both scenarios is not represented (e.g. a significant share of increases in scrap-based production). Material efficiency here refers specifically to demand reduction. Electrification here includes only direct electrification, primarily via conventional technologies, including shifts towards secondary production in EFs and electrification of ancillary process equipment like preheaters and boilers. Hydrogen here refers specifically to electrolytic hydrogen, while so-called blue hydrogen (via natural gas-based DRI with CCUS) is included under CCUS. Other fuel shifts include primarily coal to natural gas switching.

Technology performance improvements and material efficiency deliver 90% of annual emission reductions in 2030. In the longer term, innovative technologies such as carbon capture-equipped and hydrogen-based production are required for further emission reductions.

Technology performance improvements

Technology performance improvements are defined in this report as the incremental reductions in energy intensity of a specific process. By contrast, the step changes in efficiency achieved by switching to an alternative production pathway – for example, as occurs during an increase in the share of secondary steel production – are classified as electrification or other fuel shifts. Incremental change can be achieved through improvements in the operation of equipment and by upgrading process equipment to commercially available best available technology (BAT),[6] which reduces the energy demand required per tonne of process output. An energy saving of around 20% per tonne of crude steel can be achieved by improving operational efficiency and adopting BAT for all the units of the BF-BOF production pathway, relative to the global average energy intensity for this route today. It is projected that all plants adopt and efficiently operate BAT by 2040-50 in the Sustainable Development Scenario and are on track to do so by 2060-70 in the Stated Policies Scenario.

Process optimisation and integration, including predictive process control and monitoring, can reduce energy demand in steel plants, in turn also reducing operating costs. Optimisation helps make use of all available energy flows, such as off-gases, helping to eliminate their flaring and reducing emissions. Enhanced digitalisation of process controls, including the integration of artificial intelligence to increase predictive power, offers the ability to schedule maintenance at more opportune times, and better adapt to changes in the order book of a plant. The minimisation of delays across the whole process chain results in lower energy demand for reheating, as well as higher effective capacity levels. Process optimisation is also helpful to increase the reliability of processes, thus avoiding thermal losses during stopping and restarting equipment. Furthermore, adjusting inputs can have a considerable impact, such as increasing oxygen injection into the blast furnace to reduce coke consumption. These process optimisation measures play a critical role in the direct CO_2 emission reductions attributable to technology performance improvements in the Sustainable Development Scenario.

BAT relates primarily to techniques to recover and transform excess energy into useful energy throughout the different steps of existing steel production pathways. While some of these technologies directly reduce fuel inputs into steel production, a number of them are instead beneficial by producing lower-emission electricity from waste heat rather than directly from fuel. Thus, while a part of the emission benefits

[6] The energy-saving potential of implementing BAT differs on a site-by-site basis given the specific characteristics of each facility (e.g. relative size of existing equipment, operating conditions, plant layout). Our analysis is based on approximations on the energy-saving potential that was obtained in best-performing state-of-the-art facilities.

of BAT are attributable to direct steel sector CO_2 emissions, a considerable share of the impact is on the indirect proportion of emissions.

There are several specific examples of technology modifications. Waste heat recovery systems – applied either through retrofits or to new builds – can reduce the net energy consumption of certain units such as EAFs and BOFs. Deployment of waste heat recovery can reduce the average energy intensity of crude steel production via the BF-BOF route by up to 2%. This heat can be recirculated to preheat input streams and generate electricity, reducing the amount of energy consumed, or can be exported for use outside the steel mill. Coke dry quenching (CDQ) recovers the latent heat from the hot coke output of coke ovens and uses it to generate electricity, and also somewhat reduces total coke oven fuel consumption. At the same time, a higher quality coke is produced, which can facilitate a reduction in the coke rate into blast furnaces, by around 2% (Itakura, n.d.). Today about half of coke ovens are equipped with CDQ globally, with nearly all coke ovens being CDQ equipped by 2050 in the Sustainable Development Scenario through CDQ being added to new plants as capacity turns over.

Additionally, blast furnaces can be installed with top-pressure recovery turbines (TRTs), which use the pressure and heat of the blast furnace gas for electricity generation. This can yield around 30-40 kWh of electricity for each tonne of pig iron produced when using typical wet de-dusting of top gases (it can be increased to 50-60 kWh if using dry de-dusting), reducing the load on utilities and imports of power from the grid. Currently less than a fifth of blast furnaces around the world are equipped with TRTs (Steel Institute, 2018). This relatively low uptake is likely the result of their application only where it is economical, based on the level and stability of grid electricity prices for the facility. In the Sustainable Development Scenario, this more than doubles by 2030 as existing blast furnaces are retrofitted and new ones integrate this equipment when they are installed. By 2050 almost all remaining blast furnaces are equipped with this technology.

The quality of raw materials is another factor that plays a central role in the overall efficiency of the steelmaking process. For example, improved coke quality facilitates a lower coke rate into the blast furnace, which may be achieved through processes like CDQ. As already mentioned, CDQ also reduces energy consumption directly by allowing the capture of latent heat from the hot coke, although the overall impact is relatively small – energy consumption for coking using CDQ is reduced by about 5% relative to that using a regular coke oven.

Additionally, higher iron content in ores, beneficiation at the mine, or a greater degree of agglomeration before its introduction into the furnace can all reduce the energy needed for iron ore reduction and improve the overall energy intensity of the crude steel production process. High-quality iron ores are more scarce, and beneficiation at the mine would shift some energy use to the mining sector where the ore preparation occurs. The introduction of scrap to various stages in the primary steelmaking process reduces energy needs and also helps with temperature control. Therefore, increasing the share of scrap in primary routes could be an avenue to technology performance improvements. However, this strategy is limited by overall availability of scrap and competition from other potential users, given its multiple potential uses in the steelmaking process.

It should be noted that some energy consumption increases can result from implementing environmental protection measures, like air filtration systems that reduce air pollutants. These beneficial adjustments do not, however, make other efforts to reduce energy consumption any less beneficial.

Fuel switching and electrification using commercial technologies

Fuel switching – as defined in this report – refers to the full or partial substitution of coal and other fossil energy inputs with less carbon-intensive alternatives, such as natural gas and bioenergy, without requiring a switch away from commercially available technologies. Similarly, electrification refers to shifting to electricity using commercial technologies. Fuel shifts and electrification resulting from a near-zero emissions technology option are not included in these categories, but rather are discussed in detail in the next sub-section "Deploying innovative near-zero emission technologies", and are presented separately in our mitigation levers. For example, the use of electrolytic hydrogen as a primary reducing agent in DRI furnaces is considered under "hydrogen" in Figure 2.6.

While coal remains a key input to the iron and steel sector throughout the projection horizon, a partial switch to other less carbon-intensive energy carriers delivers significant emission reductions (Figure 2.7). In the Sustainable Development Scenario global consumption of coal for ironmaking – the most coal-intensive step in producing steel – is projected to drop by 8% by 2030 and almost 30% by 2050, relative to 2019. This is a result of reducing the share of primary production in total steelmaking, alongside shifts towards natural gas, biomass, electricity and hydrogen.

In the Sustainable Development Scenario coal to natural gas shifts are facilitated by increased use of gas injection blast furnaces, and by the additional deployment of natural gas-based DRI furnaces. This includes deployment of already commercially available DRI technologies producing sponge iron (e.g. Midrex and Energiron), as well as potentially in the longer term technologies that are still in development. These include the production of pig iron using natural gas-based direct reduction, as is being explored in a project by Petmin in the United States (Petmin, 2019). However, these strategies are only practical in regions with access to large quantities of low-cost natural gas, such as the United States, Russia, the Middle East, and parts of Central and South America.

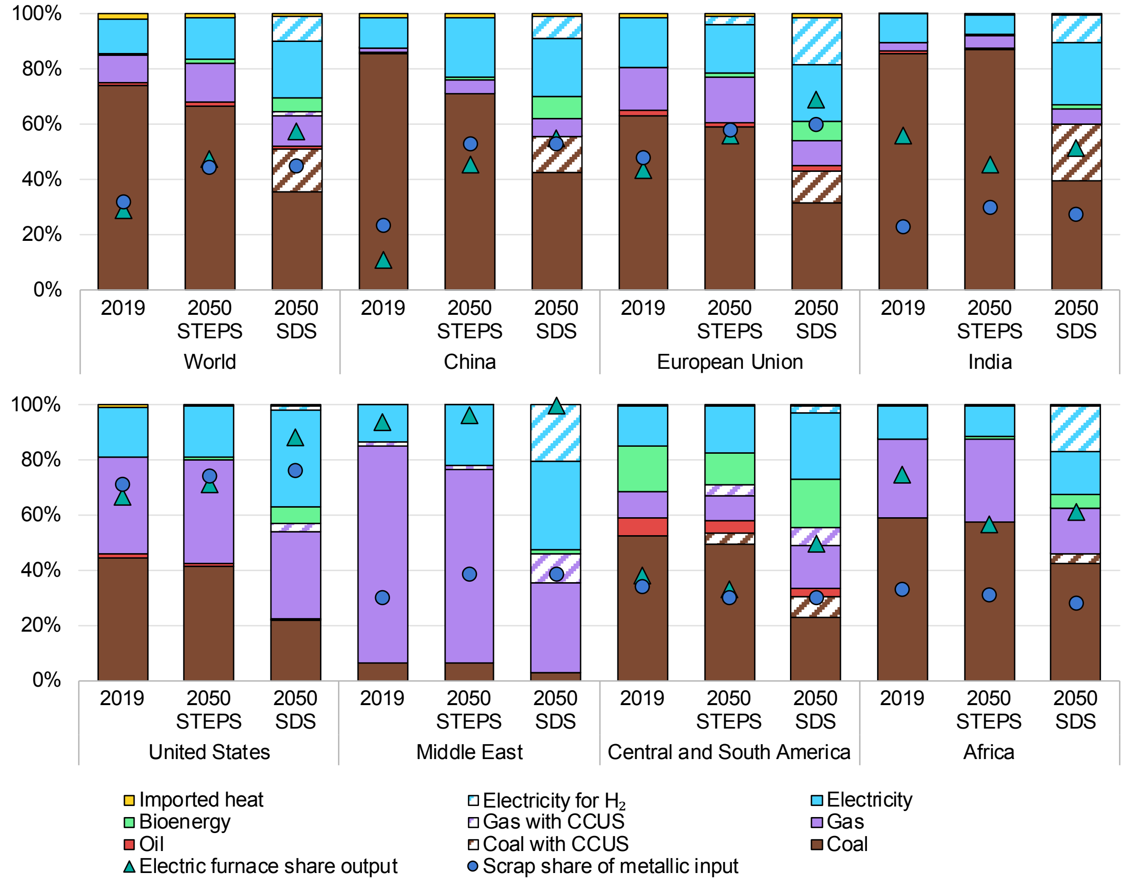
Natural gas achieves substantial emission reductions relative to coal. For example, steel produced using natural gas-based DRI-EAF typically emits about 20% fewer direct emissions than that produced using coal-based BF-BOF, and even greater reductions are targeted by the Petmin project. However, without carbon capture and storage (CCS) it does not come close to near-zero emissions. As such, it can play a useful role as a transition fuel – for example, by deploying natural gas DRI in the short term, with the longer-term objective of equipping the DRI unit with CCUS or substituting electrolytic hydrogen to fuel the unit. Given this combination of factors, coal to natural gas shifts account only for 5% of cumulative emission reductions relative to the Stated Policies Scenario.

The injection of biomass and hydrogen into both existing and newly constructed blast furnaces, and hydrogen enrichment of the synthesis gas fed into DRI furnaces, are further steps that are taken in the Sustainable Development Scenario to switch away from fossil fuels (see further discussion on hydrogen use in the following section on innovative technologies). Biomass injection into blast furnaces, at a level of up to 1.8 GJ/t of hot metal, is already applied commercially in Brazil (Nascimento et al., 2012). However, not all types of biomass are suitable for direct injection due to their chemical and physical properties. As a result, only upgraded biomass attains this level of substitution, either via pyrolysis (charcoal) or torrefaction (bio-coal), the latter of which is being researched currently as part of the Torero project (Torero, 2018).

While municipal and industrial waste could provide another partial source of biogenic hydrocarbon matter for injection (following treatment to reach the required consistency and calorific content), it is difficult to quantify the biogenic share of waste. Since the CO_2 intensity of non-biogenic waste is highly variable and can be higher than that of fossil fuels, use of waste as an alternative fuel should be regarded with considerable caution and as such is not a key strategy pursued in the Sustainable Development Scenario.

Charcoal blast furnaces – whereby almost all energy inputs can be delivered in the form of biomass – are used to a limited extent in some regional contexts, such as in Brazil. However, this is unlikely to be a scalable strategy for a global industry for two main reasons. The first is the limit on the maximum size of the installation when using charcoal due to the differing mechanical properties of charcoal compared to coke. The second, and more crucial, is the limited supply of sustainably sourced bioenergy and its need for competing uses across the energy system in the Sustainable Development Scenario. Even in Brazil, where charcoal use in steel production is currently quite prevalent, blast furnaces running almost solely on charcoal contribute only a small proportion of national production. Much of the charcoal is instead used in smaller proportions for injection into blast furnaces, as well as for other processes like coking, pelletising and in secondary production. Overall, the share of bioenergy in the sector's total energy input mix increases from less than 1% to 5% in 2050 in the Sustainable Development Scenario, of which about half is used in China and one-fifth in Brazil. Bioenergy contributes 6% of the cumulative emission reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario.

Figure 2.7 Regional energy demand for steelmaking and electric furnace and scrap shares by scenario



Notes: STEPS = Stated Policies Scenario, SDS = Sustainable Development Scenario. H_2 = hydrogen.

Regions with a higher share of scrap-based production tend to have a higher share of electricity demand. Natural gas, mainly for DRI production, is more prevalent in regions where there is advantageous access to the fuel, such as the United States and the Middle East.

The contribution to emission reductions from electrification using conventional technologies is relatively low, at 4% of cumulative reductions. Increasing the share of secondary production in electric furnaces out of overall steelmaking is included in this category, but has a quite small effect because emission reductions are measured relative to what already takes place in the Stated Policies Scenario. In the Stated Policies Scenario we also project a substantially increased uptake of the secondary route, as more scrap becomes available throughout the projection period as steel-containing products reach end-of-life. Still, the increasing use of scrap over time in both scenarios is beneficial from an emissions standpoint relative to current levels, and also reduces total energy demand given the considerably lower energy consumption of secondary production.

The total share of electric furnaces is, however, considerably higher in the Sustainable Development Scenario, reaching 57% by 2050, compared to 47% in the Stated Policies Scenario in 2050 and 29% in 2019. The increase above the Stated Policies Scenario is driven largely by greater uptake of the DRI-EAF route (including DRI with CCUS and hydrogen-based direct reduced iron [H_2 DRI]). Using electricity to substitute for fossil fuels in the provision of process heat in equipment outside the main process units, particularly in preheaters and boilers, is another option where electrification makes moderate inroads. Direct electrification of core fossil-based processes with technologies that are currently commercially available would be impractical and very costly, but could become an option in the longer term with new innovations.

Deploying innovative near-zero emission technologies

Technology performance improvements, material efficiency and various forms of fuel switching using conventional technologies contribute 75% of cumulative emission reductions from 2020 to 2050 in the Sustainable Development Scenario. However, the role of innovative near-zero emission production pathways expands rapidly in the second half of the projection period. They are represented mainly by the CCUS and hydrogen segments in Figure 2.6. Many of the technologies facilitating these reductions are not commercially available today and so a wholesale shift to near-zero emission technologies is likely to take a long time. Not all of them have the same level of maturity (see Table 2.1 in the following section). In our scenario modelling, we include technologies that have at least reached the large prototype stage – or, specifically, are judged to be at a TRL of 5 or above (Box 2.5). This is to ensure there is a reasonable degree of understanding of the technical performance and economics of a given technology to be modelled.

Near-zero emission technologies can be broadly divided into two categories: those that retain fossil carbon as the key reduction agent in ironmaking, but mitigate the CO_2 emissions that arise ("CO_2 management"); and those that seek to avoid the generation of CO_2 in the first place by minimising the use of fossil carbon ("CO_2 direct avoidance"). Generally speaking, CO_2 management technologies tend to be at more advanced stages of development today. This section provides estimates of the CO_2 emission reduction potential of those technologies. Technical aspects related to their deployment, as well as their readiness level, are discussed in further detail in the following section.

Box 2.5 The technology readiness level (TRL) scale

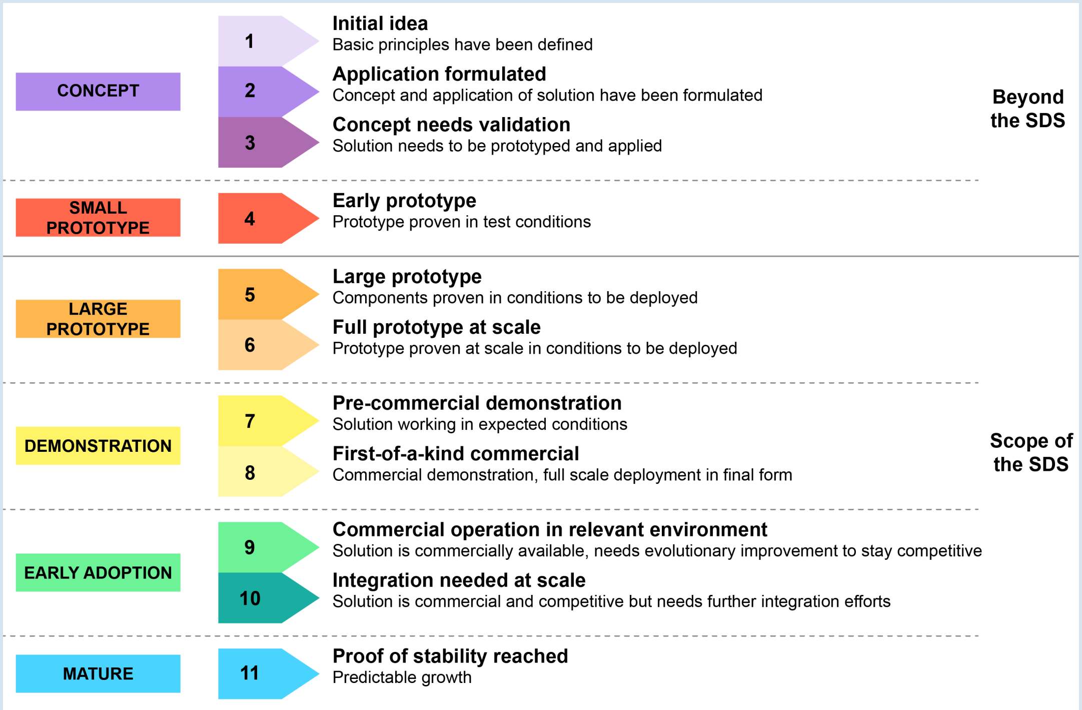
One way to assess where a technology is on its journey from initial idea to market is to use the technology readiness level (TRL) scale. Originally developed by the National Aeronautics and Space Administration (NASA) in the United States in the 1970s and used in many US government agencies since the 1990s, the TRL provides a snapshot in time of the level of maturity of a given technology within a defined scale (Mankins, 1995). The US Department of Defense has been using the TRL scale since the early 2000s for procurement, while the European Space Agency adopted it in 2008. In 2014 the TRL was applied for the first time outside the aerospace industry to assess EU-funded projects as part of the Horizon 2020 framework programme. It is now widely used by research institutions and technology developers around the world to set research priorities and design innovation support programmes.

The scale provides a common framework that can be applied consistently to any technology, to assess and compare the maturity of technologies across sectors. The technology journey begins from the point at which its basic principles are defined (TRL 1). As the concept and area of application develop, the technology moves into TRL 2, reaching TRL 3 when an experiment has been carried out that proves the concept. The technology now enters the phase where the concept itself needs to be validated, starting from a prototype developed in a laboratory environment (TRL 4), followed by testing of components in the conditions it will be deployed (TRL 5), through to testing in the conditions in which it will be deployed (TRL 6). The technology then moves to the demonstration phase, where it is tested in real-world environments (TRL 7), eventually reaching a first-of-a-kind commercial demonstration (TRL 8) on its way towards full commercial operation in the relevant environment (TRL 9).

Arriving at a stage where a technology can be considered commercially available (TRL 9) is not sufficient to describe its readiness to meet energy policy objectives, for which scale is often crucial. Beyond the TRL 9 stage, technologies need to be further developed to be integrated within existing systems or otherwise evolve to be able to reach scale; other supporting technologies may need to be developed, or supply chains set up, which in turn might require further development of the technology itself. For this reason, the IEA has extended the TRL scale used in this report to incorporate two additional levels of readiness: one where the technology is commercial and competitive but needs further innovation for its integration into energy systems and value chains when deployed at scale (TRL 10), and a final one where the technology has achieved predictable growth (TRL 11).

As technologies pass through each stage, the level of risk associated with technology performance is reduced, but the level of overall risk rises as capital expenditure requirements grow. However, innovation is rarely a linear progression. Not all technology designs make it to market or are deployed at scale. Stages of development can accelerate or slow down depending on technical or cost factors, and a given technology can be at different stages in different markets and applications. As the development of a technology generates new ideas for improvement, alternative configurations and potentially better components can appear even once a given technology configuration has become competitive. Stages overlap and run concurrently, feeding on one another.

TRL scale applied by the IEA



Note: SDS = Sustainable Development Scenario.

Source: Adapted from Mankins (1995), Technology Readiness Levels: A White Paper.

In the *ETP Clean Energy Technology Guide*[7] we have analysed the technology readiness of almost 400 individual technology designs and components across

[7] For more information please visit: www.iea.org/articles/etp-clean-energy-technology-guide.

different sectors, and have structured them hierarchically alongside others delivering the same service. This is an interactive framework that includes information on the level of maturity of different technology designs and components, as well as a compilation of cost and performance improvement targets and leading players in the field.

In this report we refer to several broader readiness categories, each of which comprises different ranges of specific readiness levels from the full TRL scale: mature, early adoption, demonstration, large prototype, small prototype and concept (technologies at "early prototype" and "concept" stages of TRL 4 or lower are not included in the Sustainable Development Scenario). Each technology type is assigned to one of these higher-level categories based on the granular levels of maturity of individual technology designs or components currently associated with that technology.

- **"Mature"** for commercial technology types that have reached sizeable deployment and for which only incremental innovations are expected. Technology types in this category have all designs and underlying components at TRL 11 (e.g. scrap-based electric furnaces).
- **"Early adoption"** for technology types for which some designs have reached the market and policy support is required for scale up. But there are competing designs being validated at demonstration and prototype phase. Technology types in this category have at least one underlying design at TRL ≥ 9 and others at lower TRLs (e.g. natural gas-based DRI with CCUS).
- **"Demonstration"** for technology types for which designs are at demonstration stage or below, meaning no underlying design at TRL ≥ 9, but at least one design at TRL 7 or 8 (e.g. innovative smelting reduction with CCUS).
- **"Large prototype"** for technology types for which designs are at prototype stage of a certain scale (e.g. 100% hydrogen-based DRI).
- **"Small prototype"** for technology types for which designs are at early prototype stage, meaning no underlying design at TRL 5, but with at least one design at TRL 4 (e.g. iron ore electrolysis).
- **"Concept"** for applications that have just been formulated but need to be validated.

The most important family of technologies within the "CO_2 management" category are those that integrate CCUS. In the Sustainable Development Scenario the iron and steel sector is projected to cumulatively capture 3.5 Gt CO_2 of its direct emissions by 2050, i.e. 6% of total direct emissions generated in the sector from 2020 until 2050.[8] On an annual basis, 400 Mt of direct CO_2 emissions are captured in 2050, or 25% of direct emissions generated in that year. Production routes equipped with CCUS account for 15% of total steel production in 2050 (or 25% of primary production).

The only commercial-scale installation today that captures and permanently stores CO_2 in the steel industry is the gas-based DRI plant of Emirates Steel in the United Arab Emirates, implemented by the CCUS company Al Reyadeh. The plant has a capture capacity of around 0.8 million tonnes of carbon dioxide (Mt CO_2) per year, using the captured CO_2 for enhanced oil recovery (EOR) applications. To reach the level of CCUS deployment globally in the Sustainable Development Scenario requires additional capacity equivalent to that capture plant to be installed on average every three weeks from now until 2050. The rate of deployment of CCUS applications is non-uniform in the Sustainable Development Scenario, due to the level of development of suitable capture concepts across production routes, particularly for existing blast furnaces. By 2030 only 1% of the direct emissions generated in the iron and steel sector are captured for storage (Figure 2.8). These early installations are mainly expected to take place in the Middle East, United States, China and India. The first two markets in particular take advantage of opportunities to supplement revenues with those from enhanced oil recovery (EOR) and the easier integration of carbon capture in gas-based DRI (which is dominant in those regions), while China and India are the first to deploy innovative CCUS technologies at a significant scale. Build-out of CO_2 transport and storage infrastructure, not only for EOR applications, will be critical to achieving the level of CCS envisaged by 2050.

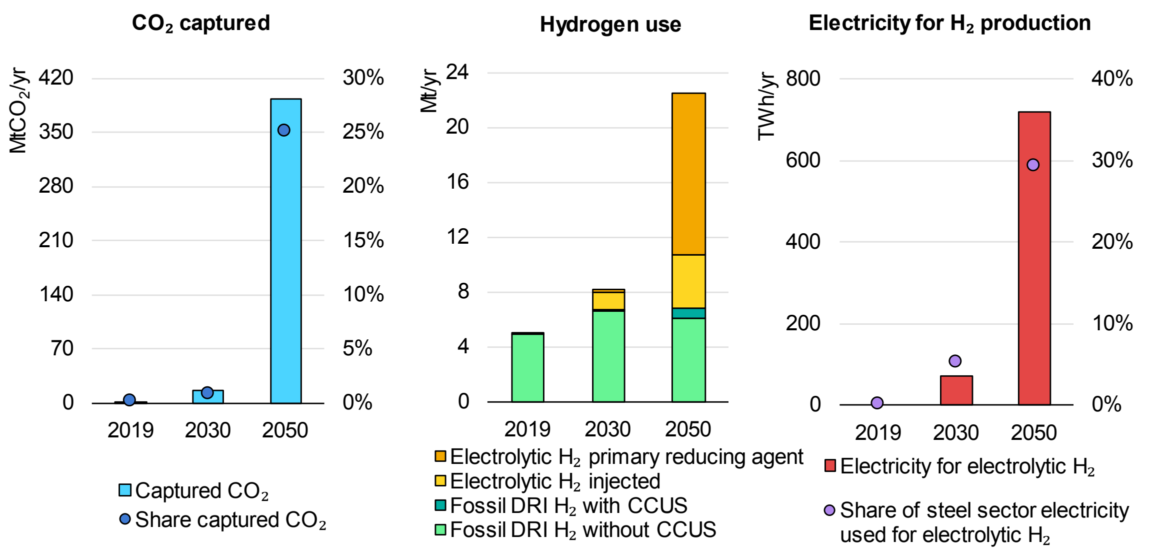
Some carbon capture and use (CCU) concepts also continue to gather pace, including those that are still under development (e.g. converting steel off-gases to fuels and chemicals in Europe) and those that are already well-developed (e.g. the use of coke oven gas for methanol production in China). However, these technologies in their current form play a transitional role, given that the CO_2 is generally later released during the resulting fuel or chemical use or at end-of-life. The principal long-term CO_2 management options – alongside CO_2 direct avoidance technologies – are either permanent geological storage (CCS), or CCU for products that do not release CO_2 emissions (are not oxidised) during use or at end-of-life. The latter may include closed carbon cycles in which the CO_2 in products produced via CCU are recycled back into the system, such as plastics being gasified and used as fuel in steel plants that then produce plastics through CCU. Given that there is likely an upper limit to the demand

[8] This does not include any CO_2 captured from electricity and heat generation equipment, or gases that are recirculated within or between steel production process units on site.

for these non-emitting CCU options, the majority of CO_2 captured in the Sustainable Development Scenario is destined for geological storage (CCS).

CCUS deployment is projected to increase at speed from the late 2020s onwards. This ramp-up follows commercial-scale demonstration of the innovative smelting reduction processes equipped with CCS (currently being demonstrated by the HIsarna project and also being explored for FINEX and COREX operations). This route targets reduced CAPEX and OPEX requirements and increased efficiency levels (including the potential to avoid the use of coke ovens and associated coking coal, and use iron ore fines directly without agglomeration), alongside the ability to obtain near-zero emissions. Equipping blast furnaces with CCUS, including retrofits to existing blast furnaces and some new builds, also plays a role. Beyond the quantities of CO_2 captured for permanent geological storage or use external to the steel plant, some process units are equipped with CO_2 removal technologies that enrich the hydrogen content of CO_2-containing off-gases that are subsequently recirculated within and between steel production process units, thus reducing fuel input requirements.

Figure 2.8 CO_2 captured and hydrogen deployment in the Sustainable Development Scenario



Notes: The share of CO_2 emissions captured and the share of electricity used for electrolytic hydrogen production are calculated as relative to the total values for the sector as a whole. CO_2 captured here refers to direct steel sector CO_2 emissions. "Electrolytic H_2 injected" corresponds to hydrogen blended into commercial blast furnaces and DRI furnaces. "Electrolytic H_2 primary reducing agent" refers to hydrogen use in the hydrogen-based DRI route.

In the Sustainable Development Scenario a quarter of the total CO_2 directly generated by iron- and steelmaking in 2050 is captured in that year. Electrolytic hydrogen as primary reducing agent is introduced at commercial scale in the mid-2030s and expands to 12 Mt used in 2050.

The use of hydrogen plays an important role in steel production in the Sustainable Development Scenario. Hydrogen arising from fossil fuels is already widespread in both coal- and gas-based unabated DRI units – hydrogen plays a major role as the reduction agent in these installations, as the fossil energy is converted into a synthesis gas composed of H_2 and CO. However, this hydrogen use does not result in a radically different direct emission intensity relative to other commercial routes if not equipped with CCUS (for example, producing steel through natural gas-based DRI emits only about 20% lower direct CO_2 emissions compared to coal-based BF-BOF). Hydrogen use produced with fossil fuels and not equipped with CCUS increases from 5 Mt in 2019 to nearly 7 Mt in 2030, then falls towards 6 Mt by 2050. Meanwhile, hydrogen use via DRI with CCUS – so-called "blue hydrogen" – increases to nearly 1 Mt by 2050. In 2050 total fossil fuel-based DRI accounts for 11% of global steel production, compared to 7% today.

Other fossil fuel-derived hydrogen options could also play a role. One example is recirculation of reformed hydrogen-rich off-gases in blast furnaces, as is being explored in Japan and France, which would partially reduce emissions through lower fossil fuel input requirements (JISF, 2011; ArcelorMittal, 2019a). Methane pyrolysis, whereby methane heated using electricity produces hydrogen gas and solid carbon, is also being investigated for applications outside the steel sector; while expected to be more competitive for those other applications, this does not preclude possible future evolution that could be relevant to steelmaking.

Electrolytic hydrogen – part of the CO_2 direct avoidance family of near-zero emission technologies – plays an important role in the Sustainable Development Scenario. In the first decade of the projection horizon, electrolytic hydrogen is mainly deployed as a blending strategy for both the commercial DRI-EAF and BF-BOF production pathways.[9] At lower levels of blending, hydrogen can partially reduce emissions without major modifications to existing equipment. For example, a steel producer in Germany is currently piloting hydrogen injection into blast furnaces of up to 40 kg per tonne of hot metal (thyssenkrupp, 2019). In the Sustainable Development Scenario a proportion of hydrogen blending occurs not as direct injection, but instead from hydrogen blending in natural gas grids (by 2050 a global average of about 2% hydrogen is blended into natural gas grids).

While hydrogen blending serves as a transitional strategy, technical process constraints put an upper limit on the amount of blending that can occur without equipment modifications, particularly for blast furnaces which have a minimum coke

[9] "Hydrogen" is a separate mitigation lever accounted for in our emissions reduction decomposition analysis, despite being an indirect form of electrification in the case of electrolytic hydrogen. Hydrogen blending is therefore counted within the "hydrogen" category, rather than fuel switching or electrification in Figure 2.6.

requirement for operation. Going a step further, DRI based solely on electrolytic hydrogen (referred to here as the hydrogen-based DRI route) is currently under development through a number of projects, mainly in Europe, and would enable emission reductions to near-zero emission levels. From the early 2030s demand for electrolytic hydrogen, in particular that produced from renewable electricity, is projected to accelerate dramatically in the Sustainable Development Scenario after market introduction of hydrogen-based DRI technology.

Low-carbon hydrogen used in steelmaking, either derived from fossil fuels via DRI equipped with CCUS, or produced via electrolysis, grows from negligible levels today to 17 Mt by 2050 in the Sustainable Development Scenario. Electrolytic hydrogen accounts for 70% of total hydrogen use in the sector by this point. Build-out of electricity generation capacity is critical to achieve the ramp-up in hydrogen use – this volume of electrolytic hydrogen use requires 720 TWh of electricity by 2050, assuming an electrolyser efficiency of 45 megawatt hours per tonne of hydrogen (MWh/t H_2), or around 60% of the total electricity consumption of the steel industry today.[10] By this time, electricity supply has decarbonised considerably, with the average CO_2 intensity falling by over 95% from current levels, to 18 gCO_2/kWh (includes both grid-supplied electricity and dedicated electricity generation for hydrogen). While the hydrogen-based DRI route is primarily being explored in Europe today, in 2050 the greatest demand for electrolytic hydrogen in steel is expected in India and China (just over 4.5 Mt of hydrogen in each) due to large production volumes and access to large amounts of low-cost renewable electricity. Globally, 8% of total steel production in 2050 relies on electrolytic hydrogen as the primary reducing agent (or 14% of primary production).

Direct electrification of steelmaking through electrolysis is not included in the Sustainable Development Scenario due to its comparatively low TRL. However, with accelerated progress on innovation, it could play a role in sustainable steelmaking in the longer term (see Box 2.6).

Readiness, competitiveness and investment

Technologies that reduce steel sector CO_2 emissions in the Sustainable Development Scenario are currently at different stages of development. Over the short to medium term, technologies that are already mature or in early stages of adoption will play the greatest role in reducing emissions, while in the longer term technologies that are currently in the demonstration or prototype phase will be required to achieve deeper

[10] The efficiency of electrolysers is assumed to increase considerably over the projection period, from 52 MWh/t H_2 (lower heating value [LHV] efficiency of 64%) in 2019 to 45 MWh/t H_2 (LHV efficiency of 74%) in 2050.

reductions, particularly from primary steel production. Many uncertainties are inherent to the innovation process, and so while the Sustainable Development Scenario provides a snapshot of a reasonably likely low-emission future technology mix, the actual roll-out of technologies will depend on the funding and success of R&D, access to affordable energy and materials inputs and infrastructure, policy stringency and character, and various other supporting conditions that enable globally competitive steelmaking.

One of the main uncertainties of developing new technologies is their future cost. Therefore, it is valuable to explore the sensitivity of technology outcomes to varying cost assumptions, in order to understand which conditions would facilitate one technology being more competitive than another. Energy prices are a key factor influencing the cost of different production routes, and therefore the competitiveness of different technologies varies by region according to the respective energy price context, among other factors. Among the pre-commercial near-zero emission technologies, the innovative smelting reduction route with CCUS has the lowest overall production cost in most regions; this is at current energy prices and estimated capital and fixed operating costs for when this technology reaches market introduction. Actual future costs could very well differ from current estimates, and regardless, regional factors like the policy environment, future scrap or hydrogen availability, and socio-political appetite for CCUS lead to different regional technology mixes.

Total investment needs in the Sustainable Development Scenario are higher than in the Stated Policies Scenario, although not drastically – an increase of about 20% in cumulative capital investment in core process equipment to 2050 is needed globally in the Sustainable Development Scenario. One contributor to this relatively low increase is that overall steel demand is lower. Nonetheless, investment in R&D and supporting infrastructure (e.g. renewable electricity generation, CO_2 storage), which are not part of the investment boundary assessed, will be crucial to enabling the deployment of near-zero emission technologies. Contributions from both public- and private-sector actors will be needed to realise clean energy transitions in steelmaking.

An array of technology options at differing levels of maturity

New technologies that have yet to be commercialised play an increasingly important role in the Sustainable Development Scenario. They pave the way for energy efficiency improvements, switching to lower-carbon energy carriers, and expanding the use of low-carbon hydrogen and deploying CCUS. In particular, they replace existing production capacity over the second half of the projection horizon. An array of technologies is under development (Table 2.1). The timing of their introduction and rate at which they are deployed in the Sustainable Development Scenario varies according to their TRL (see Box 2.5 above for IEA TRL definitions). Faster market introduction of technologies at earlier stages of maturity hinges on a substantial increase in R&D and demonstration efforts and supportive policy action (see Chapter 4). It is also essential that their required inputs (renewable electricity and low-carbon hydrogen) and infrastructure (CO_2 pipelines and storage facilities, electric grids, hydrogen networks) are available. (For further information on supporting infrastructure for hydrogen and CCUS, see *The Future of Hydrogen* [IEA, 2019] and *Special Report on CCUS* [IEA, forthcoming]).

Table 2.1 Status of main near-zero emission technologies in the iron and steel sector

Technology	TRL	Year available (importance for net-zero emissions)	Deployment status
CCUS			
Blast furnace: off-gas hydrogen enrichment and/or CO_2 removal for use or storage	5	2030 (Very high)	• Japan's COURSE 50 project completed initial experimental testing phase; second phase aims to reach full commercial scale by 2030; can be deployed with CCUS (JISF, 2011) • Top-gas recycling using vacuum pressure swing adsorption proven in an experimental blast furnace under ULCOS (European Commission, 2014). Concepts being further developed at ArcelorMittal site in Dunkirk, France. IGAR project testing reforming with plasma torches, with a lab-scale pilot successfully completed in 2017 and an industrial-scale demonstration likely to be completed by 2025-27. "3D" project launched in mid-2019 by a consortium of 11 stakeholders will test amine-based carbon capture for blast furnace process gases, aiming for pilot-scale (4 kt CO_2/yr) by 2021 and industrial-scale (1 Mt CO_2/yr) by 2025. Final arrangement would feed plasma torches with recovered CO_2 from process gases (ArcelorMittal, 2019a; ArcelorMittal, 2019b; ArcelorMittal, 2017) • ROGESA pilot testing H_2-rich coke oven gas in a blast furnace in Germany, with implementation in two blast furnaces expected as early as 2020 (Saarstahl, 2019) • STEPWISE project piloting a technology in Sweden to decarbonise blast furnace gas for use in power production (14 t/day CO_2 removal) (STEPWISE, 2020)
Blast furnace: Converting off-gases to fuels	8	Today (Medium)	• First commercial plant began operation in 2018 in China, by LanzaTech, Shougang Group and TangMing; produced 30 million litres of ethanol for sale in first year of operation (LanzaTech, 2018; LanzaTech, 2019). Second large-scale plant under construction in Ghent, Belgium under the Steelanol/Carbalyst project by ArcelorMittal and LanzaTech, to be completed by early 2021 and with a capacity of 80 million litres of ethanol (ArcelorMittal, 2019a) • FReSMe project, by a consortium of European partners, piloting steel off-gas conversion to methanol (1 t/day); builds on research from STEPWISE project on CO_2 capture and MefCO$_2$ project on producing methanol from CO_2 (FReSMe, 2020; European Commission, 2019)

Technology	TRL	Year available (importance for net-zero emissions)	Deployment status
Blast furnace: Converting off-gases to chemicals	7	2025 (Medium)	• Carbon2Chem pilot plant in Germany initiated by thyssenkrupp in 2018 has produced ammonia and methanol from steel off-gases; aiming for industrial-scale plant by 2025 (thyssenkrupp, 2020a and 2020b) • Carbon4PUR, project by consortium of 11 partners across Europe, is piloting converting steel off-gases to polyurethane foams and coatings (20 t/yr) (Carbon4Pur, 2020)
DRI: Natural gas-based with CO_2 capture	9	Today (Very high)	• Plant operating since 2016 in Abu Dhabi with 0.8 Mt/year of CO_2 capture capacity, with CO_2 used for EOR at nearby oilfield (ADNOC, 2017) • Two plants operated in Mexico by Ternium since 2008 capturing 5% of emissions (0.15-0.20 Mt/yr combined) for use in the beverage industry, with planning underway to scale up capture capacity (Ternium, 2018) • Commercial Finmet plant operating since 1998 at Orinoco Iron, Venezuela, with amine-based CO_2 separation achieving close to 100% CO_2 concentrations as an integral part of the process, but captured CO_2 is not currently used or stored (Primetals, 2020)
Smelting reduction: with CCUS	7	2028 (Very high)	• Developed by the ULCOS consortium, HIsarna pilot plant currently operating at a Tata Steel plant in Ijmuiden, Netherlands (60 kt steel produced, CCS not yet implemented) (Tata Steel, 2017); a demonstration-scale (0.5 Mt/yr) plant (TRL8) is expected in 2023-27 in India and an industrial-scale (1.5 Mt/yr) plant with CCS (TRL 9) is targeted in the Netherlands for 2027-33 • Initial testing of amine-based CO_2 scrubbing in FINEX plant (Primetals, 2020)
Hydrogen			
Blast furnace: Electrolytic H_2 blending	7	2025 (Medium)	Since 2019 thyssenkrupp has been testing use of hydrogen in a blast furnace in Germany, replacing a proportion of injected coal (thyssenkrupp, 2019)
DRI: Natural gas-based with high levels of electrolytic H_2 blending	7	2030 (High)	• In the 1990s Tenova tested 90% hydrogen use in Mexico (scale of 9 kt/yr DRI production) (Tenova, 2018) • Salzgitter steelworks is undertaking MW-scale electrolyser demonstration in Germany and conducting a feasibility study for integrating a hydrogen DRI plant into the existing site, as part of the SALCOS project (SALCOS, 2019) • thyssenkrupp is planning to build commercial DRI plants incorporating hydrogen by the mid-2020s (thyssenkrupp, 2020a)
DRI: Based solely on electrolytic H_2	5	2030 (Very high)	• Pilot plant began operation in August 2020 in Sweden as part of the HYBRIT project; targeting a 1 Mt/yr demo plant by 2025 (HYBRIT, 2020) • Pilot plant being designed in Hamburg led by ArcelorMittal, to be built by 2030 (ArcelorMittal, 2019c) • thyssenkrupp planning to transition towards eventual full hydrogen reduction (thyssenkrupp, 2020a)
Smelting reduction: H_2 plasma reduction	4	--- (Medium)	• SuSteel research project at voestalpine plant in Austria; currently in the process of upscaling a 100 g reactor to a 50 kg batch operation, aiming for commissioning in 2020 (K1MET, 2018; Primetals, 2019) • Flash ironmaking technology under development at University of Utah, with a mini pilot reactor commissioned (Sohn et al., 2017)
Ancillary processes: H_2 for high-temperature heat	5	2025 (High)	• In early 2020 Ovako and Linde completed a successful trial using hydrogen to heat steel before rolling in Sweden (Ovako, 2020) • CELSA (a recycled steel producer), Statkraft and Mo industrial park in Norway signed an agreement in mid-2020 to produce hydrogen to replace fossil fuels used in steel production (CELSA Group, 2020)

Technology	TRL	Year available (importance for net-zero emissions)	Deployment status
Direct electrification			
Electrolysis: Low-temperature	4	--- (Medium)	Siderwin project building on the ULCOWIN process (electrowinning), previously developed by the ULCOS programme; working towards a pilot-scale plant by the end of 2020 (Siderwin, 2019)
Electrolysis: High-temperature molten oxide	4	--- (Medium)	• ULCOS proposed concept called MIDEIO during its 2004-12 work programme (Wiencke et al., 2018) • Research at MIT led to founding of Boston Metal, which commissioned its first prototype cell in 2014 (more than 1 t of metal produced); now aiming for pilot-scale plant (Boston Metal, 2019)
Bioenergy			
Blast furnace: Torrefied biomass	7	2025 (Medium)	The Torero partnership project is testing use of bio-coal (torrefied waste wood) to partially substitute coal in ArcelorMittal's plant in Ghent, Belgium; the large-scale demonstration is expected to be operational by end of 2020 (ArcelorMittal, 2019a)
Blast furnace: Charcoal	10	Today (Medium)	Charcoal is currently used commercially to substitute for a proportion of the coal used in blast furnaces, primarily in Brazil. Some development continues to further optimise charcoal production to improve its product specifications for steel production

Notes: kt = thousand tonnes; t = tonne. For CO_2 capture technologies the specified TRL refers to the whole CCU or CCS value chain applied within the iron and steel sector (whichever is the higher TRL), rather than the TRL of the capture technology only.

A number of innovation efforts are aiming to lower emissions from conventional blast furnace production. Three projects are testing the recovery and reuse of off-gases from blast furnaces to reduce energy input requirements: the COURSE 50 initiative in Japan, the IGAR project in France and the ROGESA project in Germany (TRL 5). They include different techniques to reform coke oven gas or CO_2 into a hydrogen-rich syngas for use in the blast furnace as a partial reducing agent. While this top-gas recycling and hydrogen enrichment in itself can only partially reduce emissions, the set-up would enable carbon capture to be integrated more easily, as was foreseen in the European ULCOS project and is planned in the COURSE50 project.

Carbon capture of off-gases from the blast furnace will also be tested by the recently launched "3D" project at the same site as the IGAR project, using the solvent-based DMX™ capture technology that has been shown to result in a smaller energy penalty relative to the more common monoethanolamine (MEA) technology (Broutin et al., 2017). It is likely that the captured CO_2 will eventually feed the plasma torches being used for reforming by the IGAR project. The STEPWISE project also pilot tested decarbonising blast furnace gases before using them in power production. If carbon capture applied to blast furnace off-gases proves to be technologically and economically feasible, it could enable carbon capture retrofitting and may thus play an important role in addressing emissions from blast furnaces built recently or due to be built before the widespread availability of low-emission steelmaking technologies.

Innovation projects are also underway to partially reduce blast furnace emissions by replacing a proportion of injected coal with torrefied biomass or hydrogen (both TRL 7). Charcoal is already used in blast furnaces commercially, but further development of charcoal production could improve its properties to be even more suitable for steel production (TRL 10). The potential for biomass to reduce blast furnace emissions will partially depend on the availability of sustainable biomass, given that there will be competing demand from other parts of the energy system that face higher barriers to the use of non-biomass options to reduce emissions.

Other R&D projects focus on reducing emissions by adapting newer steelmaking technologies. Innovative smelting reduction presents a promising option for applying carbon capture, given that the off-gases have a very low nitrogen content (compared to a relatively high nitrogen content in typical blast furnace off-gases). This makes separation considerably more cost-efficient. The HIsarna project is developing an oxygen-rich smelting reduction technology that processes iron ore almost directly into liquid iron (eliminating the coking and iron ore agglomeration stages) and produces a single concentrated CO_2 stream that enables much easier CO_2 capture. When equipped with CCUS, it would lead to an estimated 90% reduction in CO_2 emissions relative to conventional blast furnace production. A pilot plant is operational in the Netherlands (TRL 7), although it is not yet connected to storage. There are plans to build a demonstration-scale plant in India as well as a commercial-scale plant in the Netherlands between 2023 and 2033.

Initial testing is also underway to integrate full CCS into the already commercial COREX and FINEX smelting reduction technologies. These technologies currently incorporate physical CO_2 scrubbing using pressure swing adsorption to isolate higher ratios of CO and H_2 for recirculation to the smelting reduction process or for use in a subsequent direct reduction plant. This helps save CO_2 emissions by reducing total fuel consumption, but results in CO_2 concentrations in the tail gas that are insufficient for use or storage and so the CO_2 is still emitted. Upgrading to an amine-based chemical CO_2 scrubbing capture system would facilitate CO_2 use or storage, potentially leading to substantial emission reductions. Nonetheless, unlike the HIsarna process, the off-gases of the COREX and FINEX processes still contain considerable chemical energy content along with CO_2, such that the off-gases are likely to be subsequently used elsewhere such as in a power plant. If the off-gases were used in an oxygen-based power plant, the power plant off-gases could contain high enough CO_2 concentrations for storage; otherwise, another CO_2 capture system would be needed on the subsequent unit utilising the off-gases to realise near-zero emission levels.

Other initiatives are looking to integrate electrolytic hydrogen into DRI production, either through blending to replace a proportion of natural gas, or to go even further to 100% hydrogen-based reduction. If zero-emission electricity is used to produce the hydrogen, the latter would enable fully zero-emission primary steel production. Electrolytic hydrogen displacing up to 30% of natural gas is already possible in commercial DRI furnaces, while higher blends require further development (TRL 7) and use of 100% electrolytic hydrogen is at the pilot stage (TRL 5). Tenova undertook testing of 90% hydrogen use as early as the 1990s in Mexico. More recently in Germany the SALCOS project has been demonstrating an electrolyser at the MW-scale alongside a feasibility study for integrating a hydrogen DRI plant into its existing site, while thyssenkrupp is planning to build commercial DRI plants incorporating hydrogen by the mid-2020s. In Sweden the HYBRIT project began operation of a pilot plant in August 2020 using 100% electrolytic hydrogen from non-fossil fuel sources, and a demonstration plant is being targeted by 2025. A separate project led by ArcelorMittal is also aiming for a pilot plant with full hydrogen production in Germany by 2030. Work is also underway to use hydrogen for high-temperature heat in ancillary processes such as rolling and casting (TRL 5).

A number of steel technologies at earlier stages of development (TRL 3-4), including direct iron ore electrolysis and hydrogen plasma reduction, are not relied upon in the Sustainable Development Scenario, given that they are further away from commercial readiness and reliable techno-economic information is unavailable. Nonetheless, they could make an important contribution to emission reductions if innovation projects are successful and they are able to quickly climb the R&D ladder to commercial deployment (see Box 2.6).

Several fairly advanced innovation initiatives are working to valorise steel off-gases through CCU, in which CO and CO_2 in off-gases are used for saleable fuels and chemicals. A first commercial plant converting steel off-gases to ethanol began operation in China in 2018 (TRL 8). The Steelanol project is constructing a similar industrial-scale ethanol plant in Belgium, which is expected to begin operation by early 2021, while the FReSMe project is piloting conversion of steel off-gases to methanol for use in shipping. The Carbon2Chem project has been operating a pilot plant in Germany since 2018, which uses CO_2 from steel plant off-gases to produce chemicals like ammonia and methanol, including through combination with hydrogen produced by electrolysis in the case of methanol (TRL 7). Additionally, the Carbon4PUR project is piloting use of steel off-gases to produce polyurethane foams and coatings.

These CCU efforts will play a valuable role in developing carbon capture technologies that could be converted to CCS at the same site or applied to CCS at other sites.

However, it should be kept in mind that the extent to which they reduce emissions depends on:

- The counterfactual (i.e. what fuel or chemical production process would otherwise have been used).

- The energy required for the CCU process.
- The ultimate fate of the CO_2 embodied in the fuel or chemicals.

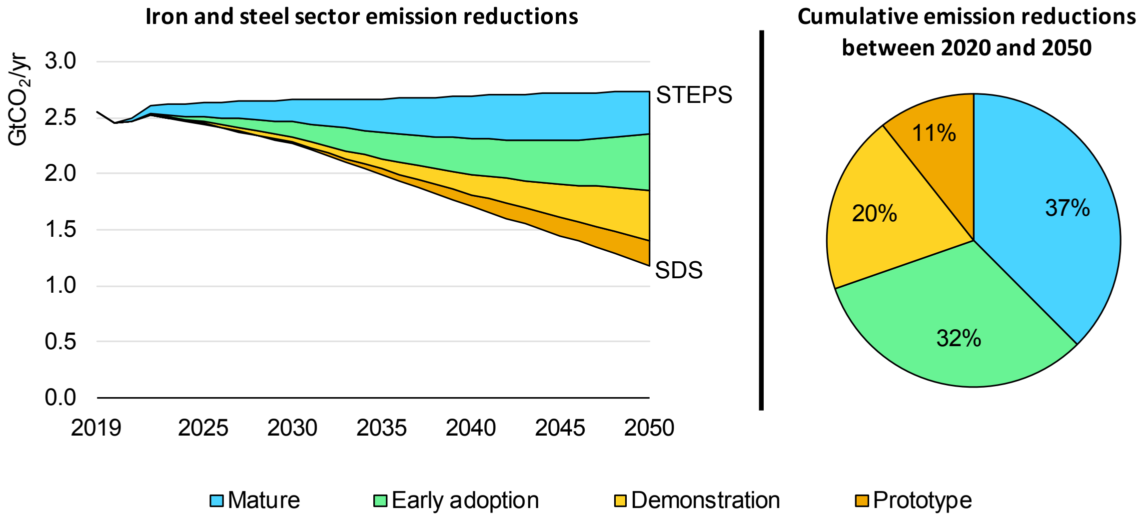
If the fuel is burned or the chemical product decomposes at end-of-life, the CO_2 will ultimately be released into the atmosphere. Using CO_2 twice through CCU reduces emissions relative to a situation in which there was unabated steel production *plus* fossil fuel-based fuel use or chemical production outside the steel sector. However, it is likely to lead to higher emissions relative to a situation in which zero-emission energy or CCS was used for both steel production and for fuels or chemical production outside the steel sector. There could be exceptions that would enable a circular and emission-free CO_2 loop. An example would be using steel off-gases for chemical production following capture using a carbon-free energy source, and then later recycling end-of-life chemicals back into steel production through torrefied or gasified waste use in blast furnaces.

While technologies that are already available today play an important role in reducing CO_2 emissions in the Sustainable Development Scenario, reliance on earlier-stage technologies rises over time to achieve increasingly demanding emission reduction objectives (Figure 2.9). Technologies categorised as mature or in the early adoption phase account for about 70% of cumulative direct CO_2 emission reductions to 2050 in the Sustainable Development Scenario relative to the Stated Policies Scenario. These already available technologies include:

- Material efficiency technologies that reduce total steel demand.
- Energy-saving technologies for existing process routes, such as top-gas recovery turbines on blast furnaces.
- Shifting from coal to natural gas and bioenergy.
- Increased electricity use through EAF-based production (including scrap-based EAF and increased use of EAFs in tandem with DRI-based routes) and electrification of ancillary processes.
- DRI with CCUS.

The last of these is a case of CCUS that has reached commercial scale (TRL 9). Two Ternium DRI plants in Mexico have been operating with CCU since 2008, capturing 5% of emissions for use in the beverage industry, with plans to increase capture capacity. The world's first commercial DRI plant with CCS was commissioned in 2016 in Abu Dhabi, with the CO_2 being stored via EOR. Carbon capture achieving close to 100% concentrations of CO_2 is also occurring at a commercial Finmet plant as an integral part of the process. While the captured CO_2 is currently not connected to use or storage and thus is simply emitted, the technology set-up is ready for CCUS, if the right policy incentives are put in place.

Figure 2.9 Iron and steel sector direct CO_2 emission reductions in the Sustainable Development Scenario by current technology maturity category



Notes: Emission reductions are measured relative to the Stated Policies Scenario. Mature = all designs and underlying components at TRL 11; early adoption = at least one underlying design at TRL ≥ 9 and others at lower TRLs; demonstration = no underlying design at TRL ≥ 9, but at least one design at TRL 7 or 8; prototype = no underlying design at TRL 7 or 8, but with at least one design at TRL ≤ 6.

In the Sustainable Development Scenario in the short to medium term, emission reductions are driven primarily by today's commercially available technologies, while in the longer term the burden shifts to those that are currently at demonstration and prototype stages.

In the longer term technologies that are now at the demonstration or prototype stage will be needed to achieve even deeper emission reductions, particularly for primary production. Demonstration and prototype technologies account for about 20% and 10%, respectively, of cumulative direct CO_2 emission reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario. As discussed above, a wide variety of innovation activities are currently underway on technologies that can achieve varying degrees of emission reduction. The extent to which each technology is ultimately deployed will depend on:

- The success of the respective R&D projects.
- The extent to which learning-by-doing in the early adoption phase can overcome remaining technological hurdles and reduce costs.
- Regional circumstances such as policy, availability of the required energy and input materials at competitive prices, and access to the necessary supporting infrastructure.

Generally, in the Sustainable Development Scenario technologies currently being demonstrated (i.e. TRL of 7 or more) start to be deployed within a decade, while those currently in the prototype phase (i.e. TRL of 5 or 6) are commercially deployed from the early to mid-2030s, with some initial ramp-up taking place in the years prior. However, the speed of innovation is difficult to predict, and thus the timing of roll-out could in fact be several years earlier or later (or certain technologies might not mature at all).

Box 2.6 What if innovation accelerated? – The Faster Innovation Case

The Sustainable Development Scenario requires monumental efforts to bring the energy system as a whole to net-zero emissions by 2070, including a considerable reliance on the development and market deployment of new technologies. Could this enormous undertaking move even more quickly? Our Faster Innovation Case explores the feasibility of bringing forward net-zero emissions for the energy system as a whole to 2050 by accelerating work on clean energy technology innovation.

There is scant precedent for the very rapid pace of innovation required in the Faster Innovation Case. It relies on the use of technologies still at lab and early prototype stages, shortened time periods for market introduction of new technologies, and faster adoption rates for new and emerging technologies. This pace does not leave any room for delays or unexpected operational problems during demonstration or at any other stage. These are, of course, bound to happen in practice. Nonetheless, mission-oriented approaches that support clean energy innovation in technology areas with attributes conducive to fast innovation cycles could speed up the pace of progress. This is particularly so if they are coupled with a once-in-a-generation investment opportunity as a result of Covid-19-related recovery plans.

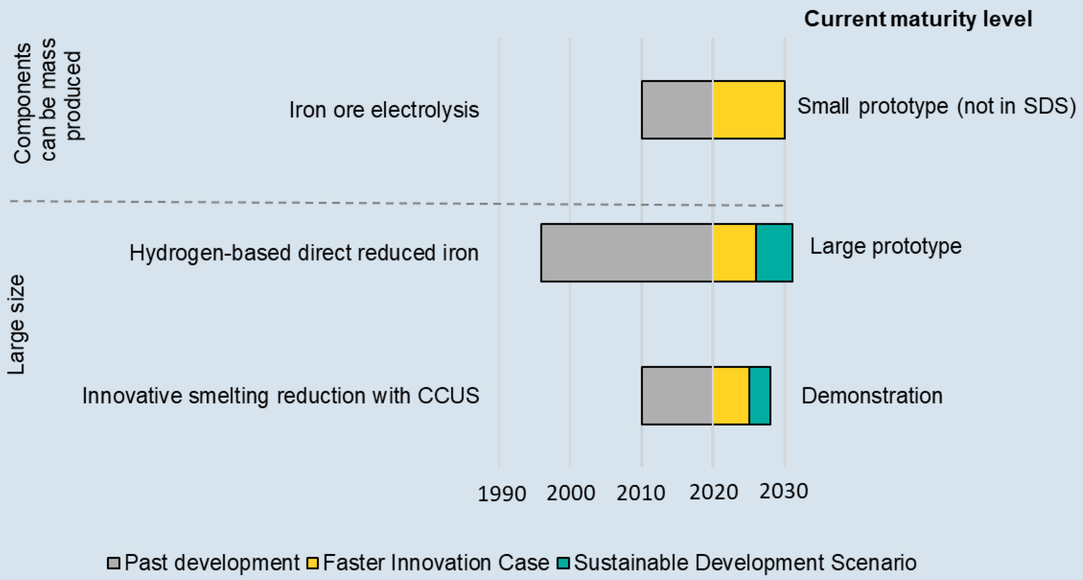
The Faster Innovation Case is not designed to be an ideal pathway to net-zero emissions by 2050; the complexity of this question goes well beyond technology innovation alone, and is likely to require fundamental changes to current lifestyles. Rather, it is designed to explore how much shorter development cycles would need to be than in the Sustainable Development Scenario, and how much more rapid technology diffusion rates would need to be to deliver net-zero emissions globally by 2050. For additional details on the design of the Faster Innovation Case, see the *ETP 2020 Special Report on Clean Energy Innovation* (IEA, 2020).

In the Faster Innovation Case, the iron and steel sector's direct CO_2 emissions would fall to reach a level in 2050 that is 75% lower than in the Sustainable Development Scenario. Although the sector would not fully reach zero emissions, the projected emissions would be only 0.3 Gt CO_2 in 2050, compared to 1.2 Gt CO_2 emitted in the same year in the Sustainable Development Scenario.

Achieving this implies an increased role for multiple clean energy technologies. Increased use of CCUS- and hydrogen-based routes in the Faster Innovation Case depends on considerably shorter time periods to reach market introduction of technologies still at the large prototype and demonstration stage today, followed by a further accelerated deployment (see figures below). Additionally, iron ore electrolysis, which is at the small prototype stage (TRL 4), and thus is not included in the Sustainable Development Scenario, is assumed to progress rapidly and thus contributes to emission reductions in the Faster Innovation Case.

The period to market is considerably shortened in the Faster Innovation Case. Innovative smelting reduction with CCUS reaches market introduction in 2025, three years faster than in the Sustainable Development Scenario. 100% H_2 DRI becomes available for commercial application in 2026, five years earlier than in the Sustainable Development Scenario. Iron ore electrolysis reaches market introduction by 2030.

Period from first prototype to market introduction for selected innovative steelmaking technologies

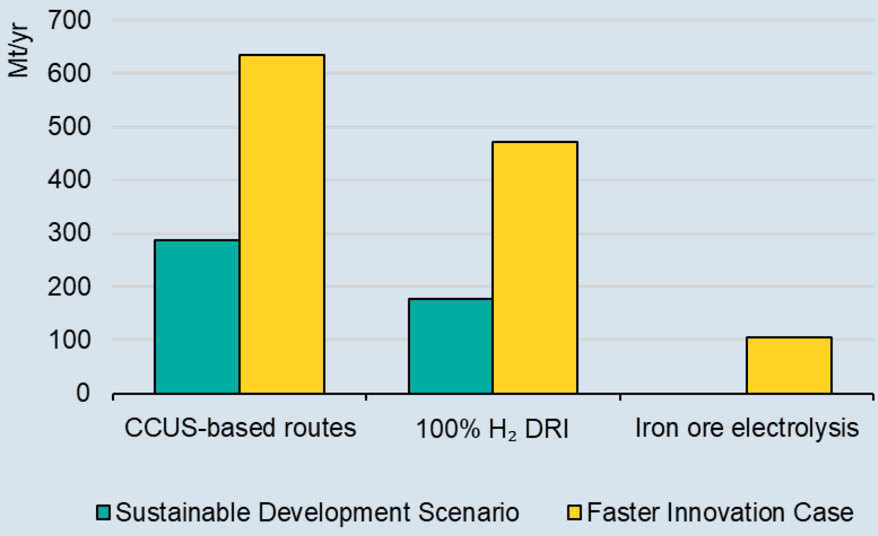


Notes: SDS = Sustainable Development Scenario. CCUS = carbon capture, use and storage. The classification between large process technologies and those dependent on components able to be mass produced is based on the characteristics of the equipment or process steps within the technologies analysed that are not commercially available today.

Following market introduction, an average of more than two CCUS-based and two 100% H_2 DRI steel plants need to be built each month through to 2050, compared to about one of every month in the Sustainable Development Scenario. Additionally, an average of one iron ore electrolysis plant is built every two months from 2030 to 2050, while the technology is not deployed in the Sustainable Development Scenario.

As a result of this rapid roll-out, steel production with CCUS is 2.2 times higher and with electrolytic hydrogen is 2.7 times higher in 2050 in the Faster Innovation Case compared to the Sustainable Development Scenario. Iron ore electrolysis accounts for 5% of steel production by 2050.

Steel production via innovative technologies in 2050 by scenario



Notes: CCUS-based routes include innovative BF-BOF with CCUS, innovative smelting reduction SR-BOF with CCUS, and DRI-EAF with CCUS.

A unique aspect of the Faster Innovation Case are the opportunities it opens for iron ore electrolysis. While hydrogen-based direct reduction can use hydrogen produced from electricity to indirectly electrify steel production, iron ore electrolysis provides a way to directly electrify primary steelmaking. The two most advanced concepts for iron ore electrolysis have to date operated only on a small scale (TRL 4). Of these, the larger is low-temperature alkaline electrolysis, which has recently moved from the scale of a few kilogrammes to a 100 kg pilot (ArcelorMittal, 2020). The other design, high-temperature molten oxide electrolysis, was validated in the laboratory in 2013, a prototype cell was commissioned in 2014 and there are plans to test full-scale cells by 2024 (Boston Metal, 2019). Iron ore electrolysis is not included in the Sustainable Development Scenario analysis due to its relatively low TRL and the subsequent uncertainty of techno-economic parameters associated with any future commercial-scale design.

Being at an earlier stage of technology readiness suggests that iron ore electrolysis has a longer path ahead of it to reach market introduction. Yet it has several features that might facilitate a faster innovation timeline, relative to some other technologies. They are exploited to accelerate progress on iron ore electrolysis in the Faster Innovation Case. These opportunities include the possibility of lower risk when scaling up due to its modular characteristics, knowledge spillovers from other electrolysis technologies, standardised and repetitive manufacturing, and the potential for it to offer grid balancing services.

In iron ore electrolysis, electrolytic cells can be stacked to provide the capacity needed, allowing the possibility to expand capacity by increments. Therefore the capital at risk in the initial stages of investment in a given plant is smaller. The layout of molten oxide electrolysis also shares many features with alumina electrolysis for aluminium production. Therefore, learnings (also known as knowledge spillovers) in design, operation and materials might be expected to flow from aluminium to steel electrolysis, including the emerging ability to modulate plant operation with the incentive of balancing a grid dominated by variable renewable electricity.

Additionally, based on the current concepts being pursued, iron electrolysis is estimated to use 15-30% less electricity overall per tonne of steel produced, relative to the hydrogen-based DRI route. This lower electricity demand could help ease the burden on electricity grids that in the transition to net-zero emissions are increasingly strained, due to higher overall demand and higher shares of intermittent renewables. This characteristic may provide an advantage in the context of the whole energy system moving more quickly to net-zero emissions.

Different regional contexts, different technology portfolios

The selection of technologies for steel production in the future – especially for primary steel production – will be influenced by multiple factors. The important ones among them are the local availability of various energy carriers, energy prices, access to required inputs and infrastructure, and the age and size of the existing stock of assets in a given region. The feasibility of adopting a given technology can also be affected by public acceptance and the local regulatory landscape, as is the case for CCUS technologies in certain regions. It is for these reasons that the journey towards zero emissions in the iron and steel sector differs by region in the Sustainable Development Scenario. There is no single technology pathway, but a toolbox of potential options for each region to utilise according to regional and local circumstances (Figure 2.10). This section highlights some of the contrasting dynamics at the regional level.

China

The Sustainable Development Scenario sees an increase in scrap availability relative to production levels in several regions. In China the dynamics are particularly striking in this respect. While its current level of secondary production is relatively low (around 10%), this increases to 45% by 2050. In metallic input terms, the share of scrap in the total inputs of scrap and iron ore rises from 25% in 2019 to more than 50% in 2050. This transition to a dominant share of secondary production is enabled by a large amount of scrap becoming available very quickly, owing to a rapid build-up of in-use steel stocks during China's boom period just after the millennium. At the same time that the availability of scrap is increasing, overall output is falling, from around 1 billion tonnes in 2019, to around 710 Mt in 2050. Because the natural phase-out profile of China's existing fleet of primary production facilities is relatively well-aligned with this new availability of scrap, the country is able to undergo a rapid transition to secondary steelmaking without early decommissioning of its existing fleet of blast furnaces.

Alongside the transition to a dominant share of secondary production in China, the country's primary production units also undergo a significant shift in the Sustainable Development Scenario. As electric furnaces fed by scrap are the first choice of new units to replace older blast furnaces in the early years of the projection horizon, innovative primary production routes begin deployment later than in several other regions. The alignment of the age profile of its existing stock of blast furnaces with the increasing availability of scrap means that retrofits to blast furnaces are not required. The innovative smelting reduction-basic oxygen furnace (SR-BOF) with CCUS and 100% H_2 DRI-EAF routes are deployed in almost equal proportions by 2050, together accounting for around one-third of primary steelmaking capacity by then. China's large endowment of low-cost renewable electricity generation potential and early experience with CCUS in other industry sectors underpin this hybrid approach (there are a handful of CCUS-equipped plants in the chemical sector already operating or in the planning phase).

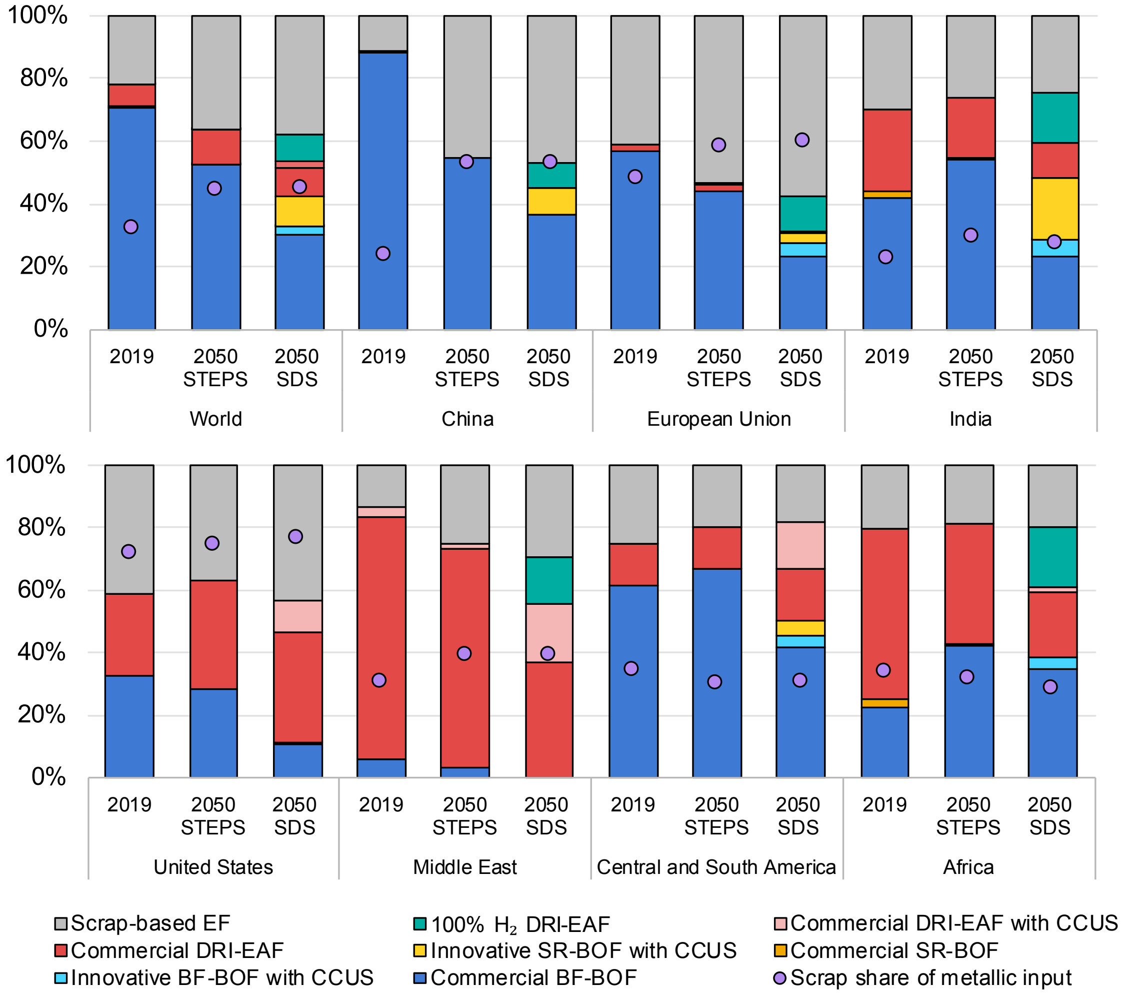
European Union

The outlook for steel production in the European Union in the Sustainable Development Scenario is one of gentle decline, as the region gives way to lower-cost and rapidly growing producer regions such as India. The strategic nature of the steel industry in many of the region's member states means output stabilises or grows slightly in key producing countries (e.g. Germany), offsetting declines elsewhere. In stark contrast to China, the availability of scrap remains fairly constant throughout the projection horizon, leading to a similar scrap share of total metallic inputs in 2050 (60%) as in 2019 (50%). This slight increase reflects the gentle decline in overall output and somewhat increased scrap availability as ageing infrastructure reaches its end-of-life.

Europe has a long-established blast furnace fleet, and an old one when measured since the year of first installation (active fleet age of 50 years on average), but the average age diminishes significantly when taking into account recent upgrades and refurbishments (10 years on average). This factor, along with the fact that the European steel industry has demonstrated commitment to a variety of research and demonstration projects for near-zero emission steelmaking technologies, leads the region to adopt a diversified portfolio of options in the Sustainable Development Scenario, including both carbon avoidance and carbon management options. Hydrogen is front and centre, building on existing projects that involve blending hydrogen into existing blast furnaces and DRI units, and a supportive policy environment for the technology. By 2050 the 100% H_2 DRI-EAF route is deployed at significant scale, with around 10 commercial-scale plants (around 15 Mt of crude steel output) replacing existing blast furnaces.

Even within the carbon management family of options, producers in the European Union adopt a diversified approach in the Sustainable Development Scenario. By 2050 around 15% of blast furnaces are equipped with carbon capture, and the innovative SR-BOF with CCUS route is deployed gradually from the late 2020s, to replace older blast furnaces at the end of their next investment cycle. Both of these routes, along with industrial facilities in other sectors (e.g. cement), require large-scale CO_2 transport and storage infrastructure. CCS faces acceptance challenges in several countries within the region (in the past decade some countries such as Germany and Austria have placed at least partial or temporary bans on large-scale geological CO_2 storage). But there are also countries where it has at various times been identified as a strategic priority (the Netherlands, the United Kingdom and Norway are key examples, and even the German government recently put CCS back on the table). Regional co-ordination of CO_2 transport infrastructure and the possible promise of offshore storage could also help alleviate lingering concerns about the technology.

Figure 2.10 Crude steel production by process route and scenario in major steel-producing regions



Notes: STEPS = Stated Policies Scenario, SDS = Sustainable Development Scenario. **Commercial BF-BOF** includes traditional coal-, gas- and charcoal-based blast furnaces, with and without top-pressure recovery turbines, without CCUS. **Innovative BF-BOF with CCUS** includes blast furnaces with process gas hydrogen enrichment and CO_2 removal for use and storage (e.g. as being developed by the COURSE50, IGAR and 3D projects), including CCUS retrofits to existing blast furnaces and those newly installed over the coming decade. **Commercial SR-BOF** refers to smelting reduction without CCUS (COREX and FINEX). **Innovative SR-BOF with CCUS** includes application of CCUS to existing smelting reduction concepts (COREX and FINEX) and novel smelting reduction concepts with CCUS (e.g. as being developed by the HIsarna project). **Commercial DRI-EAF** includes gas- and coal-based DRI without CCUS, including that with a proportion of blended electrolytic hydrogen; in some regions (particularly the United States), this route has a high ratio of scrap to DRI inputs. **Commercial DRI-EAF with CCUS** includes gas- and coal-based DRI with CCUS. **100% H_2 DRI-EAF** comprises fully electrolytic hydrogen-based DRI (e.g. as being developed by the HYBRIT project and ArcelorMittal in Hamburg). **Scrap-based EF** refers to electric arc furnaces and induction furnaces fed mostly by scrap, with India and China being exceptions, both having substantial iron charges to their induction furnaces. For further details on projects developing these technologies, see Table 2.1.

While increased scrap availability contributes to a general shift towards secondary production in the short to medium term, deploying near-zero emission technologies leads to a greater diversification of steelmaking routes in the long term.

India

India is one of the few regions – and the only one among today's large producers – that undergoes a strong growth trajectory in the Sustainable Development Scenario, despite a strong push on material efficiency strategies. Crude steel production increases from 111 Mt in 2019 to 180 Mt in 2030 and 350 Mt in 2050. Unlike regions where the stock of steel in society is mature and relatively stable in the future, India's is growing rapidly, leading to limited availability of scrap relative to overall production. The scrap share of metallic inputs still rises slightly to just over a quarter by 2050, from just over a fifth in 2019, but remains well below economies such as the United States at around 85% or the global average of 45%.

This limited availability of scrap in conjunction with rising levels of output mean that India builds large amounts of primary steelmaking capacity during the projection period of the Sustainable Development Scenario. Some of this additional capacity is required before near-zero emission technologies are ready to be deployed at scale, and conventional process technology continues to be deployed alongside innovative technologies as they scale up. Production from conventional ironmaking processes (gas- and coal-based DRI and coal injection blast furnaces) peaks around 2040, meaning there are some blast furnaces that are only 10 years old at end of our projection horizon. These dynamics underpin the need for retrofits or new-build CCUS-ready designs for these blast furnaces from the early 2030s. By 2050 around 20% of the blast furnaces in operation are equipped with carbon capture, with the remaining unabated units being left to phase out and be replaced with other – by then mature – innovative processes.

In parallel with this evolution of the blast furnace stock, the innovative SR-BOF with CCUS route is deployed rapidly from the late 2020s in the Sustainable Development Scenario. From an iron production level equivalent to a couple of units in 2030 (2-3 Mt), output via this route climbs to more than 70 Mt in 2050, which is roughly one new unit every year during 2030-50. While this rate is achievable (if ambitious), it is only half the story when it comes to new-build near-zero emission technologies. India, like China, is projected to have access to vast quantities of low-cost renewable electricity in the future, making the 100% H_2 DRI-EAF route an attractive decarbonisation option for new-build plants once it is commercially available in the early-mid 2030s. In parallel, but with a five-year lag relative to the innovative SR-BOF with CCUS route, the electrolytic hydrogen-based route is deployed at a slightly faster rate, reaching very similar levels of deployment in 2050. This faster rate of deployment is enabled in part by the modular nature of the electrolysis component of the technology, and the experience gained with hydrogen technologies throughout the energy system during this period. More detail on the scenario results for India is presented in Chapter 3.

United States

Much like the European Union, the stock of steel goods and infrastructure in the United States is mature and does not grow significantly during the projection horizon of the Sustainable Development Scenario. The production outlook is also fairly similar, with production levels not exceeding those seen before the Covid-19 crisis. However, the United States has a different starting point when it comes to scrap availability and use. In 2019 the scrap share of metallic inputs is just over 70% – higher than the European Union at 50% – with a slight increase (to around 85%) being registered by 2050. Another idiosyncrasy of the US context is the high share of scrap utilised in the DRI-EAF route (around 90% today). The overall scrap share increases throughout the projection horizon as the use of the scrap-based EAF route increases. By 2050 electric furnaces account for around 90% of production, up from around 70% today.

While there is some refurbishment and replacement of the existing blast furnace stock in the United States through to 2045, the share of DRI in total iron production grows from around a tenth today to a third in 2050. Accompanying this shift is the gradual equipping of DRI furnace assets with CCUS. This technology, already commercially deployed today in a single plant in the Middle East, proves an attractive option in a region with access to low-cost natural gas and a relatively old fleet of existing blast furnaces, which are less attractive to retrofit in this context than in the European one. This strategy alone is sufficient to address the primary steelmaking challenge in the United States, negating the need for the innovative SR-BOF with CCUS or 100% H_2 DRI-EAF routes, which are only available for commercial deployment later in the projection horizon.

Other key regions

The regions discussed above accounted for approximately 72% of crude steel production in 2019, with this share falling to around 60% in 2050. The regions that account for the remainder of global production generally follow a similar trajectory to one of those outlined above, or a combination of them.

With respect to the share of secondary production (and the share of scrap in total metallic inputs), a broad distinction can be made among the remaining key regions given their growth trajectory. The Middle East, Central and South America, Southeast Asia and Africa are regions that undergo strong growth trajectories in the Sustainable Development Scenario, with output in most rising by about 2 to 4 times, and even by over 80 times in some African regions, during the period 2019-50. These and other similar smaller regions tend to exhibit similar dynamics to India when it comes to scrap, with the scrap share of total metallic inputs typically remaining in the range of 20-45% throughout the projection horizon. Those regions that have already undergone periods of infrastructure build-up (e.g. the Middle East) tend to be at the higher end of this range, whereas those with a lagging, but in many instances steep, growth trajectory (e.g. Africa) tend to be at the lower end in 2050. Conversely, other key producing regions with a mature stock of steel (e.g. Japan and Korea) and relatively low growth rates for production tend to exhibit higher shares of scrap in the total metallic input by 2050, typically approaching 40% and higher.

Beyond those discussed in detail above, growth regions – particularly the Middle East, Central and South America and Africa, Southeast Asia and, to a lesser extent, Russia – need to add substantial amounts of primary steelmaking capacity through to 2050. As with the growth regions discussed in detail above, there are three main options for these capacity additions in the context of the Sustainable Development Scenario. Regions with access to abundant low-cost renewable electricity tend to favour the 100% H_2 DRI-EAF route, especially in the long term (e.g. Africa and to a lesser extent the Middle East). Regions with low-cost natural gas tend to favour the gas-based DRI with CCUS route (e.g. the Middle East, Central and South America and Russia). The remaining regions tend to favour the innovative SR-BOF with CCUS route (e.g. Southeast Asia). Within the Central and South America region, Brazil is an outlier in its continued deployment of charcoal blast furnaces, supplemented by gas-based DRI deployment in conjunction with CCUS and the innovative SR-BOF with CCUS.

Regions with declining production levels, and high but stable shares of scrap in the total input of metallics – especially Japan, Korea and Canada – tend to opt for technology strategies similar to those of the United States and the European Union for the evolution of their primary steelmaking capacity. Where there are large fleets of efficient blast furnaces (e.g. Japan and Korea), innovative blast furnace concepts tend to be the favoured options, including hydrogen enrichment and reinjection and top-gas recycling, deployed in conjunction with CCUS. In most other regions that see declining levels of output, the innovative SR-BOF with CCUS and 100% H_2 DRI-EAF routes replace proportions of the remaining primary steelmaking capacity during the last investment cycle of the projection period.

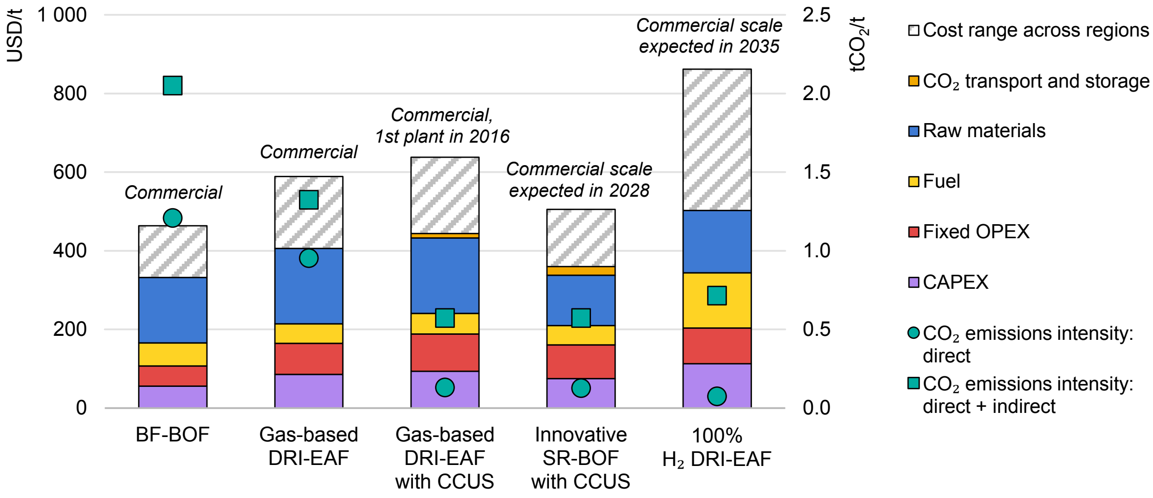
One regional dynamic that is not explicitly presented in our results is the potential for trade in intermediate materials and energy carriers. This is particularly relevant to the 100% H_2 DRI-EAF route. One example of intermediate trade in materials would be DRI that is produced in one region, perhaps endowed with large quantities of high-quality iron ore or renewable electricity for producing hydrogen, then being exported to an existing or growing demand centre. An energy example would be the export of hydrogen or hydrogen-rich fuels from a region with abundant renewable resources to one with high-quality iron ore.

While it is challenging to project precisely where these international trade routes might emerge in the context of the Sustainable Development Scenario, it is possible to identify some promising candidates. North Africa, parts of Central and South America and Australia are areas with abundant low-cost renewable electricity generation potential, particularly solar PV, but with little domestic demand for steel. This could make them suitable regions for the exporter side of this equation. Conversely, Japan and parts of Europe are examples of demand centres with existing steelmaking assets, but relatively high energy costs and limited space for multi-gigawatt-scale solar PV and wind projects, beyond those already projected to be built in the Sustainable Development Scenario.

Exploring the sensitivity of production costs

While the regional results presented in the Sustainable Development Scenario take account of many factors, these figures do not constitute a forecast and are subject to much uncertainty. One key element of uncertainty is the regional variation in energy prices, which can have a significant impact on the overall production cost of crude steel. As was done in Chapter 1 with the comparison of today's commercial routes (Figure 1.3), the simplified levelised cost can be a helpful metric to compare the relative sensitivity of important near-zero emission production pathways to variations in their input costs (Figure 2.11). The process routes considered in this analysis – those relied upon most heavily in the latter decades of the Sustainable Development Scenario – generally cost between about 10% and 50% more than their commercially available counterparts within a given regional context, a cost increase significantly exceeding production margins. Among the near-zero emission technologies, the innovative SR-BOF route has the lowest overall production cost in most regions at current energy prices and estimated capital and operating costs.

Figure 2.11 Simplified levelised cost of steel production for selected production routes



Notes: Presented costs account for regional variation. kW$_e$ = kilowatt electrical; MBtu = million British thermal units; tce = tonne of coal equivalent. Energy costs: Natural gas = USD 2-10/MBtu (USD 2-9/GJ), thermal coal = USD 35-80/tce (USD 1-3/GJ), coking coal = USD 75-155/tce (USD 3-5/GJ) and electricity = USD 30-90/MWh (USD 8-25/GJ). Scrap = USD 200-300/t. Iron ore = USD 60-100/t. CO_2 transport and storage = USD 20/t CO_2 captured. CO_2 streams are captured with a 90% capture rate. Direct CO_2 emissions do not include indirect emissions resulting from blast furnace gas and coke oven gas used for power generation. Indirect CO_2 emissions include emissions resulting from imported heat and power generation provided either from excess blast furnace gas and coke oven gas or electricity from the grid. CO_2 intensity of electricity considered for H_2 DRI-EAF = 144 gCO_2/kWh, which is the global average CO_2 intensity of power generation in the Sustainable Development Scenario in 2035. CAPEX comprises process equipment costs (including air separation units, carbon capture equipment and electrolysers where applicable) plus engineering, procurement and construction costs. Electrolyser CAPEX = USD 452/kW$_e$ and OPEX = USD 7/kW$_e$. 8% discount rate, 25-year lifetime and a 90% capacity factor are used for all equipment. 90% capture rate assumed for all CCS routes. Comparison is made assuming no price on CO_2 (price of CO_2 = USD 0/t CO_2).

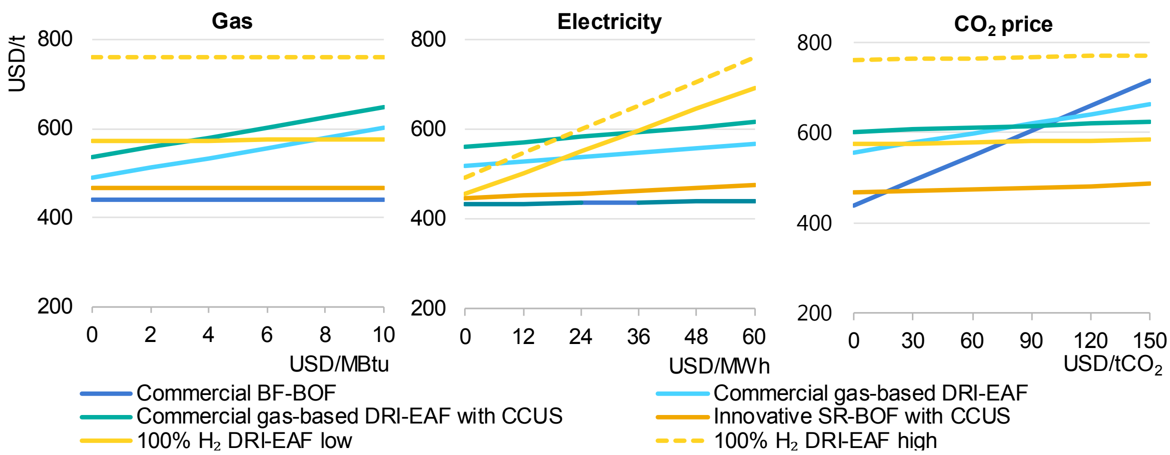
Near-zero emission technologies are between 10% and 50% more expensive than their commercially available counterparts in a context with no CO_2 pricing, with the gas-based DRI with CCS and hydrogen-based DRI being highly sensitive to the cost of natural gas and electricity, respectively.

The economics of the gas-based DRI and electrolytic hydrogen-based DRI processes (the former with CCUS) are particularly sensitive to the cost of gas and electricity respectively, as well as the policy environment. In the absence of a sufficiently high CO_2 price or other reliable global CO_2 abatement mechanism for the sector, switching to low-carbon hydrogen produced via water electrolysis in the DRI-EAF route would not be competitive with conventional gas-based DRI-EAF and BF-BOF routes, given its higher costs, except where electricity prices are very low (Figure 2.12). There would also be little incentive to pursue CCUS-based routes.

With a robust global policy framework in place, the choice becomes among the various low-emission options. To compete in the long term with its natural gas-based counterpart equipped with CCUS, the electrolysis-based hydrogen DRI would need reliable low-carbon electricity prices below USD 35/MWh (USD 10/GJ) based on current estimates of likely capital and operating costs at commercial scale, and a gas price of USD 6/MBtu (USD 6/GJ). The innovative SR-BOF with CCUS route is lower cost than both electrolytic hydrogen DRI and gas DRI with CCUS across a wide range of energy prices, making it a leading option in many regions. Nevertheless, other factors may also have a considerable impact on costs or could lead to technology choices not based solely on costs. For example, electrolytic hydrogen DRI may still be chosen over innovative SR-BOF with CCUS in some locations without suitable access to CCUS infrastructure. The natural gas DRI with CCUS route could be opted for in regions where local availability of natural gas is preferred over imports of coal.

The low electricity prices required to make electrolytic hydrogen DRI competitive may be achievable in certain regions with ample low-cost renewable resources. However, those regions may not all be endowed with sufficient reserves of iron ore and other required input materials, nor adequate infrastructure for raw material import and steel export. Furthermore, existing industrial hubs are likely to act as significant inertia in determining where future production will be located. Ports, railways, pipelines, electricity transmission grids and other trade infrastructure can take decades to develop and are not usually viable propositions on the basis of a single project. Therefore, a portfolio of options is likely to be used to achieve global steel CO_2 reductions, with different options favoured in various steel-producing regions, rather than all production migrating to areas with cheap electricity.

Figure 2.12 Levelised cost of steel production for selected production pathways at varying gas, electricity and CO_2 prices



Notes: Energy costs: Natural gas = USD 6/MBtu (USD 6/GJ), thermal coal = USD 70/tce (USD 2.4/GJ), coking coal = USD 140/tce (USD 4.8/GJ) and electricity = USD 45/MWh (USD 13/GJ). CO_2 transport and storage = USD 20/t CO_2 captured. CO_2 streams are captured with a 90% capture rate. Considered CAPEX for this calculation comprises process equipment costs (including air separation units, carbon capture equipment and electrolysers where applicable) plus engineering, procurement and construction costs. Comparison for the left-hand and middle graphs is made assuming no price on CO_2 (price of CO_2 = USD 0/t CO_2). H_2 DRI-EAF low corresponds to an electrolyser cost of USD 285/kW$_e$ and LHV efficiency of 74%. H_2 DRI-EAF high corresponds to an electrolyser cost of USD 1 067/kW$_e$ and LHV efficiency of 64%. Left- and right-hand graphs use electricity costs of USD 60/MWh (USD 17/GJ) for H_2 DRI-EAF high and USD 30/MWh (USD 8/GJ) for H_2 DRI-EAF low. 8% discount rate, 25-year lifetime and a 95% capacity factor are used for all equipment.

At a gas price of USD 6/MBtu, the hydrogen-based DRI route becomes competitive with its gas-based counterpart equipped with CCS at electricity prices below USD 35/MWh.

While the uplift in cost from producing steel via near-zero emission processes is considerable on a "per tonne of primary steel production" basis relative to conventional routes, the overall impact at the global level in the Sustainable Development Scenario is much more muted. By 2050 the average increase in cost of production is estimated at around 7% relative to today. The uplift in the cost of primary production is countered by the much larger share of secondary production, which is substantially less energy-intensive and therefore lower cost at the system level. It should be noted that this estimate has considerable uncertainties, including that it looks at the production costs rather than the price of steel, the latter of which can be affected by supply-demand dynamics that are difficult to predict, and the costs are subject to uncertainties on the future prices of iron ore or scrap. Nevertheless, it provides an indication that the increase in costs is unlikely to be astronomical.

There is more good news at the consumer end of the supply chain, because only a small fraction of the cost of end-use goods is attributable to the cost of the steel embedded in them. We estimate that the construction cost of a family home (costing USD 300 000) would be 0.2% higher in 2050, while an average mid-sized car (costing USD 25 000) would increase in cost by around 0.1%. The challenge for steel producers and policy makers will be to find methods to pass this cost along competitive supply chains (see Chapter 4 for further discussion).

Investment required to facilitate the transition

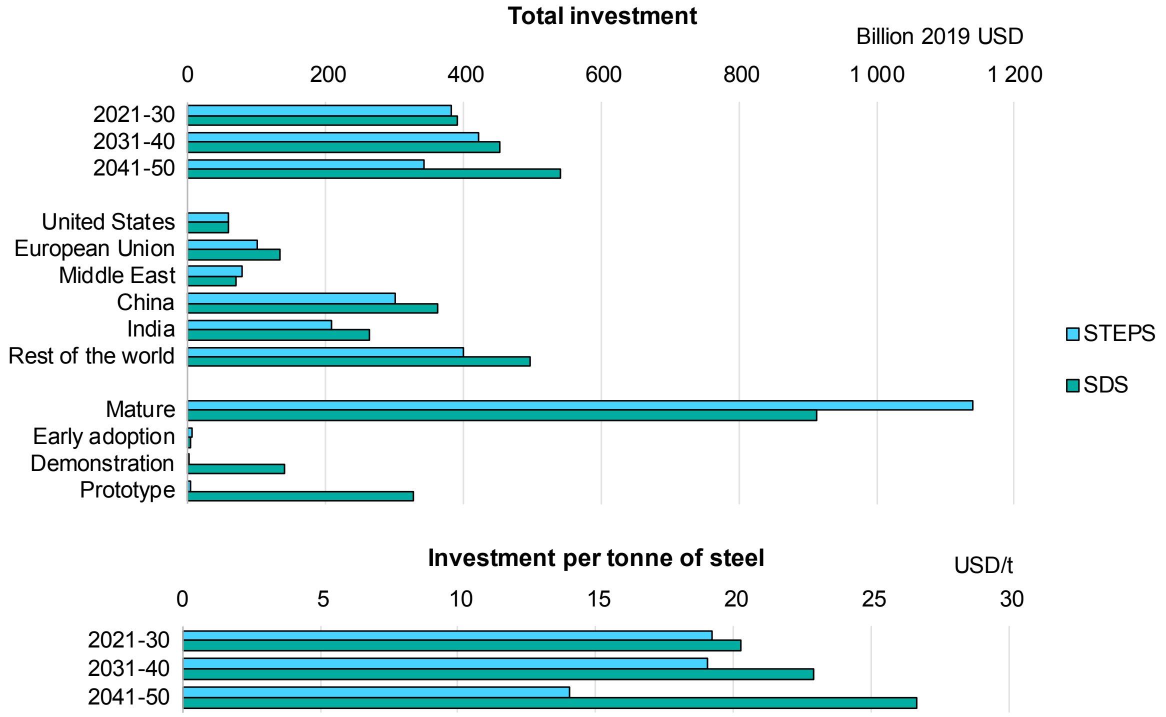
In the Sustainable Development Scenario additional investment in core process equipment (including, for example, pelletisers, blast furnaces and electric arc furnaces) is needed to achieve substantial CO_2 emission reductions in the iron and steel sector. Yet the additional investment is moderate relative to the total required in the Stated Policies Scenario – cumulative capital investment in core process equipment between 2021 and 2050 in the Stated Policies Scenario is estimated at USD 1 150 billion, while in the Sustainable Development Scenario this increases by about 20% to USD 1 390 billion (Figure 2.13).[11] The increase in investment costs grows over time, with the required capital investment in the 2041 to 2050 period being about 60% higher in the Sustainable Development Scenario than the Stated Policies Scenario.

The increase in investment is moderated in part by lower overall steel demand in the Sustainable Development Scenario, with cumulative demand 10% lower than in the Stated Policies Scenario. This means that lower total investment in steel production capacity will be required. Yet these material efficiency savings are not without cost. While it is difficult to assess the precise cost of material efficiency measures, it is estimated that an additional USD 200 billion could be required cumulatively to 2050

[11] The boundary for investments includes CAPEX only for core process equipment within the IEA's crude steel boundary (see Box 1.3 in Chapter 1). Core equipment includes that for capturing CO_2 and producing hydrogen, but does not include fixed OPEX, fuel costs, CO_2 transport and storage costs, or investment in technology R&D.

to achieve the steel demand savings.[12] This comprises all financial costs (not just capital costs) incurred by actors both within and outside the steel sector, for example for improved equipment to increase semi-manufacturing and manufacturing yields, new building design technologies and construction technologies to reduce material use in structures, and setting up steel tracking, collection, testing and quality control systems to enable direct reuse. The moderating effect of material efficiency also means that the increase in capital costs for steel process equipment per tonne of steel produced in the Sustainable Development Scenario compared to the Stated Policies Scenario is higher than the total investment increase: in 2041-50 investment per tonne of steel produced increases by 90% (compared to the 60% increase in total investment).

Figure 2.13 Cumulative capital investment in process equipment in the iron and steel sector by scenario



Notes: STEPS = Stated Policies Scenario, SDS = Sustainable Development Scenario. Unless otherwise stated, investment is cumulative from 2021 to 2050. Investment is CAPEX in core process equipment, plus engineering, procurement and construction costs. This includes CO_2 transport and storage for CCUS and hydrogen production for hydrogen-based routes. Costs to achieve material efficiency savings are not included.

In the Sustainable Development Scenario USD 1 390 billion of investment in core process equipment is required cumulatively, 20% more than in the Stated Policies Scenario.

[12] The costs associated with material efficiency strategies are derived from IEA modelling and marginal abatement costs presented in Material Economics (2018). These costs include all financial costs (capital investment, labour, energy and material costs), but exclude the costs of direct emission reduction strategies in other sector (for example, the costs of vehicle lightweighting in the transport sector to achieve fuel economy savings are not included). These are indicative estimates with high levels of associated uncertainty.

The regional spread of investment is closely tied to the distribution of steel production across regions. As such, China sees the largest cumulative investment at about 26% of the total in both scenarios, directed at refurbishment and replacement of its already very large stock of capacity. India comes second with about 18% of investment in both scenarios in order to build up its capacity as production levels increase.

In the Sustainable Development Scenario most regions require higher investment relative to the Stated Policies Scenario. However, the Middle East requires somewhat lower investment and investment in the United States remains almost the same. This is largely driven by a higher share of scrap-based production relative to the Stated Policies Scenario. Secondary production is considerably less capital-intensive, avoiding expenditure on furnaces for producing hot metal or DRI, as well as on coke ovens, pelletisers and sinter plants for iron ore and coke processing. As a result of the combined effect of a higher secondary share and material efficiency driving lower demand in the Sustainable Development Scenario relative to the Stated Policies Scenario, these regions have a smaller primary production envelope that requires investment in near-zero emission technologies. This is enough to result in lower investment requirements while achieving substantial emission reductions. In regions like India that are building up considerable capacity, the European Union with its ageing capacity, and China where younger capacity will require retrofitting or replacement, coupled with a smaller increase in secondary production share, the need to invest in near-zero emission technologies is the main driving force behind higher capital investment needs in the Sustainable Development Scenario.

While almost all investment in the Stated Policies Scenario is for technologies that are already mature today, in the Sustainable Development Scenario around 35% of cumulative investment is in technologies that are currently in the demonstration or prototype phases. This investment in currently earlier stage technologies occurs later in the modelling horizon once they have become commercially available, and thus the increased investment in the Sustainable Development Scenario is greatest in the 2041-50 period.

In contrast to these increased investment costs, the Sustainable Development Scenario actually results in somewhat lower cumulative energy costs relative to the Stated Policies Scenario: about 10% less is spent on energy inputs over 2021-50. While the costs of electricity are higher in the Sustainable Development Scenario and more electricity is consumed, fossil fuel costs – which still account for the majority of cumulative fuel consumption – are lower. Furthermore, overall fuel consumption in the Sustainable Development Scenario is reduced owing to a combination of technology performance improvements to existing process equipment, shifts to process routes that are less energy-intensive, and a reduction in total steel demand.

In the earlier half of the projection period, the reduced energy consumption and lower fossil energy prices outweigh the increased expenditure on electricity, leading to overall reduced energy costs. Towards the end of the projection, however, the higher costs of electricity for direct use and for hydrogen production (or of hydrogen purchase) have a larger impact, such that by 2050 annual expenditure on energy inputs is about 5% higher on an absolute basis (30% higher on a per tonne of crude steel basis) in the Sustainable Development Scenario than the Stated Policies Scenario.

Prior to investment in the deployment of near-zero emission technologies, investment in R&D and demonstration will be needed to bring these technologies to market introduction. This includes investment from both public and private sectors. In addition to various government-funded innovation programmes (see Chapter 4), in recent years there have been promising signs of venture capital and corporate investment in innovative technologies. For instance, in 2019 Boston Metal, an American company, raised more than USD 32 million to develop the first industrial-scale molten oxide electrolysis pilot plant (Cleantech Group, 2019). The German company Sunfire received USD 29 million from venture capital investors to develop hydrogen solid oxide fuel cells for steelworks. Other investments have been made in advanced artificial intelligence to optimise energy use, such as the services that French company Metron is providing to ArcelorMittal among other companies, with investment of USD 11 million raised last year. These are just a few illustrative examples of the numerous investments occurring throughout the world in iron and steel sector innovation.

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Chapter 3. India in the spotlight

HIGHLIGHTS

- The iron and steel sector is responsible for around one-fifth of industrial energy consumption in India, with coal accounting for 85% of its roughly 70 Mtoe of total energy inputs. As a result, the sector is highly emissions intensive, contributing almost a third of direct industrial CO_2 emissions, or 10% of the country's total energy system CO_2 emissions.
- Since 2010 steel production in India has increased fourfold. In the Stated Policies Scenario production is expected to continue growing rapidly, almost doubling by 2030 and quadrupling by 2050. The People's Republic of China's multiple of India's production decreases from 9 today to 2 in 2050. As the absolute quantity of scrap available grows at a slower rate than steel production, additional primary production capacity, which is coal-intensive, fulfils much of this additional demand. Coal demand grows by 250% and emissions from the sector by 230% in the Stated Policies Scenario.
- India's steel industry is more energy- and emissions-intensive than many other countries', due to the presence of many small production facilities, the heavy reliance on coal for DRI furnaces and the low proportion of scrap in total metallic input. In the Sustainable Development Scenario the sectoral emission intensity of crude steel production falls by over 60%, from 2.3 t CO_2/t today to 0.9 t CO_2/t in 2050.
- Material efficiency and performance improvements to existing technologies are key emission reduction measures in the short to medium term, together accounting for 95% of cumulative emission reductions by 2030 in the Sustainable Development Scenario. The existing National Resource Efficiency Policy 2019 and the landmark Perform Achieve Trade scheme are key examples of policies that can be built upon to achieve these savings.
- In the longer term emission reductions are harder won, with the need for a rapid roll-out of innovative near-zero emission steelmaking technologies. Innovative retro-fit concepts are deployed to tackle the young existing blast furnace stock (15 years on average, compared to a typical lifetime of 40 years) and those blast furnaces that will need to be installed in the coming decade when few alternatives are available. In the latter half of the Sustainable Development Scenario, the hydrogen-based DRI and innovative smelting reduction with CCUS routes take over when it comes to capacity additions. By 2050 near-zero emission routes account for 55% of primary production.

India is currently the second-largest steel-producing country in the world after the People's Republic of China ("China"). The National Steel Policy of 2017 (NSP 2017) set a target to more than double capacity by 2030, with further growth expected in the long term to meet the demand for steel from a number of key national sectors, such as the construction industry, infrastructure development and the automotive industry (Ministry of Steel, 2017).

During the first half of 2020 the Covid-19 pandemic crisis strongly affected the Indian steel sector, which saw a steep reduction in demand and consequently production levels. There is significant uncertainty about how rapidly various aspects of the economy will recover from this shock, if at all, and output from the Indian steel sector is likely to remain below the levels projected before the crisis for several years. In the longer term, domestic demand growth coupled with strong government support to develop the national steel industry should open up important opportunities to deploy best available technologies (BATs) and new clean steelmaking technologies.

The Indian iron and steel sector is characterised by a relatively diversified technology portfolio, producing large quantities of both pig iron and sponge iron, in conjunction with both primary and secondary steel production. The strong knowledge base and versatility in its portfolio are a promising starting point for the transition that needs to take place. In any projection of a sustainable future for the global steel industry, India will play a critical role, especially when it comes to the deployment of state-of-the-art near-zero emission technologies.

This chapter explores the golden opportunity for India to reshape the current course of its iron and steel sector, making it more sustainable. The new capacity additions projected to take place over the next 10 years are expected to account for 40% of the country's steelmaking capacity still operating in 2050, barring any early retirements. For this reason, investment needs to be directed towards near-zero emission technologies as soon as possible. This chapter provides a detailed look at the transition outlined for India's iron and steel sector in the IEA Sustainable Development Scenario, starting with an overview of the industry as it exists today. The scenario results outline one possible – and plausible – pathway for the sector to play its role in achieving energy and environmental goals. The chapter concludes with a context-specific look at how policies could support the transformation of the iron and steel sector, providing a complement to the broader overview of this topic provided in Chapter 4.

Steel: A critical ingredient for India's development

India is growing fast by almost any measure. Its population is the second-largest of any country and is projected to overtake that of China by the mid-2020s. Since the liberalisation of India's economy in the early 1990s, GDP has grown more than sixfold and its human development index value[1] has increased by 50% (UNDP, 2020). Industrialisation has been a central component of this development, with industry's share of total final energy consumption rising from 34% in 1990 to over 40% in 2019, during which time industrial productivity doubled.[2] The steel sector has played an important role in the country's industrialisation and accounted for around one-quarter of the growth in industrial energy consumption in the 1990-2019 period.

As discussed in Chapter 1 in the global context, steel is a critical input to infrastructure, housing and the automotive sector, among others, and the same is true in India. As Indian citizens increasingly gain access to higher quantities and qualities of education, healthcare, shelter and mobility, demand for steel and other industrial materials will rise rapidly. Steel is therefore a key ingredient in supporting India's development in the decades to come. In the IEA baseline projection – the Stated Policies Scenario (STEPS) – these trends are projected to continue, with steel playing a critical role in the country's ongoing economic development. Relative to 2019, GDP is projected to almost double by 2030 and the population to increase by 10%, compared to an increase of more than 500% in GDP and more than 50% in population between 1990 and 2019.

Steel is also a key component of India's energy system (Figure 3.1). In addition to being an important input to much of its energy infrastructure, the sector itself is a major energy consumer. During the past two decades in particular, the growth of steel production has been strongly coupled with the growth in energy demand in the sector, and in industry overall. The iron and steel sector is now the largest single contributor to industrial energy demand, with a strong reliance on coal (85% of energy inputs) and, to a lesser extent, electricity. Currently the steel industry consumes final energy of around 70 million tonnes of oil equivalent (Mtoe), representing almost 23% of total energy inputs to the industrial sector.

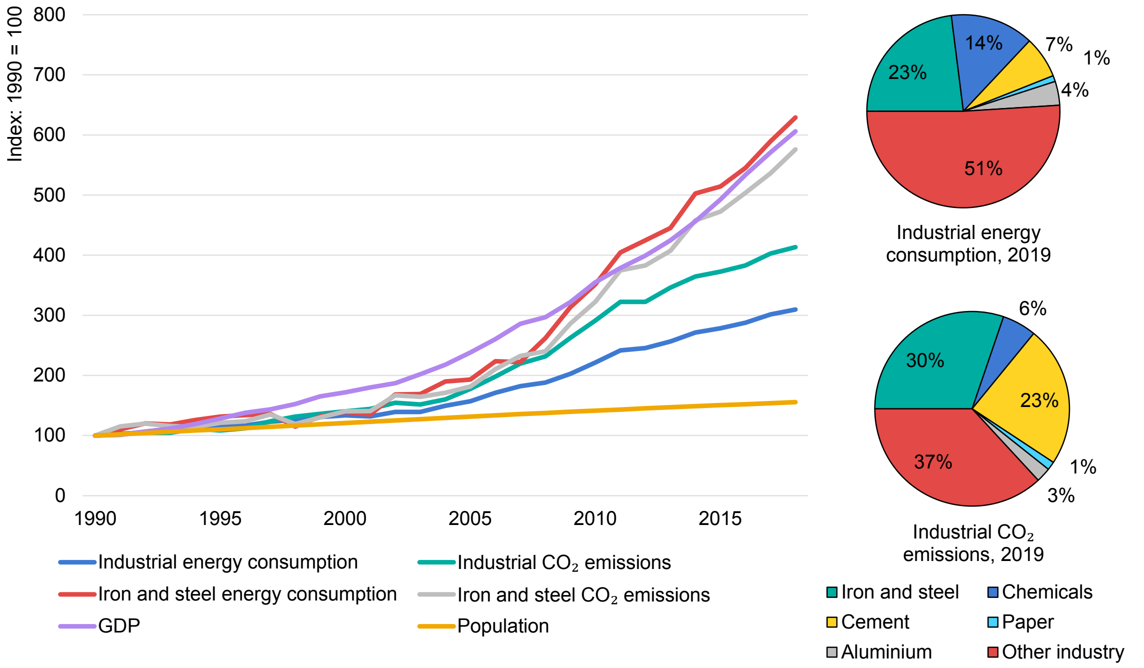
With this rising demand for industrial materials comes an increasing environmental burden. Emissions from the Indian industrial sector have risen more than fourfold since the millennium, with steel now accounting for the largest share at 30%

[1] Incorporating measures of life expectancy, education access and income.

[2] Industrial productivity is equal to value added per unit of energy consumed. It is an indicator of the efficiency of energy use.

(252 million tonnes of CO_2 [Mt CO_2]) in 2019, corresponding to more than 9% of India's total energy-related CO_2 emissions. While the country's development continues to be a policy priority, iron and steel sector emissions – and those from other parts of the energy system – must fall if India is to make progress on its global climate targets. Moreover, while water stress and air pollution are beyond the scope of this analysis, they are important dimensions to consider as India looks to reduce its CO_2 emissions.

Figure 3.1 Energy consumption and CO_2 emissions of India's industrial sector



Note: Industrial energy consumption refers to the IEA Energy Balance boundaries of total final consumption by industry, non-energy use for chemical feedstocks, and energy consumed in the transformation sector by blast furnaces and coke ovens. "Iron and steel sector" corresponds to the IEA Energy Balances "iron and steel" sub-sector's final energy consumption in addition to energy use in blast furnaces and coke ovens in the transformation sector. Industrial CO_2 emissions refers to CO_2 emissions from fossil fuel combustion within the industrial energy consumption boundary described above, along with CO_2 emissions from industrial processes within these sub-sectors.
Source: IEA (2019), *World Energy Balances*.

The iron and steel sector is the largest single energy consumer and CO_2 emitter in the industrial sector in India.

Steelmaking in India past and present

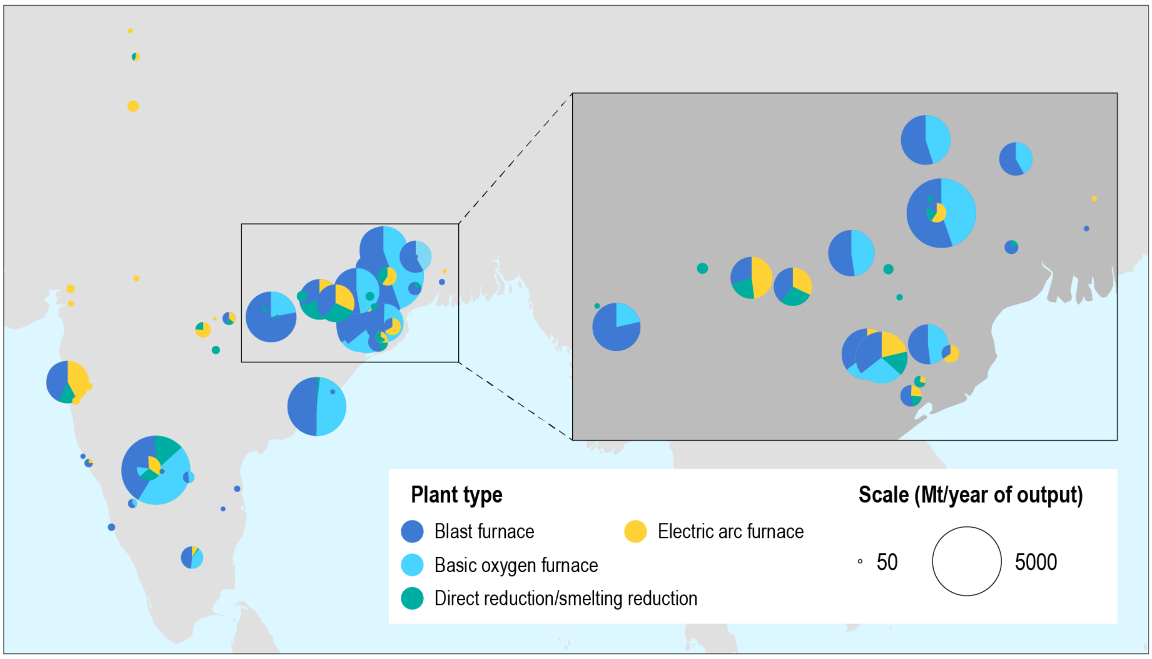
India is home to what is claimed to be the world's oldest blast furnace still in operation, which opened in Jamshedpur in 1911, although the plant has undergone many refurbishments and upgrades since then. Since the country's independence in 1947, the steel industry has boomed, gradually at first, and then rapidly after the liberalisation of the country's economy in the early 1990s, with crude steel production de-licensed in 1991 and de-controlled in 1992. These reforms removed licensing requirements for capacity creation (with the automatic approval of foreign equity investment up to 100% of investment needs), abolished price regulations, and allowed free imports and exports of raw materials, semi-finished and finished iron and steel products (JPC, 2019a). This all spurred an influx of private and foreign investment into India's industrial sectors, including the steel industry, and since then steel has seen almost linear growth in domestic demand and production.

International trade in semi-finished and finished steel products and raw materials has grown over time. India started exporting steel in 1964 and in 2019 exported 13.4 megatonnes (Mt) of steel (JPC, 2019a; World Steel Association, 2020a). With 8.9 Mt of steel imported in 2019, it is a net exporter. India is also a modest net exporter of iron ore, with domestic consumption in 2018 of 203 Mt compared with 205 Mt of production.[3] The country is a net importer of coke, coking coal and bituminous coal,[4] together with minerals for certain specialist steel grades (such as high-grade manganese ore and chromite), which are required for its domestic automotive sector. Steel-grade limestone, refractory raw materials, nickel and scrap are also currently imported.

Installed steel production capacity is equivalent to 133 Mt, with capacity utilisation varying significantly, from 77% for integrated steel plants down to 69% for sponge iron production, 56% for pig iron production and as low as 16% for smaller steel melting shops (Ministry of Power, 2018a), compared to a global average for all routes of around 80%. Capacity is highly concentrated in the central and eastern regions, in the states of Jharkhand and Chhattisgarh (Figure 3.2). These states offer convenient access to some of the country's largest iron ore and coal reserves, in Jharkhand, Odisha, West Bengal and Chhattisgarh (albeit not the highest quality), and the key seaports of Paradip and Haldia for receiving imports of raw materials and delivering exports of finished product. Basic oxygen furnaces account for around 44% of crude steel output capacity, with induction furnaces and electric arc furnaces accounting for the remaining 27% and 29% respectively.

[3] National reserves are currently estimated at around 5 400 Mt (USGS, 2019).
[4] Both coking coal and bituminous coal can be used for coke production.

Figure 3.2 Map of installed capacities in the iron and steel sector in India, 2018



Note: This map is without prejudice to the status of or sovereignty over any territory, to the elimination of international frontiers and boundaries, and to the name of any territory, city or area. The size of the bubbles reflect the installed capacity by city. Installed capacity is in terms of output: hot metal for blast furnaces, crude steel for scrap-based electric furnaces, and sponge iron or hot metal for direct reduction/smelting reduction furnaces.

Steel production capacity is mostly along coastal areas in India, with the largest capacity in the central and eastern regions of the country, in the states of Jharkhand and Chhattisgarh.

India is now the world's second-largest steel-producing country, with an annual output of crude steel equating to 111 Mt, recently overtaking Japan (99 Mt), but trailing China (996 Mt) by a large margin (World Steel Association, 2020a). Large steel producers[5] account for around 63% of the total production, with the rest of the capacity being run by small producers (Ministry of Steel, 2019a). Eight producers under the administrative control of the Ministry of Steel, known as Central Public Sector Enterprises,[6] represent around 21% of total steel production (Ministry of Steel, 2018), with the remaining share run by the private sector. The country is also the third-largest consumer of finished steel products, after China and the United States, which feed a wide range of manufacturing processes (JPC, 2019b).

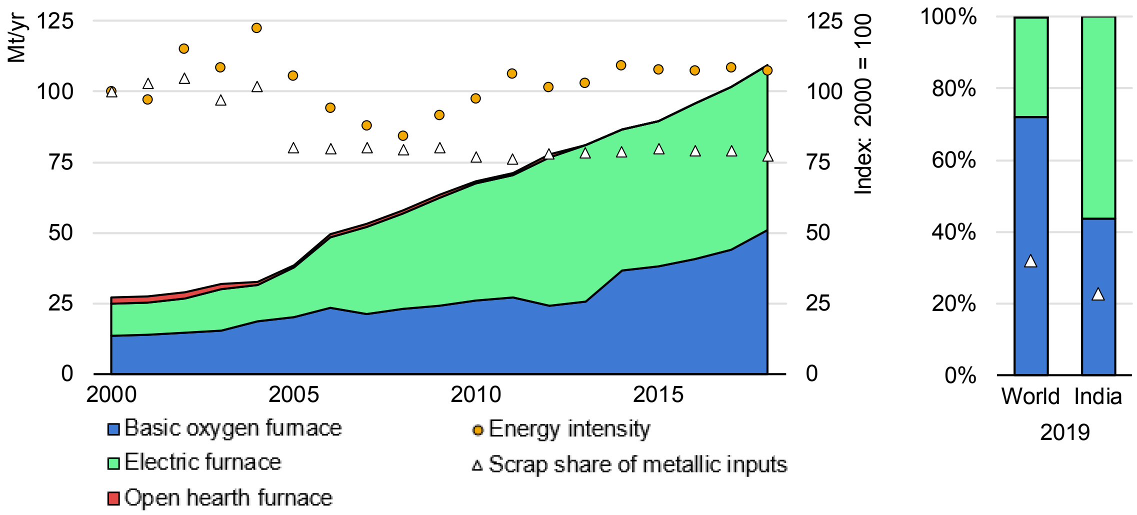
Focusing in on production pathways, India is the world's largest producer of sponge iron, owing to the widespread use of direct reduced iron (DRI), electric arc furnace (EAF) and induction furnace routes in the country. Electric furnace production

[5] Defined as those with annual steel production above 1 Mt.

[6] Steel Authority of India Ltd (SAIL), Rashtriya Ispat Nigam Ltd (RINL), NMDC Ltd, MOIL Ltd, MSTC Ltd, Ferro Scrap Nigam Ltd (FSNL), MECON Ltd, and KIOCL Ltd.

accounts for around 56% (62 Mt) of crude steel output, of which just under half is from induction furnaces and the rest from EAFs (Figure 3.3). The remaining 44% (49Mt) is produced via the blast furnace-basic oxygen furnace (BF-BOF) route, using a mixture of scrap and hot metal as charge to the BOF. The country consumes around 30 Mt of scrap, of which a considerable proportion is used in EAFs and induction furnaces in combination with iron.

Figure 3.3 Production of steel by route and sector energy intensity in India



Notes: Electric furnace includes electric arc furnaces and induction furnaces. Energy intensity is calculated based on crude steel production volumes and the sectoral energy consumption of the iron and steel sector as defined in Box 1.3.
Sources: World Steel Association (2020a), IEA Energy Balances (2019) and IEA analysis.

Around 56% of steel production in India comes from electric furnaces, compared to a global average of about 28%.

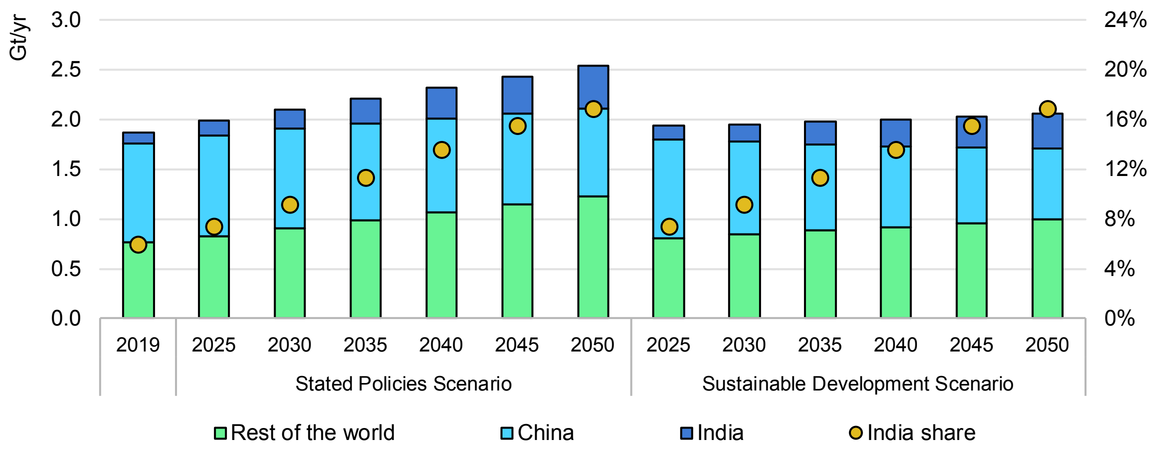
Aside from its high share of DRI in total iron production (the second-largest globally following the Middle East), there are two other distinguishing features of the current production pathways being used in India. Firstly, there is a large ferrous casting industry, which consumes 13 Mt per year of iron beyond that used for crude steel. Ferrous castings are used for a wide range of applications, notably engine blocks and gears in the automotive sector. Cast iron is also used for various domestic cooking utensils (e.g. cast iron pans). India accounts for 12% of the global castings industry, second only to China (44%) (CAEF, 2020). Secondly, India has a large share of induction furnaces in its total electric furnace stock, several of which appear to be charged with large proportions of iron in addition to scrap, sometimes produced in small blast furnaces.

India's steel industry is particularly energy-intensive compared to international benchmarks (TERI, 2020). Some factors that explain this lower-than-average energy performance are a heavy reliance on coal to supply its DRI furnaces, the low quality of domestic coal and iron ore, often very small production sites and the relatively old stock of blast furnaces in the country (on average around 25 years since installation, and around 15 years since the last major refurbishment), which tend to consume more energy per unit of output. India also has a smaller share of scrap in the sector's total metallic inputs (23%) compared to the global average (32%) (Figure 3.3).

A key country for the global steel industry transition

While China is by far the largest steel-producing nation in the world today, both the Stated Policies Scenario and Sustainable Development Scenario see a contraction in China's output as domestic demand plateaus and subsequently declines through to 2050. Contrastingly, India's output is projected to follow a very different trajectory (Figure 3.4). In the Stated Policies Scenario Indian steel production almost doubles by 2030 and almost quadruples by 2050, relative to 2019 production levels (111 Mt). This growth is driven by a number of domestic projects and ambitions (Box 3.1), underpinned by the country's NSP 2017 (Ministry of Steel, 2017).

Figure 3.4 The role of India and China in global steel production in the Sustainable Development Scenario



Even in the Sustainable Development Scenario India remains the fastest-growing producer of steel, due to demand growth and the contraction of steel production in China.

Box 3.1 Principal factors driving steel demand in India

In the Stated Policies Scenario the growing demand for steel in India continues to stem from a number of key domestic sectors. These include the construction industry (35% of current total steel consumption), infrastructure development (20%) and the automotive industry (12%) (Ministry of Environment Forest and Climate Change, 2019). These are supported by specific projects and announced government measures aimed at modernising, industrialising and better connecting the country to maintain its development trajectory in the coming decades. The construction of new cities and the redevelopment of existing ones, and the provision of new infrastructure, ports and transport links, will require millions of tonnes of steel under various projects, as described below. Major projects include the following:

The Smart Cities Mission (100 Smart Cities) is an initiative to support the economic and social development of 100 smart cities throughout the country (Ministry of Urban Development, 2015). The initiative was launched in 2015 and, after five rounds of funding, has identified nearly all of the 100 cities. Although the definition of a "smart city" is not precisely defined, the Indian government is aiming to retrofit and redevelop existing city districts as well as building entirely new settlements. Committed central government funds for the project equate to INR 48 000 crores (around USD 7.5 billion), with an equivalent amount being provided by the individual states where the selected cities are, or will be, located.

Another construction-related initiative aimed at providing housing for all in urban areas by 2022 is the Pradhan Mantri Awas Yojana (Urban) Mission (also called Housing For All), which was launched by the Ministry of Housing and Urban Affairs in 2015. It has the goal of providing affordable accommodation for the growing urban population (Ministry of Housing and Urban Affairs, 2020). So far, the government has invested INR 6.16 trillion (around USD 87.5 billion) in this initiative (The Economic Times, 2020).

The Delhi Mumbai Industrial Corridor (DMIC) is an infrastructure project aimed at developing the Indian industrial sector in the corridor between the capital Delhi and the financial centre of Mumbai. The implementing agency of the project, the DMIC Development Corporation (DMIDC), was established in 2008 with 49% of the equity being held by the Government of India (Department for Promotion of Industry and Internal Trade, 2019). The main goal of the project is to develop the area as a global, interconnected manufacturing and trading hub, developing around new industrial cities (eight cities will be developed in the first phase of the project), with a total estimated investment of around USD 100 billion (DMICDC, 2019).

The SagarMala Programme is a project aimed at promoting port-led development in India. As part of this programme, a National Perspective Plan (NPP) was approved in 2016 in order to modernise existing ports and develop new ones, enhance port connectivity to their hinterlands, develop industrial clusters near existing and new ports, and promote the sustainable development of coastal communities (Government of India, 2019a).

The Indian government is supporting public and private investment (up to 100% foreign ownership through the Foreign Direct Investment Policy) to meet the goals of the National Rail Plan for 2030. The plan aims to modernise the network while taking into account different perspectives from state governments, elected representatives and private stakeholders (Ministry of Railways, 2016). Currently the Indian Railways network comprises 12 617 trains running over more than 68 442 kilometres, transporting 23 million passengers a day and employing 1.3 million people (Government of India, 2019b).

The NSP 2017 sets a target to increase Indian steel capacity to 300 Mt per year by 2030-31 and per-capita steel consumption to 160 kilogrammes (kg) in the same timeframe from the current 80 kg (relative to a global average of around 250 kg/capita in 2019). Micro, small and medium-sized enterprises are targeted as key drivers to increase steel capacity in the country. The policy also aims by 2030-31 to meet domestically the demand for high-grade automotive steel, electrical steel, special steels and alloys for strategic applications, and to reduce by 50% India's dependence on imported coking coal. In addition, the Domestically Manufactured Iron and Steel Products Policy of 2017, revised in 2019, helps support domestically manufactured iron and steel products by giving preference in government procurement to domestic products (Ministry of Steel, 2019b).

The Covid-19 pandemic triggered a steep decline in Indian steel production – output was 24% lower in the first half of 2020 compared to the first half of 2019 (World Steel Association, 2020b). This compares to a decline of only 5% for the same period at the global level, driven largely by a rapid recovery in China. With the exception of China, many other countries have seen production declines of a magnitude closer to India's. The global economy may take at least a couple of years to recover, if not longer in case of a second wave of infections. Consequently, in the Stated Policies Scenario Indian installed capacity remains below the ambitions outlined in the pre-crisis NSP 2017. The country's crude steel capacity reaches around 200 Mt by 2030, corresponding to an output of around 130 kg/capita.

In the Stated Policies Scenario India accounts for 9% of global steel production by 2030, up from 6% today. By 2050 its share of global production increases to around

17%, while China's share decreases to 35% (Figure 3.4). As discussed in Chapter 2, in the Sustainable Development Scenario material efficiency plays an important role in reducing global steel demand, while still ensuring the provision of the same material services. The impact of material efficiency strategies in India – the key differentiator in the outlook for production between the Stated Policies Scenario and the Sustainable Development Scenario – is marked. India's steel production in the Sustainable Development Scenario is 14% lower in 2040, and 19% lower in 2050, relative to the Stated Policies Scenario.

Similar to the trends visible at the global level, the largest contributors to demand reduction include the extension of building lifetimes, improved building design and construction, modal shift that reduces total vehicle sales, vehicle lightweighting and improved product manufacturing yields. While extending building lifetimes is one of the most important levers, its contribution in India is somewhat lower than at the global level, given the younger building stock. This gives way to a larger role in India for strategies focused on design and fabrication of new buildings and vehicles. Despite these demand reductions, India retains the title of the fastest-growing large region in the Sustainable Development Scenario.

India's growth trajectory in the coming decades makes it a critical country for the sustainable transition of the global iron and steel sector. Its growth brings with it two related challenges. Firstly, many of the near-zero emission steelmaking technologies that are relied upon to deliver deep emission reductions in the Sustainable Development Scenario will not be sufficiently developed to provide the next 10-15 years of capacity additions. India is projected to bring online over the next 10 years over 40% of the steelmaking capacity that would still be operating in 2050, assuming no early retirements. This complicates the question of how to deal with existing emissions-intensive infrastructure, both now and with respect to facilities installed over the next decade. It also means that investments in less carbon-intensive technologies need to be made as soon as possible.

Secondly, India's growth trajectory in combination with its relatively young stock of steel infrastructure, buildings and goods mean that increases in the domestic supply of scrap will be insufficient to meet all the growth in steel demand. In the Stated Policies Scenario scrap availability grows considerably – by around 120 Mt over the projection horizon – but this is far less than the more than 310 Mt growth in steel production. The remainder that cannot be met by scrap-based production will need to be met by primary production. This contrasts with China, whose growing scrap availability and declining steel production enable a greater reliance on less emissions-intensive secondary production – commercially proven and rapidly scalable – as a means to dramatically reduce overall emissions.

Technology pathways towards zero emissions in India

In the Sustainable Development Scenario India's steel sector is projected to triple production by 2050, while CO_2 intensity decreases by 60%. With the absolute quantity of scrap growing at a slower rate than that of steel production, achieving this goal requires a rapid transformation of the relatively young primary production fleet, which is almost exclusively supplied by coal today. This section examines the technology trajectory that India follows in the Sustainable Development Scenario, including the contribution and readiness of the main options that it relies on.

Energy consumption and CO_2 emissions

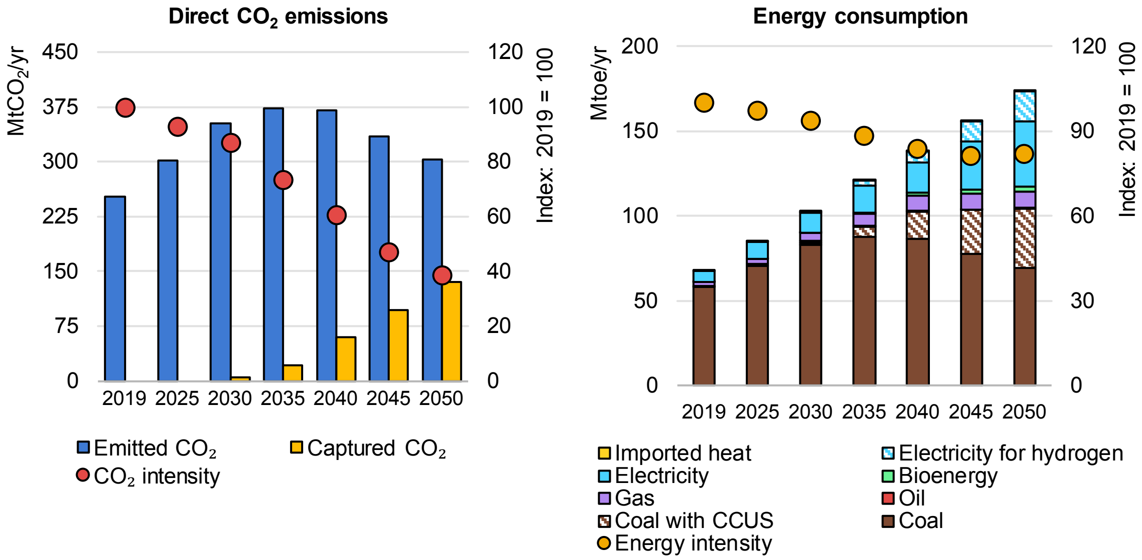
The Indian steel sector is currently energy- and carbon-intensive, consuming around 70 Mtoe of energy and directly emitting around 250 Mt CO_2 in 2019.[7] The sector also resulted in an additional 75 Mt CO_2 of indirect emissions to generate the power and imported heat it consumes.[8] Of the direct emissions, most come from coal (90% of total emissions), mainly used in coke ovens, blast furnaces and coal-based direct reduction furnaces. Much of the remaining direct emissions are process emissions resulting from the use of lime fluxes and ferroalloy production, with only small contributions from gas and oil consumption. After coal, electricity is the second-largest energy commodity consumed in the sector (10% or around 80 terawatt hours [TWh]). EAFs and induction furnaces account for about half of the electricity input to steelmaking in India. This electricity consumption results in indirect emissions.

In the Stated Policies Scenario both the energy consumption and CO_2 emissions of the Indian steel sector are projected to more than triple by 2050. However, in the Sustainable Development Scenario energy consumption increases by two and half times and the direct CO_2 intensity of crude steel production declines by just over 60% by 2050. As a consequence, despite the threefold increase in production, total direct CO_2 emissions only increase by 20% (Figure 3.5). The sector remains heavily dependent on coal, although its share does drop from 85% to 60% of final energy consumption by 2050. Additionally, one-third of the remaining coal in 2050 is used in facilities with CCUS, and by 2050 1.3 Gt CO_2 has been captured and permanently stored cumulatively. Electricity consumption grows eightfold over the projection horizon, such that electricity accounts for 32% of final energy consumption in 2050, driven by increases in secondary production and deployment of electrolytic hydrogen-based production.

[7] Fuel combustion and process emissions.

[8] See Box 1.3 in Chapter 1 and Box 2.4 in Chapter 2 for further discussion of indirect emissions.

Figure 3.5 Direct CO_2 emissions and energy consumption in the iron and steel sector in the Sustainable Development Scenario in India



Note: CCUS = carbon capture, use and storage.

In the Sustainable Development Scenario the direct CO_2 intensity of crude steel falls by 60% by 2050 despite coal maintaining a large share of the sector's energy consumption.

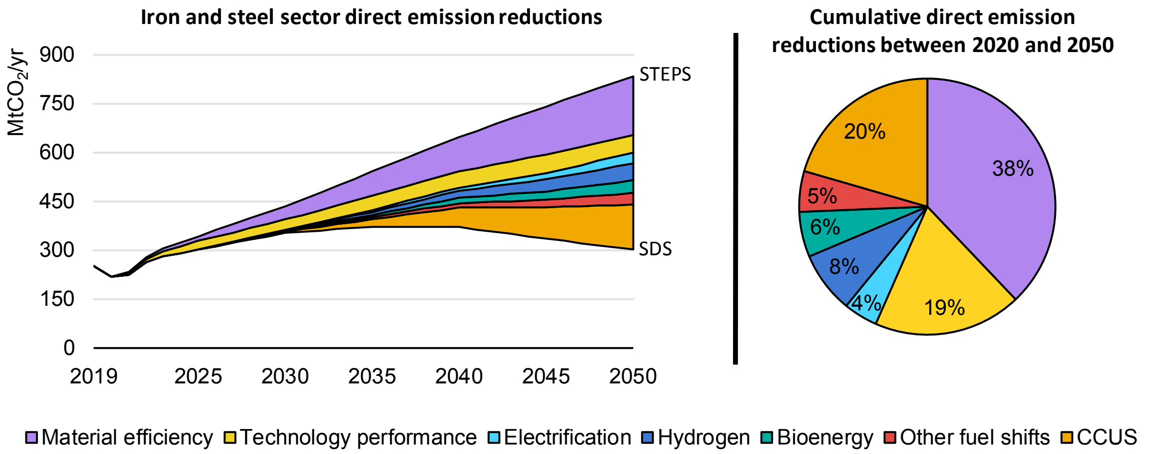
A portfolio of mitigation options

Compared to other large producers, such as China, the United States, the Middle East and Europe, India has a middling production fleet with regard to the average age of its capacity. At the process route level, we estimate an average age of 12 years for its gas-based DRI furnaces, 14 years for its coal-based blast furnaces and 17 years for its coal-based DRI furnaces, with all figures taking into account the year of last major refurbishment. Thus, the steel-producing fleet in India is only a little more than one third of the way through its typical lifetime, which is around 40 years on average for these assets. Many more blast furnaces and DRI furnaces will need to be built in India before alternative near-zero emission routes are ready to enter the market, and the country is projected to have a comparatively young fleet in 2030. Even excluding additional plants built through to 2030, cumulative emissions of around 6 Gt CO_2 can be expected from the existing capacity if nothing is done to address these assets.

Therefore, in the near term it is crucial to maximise operational efficiency in existing assets and to minimise additional emissions from new infrastructure by investing in the BAT for commercial production routes until near-zero emission alternatives reach market introduction. Around 40% of blast furnaces in India are currently equipped with top-pressure recovery turbines (TRTs), and more than 30% of coke ovens are equipped with coke dry quenching (CDQ), two examples of BAT. In the Sustainable

Development Scenario by 2030 both these shares rise to around 70%. These and other measures, including those that optimise operational efficiency, considerably improve technology performance, which accounts for almost 40% of emission reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario in 2030 (Figure 3.6). In the latter half of the projection period in the Sustainable Development Scenario, the contribution from this lever drops to 10% of annual emission savings in 2050, as most plants have already adopted BATs, even in the Stated Policies Scenario. However, at 19% of cumulative emission reductions to 2050 in the Sustainable Development Scenario, improving technology performance is an important tool in the toolbox, assuming early action can be taken on new capacity additions.

Figure 3.6 Steel sector direct CO_2 emission reductions in India in the Sustainable Development Scenario by mitigation strategy



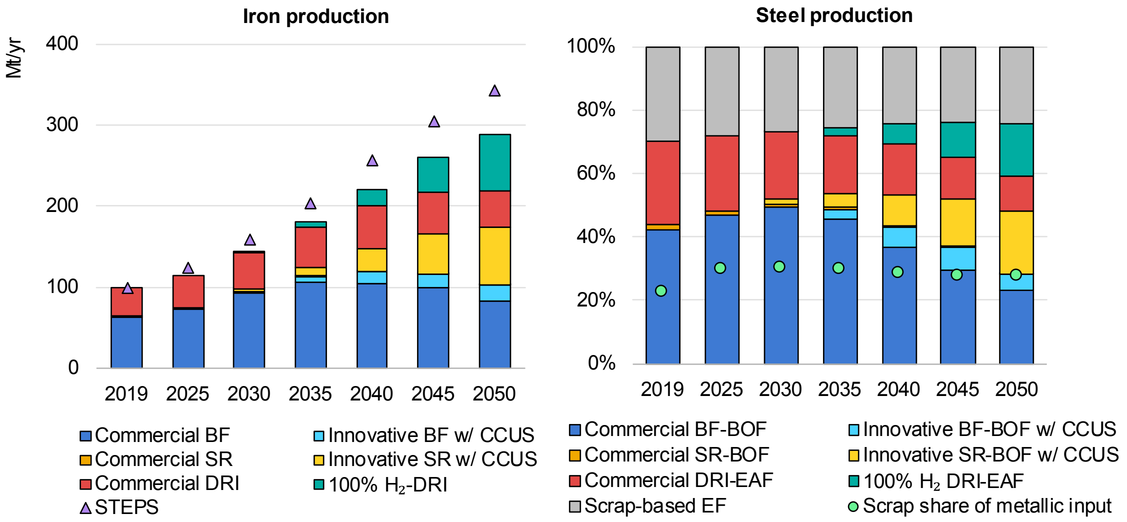
Note: Emission reductions are measured relative to the Stated Policies Scenario; as such, the improvements relative to today that occur in both scenarios are not represented (e.g. a significant proportion of increases in scrap-based production). “Other fuel shifts” primarily comprises coal to natural gas switching. Electrification here includes only direct electrification, primarily via conventional technologies, including shifts towards secondary production in electric furnaces and electrification of ancillary process equipment like preheaters and boilers. “Hydrogen” refers specifically to electrolytic hydrogen, while so-called blue hydrogen (via natural-gas-based DRI with CCUS) is included under CCUS. Material efficiency here refers specifically to demand reduction.

In India, technology performance improvements, material efficiency and CCUS contribute more than 75% of cumulative CO_2 emission reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario by 2050.

Material efficiency measures play the largest role overall in cumulative emission reductions in India in the Sustainable Development Scenario, delivering almost 40% of total reductions relative to the Stated Policies Scenario. These reductions are achieved while providing the same degree of material service as in the Stated Policies Scenario. On the demand side, key strategies mirror those discussed at the global level in Chapter 2. The most influential downstream measures are the prolongation of building lifetimes and improved methods of design and construction, the lightweighting of personal vehicles and the increased use of public transport. Because India's buildings and transport sectors are expanding rapidly over the projection horizon, there is an increasing volume of assets to which these strategies apply. In terms of steel manufacturing, the key measures are the improvement of manufacturing and semi-manufacturing yields, which apply to India as they do to any other region in the Sustainable Development Scenario. The overall contribution of India to total demand reduction due to material efficiency strategies in 2050 is around 80 Mt, or around 17% of the global total.

India sees a diversified portfolio of near-zero emission production routes being adopted in the Sustainable Development Scenario, reflecting the idiosyncrasies of the current production fleet, good access to low-cost renewable energy resources (particularly solar PV and wind) and an openness to the development of CCUS (not just in the steel industry). The hydrogen-based DRI route (alongside blending of electrolytic hydrogen into existing blast furnaces and DRI units) and the integration of CCUS in various production pathways each account for substantial shares of emission reductions in 2050 in the Sustainable Development Scenario (Figure 3.7). The proportion of emission reductions attributable to hydrogen in India (mainly the deployment of the hydrogen-based DRI route) at 8% cumulatively is similar to that seen in the global results.

Figure 3.7 Production of iron and steel by route in India in the Sustainable Development Scenario



Notes: STEPS = Stated Policies Scenario. **Commercial BF-BOF** includes traditional coal-, gas- and charcoal-based blast furnaces, with and without top-pressure recovery turbines, without CCUS. **Innovative BF-BOF w/ CCUS** includes blast furnaces with process gas hydrogen enrichment and CO_2 removal for use and storage (e.g. as being developed by the COURSE50, IGAR and 3D projects), including CCUS retrofits to existing blast furnaces and those newly installed over the coming decade. **Commercial SR-BOF** refers to smelting reduction without CCUS (COREX and FINEX). **Innovative SR-BOF w/ CCUS** includes application of CCUS to existing smelting reduction concepts (COREX and FINEX) and novel smelting reduction concepts with CCUS (e.g. as being developed by the HIsarna project). **Commercial DRI-EAF** includes gas- and coal-based DRI without CCUS, including that with a proportion of blended electrolytic hydrogen; in some regions (particularly the United States), this route has a high ratio of scrap to DRI inputs. **100% H_2 DRI-EAF** comprises fully electrolytic hydrogen-based DRI (e.g. as being developed by the HYBRIT project and ArcelorMittal in Hamburg). **Scrap-based EF** refers to electric arc furnaces and induction furnaces fed mostly by scrap. In India this category includes induction furnaces with a substantial iron charge. For further details on projects developing these technologies, see Table 2.1.

Despite some technology shifts in iron production as a result of the roll-out of near-zero emission routes, the ratio between electric furnace and BOF crude steel production remains fairly stable in the Sustainable Development Scenario.

Blast furnaces and DRI furnaces maintain a substantial share of primary steelmaking production in India in the Sustainable Development Scenario, although it decreases over time, giving space to the rapid growth in deployment of near-zero emission pathways. Innovative smelting reduction with CCUS is the first near-zero emission technology introduced in India, and it is also responsible for a surge in smelting reduction-based iron production. This route accounts for around a quarter of primary steelmaking by 2050, deployment starting just before 2030. Assuming an average plant size of 1 Mt of crude steel per annum, this would require a new plant of this design to be built about every 3 months.

The leading role that India plays globally with respect to DRI production provides the perfect knowledge base upon which to advance alternative, more sustainable arrangements for this route. They include both the integration of carbon capture in fossil-based DRI assets, which has been relatively recently put into commercial practice in the Middle East, and introducing the 100% hydrogen-based DRI process. In the Indian context it is the latter technology option that is favoured, as it facilitates the integration of India's rapidly expanding renewable electricity production at reasonable cost later in the projection horizon (see Box 3.2 for an examination of the challenges of using variable renewable energy [VRE] for near-zero emission steelmaking). Total DRI production in India accounts for around 40% of total iron production in 2050 in the Sustainable Development Scenario, of which the hydrogen-based DRI accounts for 60%. The hydrogen-based DRI component of this DRI capacity growth begins in the early 2030s, once the technology concept has been proven at commercial scale. Assuming a 1 Mt per year of crude steel average unit size, the growth rate is equivalent to building one new plant every 3.5 months.

As described above, substantial capacity additions will be required in India in advance of near-zero emission concepts being available to deploy at commercial scale, and these will have to be met with commercially available technologies. While energy efficiency and BATs can help minimise future emissions from this new capacity, this strategy alone is not sufficient to achieve deep emission reductions. Many of the near-term capacity additions are blast furnaces, which are better at handling the relatively low-quality iron ore inputs that are more accessible and cost-competitive in India. Blast furnace-based production grows by 16% over the period 2019-25 in the Sustainable Development Scenario. The legacy of those capacity additions is, in part, the reason why India still has a considerable amount of blast furnace-based iron production in 2050 in that scenario.

Adopting BATs for new capacity additions through to 2030 allows the retrofitting of carbon capture to the existing blast furnace stock, including top-gas recycling arrangements that include CO_2 removal. By 2050 in the Sustainable Development Scenario around 19 Mt of total production (or 19% of total blast furnace output) is from blast furnaces equipped with CCUS. Such dynamics in iron production routes and a growing absolute quantity of full scrap-based steel production in the long run result in electric furnaces and BOFs producing similar volumes of crude steel by 2050 in the Sustainable Development Scenario in India. This is a very similar distribution of technologies that convert iron and scrap into crude steel today in India, with the exception that the typically more efficient EAFs (as opposed to induction furnaces) dominate scrap- and DRI-based production in the long run.

Innovation and RD&D are necessary to shift emerging technologies from lab scale to commercial scale, passing through prototype and demonstration. Innovation initiatives in India are mainly focusing on efficiency improvement at the moment. In future they will need to expand beyond efficiency with the further support of both private and public sectors (see Box 3.3 for an overview of existing support programmes in India). India would also do well to capitalise on learnings from, and opportunities for, collaboration with other countries pursuing innovation in near-zero emission steelmaking technologies.

Meeting the long-term goals of the Sustainable Development Scenario calls for the Indian iron and steel sector to invest consistently over time in the various measures to reduce its CO_2 intensity. It would require about 25% greater capital investment cumulatively to 2050 than is required in the Stated Policies Scenario.

The vast majority of investment in the Stated Policies Scenario would go into mature commercial technologies – about 40% goes to the DRI-EAF route, 25% to the BF-BOF route, 25% to scrap-based EAFs and inductions furnaces, and much of the remainder to finishing processes spread across the different routes. In the Sustainable Development Scenario, on the other hand, just under half of cumulative investment to 2050 goes into mature commercial technologies, of which about 15% is for the BF-BOF route and conventional BOFs using iron from innovative routes, 35% for conventional DRI-EAF technologies, 30% for scrap-based EAFs, and the remainder for finishing processes. A further 12% of cumulative investment is for innovative smelting reduction, which is at the demonstration stage currently. Additionally, around 30% of investment is for the hydrogen-based DRI-EAF route and 4% is for innovative blast furnaces, both of which are at the prototype stage today. Carbon capture technologies applied to various routes account for 6% of cumulative investment.

Box 3.2 Harnessing variable renewable electricity (VRE) for steel production in India

Hydrogen-based DRI plays an important role in the Sustainable Development Scenario, particularly in India. Of the approximately 180 Mt of crude steel produced globally via this pathway in 2050, India accounts for around one-third. Assuming a reliable source of grid electricity, and therefore a high capacity factor at the installation (95%), the levelised cost of steel production via the hydrogen-based DRI route in India, as with other locations, is determined in large part by the cost of electricity powering the process. Levelised costs of USD 500-860 per tonne of crude steel are achievable, assuming a grid electricity price range of USD 30-90 per megawatt hour (MWh). Figure 2.11 in Chapter 2 shows how this range of costs compares to other major innovative process routes. Levelised costs for alternative routes that achieve a similar level of CO_2 intensity decline with the use of CCUS are typically in the range of USD 360-650 per tonne of crude steel, assuming the same range of electricity prices.

An alternative approach to using grid electricity is to harness VRE directly, in a captive installation. By 2035 solar PV generation is expected to achieve costs of around USD 20/MWh and wind around USD 30/MWh in certain locations in India, where capacity factors, wind speeds and irradiation potential are highest. While our core analysis results are not prescriptive as to the geospatial location of future installations, this low cost of VRE – together with the need for significant capacity expansion – is an important explanatory factor behind the outsized role that the hydrogen-based DRI route plays in India.

In addition to its low cost, VRE is an attractive energy vector for steel production via the hydrogen-based DRI route because this electricity can be generated emissions free. While a small amount of grid electricity (or some other form of dispatchable power generation, such as a hydropower plant, a battery or a diesel generator) is still likely to be required in an installation run on VRE, the CO_2 intensity is lowered substantially relative to a 100% grid electricity installation. Direct use of VRE in steelmaking and other industrial processes could also ease the burden faced by the electricity grid by accommodating the variability directly, or by varying the proportions of grid electricity consumed at times of supply shortage or surplus.

This low-cost and ultra-low CO_2 intensity VRE utilisation does impose constraints. Because of the mismatch between the variability of VRE and the need for fairly stable operating conditions for large-scale industrial processes, flexibility is vital. It can either be provided on the supply side (principally through the use of hydrogen buffer storage or battery electricity storage) or on the demand side (a tolerance of a certain degree of ramping or periods of ceasing production). Both options result in additional cost, either in the form of additional equipment (e.g. hydrogen or electricity storage) or lower utilisation and increased maintenance costs for core process equipment (e.g. the hydrogen-based DRI furnace).

To explore this trade-off in more detail in the Indian context, we have examined three specific locations in the country which display both significant potential for and low cost of VRE from solar PV and wind. The main parameters for these sites are presented in the table below and are based on data for 2035 in the Sustainable Development Scenario. All three locations have excellent solar PV resources (typical in many parts of the country), while the Gujarat and Karnataka locations also have favourable wind resources (only representative of the western part of the country, in the mountainous areas and near the coast).

Parameters for three low-cost VRE sites in India in 2035

Parameter	Rajasthan	Gujarat	Karnataka
Solar PV capacity factor	23%	24%	24%
Wind capacity factor	15%	46%	44%
Electrolyser capacity factor	41%	40%	41%
Hydrogen storage (low-cost case) (days)	18	21-24	11-17
Hydrogen storage (high-cost case) (days)	1-8	1-8	1-3
Levelised cost solar (USD/MWh)	20	19	19
Levelised cost wind (USD/MWh)	89	28	29
Share of solar PV	100%	65-81%	64-83%
Curtailment of electricity	7%	7-8%	3-5%
High process flexibility assumptions	> 60% utilisation required, with a ramp rate of 10% per hour. Full stops allowed with minimum 24-hour duration.		
Low process flexibility assumptions	> 90% utilisation required with a ramp rate of 10% per hour. No stops allowed.		
Low-cost hydrogen storage	Cavern storage, CAPEX = USD 0.4/kWh		
High-cost hydrogen storage	Steel tanks, CAPEX = USD 15/kWh		

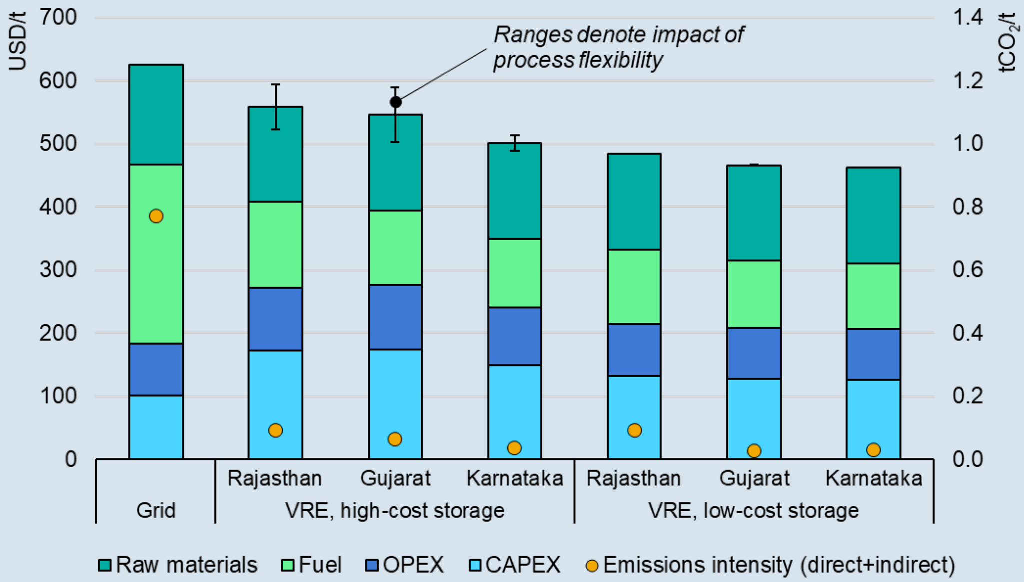
Notes: The methodology used to find the optimal sizing, arrangement and operating regime at each site, in order to minimise levelised cost, is similar to that used in a study of ammonia from VRE (Armijo and Philibert, 2020). "Solar PV" refers to utility-scale horizontal-tracking PV cells; CAPEX = USD 360/kW. "Wind" refers to Class 2 wind turbines; CAPEX = USD 980/kW. The quantity of hydrogen storage in days is denoted on the basis of the annual average output of the electrolyser. The levelised cost of hydrogen is USD 1.7-2.1/kg across the cases and locations considered. "Share of solar PV" is stated on the basis of its contribution to the levelised cost. The ranges of values denoted for "Hydrogen storage", "Share of solar PV" and "Curtailment of electricity" correspond to the range of flexibility assumptions considered. kW = kilowatt; kWh = kilowatt hour; MWh = megawatt hour.

Two sets of assumptions are used to explore the impact of process flexibility on levelised cost. The "High process flexibility assumptions", as denoted in the table above, describe a situation in which the utilisation of the DRI furnace can ramp down to 60% of its rated capacity, at a rate of 10% per hour. Full stops in the operation of the process, for a minimum period of 24 hours, are also permitted under these assumptions. In the "Low process flexibility assumptions" case, full process stops are not permitted and the DRI furnace may only ramp down to 90% of its full utilisation, taking one hour to do so. The mid-point of these flexibility assumptions is used as the central case for the results.

In each flexibility case, two costs of hydrogen storage are also considered: "Low-cost hydrogen storage", corresponds to naturally occurring geological storage; "High-cost hydrogen storage" corresponds to high-pressure steel tanks. Higher process flexibility and lower cost storage result in smaller amounts of cheaper storage being used, having the effect of lowering the levelised cost of production. Lower process flexibility and higher cost storage have the opposite effect.

The chosen analytical approach aims to minimise the levelised cost of steel production by optimising the size and utilisation of the main assets used in the hydrogen-based DRI process. They include the solar PV and wind installations used to generate the electricity, and the core process units (the electrolyser, the DRI furnace and the EAF).

Simplified levelised cost of hydrogen-based DRI steel production with VRE in India in 2035 under a range of flexibility and storage cost assumptions



Notes: Electrolyser: CAPEX = USD 500/kW, 70% efficiency on a lower heating value basis including compression to 60 bars for storage. Grid electricity = USD 68/MWh and 184 gCO_2/kWh. The ranges shown for the high-cost storage cases correspond to the flexibility assumptions described in the table above, with the central estimate being the midpoint of the two sets of assumptions. Flexibility has virtually no impact on the levelised cost when low-cost storage is available.

There are three key findings that signal the broader implications of this assessment for the Indian VRE steelmaking context:

Process flexibility is a prerequisite for VRE steelmaking, and the more that is available, the lower the cost of production, especially in situations when only high-cost hydrogen storage is an option. When low-cost storage is available, there is virtually no additional advantage of flexibility beyond the minimum required for stable operation. The degree of flexibility that may eventually be realised in the hydrogen-based DRI process remains uncertain. Commercial-scale operation is not currently expected before the 2030s and significant development still needs to take place (see Table 2.1, Chapter 2). However, for the high-cost hydrogen storage case, the range of flexibility explored in this analysis results in a reduction in levelised cost of around 5-15%, among the locations examined.

Low-cost hydrogen buffer storage offers the potential for significant further cost reductions, especially when considering lower process flexibility conditions. Low-cost buffer storage is unlikely to be available in many instances, so expensive high-pressure steel tanks (up to 40 times more costly than cavern storage) become the fall-back option, significantly raising the cost of stabilising the supply of hydrogen to the DRI furnace. In each of the locations explored, low-cost hydrogen storage reduces the levelised cost of production by around 5-20%, relative to the case where high-cost storage is used. Advances in hydrogen storage (cost reductions) will be critical to making this cost advantage less site-specific, but geological variation between sites is always likely to create an imbalance.

The **CO_2 intensity** of hydrogen-based DRI production (including indirect emissions from power generation) is significantly reduced by harnessing VRE directly in the Indian steelmaking context. Few large producing countries and regions will have a fully decarbonised electricity grid in the short to medium term, and demand for low-carbon grid electricity is projected to increase dramatically in the Sustainable Development Scenario. The VRE cases explored result in around an 85-95% reduction in the CO_2 emission intensity of steel production in India in 2035, relative to production via the same route using grid electricity. The residual emissions in the VRE cases stem from the use of "firm-up" electricity from the grid (or another dispatchable source) for the DRI furnace and EAF electricity requirements during periods of high intermittency – the CO_2 intensity of power generation in India is around 185 grammes (g) of CO_2 per kilowatt hour (kWh) in 2035 in the Sustainable Development Scenario, compared to a global average figure of 540 gCO_2 per kWh in 2019. Battery electricity storage or electricity generation using hydrogen could further reduce this reliance on grid electricity, but would likely add to overall costs.

Accelerating the sustainable transition in India

The projected growth in India's steel production is a challenge as much as it is an opportunity for the country. It is a challenge because the overriding importance of steel for India's economic growth means that production capacity has to be available and sufficient to meet growing demand. It is an opportunity in that actions taken by government and industry over the coming years can put India's steel sector at the forefront of technological development to support the global transition to clean energy in iron and steel production. This section discusses current policies towards that end and recommendations to accelerate progress.

Current policy and innovation landscape

Alongside the Indian government's recent adoption of policies to support industrialisation and steel sector growth, including the NSP 2017 (see discussion above), India has also rolled out a number of policies to improve industrial efficiency and environmental performance. For example, the Clean Energy Tax (or "coal cess"), enforced between 2010 and 2017 (when it was subsumed under the Goods and Services Tax), aimed to reduce the consumption of domestic and imported coal, putting pressure on industry to improve efficiency (IEA, 2020). Other key policies include the Perform Achieve Trade (PAT) Scheme and the National Resource Efficiency Policy. Additionally, the government has provided R&D support to improve the sustainability of the steel sector (see Box 3.3).

The PAT Scheme has been successful in reducing the energy consumption of a number of energy-intensive industrial sectors, including the iron and steel sector.[9] This regulatory instrument aims to reduce industrial specific energy consumption using a market-based mechanism. The mechanism enhances the cost-effectiveness of sectoral energy savings by providing certificates to entities that reduce energy consumption beyond the required threshold. The certificates can be sold to other entities that need to achieve compliance. Cumulatively, the PAT Scheme is aiming to reduce the energy consumption of India's iron and steel sector by about 30 Mtoe between 2012 and 2030, relative to business as usual (Ministry of Power, 2018a).

During the first PAT cycle in 2012-15 relatively low-cost measures were implemented, such as process optimisation measures, installation of TRTs and adoption of CDQ processes. These were internally financed by the regulated industrial facilities, referred to under the scheme as the Designated Consumers (DCs). During the second cycle (2016-19) the Indian government provided supporting instruments such as the Partial Risk Guarantee Fund for Energy Efficiency and equity funding through the Venture Capital Fund for Energy Efficiency.

In the iron and steel sector 67 enterprises were designated as DCs and managed to reduce their emissions by about 6 Mt CO_2, equivalent to an energy saving of 2.1 Mtoe and well above the initial target of 1.5 Mtoe. Through the scheme, a number of major energy-saving opportunities have been identified for the iron and steel sector. The most promising options that are currently commercially available and with paybacks equal to or lower than three years include adoption of:

- multi-slit coke oven gas burners (to improve oven ignition efficiency)

[9] The PAT Scheme is a component of the National Mission for Enhanced Energy Efficiency, one of the eight missions under the National Action Plan on Climate Change.

- regenerative burners for reheating furnaces (heat recovery systems to recover the waste heat of the furnace exhaust gas to heat up the combustion air into the furnace)
- gas recovery systems (to recover top gas and produce power using turbines)
- waste heat recovery strategies (Ministry of Power, 2018b).

The National Resource Efficiency Policy 2019, an initiative of the Indian Ministry of Environment, Forest and Climate Change, aims to enhance resource efficiency and promote the use of secondary (i.e. recycled) raw materials. Although this policy applies to all materials and sectors, it recognises the important role of the steel sector and its strong linkages to the construction and automotive sectors (Ministry of Environment, Forest and Climate Change, 2019). The suggested interventions to increase domestic resource efficiency in the steel sector include incentives to invest in steel recycling technologies and joint ventures between scrap trading and steel companies (to reduce procurement costs), together with the imposition of an import duty on scrap imports above a certain threshold (to promote domestic scrap collection). The most ambitious targets of this policy include the goal to eliminate scrap imports by 2030 (they are at 20-25% today), increase the steel recycling rate to 90% and increase the slag utilisation rate to 50% by 2025 and 85% by 2030.

Increasing the steel recycling rate is also the main goal of the Steel Scrap Recycling Policy (Ministry of Steel, 2019c), which promotes the 6Rs: reduce, reuse, recycle, recover, redesign and remanufacture. It also aims to create a hub-and-spoke working model based on dismantling centres and scrap processing centres, dealing with electric vehicles, consumer durable white goods and other scrap without legal liabilities.

Box 3.3 Private- and public-sector support for iron and steel R&D in India

Both private and public funds are important for R&D to improve efficiency and lower CO_2 emissions in the iron and steel sector. Private iron and steel companies in India currently invest between 0.07% and 0.58% of their sales turnover in R&D projects[10] (compared with up to 1% in China, Japan and South Korea), with some leading companies such as SAIL, RINLS, Tata Steel and JSW investing cumulatively USD 83.3 million in R&D per year.

As regards public-sector funding, the Indian government through the Ministry of Steel has been supporting a number of R&D projects under the scheme “Promotion

[10] R&D expenditure by some leading steel companies in 2017-18: SAIL INR 335.50 crore (USD 49.1 million); RINLS INR 20.06 crore (USD 2.9 million); Tata Steel INR 182 crore (USD 26.6 million); JSW (Vijaynagr Works) INR 32 crore (USD 4.7 million) (Ministry of Steel, 2019a).

of R&D in Iron & Steel Sector", with a total cumulative budget of more than USD 17 million over the past five years (Ministry of Steel, 2019a). So far, the budget has been allocated to 36 private and academic R&D projects, focusing on upgrading Indian low-grade iron, production of low-phosphorous steel, laboratory testing of smelting reduction using hydrogen plasma and the utilisation of mill-scale in-tunnel kilns for DRI production (Ministry of Steel, 2019a).

Other relevant public initiatives supporting R&D in the Indian steel sector include the following:

- Under the Impacting Research Innovation & Technology and Uchchatar Avishkar Yojana schemes (launched by the Ministry of Human Resource Development), the Ministry of Steel supported six R&D projects with a total budget of INR 8 crore (USD 1.1 million).
- In 2014 the Indian government set up the Steel Research & Technology Mission of India aimed at supporting national R&D programmes, international collaborations and skills development to meet the goals of the NSP 2017 by means of best available technologies and optimum utilisation of natural resources (Government of India, 2020). The mission aims to increase the R&D spending of leading steel companies to 1% of their turnover.
- The Steel Development Fund, set up in 1978 and now closed, supported R&D in iron and steel making. The scheme approved almost 90 R&D projects, covering basic as well as applied research programmes. The results from some projects were implemented in SAIL and Tata Steel plants.

Opportunities for accelerating progress

India's iron and steel sector is characterised by a relatively young fleet, much of which will still be producing many years from now, and a growing demand for steel, which will require a substantial increase in production capacity. Furthermore, India has a young and rapidly growing steel stock, which will start to reach end-of-life and provide scrap to markets in the coming decades. While a young fleet presents challenges for reducing emissions, growing demand and scrap availability are an opportunity to both increase scrap-based production and deploy clean primary production routes based on innovative technologies like hydrogen and CCUS. With strong policy and planning, India could be a leader in clean energy transitions in the iron and steel sector. While existing policies mentioned above provide a starting point, India can benefit from an expanded policy portfolio to drive down emissions from the sector.

Policies to support clean energy transitions will need to provide the overall framework for moving towards lower-emission production, as well as targeted support for different technologies and strategies. This includes allowing for retrofitting of existing assets and deployment of new, more sustainable assets. Taking into account the challenges that the iron and steel sector in India is currently facing and the country's existing policies, opportunities for its sustainable development are as follows:

- **Long-term climate and industrial planning and policy:** There is a strong link between economic development and steel production, and India is no exception. It is therefore important for the growth and modernisation of the steel fleet to take into account environmental goals. Existing near-term goals in the NSP 2017 and the PAT Scheme could be extended and integrated to develop an ambitious long-term and unified vision to achieve economic, energy and CO_2 emission reduction objectives. Long-term planning is particularly important given the long lifetime of production assets and the long lead times involved with the development of new clean technologies. Planning is best backed by clear policy requirements. For example, a PAT Scheme style of regulatory trading system could be expanded to set performance requirements for CO_2 emissions rather than for energy consumption alone, allowing for broader coverage and greater ambition.
- **Promotion of higher steel recycling rates and material efficiency strategies:** Recycling requirements can be further strengthened to promote the use of steel scrap whenever possible. Adequate recycling networks should be planned for and set up to accommodate not only the amount of scrap that is currently available, but the amount that will be available in the coming decades. Steel capacity additions should be planned with future scrap availability in mind, in order to avoid excess capacity that could result from overbuilding of primary capacity. It is also valuable to promote efficient use of steel through design regulations, in such a way that limits overuse and ensures that steel products and structures are well built for maximised lifetimes and future modularity and reuse.
- **Managing existing and near-term assets:** The first PAT Scheme cycle has demonstrated how effective energy efficiency measures can be, especially when the portfolio of steelmaking technologies is as wide as in India. However, given the average age of the existing fleet and the substantial but limited CO_2 emission reduction potential of energy efficiency measures, future policies will have to address emissions from existing assets. This can be done through additional measures that consider fuel switching and opportunities for retrofitting to integrate near-zero emission technologies as they become available. At the same time, policies such as retrofit-ready requirements can ensure that new assets are built with the adequate technical capacity for future retrofitting. It would also be valuable to plan for new capacity additions to be located in industrial clusters where possible, so that infrastructure for near-zero emission technologies can be shared (e.g. CO_2 transport pipelines and storage).

- **R&D and market creation for clean technologies:** More public-sector policy and funding are needed to incentivise private-sector investment in R&D in near-zero emission steelmaking technologies. While India's iron and steel corporates currently invest less in R&D than the global average, some operate internationally and could play a leading role in building experience of more innovative steelmaking routes and then importing them to India. Public funding and low interest loans would help de-risk private-sector investment into new technologies still to be proven at large scale. Additionally, market creation for clean steel is needed through policies such as public procurement or minimum content regulations for near-zero emission steel. This would have two simultaneous benefits. On the one hand, it would push the deployment of these technologies for the benefit of domestic emission reductions. And on the other, it would help safeguard the sector as it works towards India's stated goal to become a net exporter of steel, anticipating a possible carbon border adjustment in key regions such as Europe.
- **Promoting infrastructure readiness:** Certain innovative steelmaking routes will need to rely on new infrastructure networks to be able to operate. This infrastructure is going to be needed both upstream (to supply hydrogen and electricity where needed) and downstream of the steel production step (for instance, to collect and transport CO_2 to a suitable storage site). CO_2 sink-source matching and storage assessments are needed to understand if and where CO_2 could be stored, and at what cost (which would depend on the location of the storage site itself and its accessibility). Furthermore, planning is needed to take advantage of India's high potential for renewable energy generation, which could be used for hydrogen-based steel production. Given the large-scale and shared nature of such infrastructure, public planning and funding will be essential.
- **International co-operation:** Given that steel is highly traded, international co-operation will be important to facilitate clean energy transitions without penalising production in countries with more stringent policies. As a leading steel-producing nation, it will be important for India to continue to actively engage and participate in international forums and sector associations that seek to reach agreements on a common ambition for the steel sector. India should also continue advancing innovation through collaborative R&D and demonstration projects. As an emerging economy, India may be eligible for international climate finance, such as the Global Climate Fund, which would reduce the financial cost of emission reduction projects. Additionally, co-operating with other countries can be useful for sharing best practices and technology learnings.

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Chapter 4. Enabling more sustainable steelmaking

HIGHLIGHTS

- Efforts to reduce CO_2 emissions within the iron and steel sector are underway, from both governments and the private sector. Many countries have already implemented policies to support improvements in energy efficiency; some have deployed emissions trading systems covering the steel industry; some producers have set targets for carbon-neutral steelmaking by 2050. Despite this, the sector's emissions continue to rise, and greater ambition is needed.
- Governments will need to play a central role in the transition. Countries should develop transition plans – including national roadmaps – that take explicit account of the iron and steel sector and adopt robust policies to implement them. Funding will be required to cover additional costs, including support for R&D, market creation for near-zero emission steelmaking technologies and support for demonstration projects. A cross-sectoral approach to supporting CCUS transport and storage infrastructure and hydrogen production will be critical, along with international co-operation to ensure a level playing field.
- The steel industry should engage with governments during national roadmapping work and policy design. Steel producers should take initiative to improve the performance of existing plants, collect and share process data to support benchmarking efforts, and employ the technical expertise they possess to undertake R&D and demonstration projects.
- Researchers and non-governmental organisations should contribute to the development of low-emission steel labelling schemes as well as assessing the performance and cost of low-carbon technologies. They should also continue lab-scale research and development of new designs of products that reduce material waste or extend their lifetime.
- Financial institutions and investors should use sustainable investment schemes to guide finance towards emission reduction opportunities, while steering away from investments into emissions-intensive technologies, which could lead to stranded assets in the future.
- The timing for such developments is critical. Given the speed with which action is needed, as well as the long timeframes for innovation and steel plant investment cycles, establishing reliable policies and support mechanisms, and planning initiatives as early as possible, are critical to long-term success.

Alongside the technical challenges outlined in Chapter 2, a clean energy transition also presents a series of opportunities for the steel industry. It offers the possibility of contributing to a more sustainable energy system by reducing production emissions, and the potential to benefit from new market opportunities. These include meeting greater demand for steel from segments such as sustainable public transport systems and clean electricity infrastructure, developing new steel grades for clean energy technologies, and playing a leading role in the circular economy as a highly recyclable material.

If policy makers provide the industry with a strong and supportive policy framework and a level playing field, proactive stakeholders can get ahead of the game by developing low-emitting steel production technologies, securing considerable long-term benefits in a new competitive landscape. However, a range of actors will need to make increased and sustained efforts to overcome the challenges the transition poses.

This section provides an overview of existing policies and efforts that are helping to reduce steel emissions from the iron and steel sector. It then describes the actions that stakeholders, particularly policy makers, need to take to accelerate the transition.

The current policy and innovation landscape

Efforts are already underway around the world to kick-start the transition towards a near-zero emissions steel industry. Governments, the private sector and financial institutions are putting in place various policies, programmes and initiatives. While these endeavours are a promising start, they are far from sufficient to drive the clean energy transitions that the steel sector needs. Stakeholders therefore need to accelerate their action.

Ongoing efforts by governments

Governments will play an essential role in any sustainable transition for the iron and steel sector. Without strong policy frameworks in place, the steel industry will be hard-pressed to achieve large emissions cuts while remaining competitive. Most major steel-producing countries already have policies and programmes in place to reduce the sector's emissions (Table 4.1), although none yet have all the elements of a comprehensive strategy to facilitate deep emission reductions (see following section, "Recommendations for accelerating progress"). A few countries have explicit roadmaps and targets for steel, but many of the policies applying to the iron and steel sector so far relate to the industrial sector more broadly, or are economy-wide rather than being specific to the steel industry. Other government programmes and policies should also assist the steel sector transition, such as those working to develop infrastructure for low-emission electricity and hydrogen production, and for CO_2 transport and storage, although they are not discussed in detail here.

A number of countries have adopted carbon pricing schemes, which provide a broad signal for the steel sector to shift towards lower-emission technologies. The EU Emissions Trading System (ETS), launched in 2005, had little visible impact on industrial emissions for much of its first decade. This is likely the result of low permit prices, driven by an overabundance of allowances, and the need to allocate free emission allowances to industry to maintain its international economic competitiveness. The overabundance of allowances was caused in large part by a combination of high imports of international carbon credits, the 2008-09 financial crisis (which reduced industrial activity and in turn emissions, leaving more emissions allowances in circulation), and renewables policies.

In recent years prices have risen considerably to as high as EUR 29 (USD 34) per tonne CO_2, seen in July to August of 2019. Following a temporary decline due to the Covid-19 crisis, they have recovered thanks to the new Market Stability Reserve mechanism, with an average price of around EUR 27 (USD 31) per tonne and daily highs up to EUR 30 (USD 35) per tonne in August 2020 (EEX, 2020). The revised rules for the next phase of the emissions trading system (ETS) (2021-30) include an increase in emissions cuts, with allowances declining at an annual rate of 2.2% compared with the current 1.74%, and reinforced use of the Market Stability Reserve to reduce and prevent emissions allowance surpluses (European Commission, 2020a). This increased stringency may help drive greater emission reductions in industry. With respect to the longer term, the signalling effect of the ETS may already be helping motivate some of the various industry R&D projects underway, which could enable future emission reductions.

The European Union has significantly reduced the allocation of free ETS allowances to non-trade-exposed industries; however, highly trade-exposed industries like steel continue to receive free allowances for emissions equivalent to production at a benchmark emission intensity. This is driven by the desire to avoid eroding competitiveness and causing carbon leakage, at least in the short term until other mechanisms to protect competitiveness are adopted and free allocation could be phased out. Free allocation maintains the marginal price signal (due to the need to purchase allowances for emissions above the benchmark and the ability to sell allowances for reductions below the benchmark), but it may lower the overall pressure to reduce emissions given the considerably reduced average CO_2 price. The European Union is now developing proposals for a carbon border adjustment mechanism, with the aim of providing an alternative or additional method to help address the potential impact of the ETS on industrial competitiveness as the system's stringency continues to increase.

Table 4.1 Selected current government policies and programmes that could enable progress towards low-emission steelmaking

Country or region	Carbon pricing and standards	Energy and material efficiency policies	RD&D programmes for clean technologies	Deployment incentives for clean technologies	Collaboration and knowledge sharing	Roadmaps and targets for steel CO_2 emission reductions
China*	-	Top 100/ 1 000/10 000 enterprises programme	National Key Technologies R&D Program	-	-	-
European Union	Emissions Trading System	Eco-design directive	Innovation Fund; Horizon 2020**	-	ZEP and EERA under the SET Plan	Steel zero-emission technology development by 2030 (EU Green Deal)
India	-	Perform, Achieve, Trade Scheme; Steel Scrap Recycling Policy	Promotion of R&D in Iron & Steel Sector scheme; Steel Research & Technology Mission of India	-	-	-
Japan	-	Energy benchmark system	COURSE 50 Programme	-	International Technology Transfer Programme	-
United States	-	Energy Star guide for iron and steel industry	ARPA-E; AMO cost-sharing	Section 45Q tax credit for CCUS	-	-
Korea	Emissions Trading Scheme	-	Technology Development Program to Solve Climate Change	-	-	-
Canada	Output-based carbon price	Energy Star for Industry certification and performance indicators	EIP; PERD	-	Canadian Industry Partnership for Energy Conservation	-

Country or region	Carbon pricing and standards	Energy and material efficiency policies	RD&D programmes for clean technologies	Deployment incentives for clean technologies	Collaboration and knowledge sharing	Roadmaps and targets for steel CO_2 emission reductions
Sweden	-	-	Industriklivet (including co-funding for HYBRIT project)	-	-	Steel industry roadmap via Fossil Free Sweden initiative

* China = the People's Republic of China.

** Horizon 2020 will end in 2020; a proposal is underway for a subsequent programme, Horizon Europe, which would run during 2021-27.

Notes: This table features examples of key policies in a number of countries that are major steel producers and/or have ambitious steel emission reduction policies; it is not intended to be comprehensive of all policies in all countries. Policies of sub-national governments are not included, nor are proposed programmes (e.g. the China ETS expanding coverage to industry). ARPA-E = Advanced Research Projects Agency-Energy; AMO = Advanced Manufacturing Office; CCUS = carbon capture use and storage; EERA = European Energy Research Alliance; EIP = Energy Innovation Program; PERD = Program of Energy Research and Development; SET Plan = Strategic Energy Technology Plan; ZEP = Zero Emissions Platform (a European Technology and Innovation Platform for CCS).

Sources: Government of China (2016); Ministry of Science and Technology (2020); European Parliament (2003; 2009); European Commission (2019; 2020b; 2020c; 2020d); Bureau of Energy Efficiency (2020); Ministry of Steel (2019a, 2019b); Government of India (2020); Ministry of Economy, Trade and Industry (2011); JISF (2011; 2020); Energy Star (2020); Department of Energy (2020); Office of Energy Efficiency and Renewable Energy (2020); US House of Representatives (2018); Republic of Korea (2020); National Research Foundation of Korea (2019); Government of Canada (2019; 2020a; 2020b; 2020c); Swedish Energy Agency (2018); HYBRIT (2020); Fossil Free Sweden (2020).

The People's Republic of China ("China") launched an ETS platform in 2017 that will initially only cover the power sector, with the first real spot trading set to start in 2020. But there are plans to eventually include several industry sub-sectors, including the steel industry, at an unspecified future date. The Chinese administration requires key energy-intensive industries to report their emissions in 2020, which signals a move towards better data collection for their eventual inclusion in the ETS (Reuters, 2020). Korea has had an ETS since 2015, which reached an average price of KRW 29 800 (USD 26) per tonne CO_2 in 2019 (ICAP, 2020).

Other countries are adopting alternative formulas to carbon pricing for industry. Canada, for example, has adopted an output-based carbon pricing system, which resembles a tradeable performance standard (Government of Canada, 2019). It is applied in those provinces without their own equivalent or more stringent carbon pricing system. The scheme is designed to reduce the impact on trade-exposed industry by only charging for emissions above a specified emission intensity threshold. It still provides an incentive for additional reductions by issuing credits for performance improvements beyond what is necessary to stay just under the threshold. For further analysis and lessons learned on carbon pricing systems implemented to date, see "Implementing effective emissions trading systems" (IEA, 2020).

Many of the other notable policies adopted so far have focused on energy efficiency, including, for example, China's top performer programmes (called the Top 100, Top 1 000 and Top 10 000 Energy-Consuming Enterprises Program in the 2016-20 Five-Year Plan) and India's Perform, Achieve, Trade (PAT) Scheme (Government of China, 2016; Bureau of Energy Efficiency, 2020). In addition to improving the energy efficiency of its domestic steel sector, the Japanese government has collaborated with the Japanese Iron and Steel Federation on international technology transfer activities. Japan has provided support and expertise to improve the energy efficiency of steel plants in India and other Asian countries through steel plant diagnoses and "Technologies Customized Lists" that outline energy-saving technologies for the region (JISF, 2020).

R&D programmes are another important area of government initiative, with numerous innovation programmes offering funding for which low-emission steelmaking technologies could be eligible. For example, the US Department of Energy's Advanced Manufacturing Office has a cost-sharing programme on energy-efficient technologies. It has provided funding for a novel flash ironmaking process in partnership with the American Iron and Steel Institute (Office of Energy Efficiency and Renewable Energy, 2020). The Japanese government launched the "CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50" (COURSE 50) programme in 2007, with the aim of developing technologies to substantially reduce emissions from the blast furnace (JISF, 2011). In the European Union the New Entrants' Reserve (NER) 300 fund aimed to advance commercial-scale demonstration of innovative carbon capture and renewable energy technologies, with calls for proposals in 2012 and 2014 (European Commission, 2010). This has now been superseded by the Innovation Fund, funded by revenues from the EU ETS, with the first call for proposals in 2020 (European Commission, 2020b).

In addition to funding, knowledge-sharing programmes are also important. An example at the regional level is IN4climate.NRW, a platform developed by the German State of North Rhine-Westphalia. It brings together industrial stakeholders for dialogue and collaboration on research towards a climate-neutral industrial sector. Meanwhile at the national level the German government has launched a competence centre on climate change mitigation in energy-intensive industries (KEI) to advise and support them in reducing emissions (IN4climate.NRW, 2020; KEI, 2020).

Targeted policies are also in place that could help incentivise the deployment of new low-emission steelmaking technologies. Carbon capture and storage (CCS) projects in the United States are eligible for a tax credit under the Internal Revenue Code Section 45Q (US House of Representatives, 2018). While this tax credit has encountered challenges related to monitoring, reporting and verification of claimed CO_2 storage (Department of the Treasury, 2020), with improvements to its oversight procedures this type of credit could provide a robust and valuable incentive for CCS deployment. The United Kingdom announced in 2019 plans to set up a GBP 250 million (USD 320 million) Clean Steel Fund, due to open in 2024 after a period of consultation and development. It is intended to support the sector's uptake of new lower-emission technologies and processes (UK Government, 2019).

Meanwhile, the state of California is using public procurement to drive lower emissions through the Buy Clean California Act. From 2021 the state will set a benchmark for the greenhouse gas intensity of building materials, including steel, to be eligible for use in state-funded projects (California Legislative Information, 2017). The Swedish Transport Authority has also developed a methodology to integrate life-cycle accounting into its procurement decisions, which can promote low-emission material purchases (Swedish Transport Administration, 2017).

Encouraging progress in the private sector

Private-sector stakeholders are also making efforts to reduce emissions from the steel industry. A number of steel producers and industry associations have set low emission targets and developed sustainability roadmaps. For example, ArcelorMittal Europe, thyssenkrupp, Tata Steel Europe and the Canadian Steel Producers Association have each set a 2050 target of carbon neutrality for their steelmaking, although most mention carbon neutrality in general and do not specify whether they would allow use of offsets to achieve neutrality. SSAB's goal for all its steel to be fossil-free by 2045 is more ambitious, while Liberty Steel Group plans to achieve carbon neutrality by 2030, with a focus on scrap-based production and offsets.

Some notable roadmaps include those produced by Eurofer (the European steel association), the Japan Iron and Steel Federation and The Energy and Resources Institute in India (EUROFER, 2019; JISF, 2019; TERI, 2019). Work is also underway to develop a steel sector initiative under Science Based Targets, a collaborative project promoting company-based CO_2 emission reduction targets (Science Based Targets, 2016). Furthermore, the World Steel Association is working on a number of emission-reduction initiatives, such as its "step up" programme (Box 4.1).

Box 4.1 World Steel Association "step up" programme

The World Steel Association is the industry association for the global steel industry. Its membership covers around 85% of global steel production, and includes several national and regional associations and research institutes. The organisation places a strong focus on the impact of its industry on climate change and the environment, alongside its other core activities of providing data and insights on a range of strategic issues facing the sector. One example of its environment-orientated activities is its "step up" programme (World Steel Association, 2020a).

Launched in 2019, step up is an initiative to accelerate the industry's progress in operational and environmental performance in the short term towards the levels achieved by its top performers. It aims to ensure that the industry adopts operational best practices and efficiency improvements where possible. A voluntary programme, it uses lean techniques to incrementally improve on the four parameters that most influence the CO_2 emissions of commercially available primary steelmaking processes: 1) raw material quality, 2) process yield, 3) energy intensity, and 4) process reliability.

Making use of the existing worldsteel benchmarking system, steel producers can submit data in a standardised format using common conversion factors. This allows external variability to be eliminated and the industry to focus on the four levers under its direct control. After submitting data, each member analyses its own performance, carrying out internal assessments across all of its plants and identifying the best performance within the organisation. As part of the programme, worldsteel requires members to submit an annual improvement plan and performance report for the site and organisation. If requested, worldsteel can also carry out a verification step to support the development of the improvement plan.

In developing the programme, worldsteel found that yield and energy improvements can result in significant OPEX savings (in the range of USD 12-20 /t crude steel), thus providing a significant financial incentive for participation. In 2019, nine sites were audited and seven reports were prepared and accepted. Learning from physical site visits means that future reviews can be carried out virtually.

The steel industry is also developing new clean technologies to reduce emissions further in the long term. One of the largest initiatives in this area was the Ultra-Low Carbon Dioxide Steelmaking (ULCOS) programme. Launched in 2004 by a consortium of 48 European companies and organisations, and funded by the participating companies and the European Commission, the programme aimed to develop technologies to reduce CO_2 emissions by at least 50% relative to the modern blast furnace-basic oxygen furnace route. While the project put forward several technology concepts, its proposed pilot project to retrofit the Florange steel plant in France with post-combustion CCS did not go ahead – the project withdrew its application from NER300 in 2012. Despite the ULCOS programme itself ending, several of its technologies have been carried forward: the HIsarna project to develop innovative smelting reduction by Tata Steel; blast furnace with top-gas recycling by ArcelorMittal; and the ideas for both alkaline and molten direct electrolysis (Birat, 2020; Tata Steel, 2017; ArcelorMittal, 2019).

A renewed push for very low-emission steelmaking now appears to be underway, with numerous other projects making progress. These include the launch of the first commercial steel carbon capture and storage (CCS) project by Al Reyadah and Emirates Steel at a gas-based direct reduced iron (DRI) plant in Abu Dhabi; the HYBRIT, ArcelorMittal Hamburg, Salcos and other projects developing electrolytic hydrogen-based DRI; and Carbon2Chem, Steelanol and others developing carbon capture for use (see additional projects and details in Table 2.1 in Chapter 2). Furthermore, the World Steel Association's Global Technology Innovation Expert Group is playing an important role in facilitating industry collaboration and information sharing on technology R&D.

With regard to emissions data and certification, the global non-profit organisation ResponsibleSteel has worked with steel producers and users to develop a social and environmental sustainability standard and certification programme for steel. The first version of the standard was published in late 2019 (ResponsibleSteel, 2019). Additionally, the International Organization for Standardization and the World Steel Association have each developed standardised methodologies for conducting life-cycle inventories of steel products (ISO, 2018; World Steel Association, 2017). These types of standards will be important to establish common and robust criteria for differentiating low-emission steel for buyers, incentive programmes and regulation.

The World Steel Association has also developed a programme to collect and report CO_2 emissions data for steel producers according to standardised data collection guidelines. This is a useful initiative for steel plants to benchmark themselves amongst their peers (World Steel Association, 2020b). The recently launched "step up" programme builds on this, using benchmarking to promote short-term CO_2 emission reductions and operational efficiency improvements (see Box 4.1).

Partnerships between the private sector, governments and other organisations have an important role to play, as seen through examples like COURSE 50 and ULCOS. As a more recent example, a coalition of governments and companies launched a new Leadership Group for Industry Transition at the 2019 UN Climate Action Summit. The group is aiming for transformational change in hard-to-decarbonise and energy-intensive sectors, including steel (UN Climate Action Summit, 2019). Additionally, in 2019 the World Economic Forum and the Energy Transitions Commission launched the Net-Zero Steel Initiative. Part of the Mission Possible Platform, it aims to mobilise industry leadership in support of policies favourable to low-emission steel (Energy Transitions Commission, 2019; World Economic Forum, 2020). China's Baowu Steel Group also proposed in late 2019 the formation of a Global Green Low Carbon Metallurgy Alliance, although details are yet to be unveiled (Asian Metal, 2019).

Initiatives involving financial institutions and investors

The financial sector is also making efforts to promote more sustainable investments, which will have an impact on the iron and steel sector. The Task Force on Climate-related Financial Disclosures (TCFD), established by the Financial Stability Board, is helping companies understand the information financial markets want so they can measure and respond to climate change risks. It is developing voluntary climate-related financial risk disclosures to better inform investors (TCFD, 2020). Various non-profit organisations are encouraging stakeholders to integrate climate risks in their investment strategies and financial regulations. Some financial institutions are now offering sustainability-focused investment information. For example, S&P Global Ratings is working towards incorporating environmental, social and governance (ESG) factors into its credit rating methodologies (S&P Global, 2018).

For steel in particular, a consortium of sustainability and climate change investor groups has laid out a series of expectations for steel companies, which their investors can use for investment decisions and proxy voting (IIGCC, 2019). Additionally, the CDP, a non-profit that runs a global environmental disclosure system, has launched a CDP League Table that ranks 20 of the largest steelmakers according to their business readiness for a low-emission transition, including their transition risk and climate strategy (CDP, 2019). It has the objective of providing guidance to investors on climate-related topics that they can raise with the companies they invest in.

An important aspect of sustainable investments is setting criteria for what constitutes "green" or "sustainable". This can be done through standards and classification (or "taxonomy"). The International Organization for Standardization is currently developing a standard for green bonds (ISO 14030), building upon the Green Bond Principles established by the International Capital Market Association and other existing classifications (ISO, 2020). It aims to provide credibility and uniformity for assuring green bonds.

Meanwhile, the European Union is developing a sustainable finance taxonomy, a classification system covering six environmental objectives (including climate change mitigation) (European Council, 2020). The Taxonomy Regulation was approved by the European Parliament in June 2020, and the system will be further developed over the course of 2020-21 (European Commission, 2020e). The

Technical Expert Group on Sustainable Finance has already laid out a recommended taxonomy for climate change mitigation and adaptation performance (European Commission, 2020f). For iron and steel, the suggested mitigation threshold for eligibility as a sustainable investment is steel production with greenhouse gas emissions lower than the EU ETS benchmarks, including mitigation measures that are part of a concrete plan to meet the threshold. It is noted that once breakthrough technologies become commercially available, the threshold will need to be updated to reflect the possibility of achieving lower emissions.

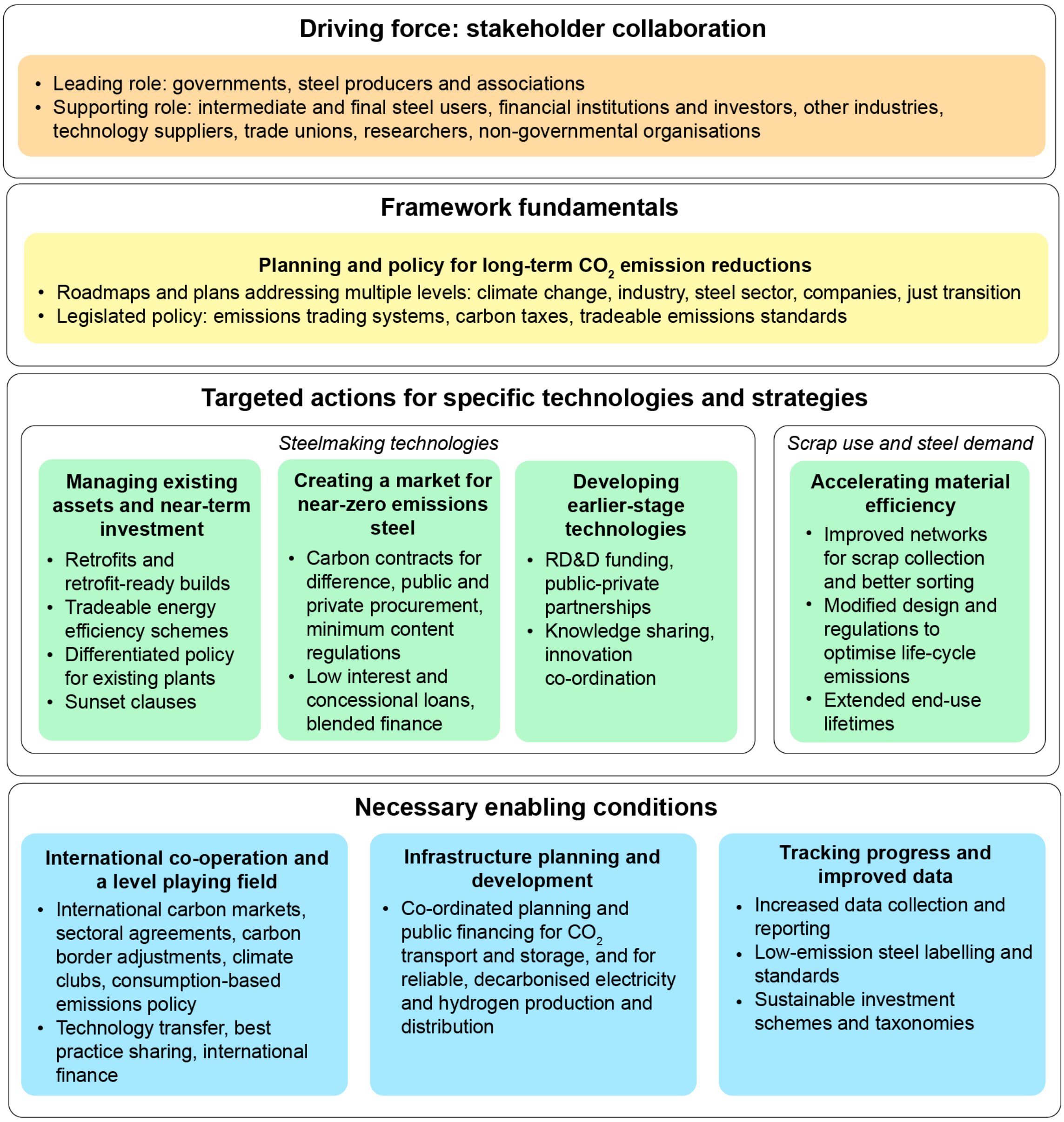
Dialogue is also ongoing between stakeholders to create a market consensus on standards for "transition bonds". This includes bonds for emissions-intensive industries that may not yet be eligible for finance through "green" bonds, but will need finance for their transition towards near-zero emissions.

Recommendations for accelerating progress

Despite the encouraging efforts, the iron and steel sector's absolute emissions continue to rise because of the increased output required to meet global demand. Greater ambition in policymaking and innovation is needed to put the sector on a path to achieving deep CO_2 emission reductions. Effort is called for on many fronts from a diversity of stakeholders (Figure 4.1), as discussed in further detail in the following sections.

The overarching driver of change lies in setting long-term plans and establishing a clear, reliable long-term policy signal for emission reductions early on. Governments must put these in place to support the steel industry's transitions. Additionally, targeted policies are needed for specific technology categories, including emissions-intensive technologies that will still be required for some years to come, clean technologies that are market ready, and clean technologies that are at earlier stages of development. Similarly, a focus on material efficiency can help increase scrap available for secondary production and achieve more from each tonne of steel, thereby reducing the need for new steel. Conditions need to be put in place to support initiatives targeted at steel technology, including establishing a level playing field for steel companies around the world, developing supporting infrastructure such as decarbonised power inputs, and improving data collection and reporting.

Figure 4.1 A framework for accelerating the iron and steel sector's clean energy transitions



Stakeholders will need to collaborate on multiple fronts to drive the iron and steel sector's transition to a more sustainable pathway, including long-term planning and policy signals, targeted technology strategies and enabling conditions.

Given the speed with which action is needed, as well as the long timeframes involved, it is critical to long-term success to establish as early as possible reliable policies, support mechanisms and planning initiatives (Box 4.2). In the shorter term, many of the emission reductions will be driven by policies that address existing emissions-intensive assets, deploy commercially available low-emission steelmaking technologies and accelerate material efficiency. Nonetheless, the groundwork for long-term emission reductions needs to be laid in the next decade, including demonstrating very low-emission technologies and developing the necessary supporting infrastructure and data tracking schemes.

While many of these same components are needed everywhere, varied regional circumstances will affect their relative importance and the specifics of planning and policy design. For example, in regions where a large proportion of in-use stocks of steel in society are approaching end-of-life, it will be important to maximise scrap collection rates and improve the segregation of different qualities of scrap. This enables rates of scrap use to be as high as possible (in that region itself or in other scrap-importing regions). In regions with relatively young fleets of emissions-intensive primary production, it will be important to explore opportunities for retrofitting and, where economically preferable, perhaps even early retirements. Where growth in capacity is expected, in the near term it will be particularly important to build plants "retrofit-ready", that is, with a configuration that more easily accommodates low-emission processes as they become available. Also, plants could be built in industrial clusters for future shared access to infrastructure.

Collaboration between governments and steel producers is a fundamental aspect of accelerated action. Support from other stakeholders will also be important, including intermediate and final steel users, financial institutions and investors, other industries, technology suppliers, trade unions, researchers and non-governmental organisations. Collaboration both internationally and regionally will be helpful in numerous ways, including:

- establishing common levels of ambition
- planning low-emission pathways
- designing suitable policies
- sharing knowledge and best practices
- co-ordinating and partnering in innovation
- pooling funds for investment in new technologies
- transferring technologies
- developing shared clean energy supplies, CO_2 transport and storage infrastructure, and recycling networks
- formulating common data schemes.

Box 4.2 Laying the groundwork: Critical steps for the next ten years to enable long-term progress towards sustainable steelmaking

The transformation envisioned for the iron and steel sector by 2050 in the Sustainable Development Scenario may seem daunting to some. Over the span of only 30 years, conventional blast furnace-basic oxygen furnace production would decline from 70% of production today to only 30%. Scrap-based electric furnace production would double. And innovative technologies incorporating CCUS and hydrogen would grow to account for nearly 40% of primary steelmaking.

Given the long lifetimes of steel plants and the time required for innovation and infrastructure roll-out, the transition cannot happen overnight. That is why the next ten years – from now to 2030 – is a critical window to lay the groundwork needed for long-term success. Governments and decision makers should consider the following three important areas for short-term action and policy:

- **Technology performance and material efficiency.** Measures can already be taken today to make more efficient use of energy in steelmaking and of steel itself. They include operational performance improvements and adoption of best available technologies in steel plants, and material saving measures across value chains. In addition to achieving short-term emission reductions, improving the performance of existing steel plants and setting the stage for long-term reductions in demand for steel leads to lower emissions for the sector in the longer term. This would ease the burden by reducing the absolute number of steel plants with innovative technologies needing to be deployed.
- **Existing assets and new infrastructure.** A plan must be put in place to deal with existing steel plants that acknowledges the decline in the CO_2 intensity of production required just one investment cycle away. At the same time, a co-ordinated push to plan and build new supporting infrastructure – for hydrogen, low-emission electricity generation and CO_2 transport and storage – is needed in the short term so that it will be ready for rapid deployment of innovative steelmaking technologies post-2030. Establishing early on a clear, stable policy signal for long-term emission reductions will be an important catalyst for making decisions about existing and new infrastructure.
- **R&D and demonstration.** Pilot and demonstration projects for innovative near-zero emission technologies over the next decade must be consistent with deployment ambitions post-2030. Government financial support and co-ordination will be critical. Additionally, preparations can already begin on demand-pull mechanisms so that the market is ready to support higher-cost near-zero emission steel when it becomes available.

We are in unprecedented times – the economic crisis in the wake of the Covid-19 pandemic will surely pose some challenges for short-term action. But sustainable recovery plans can also present an opportunity to spur action and support clean technology development and deployment. The decisions taken today will set the path for the steel sector for decades to come, and we cannot afford further delays.

Governments and decision makers should have 2030 firmly in mind as a critical milestone for laying the groundwork for a near-zero emission steel sector. Through decisive short-term action and co-operation among stakeholders – both regionally and internationally – the path to 2050 and beyond will become all the more achievable.

Framework fundamentals: planning and policy for long-term CO_2 emission reductions

A clear vision of the trajectory ahead – and a solid commitment to that path – will serve as the foundation for more rapid progress. Developing plans, setting targets and legislating long-term policy are all key components of commitment. While the Covid-19 crisis has demonstrated the unpredictability of events, it is nevertheless essential to have a clear vision about the overall direction and ambition.

Governments should provide clarity and certainty for stakeholders with a two-pronged approach: by developing a clear long-term vision for the steel industry's sustainable energy transition in national energy and climate strategies; and adopting a comprehensive industrial policy framework that is compatible with, and supportive of, climate objectives. Such policy commitment will help steel companies and intermediate steel users establish a business case for the necessary investments, and provide confidence that innovating today is likely to be profitable in the longer term. Actively involving the steel industry in planning or roadmapping exercises is vital to ensuring a shared vision.

A just transition lens will be important, and therefore plans should include provisions for minimising employment and other social impacts. These could provide training for workers to operate new low-emission steelmaking technologies and perhaps also for entirely new roles, such as in more materially efficient construction and steel reuse networks.

Long-term planning should be backed by mandatory long-term emissions reduction policy, ideally enforced by legislation. This may include carbon pricing in the form of carbon taxes or an ETS, or a tradeable emissions performance standard that would require a decreasing average emission intensity of steel. Policy stringency should increase over time in a predictable manner. It could begin at lower levels to incentivise early action such as energy and material efficiency improvements, moving to levels that in time are sufficient to incentivise a large-scale shift to low-emission production once the required technologies have been commercialised and supporting infrastructure built.

Careful policy design will be crucial to ensure that steel companies remain competitive throughout the transition. This may include measures such as:

- The free allocation of permits below a benchmark in an ETS.
- The well-thought-out use of revenues from carbon pricing schemes to assist steel companies while accelerating the transition (e.g. funding innovation in and deployment of low-emission steelmaking technologies).
- Measures to maintain international competitiveness (see further discussion below in "International co-operation and a level playing field").

Furthermore, a mandatory emission reduction policy alone will not be enough to drive deep emission reductions – it must be complemented and supported by the other components discussed in subsequent sections.

In the private sector, developing corporate strategies for the energy transition can facilitate long-term business planning, bring shareholders and employees of the company on board with a common vision, and show commitment to investors whose continued support will be needed. Strategies should include clear long-term targets and lay out a pathway to achieve them, including investment and retrofitting planning, R&D and risk management. One component could be sustainability training and capacity development for company employees, including at the executive and management level. The steel industry can also engage with government through roadmapping exercises, voicing support for introducing CO_2 emission reduction policies, and providing feedback to ensure appropriate policy design.

Non-governmental organisations and researchers can play a supporting role by providing information about the current status of the industry and galvanising support for emission reductions in the steel sector and the energy system as a whole.

Key actions:

- **Government:** develop a sustainable transition plan for the steel industry, coinciding with the national climate plan and industrial strategy, through engagement with the steel industry; establish long-term emission reduction policy such as legislating an ETS or tradeable standards; develop or fund programmes to train steel industry workers to use clean steelmaking technologies or for new roles as needed.

- **Steel industry:** develop company strategies for the sustainable energy transition; engage with other stakeholders in sectoral roadmapping exercises, including cross-sector approaches and roadmaps; actively support and provide feedback on the design of government emission reduction policies.
- **Researchers and non-governmental organisations:** contribute to regional roadmaps that identify key challenges and action plans tailored to local circumstances; galvanise support for industry transition.
- **Financial institutions and investors:** develop and invest in sustainable investment schemes.

Targeted actions for specific technologies and strategies

Managing existing assets and near-term investment

Given that steel plants typically have a lifetime of around 40 years and investment cycles of around 25 years, emissions-intensive plants built recently will need careful management. This also applies to plants added to the fleet in the next decade before very low-emission steelmaking technologies are commercially available.

For existing assets, owners and operators can pursue energy efficiency gains to meet best available technology standards, adding equipment like waste heat recovery and improving process operations to ensure maximum potential efficiency. Governments can assist by introducing benchmarking schemes, tradeable energy performance standards and incentives for waste heat recovery, and by offering public financing schemes, tax relief and accelerated depreciation to help with large upfront investment costs. While efficiency improvements can pay for themselves in a reasonable time period, they should be balanced with the need for fundamental technology shifts in a decade or two, and thus should be pursued to the extent that they do not create investment "lock-in". Mandatory efficiency policies could include exemptions for plants close to retirement, and could be phased out as the stringency of carbon pricing or emission standards are ramped up to enable firms to make their own cost-effective decisions.

Opportunities to retrofit or convert existing assets to very low-emission technologies (such as CCS or hydrogen) should be pursued as technologies and decarbonised energy inputs become available. Where this is not possible due to plant configuration or other complications, governments could exempt existing capacity – for a time-limited period – from emission policies applied to new plants to reduce the costs of stranded assets. Alternatively, governments could directly support the retirement of emissions-intensive technologies prior to the end-of-life.

With regard to near-term investment, an important step is for any new plants to be built retrofit-ready – that is, with adequate space and technical characteristics to allow the smooth transition to very low-emission pathways, such as those involving CCS, hydrogen or biomass. This will help avoid the potential for stranded assets resulting from increasingly stringent regulatory requirements in the future. Decision makers should also prioritise, where possible, bridging technologies that already achieve emission reductions relative to conventional production, and which can also be easily converted to near-zero emissions. An example of this is natural gas-based DRI, which can later be converted to hydrogen or CCS. Strategically locating new-build plants in industrial clusters can provide opportunities for heat cascading, enabling waste heat to become a resource, and in some cases opportunities for CCU and future shared access to the infrastructure needed to incorporate near-zero emission processes.

Governments can also apply so-called "technology sunset" policies to prevent high-emission facilities from being built beyond a certain future date, taking into account the time needed to develop low-emission production pathways. The policy may also include a requirement for already-built high-emission facilities to either retrofit low-emission technologies or shut down by a certain date. Similar policies that countries have implemented to phase out coal-fired power generation provide a model. The timing of such policies is critical to provide the appropriate signal for industry actors. For them, it may be preferable to slightly postpone retirement of an existing plant that has reached the end of its investment cycle until it can be replaced by one with much lower emissions, rather than retire the plant and replace it with a conventional plant that would have the incentive to operate for decades.

Financial institutions and investors also have a role to play here, since finance is key to steel plant capacity additions. Sustainable finance schemes, classifications and sectoral risk assessment frameworks can help set the bar for what are acceptable emission levels and guide investment away from potentially stranded assets. These tools should be well-designed, using appropriate technical expertise and taking into account regional circumstances. If enough investors take part, they could put a real constraint on the ability to build new emissions-intensive capacity, while making it easier to access finance for low-emission technologies. The steel industry itself should begin planning appropriately for the roll-out of breakthrough technologies, with the expectation that the next generation of production capacity will need to be near-zero emission.

While the steel sector should make all reasonable efforts to reduce its own emissions, in the shorter term while breakthrough near-zero emission technologies are still being developed, this may be very challenging in some instances. Steel companies with ambitious emission reduction targets may, in the near term, prefer to purchase verified offsets for the emissions they cannot avoid. They would thus be contributing to global emission reductions while awaiting and working towards market introduction of new technologies.

Key actions:

- **Government:** develop energy efficiency improvement schemes; provide incentives for low-emission technology retrofits; adopt retrofit-ready requirements for new-build plants and sunset clauses to restrict new-build capacity from using emissions-intensive technologies; consider differentiating requirements for existing and new plants in emission regulations.
- **Steel industry:** consider opportunities for improving process operations in existing plants by participating in schemes like worldsteel's step-up programme and retrofitting them with low-emission technologies; build new plants retrofit-ready; carefully plan timing of retrofits, retirements and new builds according to availability of low-emission technology.
- **Financial institutions:** provide finance for energy efficiency measures aimed at immediate CO_2 emission reductions, before breakthrough near-zero emission technologies are commercialised; use sustainable finance classifications and indices, and climate-related financial risk assessment frameworks and credit ratings to guide investments away from emissions-intensive technologies and avoid stranded assets.

Creating a market for near-zero emission steel

New near-zero emission technologies are likely to be considered higher risk and initially to be significantly more expensive than incumbent technologies as they reach market introduction. They may therefore struggle to secure private finance and to compete in the market. This means it will be important to establish stable, early market demand for near-zero emission steel production, giving greater certainty to investors in earlier stages of development (piloting and demonstration) and in the first commercial projects. Doing this will enable continued development to bring costs down.

"Niche markets" have played a critical role in the deployment of innovative technologies in the past, a prominent example being feed-in tariffs for solar and wind. Setting clear standards and certification for low-emission steel will be integral to market creation (see further discussion in "Tracking progress and improved data" section). Targeting markets for near-zero emission primary production will be particularly important, so as to avoid the niche market being filled mostly by secondary production – this would limit the incentive to develop innovative primary production technologies, which are a higher risk but essential.

Early demand-pull could be generated through public or private procurement, where government or intermediate steel users like car manufacturers or construction companies would pay a premium for low-emission steel. This could take the form of:

- fixed contracts with specific steel producers for first-of-a-kind production
- longer-term purchase commitments for low-emission steel in general
- a pooled purchase commitment with other interested parties
- legislated requirements for low-emission steel in publicly funded projects in the case of public procurement.

This could benefit the steel purchaser by improving its corporate sustainability image or providing opportunities to market to green consumers. “Low-carbon” aluminium is already being offered at a premium on the market, driven in part by demand from electronic and car companies like Apple and Toyota, and could provide learnings for the development of a low-emissions steel market (Carbon Trust, 2020; Reuters, 2017).

Another option is for governments to grant a premium for low-emission production, referred to as a “carbon contract for difference”, a policy concept conceived in the power sector. Rather than purchasing steel directly, government would put out a tender for low-emission steel and fund the difference in the cost of production relative to conventional higher-emitting production (including differences in OPEX) for a guaranteed volume of steel, somewhat similar to a feed-in tariff for renewable energy. The policy would act like a guaranteed carbon price that is sufficient for low-emission production to become economically viable. The certainty provided by a contract for difference could present a considerable advantage over other instruments that may provide shorter-term, less certain and more fragmented demand pull (Vogl, Åhman, and Nilsson, 2020; Sartor and Bataille, 2019). The cost of a project like this may be large – possibly several hundred million US dollars paid out over a decade or two to support the cost difference between near-zero emission and conventional production for a commercial-sized steel plant producing 1 Mt of steel annually. Governments could seek out partner governments willing to share the cost. The level of support would gradually fall as deployment increased and costs came down.

Particularly after the first-of-a-kind commercial plant has been successfully deployed, governments could apply content regulations to support the roll-out of additional plants. Regulations could be formulated as a tradeable quota or certificate system requiring a minimum and increasing share of steel purchased in the market to be near-zero emission. There is a rationale to apply such regulations to intermediate steel consumers – they should be able to more easily pass the cost onto end-use consumers because, as noted in Chapter 2, the additional cost of low-emission steel for a house or car is likely less than 1%, and because they may be less exposed to international competition, at least in the case of construction.

Applying CO_2 regulations or taxes to the embodied emissions of end-use products could be another method to generate demand for low-emission steel and assist with cost pass-through. They could take the form of life-cycle emission regulations or carbon added taxes.

Finance will also be key to getting first-of-a-kind and subsequent commercial projects built. It is likely that the public sector will need to take on some of the financial risk of these early projects, which can reduce total finance costs for the project and some of the need for other forms of subsidy. Measures that the public sector can use to help with finance and risk include:

- concessional loans (including lower interest and/or longer grace period) and/or subordinated loans or equity
- debt guarantees
- early-stage equity investment
- tax incentives to encourage investment, such as tax rebates on new low-emission investment and a lower tax burden on new low-emission assets.

Public and private financial organisations could also collaborate to develop blended finance mechanisms that mobilise private finance coupled with public funding taking on the higher risk. Financial sector sustainability schemes, such as green bonds or transition bonds, can again channel investment towards new low-emission technologies.

Finally, governments may need to adapt regulations and permitting procedures as they apply to new technologies, so that the legal framework does not pose a barrier to low-emission technology diffusion.

Key actions:

- **Government:** procure low-emission steel; develop contracts for difference for low-emission steel, perhaps in collaboration with partner governments; establish low-emission steel content regulations; help finance initial commercial projects.
- **Steel industry:** seek out buyers willing to pay a premium for low-emission steel.
- **Intermediate and final users:** consider establishing contracts and campaigns to pay a premium for low-emission steel, perhaps along with other buyers.
- **Financial institutions:** develop blended finance mechanisms for low-emission steel projects, using public funding to mobilise private finance; develop sustainable finance products (e.g. green bonds, transition bonds) to channel investment towards low-carbon technologies.

Developing earlier-stage low-emission technologies

Action is needed to bring very low-emission steelmaking technologies to the early commercial stage, given that important advances are still at the prototype and piloting stages (see Table 2.1 in Chapter 2). While the greatest efforts may be directed towards more advanced technologies, such as innovative smelting reduction with CCUS and hydrogen-based direct reduction, it is prudent to continue work on other technologies such as direct electrolysis. This would increase the likelihood of success and diversify the portfolio of options for different regional contexts. Innovation can also improve material efficiency, for example by developing improved recycling techniques or digitalised techniques for lightweight construction.

Steel producers have a leading role to play in technology development, possibly in partnership with researchers, equipment manufacturers, other industry players and governments. Contributions from university researchers are particularly important for lab-scale R&D of new low-emission technologies.

Public financial support is needed at all stages of innovation, from early lab-scale stages and piloting, to initial demonstration and large-scale demonstration. Given the considerable risks and uncertainties of large-scale demonstration, the availability of sufficient public funding for this stage is particularly important. Financial support can take various forms, including grants (perhaps funded through carbon pricing), low-interest loans, concessional finance and public-private partnerships. Procurement and contracts for difference, mentioned in the preceding section, could also begin to play a role in large-scale demonstration. Since the funding requirements are quite large and the risk potentially high, one proposed idea is a multinational institution, owned by industry associations and interested governments, that funds a portfolio of emission reduction pilot projects in industry, thus pooling learning and risk (Bataille et al., 2018).

Non-financial support from government may also be important, such as co-ordinating knowledge sharing and collaboration by setting up incubator programmes and innovation research networks. Steel industry associations similarly can contribute to innovation co-ordination.

Key actions:

- **Government:** provide funding for R&D and early demonstrations in low-emission steelmaking; co-ordinate and incentivise innovation knowledge sharing.
- **Steel industry:** undertake development and demonstration of low-emission steelmaking technologies, including through public-private partnerships; engage with other steel companies and other partners to co-ordinate innovation efforts and share learning.

- **Researchers:** continue lab-scale research for low-emission steelmaking technologies.

Accelerating material efficiency

Material efficiency is an opportunity that is already commercially available, and can contribute to both near-term and long-term emission reductions.

Effort is needed to maximise scrap collection, direct reuse and recycling, particularly for end uses and in regions that currently have lower collection rates. The steel industry and companies involved in demolition and material recovery – perhaps with co-ordination from government – can work towards streamlining reuse and recycling channels, improving waste-handling infrastructure, creating materials inventories to enable direct reuse, and implementing robust testing standards to ensure quality of reused steel. Government-led extended producer responsibility regulations, scrap recovery and collection requirements, and consideration of future reuse and recycling in design regulations can all help. Actors involved in recycling should work towards better separation and reduced contamination during demolition, dismantling and the recycling process to reduce trace elements like copper. This ensures the majority of steel grades can be produced via the secondary route. In instances where a country produces more scrap than it needs for domestic production, trade in scrap can maximise global scrap use.

Work to increase the efficiency of steel use is also important, extracting more value from each tonne of steel and reducing demand growth. Within the steel industry, equipment and operating improvements could reduce in-house scrap generation. Much of the efficiency improvement, however, can be achieved by steel users: intermediate consumers that produce steel products can work towards lightweight, modular designs and less waste; and final users can reduce steel demand with the "sharing economy", for example ride, product and desk sharing (aided by new sharing-based business models) and by repairing and refurbishment to extend lifetimes.

Policy can help by:

- Incorporating life-cycle emission requirements into climate and design regulations for products and construction.
- Modifying design standards to include performance-based rather than prescriptive requirements and considerations on durability.
- Adopting demolition fees and incentives for refurbishment to promote the extension of building lifetimes.

For further details on improving material efficiency, see "Material efficiency in clean energy transitions" (IEA, 2019).

Key actions:

- **Government:** co-ordinate improved recycling networks and mandate recycling collection, testing and quality standards; modify emissions and design regulations to optimise life-cycle emissions performance.
- **Steel industry:** improve steel recycling and sorting systems, including quality control measures; improve operations to reduce in-house scrap generation; develop new business models that are based on value rather than quantity of material supplied.
- **Intermediate and final users:** develop lightweight and modular designs; reduce material waste and direct unavoidable scrap to recycling; increase the use of sharing business models; retrofit and reuse to extend lifetimes; track steel grades employed and ensure data availability upon recycling.

Necessary enabling conditions

International co-operation and a level playing field

As steel is a highly traded product, policy makers must design emission reduction policies with care to ensure that uneven policy ambition in different regions does not lead to the relocation of production to regions with lower ambition – so-called "carbon leakage". The best approach would be for governments across the globe to work in concert to develop a policy framework that ensures a level playing field for steel producers across all regions, underpinned by robust accounting methods and verification. While a uniform international carbon price would be a least-cost solution from a purely economic perspective, it might be very challenging to achieve in practice (at least in the short to medium term), may not constitute a fair approach given the diversity of regional resources and circumstances, and would alone be insufficient to catalyse development of innovative technologies for near-zero emission steelmaking. Such a concerted approach is also likely to face a variety of other barriers in practice.

An international steel sectoral agreement may be another option, in which governments or industry players, or both, make a formal commitment to commonly agreed upon CO_2 emission reduction objectives. It may not be an easy endeavour, particularly given the highly competitive nature of the sector. But it is likely that only a relatively small number of players would be needed to create a critical mass, given that the top ten producing countries currently account for 85% of global steel production and the top 50 steel companies account for nearly 60% of production (the top 25 account for just over 40%). Furthermore, existing collaborative structures, such as the frameworks for international co-operation under the Paris Agreement (discussed below) or co-ordination by international associations, might provide a helpful starting point for an agreement. Bringing other bulk material sectors into such an agreement would be optimal, enabling fair competition among potential material substitutes.

Despite the practical barriers, governments and industry should continue working to increase global ambition. But a lack of full policy coherence should not be reason to delay action. Initially individual governments may be able to implement carbon prices that incentivise some changes, but which are low enough to avoid major competitiveness concerns. They may be able to include special provisions for globally traded industries, such as free allowances for emissions below a target benchmark in a cap and trade system. At higher levels of policy ambition, however, other solutions are likely needed to account for the risks of carbon leakage and ensure that strong policies can achieve actual emission reductions in global terms.

One approach being discussed in some regions, such as at EU level, is carbon border adjustments, in which countries with more ambitious policy place a tariff on imports based on their CO_2 footprint. These could be placed on individual products or materials, such as steel or steel-containing goods, and would require appropriate tracking of material carbon intensities. This can present substantial technical complexities and is likely to require considerable resources for robust certification and tracking. Doing so would account for the added costs of both explicit carbon pricing and other regulations that implicitly price carbon, so that domestically produced and imported steel face the same CO_2 emission requirements. "Climate clubs" have also been posited by the research community as an alternative formulation, in which a coalition of willing countries agrees to a common policy ambition and places a blanket tariff on all imports from countries outside the club (Nordhaus, 2015).

Careful design of such tariff policies would be imperative to ensure compliance with international law, notably World Trade Organization requirements. Furthermore, tariffs would need to consider design elements, firstly to avoid penalising primary production relative to already lower-emission scrap-based production (which could simply lead to more trade of steel produced from scrap without providing any overall emissions benefit or incentive to reduce primary production emissions), and secondly to encompass (as far as reasonably possible) indirect steel imports in goods made largely of steel, to maintain the competitiveness of steel-based value chains. It also should be noted that while tariffs would support the competitiveness of domestic production relative to imports, exports would still face competitiveness challenges in the global market.

Export subsidies to address this would likely be costly and perhaps be very challenging to apply while remaining compliant with international trade law.

An alternative and potentially less politically challenging solution than tariffs could be consumption-based regulations for materials. With this approach, emissions reduction regulations are placed on the materials going into end-use products like cars and buildings, rather than material production itself. Regulatory formulations could include a mandate for a rising share of low-emission steel use, a carbon tax, or a declining cap on the embedded emissions of the product. Placing the requirement on domestic steel use means that domestically produced and imported steel would face the same carbon requirements. Furthermore, this policy approach would reduce the burden on steel producers by facilitating cost pass-through – product manufacturers would need to pay for the additional cost of lower-emission production, and could pass on the cost to the final consumer. As with carbon border adjustments, a major challenge of this approach would be developing systems for tracing the carbon content of materials, and the approach would address only competitiveness for imports, not exports.

Regardless of the extent to which countries move in step on policy ambition, increased international co-operation will remain central to the sector’s transition. A key aspect will be international technology transfer, so that technologies developed in one country can lead to emission reductions globally. International climate finance, such as concessional finance provided by multilateral development banks, may also be helpful so that emerging economies can deploy low-emission technology, particularly those that may be just starting to build up their steel industry.

Article 6 of the Paris Agreement could provide a valuable framework for various aspects of international co-operation. While its rulebook has proved contentious and remains to be agreed upon within the United Nations Framework Convention on Climate Change (UNFCCC) negotiations, Article 6 proposes to establish three voluntary pathways for international cooperation:

- direct bilateral cooperation (Article 6.2)
- an international carbon market for trading mitigation efforts (Article 6.4)
- non-market based co-operation (Article 6.8) (UNFCCC, 2015).

Direct bilateral co-operation could enable countries leading in low-emission steel technology to deploy their technologies in other countries, particularly emerging economies. The international carbon market is intended to include participation by private-sector actors. This could enable steel companies to put their own mitigation measures on the market for international support, thus generating an additional revenue stream for the steel company and contributing to "Overall Mitigation of Global Emissions" under the Paris Agreement.[1] The steel sector's past participation in international carbon markets (such as the Clean Development Mechanism) has been very low (UNFCC, 2020). This is likely because the sector is hard to abate and due to difficulties in demonstrating the additionality of projects, but the sector could choose to increase participation in future. Additionally, the rulebook for non-market-based co-operation (Article 6.8) could provide a formal basis for initiatives such as an international steel sectoral agreement and technology transfer.

Key actions:

- **Government:** introduce provisions or mechanisms in emission policies that ensure domestic and imported production face the same emission requirements; work towards greater policy coherence and ambition on an international level; assist international technology transfer and finance.
- **Steel industry:** explore possibilities to form a multi-national steel sector emissions reduction agreement.
- **Non-governmental organisations:** facilitate international dialogue and collaboration through research networks, events and targeted programmes.
- **Financial institutions:** multilateral development banks to create green finance mechanisms that incentivise investment in low-emission steelmaking technologies across countries.

Infrastructure planning and development

Large-scale infrastructure planning and development will be needed to enable low-emission steel production routes. Routes relying on CCUS will call for CO_2 transport and storage infrastructure. Meanwhile, electrolytic hydrogen-based production will require large-scale low-emission electricity generation and infrastructure to produce and distribute hydrogen, or to distribute electricity for on-site hydrogen production.

Governments, the steel industry and other industries, and researchers will need to collaborate to plan and develop such infrastructure – including identifying suitable sites for carbon storage, large-scale low-carbon power generation and industrial

[1] Under the Paris Agreement, the Article 6.4 carbon market is intended to deliver "Overall Mitigation of Global Emissions", which means that buying one credit would not only "offset" one tonne of CO_2, but would also lead to more than one tonne of CO_2 being reduced, thus resulting in a net reduction in overall global emissions.

clustering, which may facilitate shared use of infrastructure. Given the large scale of such networks and investments, the public sector is well-suited to play a leading role in:

- co-ordinating the planning process
- providing funding for infrastructure build-out
- establishing clear regulatory frameworks for CCUS and electricity infrastructure
- ensuring equal and affordable access to infrastructure regardless of regional constraints.

All stakeholders, including non-governmental organisations in particular, can assist with raising awareness and increasing acceptance of CCUS among the public.

Key actions:

- **Government:** co-ordinate, explore business models and provide financing for the build-out of CCUS and low-emission electricity and hydrogen infrastructure, in collaboration with industry; establish a reliable legal framework for infrastructure, including in particular for CO_2 transport and storage.
- **Steel industry:** take part in planning and development of infrastructure.
- **Researchers:** provide research into suitable locations for CO_2 storage, low-emission electricity generation and industrial clustering.
- **Non-governmental organisations:** raise awareness and increase acceptance of CCUS.
- **Other industries:** collaborate with governments, the steel industry and other industrial stakeholders in the development of CO_2 transport and storage infrastructure.

Tracking progress and improved data

Good data on the emissions, energy use and technology profile of the steel sector and steel companies, as well as whole value chains involving steel, are essential to support the steel sector transition. They are useful for identifying best practices and opportunities for accelerated action (including through benchmarking schemes), monitoring progress towards objectives, developing balanced and industry-appropriate regulation, and differentiating produced steel according to its emissions performance for incentive and regulatory purposes.

The steel sector data currently available has various limitations and gaps, which could be reduced through enhanced data collection initiatives led by governments and industry associations, building upon existing systems. Particular areas for improvement include promoting greater participation in data collection among steel companies and increasing accessibility of regionally aggregated data for researchers and governments. In some cases, governments may want to consider reviewing competition laws to ensure they are not a barrier to improved data accessibility and transparency, for steel as well as other industrial sectors, and to assist in the development of data collection systems that comply with competition requirements. They also might consider instituting mandatory emissions reporting.

Steel companies themselves can benefit from better tracking of their own emissions. It can help them understand where they stand, identify opportunities for improvement and track progress. Governments and industry associations could undertake benchmarking and other initiatives to identify best practices and promote progress among lower performers. It can also be valuable to develop indicators that track progress towards broader sector-wide emission reduction goals in government policies and plans. If indicators reveal that interim objectives are not being achieved, policy measures can be adjusted to get back on track.

An aspect of monitoring will be designing and applying standards for near-zero emission steel and labelling the CO_2 intensity of steel. This will ideally be agreed upon internationally and through co-operation between governments and industry, including intermediate steel users. The methods should be practical and uncomplicated, to the extent possible, and build on methods suggested by the academic community (see, for example, Vogl and Åhman, 2019) and existing standards (e.g. ResponsibleSteel standard, World Steel Association life-cycle inventory methodology, ISO 20915). Such standards and labelling will be important for regulation and for buyers willing to pay a premium for low-carbon steel.

Financial organisations can improve the information they provide to their investors by developing responsible investment schemes based on stringent performance criteria. They could issue green bonds or transition bonds that include opportunities to fund emission reduction and innovation projects in the steel sector. This would help investors who are looking for "green" investment opportunities, motivated by a combination of ethics and concern about climate transition risks. An aspect of this would be defining a customised transition risk framework for the steel industry, considering linear risks as well as circular models, in line with recommendations of the Task Force on Climate-related Financial Disclosures. To improve consistency and reduce data collection requirements, stakeholders can look for synergies between methodologies and standards for sustainable steel sector investments, CO_2 performance data collection and sustainable steel labelling.

Steel companies can assist by disclosing their environmental performance to sustainable investment schemes or issuing their own green or transition bonds in line with accepted sustainability criteria – important steps towards greater transparency and securing finance from investors. Using internal carbon pricing can also help steel companies understand and manage their climate transition risks.

Key actions:

- **Government:** help develop improved and verifiable data collection and performance evaluation schemes, building on synergies with existing data collection; consider adopting mandatory emissions reporting; help develop low-emission steel labelling schemes; review competition laws to ensure compatibility between CO_2 emission reporting and competition requirements; lead or participate in development of sustainable finance classifications.
- **Steel industry:** monitor own performance transparently without revealing confidential data relating to competitiveness; help develop and provide data to improved data collection schemes; help develop low-emission steel labelling schemes; disclose environmental performance to sustainable finance schemes and issue green or transition bonds according to accepted criteria.
- **Financial institutions:** develop sustainable/responsible investment schemes and transition risk frameworks; issue green or transition bonds to finance emission reduction projects in the iron and steel sector.
- **Researchers and non-governmental organisations:** help develop low-emission steel labelling schemes; conduct research on regional trends, the performance and cost of technologies, policy performance and trade-offs within value chains involving steel.

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Annexes

Abbreviations and acronyms

AMO	Advanced Manufacturing Office
ARPA-E	Advanced Research Projects Agency – Energy
BAT	best available technology
BF-BOF	blast furnace-basic oxygen furnace
BOF	basic oxygen furnace
BPT	best practice technology
CAPEX	capital expenditure
CDQ	coke dry quenching
CO_2	carbon dioxide
CCS	carbon capture and storage
CCU	carbon capture and use
CCUS	carbon capture, use and storage
DC	Designated Consumer
DMIC	Delhi Mumbai Industrial Corridor
DMIDC	Delhi Mumbai Industrial Corridor Development Corporation
DRI	direct reduced iron
EAF	electric arc furnace
EERA	European Energy Research Alliance
EF	electric furnace
EIP	Energy Innovation Program
EOR	enhanced oil recovery
ETP	Energy Technology Perspectives
ETS	emissions trading system
EU	European Union
GDP	gross domestic product
H_2	hydrogen
H_2 DRI	hydrogen-based direct reduced iron
IEA	International Energy Agency
IF	induction furnace
LHV	lower heating value
NSP	National Steel Policy
OPEX	operational expenditure
PAT	Perform Achieve Trade
PERD	Program of Energy Research and Development
R&D	research and development

RD&D	research, development and demonstration
SDS	Sustainable Development Scenario
SET Plan	Strategic Energy Technology Plan
SR-BOF	smelting reduction-basic oxygen furnace
STEPS	Stated Policies Scenario
TRL	technology readiness level
TRT	top-pressure recovery turbine
ULCOS	Ultra-Low Carbon Dioxide Steelmaking
UNFCCC	United Nations Framework Convention on Climate Change
w/	with
ZEP	Zero Emissions Platform

Units

bcm	billion cubic metres
EJ	exajoule
gCO_2	gramme of carbon dioxide
gCO_2/kWh	grammes of carbon dioxide per kilowatt hour
GJ	gigajoule
Gt	gigatonne
Gt CO_2	gigatonne of carbon dioxide
GW	gigawatt
kcal/kg	kilocalories per kilogramme
kg	kilogramme
kJ/kg	kilojoules per kilogramme
kt	thousand tonnes
kW_e	kilowatt electrical
kWh	kilowatt hour
MBtu	million British thermal units
mm	millimetre
Mt	megatonne
Mtce	million tonnes of coal equivalent
Mt CO_2	million tonnes of carbon dioxide
Mtoe	million tonnes of oil equivalent
MW	megawatt
MWh	megawatt hour
m^3	cubic metre
t	tonne
tce	tonne of coal equivalent
t CO_2	tonne of carbon dioxide
TWh	terawatt hour
yr	year

Glossary

Apparent steel use	Crude steel production plus imports less exports of both crude steel and intermediate steel products; steel use by next-tier manufacturers, such as vehicle makers, fabricators and construction companies.
Basic oxygen furnace	A steelmaking furnace that produces steel from molten iron, often in conjunction with some scrap, by reducing the carbon content of the mixture with the aid of pure oxygen.
Best available technology	Technology designs and configurations that enable the lowest energy intensities practically achievable for a given process unit with commercial technology.
Blast furnace	The main process unit used globally for the production of iron from iron ore.
Carbon steel	A collective term for steel where the main alloying element is carbon.
Clinker	The main active ingredient in Portland cement. Cement is typically composed of < 100% clinker, with clinker substitutes, including blast furnace slag sourced from the steel industry, used to make up the remainder.
Coke	Carbonised coal used in the blast furnace to chemically reduce iron ore.
Coke oven	An industrial oven for producing coke from coking coal.
Coking coal	Coal with a quality that allows the production of a coke suitable to support a blast furnace charge. It is a type of hard coal and has a gross calorific value greater than 23 865 kJ/kg (5 700 kcal/kg) on an ash-free but moist basis.
Crude steel	Steel as it emerges in its first solid state, before rolling and other finishing processes.
Direct emissions	CO_2 emissions that are directly attributable to the iron and steel sector as defined in this publication, including direct process emissions (e.g. from the production and use of lime fluxes) and energy-related emissions (e.g. from the combustion of coal). See Box 1.3 for further details.
Direct reduced iron	Iron produced from iron ore pellets in a DRI furnace.
DRI furnace	An alternative process to the blast furnace for making iron from iron ore in the solid phase.
Electric arc furnace	An electric furnace for making steel from scrap and/or DRI by melting it with an electric arc. Oxygen and other elements are introduced to adjust the final composition of the steel.

Electric furnace	A furnace grouping including electric arc furnaces and induction furnaces, both of which are powered using electricity.
Electrolyser	An electrochemical process unit for producing hydrogen from water using electricity.
End-of-life scrap	Scrap steel generated at the end of a steel-containing product's lifetime. Synonyms include old scrap, post-consumer scrap and obsolete scrap.
End-use demand	The quantity of steel that makes its way into end-use products (buildings, vehicles, machinery, etc.), excluding the quantities that become scrap during semi-manufacturing and manufacturing (home scrap and prompt scrap). As such, total end-use demand is lower than total production.
Finished steel	Steel products in their final finished form, ready to be used in the manufacture of steel-containing goods. Key examples of finished steel products include coil, sheets, strips, wire, bars, rods, tubes, pipes, rail and plated/coated versions of each of these products.
Home scrap	Scrap steel generated due to the imperfect yields of steelmaking, rolling and finishing processes within a site. Synonyms include return scrap, internal scrap and semi-manufacturing scrap.
Hot metal	Molten iron produced in the blast furnace or smelting reduction furnace.
Hydrogen-based DRI	An alternative DRI process currently under development to produce sponge iron from pellets using hydrogen as the reduction agent instead of a mixture of hydrogen and carbon monoxide as in a regular DRI furnace.
Indirect emissions	CO_2 emissions from the generation of electricity and imported heat that are consumed in the iron and steel sector.
Induction furnace	An electric furnace that utilises electromagnetic induction to make steel from scrap (sometimes iron is also used).
Innovative blast furnace	A class of retrofit and new-build processes currently under development to adapt commercial blast furnace designs to make them more amenable to CO_2 capture.
Innovative smelting reduction	An alternative class of smelting reduction process currently under development that reduces energy consumption and produces a concentrated stream of CO_2 that is more amenable to capture.
In-use stocks	The amount of iron and steel contained in end-use products (buildings, vehicles, machinery, etc.) in use in society at a given point in time.
Iron ore	The primary virgin raw material input to steelmaking.

Lime fluxes	Limestone and dolomite, either used directly or after processing (e.g. into lime) that help remove impurities such as sulphur, phosphorus and silica in the ironmaking and steelmaking processes.
Lump ore	A type of iron ore that is already of the correct size and concentration to be added to the ironmaking process directly, without intermediate upgrading processes.
Metallic inputs	The combined total of scrap and iron inputs to a steelmaking furnace.
Open hearth furnace	A largely superseded furnace design for producing steel from iron and often some scrap.
Pellets	An enriched form of iron ore used as an input to DRI furnaces and blast furnaces.
Pig iron	A solid form of iron with a high carbon content produced from iron ore in a blast furnace or smelting reduction process.
Primary production	Steel production that uses iron ore as its primary source of metallic input.
Prompt scrap	Scrap steel generated during the manufacture of steel products by first-tier customers, such as vehicle makers. Synonyms include new scrap, industrial scrap and manufacturing scrap.
Rolling processes	After steel is cast, it makes its way through a variety of semi-finishing and finishing processes to adjust its size and material properties. Rolling is a key process among these, and can be carried out hot or cold.
Scrap	A collective name for home scrap, prompt scrap and end-of-life scrap.
Secondary production	Electric furnace production that is primarily fed by scrap, as opposed to pig iron or sponge iron.
Semi-finished steel	Steel after it proceeds through its first round of finishing processes, such as rolling. The main examples of semi-finished steel products are blooms and billets.
Sinter	An upgraded form of iron ore used mainly in blast furnaces. Iron ore fines are mixed with limestone and coke breeze, and then heated to form clumps that are more suitable for use in the blast furnace.
Slag	A co-product generated in blast furnaces and other ironmaking and steelmaking process units.
Smelting	A general term for the extraction of a metal from its ore using heat.
Smelting reduction	A commercial class of ironmaking processes that form an alternative to using a blast furnace and a coke oven.
Sponge iron	Iron produced in a direct reduced iron furnace in the solid phase.

Steel off-gases	Co-product gases with significant energy content that are generated in various process units, most notably coke oven gas and blast furnace gas.
Technology readiness level	A scale used to assess where a technology is on its journey from initial idea to maturity; the IEA uses a scale with 11 increments which are grouped into six categories: Concept (TRL 1-3), Small prototype (TRL 4), Large prototype (TRL 5-6), Demonstration (TRL 7-8), Early adoption (TRL 9-10) and Mature (TRL 11). See Box 2.5 for further details.
True steel use	In addition to apparent steel use, this metric incorporates to some degree the indirect trade of steel in steel-containing products with the aim of better-representing steel use by final consumers.
Torrefaction	A pyrolytic process used to upgrade the properties of biomass to make it suitable for use in several steelmaking processes.

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