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TECHNOLOGIES TO DECARBONISE THE EU STEEL INDUSTRY

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Contents

Abstract

The iron and steel industry is one of the building blocks of modern society, but is currently responsible for around 7% of global and 5% of EU CO_2 emissions. While facing global competition and a challenging business environment, the EU steel sector needs to decarbonise its production processes to comply with the EU's ambitious 2030 and 2050 climate targets. This report provides a snapshot of the current steel production landscape in the EU and discusses the future technologies that are being explored by the sector to decarbonise its processes, describing the transformational change the industry faces. This report compiles the current pilot projects and announcements to deploy breakthrough steelmaking technologies, which will require high capital investments. However, with 2050 just one investment cycle away, the sector needs to commercialise new low-CO_2 technologies this decade to avoid the risk of stranded assets. As the blast furnace-based production route is highly CO_2-intensive and EU mills are already operating close to optimum efficiency, the industry appears to be focussing on hydrogen-based steelmaking, while carbon capture storage and utilisation technologies are still being explored to reduce emissions in the interim. As this report shows, the EU has played an important role in supporting early stage R&D for these technologies, however there is still a funding gap in the commercialisation of breakthrough technologies. The recent momentum towards CO_2-free steel provides the EU with the opportunity to be a frontrunner in creating markets for green steel and setting standards for green public procurement.

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Executive summary

The steel sector is of strategic importance to the EU economy, however it is responsible for some 5% of EU CO_2 emissions, due to its reliance on the fossil fuel-intensive blast furnace process. The industry now faces the difficult task of drastically reducing its CO_2 emissions to be in line with the EU's climate targets while remaining competitive in a global industry suffering from overcapacity. This report reviews the current state of the steel industry and presents an overview of the technologies that are being developed to decarbonise the sector and the momentum that the industry is gathering towards their implementation.

Policy context

The EU has set clear, ambitious targets towards decarbonisation, with the goals of reducing emissions by 55% by 2030 and becoming the first climate-neutral continent by 2050. The imperative for the EU's energy-intensive industries to accelerate their transition was highlighted in the Commission's 2020 Industrial Strategy and its 2021 update. The EU's steel sector is rising to the challenge, becoming a global leader in developing breakthrough technologies. However, with 2050 just one investment cycle away, the sector needs to commercialise new low-CO_2 technologies this decade or face the risk of stranded assets.

Report structure

This report provides a snapshot of the European steel industry, its current production processes and the low-CO_2 technologies it is developing. Chapters 1 and 2 set the scene by describing the steel sector's place in the EU economy, the political drive by the EU towards carbon neutrality and the main policy tools aiming to impact the sector's emissions. Chapter 3 provides an overview of where steel is made, both globally and in the EU, and a description of the main steelmaking processes, with their energy and CO_2 intensities. The potential of increased circularity and digitalisation in reducing the sector's emissions is also discussed. Chapter 4 details the main decarbonisation technologies being explored by the steel industry and outlines major ongoing projects. The possible future cost of these technologies is examined based on external scenarios, followed by a look at the past and future role of R&D support in the EU. Chapter 5 shows evidence of recent momentum in industry towards net-zero, and of how the creation of markets for green steel can accelerate its uptake.

Key conclusions

- The EU steel sector directly employs around 330 000 people and creates some EUR 29 billion of added value. Steel is a building block for many strategic sectors of the EU economy. At the same time, the EU steel industry faces a challenging business environment characterised by long-term global overcapacity combined with the rising costs and investments required to decarbonise.
- Around 60% of EU steel is made via the energy- and CO_2-intensive blast furnace process, and 40% from recycled steel scrap in electric arc furnaces. While EU steel producers are among the most efficient worldwide, there is little further scope to reduce the CO_2 intensity of the current processes. Achieving deep emissions reduction in line with the EU's targets will require transformational change to the industry.
- Steel is a highly circular material – some 85% of end-of-life steel is recycled, emitting only a fraction of the CO_2 of new primary steel. **Maximising the share of recycled steel** is an important lever to reduce CO_2 emissions. However, due to limits in **quality**, old scrap is mostly down-cycled to lower quality steel and a significant demand for primary steel will persist in the future.
- The EU steel sector is actively developing new technologies to reduce CO_2 emissions. There appears to be a strong trend towards **steelmaking based on the direct reduction of iron using hydrogen (H-DRI)**, with close to 20 announced projects across Europe. Several steelmakers are exploring the use of natural gas as a transition fuel, gradually increasing shares of hydrogen as it becomes economically viable. Deploying renewable hydrogen-DRI to decarbonise steelmaking could require over 350 TWh of low-CO_2 electricity per year. This is a substantial amount of renewable electricity, representing over 35% of the EU's total renewable electricity production in 2019.
- **Carbon capture technologies** are still being explored as a possible solution for reducing CO_2 emissions in steelmaking, but they would need to be combined with extensive process modifications to achieve deep emission cuts. A handful of pilot projects in partnership with the chemical industry are utilising captured CO_2 to make chemicals.

- Producing steel via **iron ore electrolysis** using only electricity could be a potential **game changer**, however the technology is still at an **early stage of development** and is unlikely to be market ready before 2040-2050. The estimated electricity demand is comparable to that of the H-DRI process.
- Making low-CO_2 steel will likely be **more expensive** than current steel production, however future costs are highly uncertain. For H-DRI, the future costs of hydrogen and renewable electricity are the main variables affecting the operating cost (OpEx) of low-CO_2 steel. By 2050, with a cost range for renewable hydrogen between 1 €/kg to over 5 €/kg, external studies find that H-DRI in Europe could be cheaper or 60% more expensive than today's steelmaking costs.
- The EU's R&D programmes have played an important role in supporting the early stage development of technologies and allowed EU companies to lead global decarbonisation efforts. However, major investments are required to commercialise these technologies and replace existing plants, with total investment needs between EUR 70 billion and EUR 100 billion, as well as additional infrastructure investments in renewable electricity, hydrogen and/or CO_2 infrastructure.
- There is a recent momentum shift among major industry players – globally and especially in the EU – to decarbonise steel production. The five biggest steelmakers in the world, as well as all the biggest EU steelmakers, have announced net-zero CO_2 emission targets. The EU has the opportunity to be a frontrunner in creating markets for green steel, building on the momentum provided by the decarbonisation pledges of the major steel actors. Regulatory initiatives such as setting **green steel standards** to be used in **green public procurement** can support the creation of lead markets to accelerate the decarbonisation of steel production.

1 Introduction

The iron and steel industry is a strategic sector of the EU economy, producing a material that is crucial to most of the EU's industrial ecosystems. However, the sector is also a major CO_2 emitter, responsible for some 5% of the EU's total CO_2 emissions. The iron and steel industry currently depends on large quantities of coal to produce new steel and operates within complex, globalised value chains. The EU has enshrined ambitious targets to reduce emissions by 55% by 2030 and to become the first climate-neutral continent by 2050 in the European Climate Law (European Commission, 2021f). This gives the sector the difficult task of aligning its production with the EU's climate targets while remaining competitive in a challenging global business environment.

Steel is currently made in two main ways in the EU. In the primary (integrated) route, steel is produced from iron ore, requiring carbon in the form of coke (made from coking coal) and injection coal to provide high-temperature heat and to reduce iron ore in a blast furnace; CO_2 emissions are an inevitable product of this process. Integrated steel plants combine sinter plants, coke ovens, blast furnaces and basic oxygen furnaces in highly optimised and interconnected energy and materials streams. EU integrated plants are already among the most efficient worldwide, operating at close to optimal thermodynamic levels, and there is little further scope to reduce CO_2 emissions. In the secondary (recycling) route, steel is made by melting recycled steel scrap in an electric arc furnace. This process is nearly fully electrified and emits only a fraction of the CO_2 emissions of integrated steel plants. In the EU, 60% of steel is made via the primary route and 40% in electric arc furnaces. Increasing the share of recycled steel is an important lever to reduce CO_2 emissions, however quality and quantity constraints currently mean that virgin steel will still be needed in the future.

A number of scientific studies (Arens et al., 2017; Bataille et al., 2018; Fischedick et al., 2014; Toktarova et al., 2020) as well as private sector and institutional reports (Agora Energiewende and Wuppertal Institute, 2021; BloombergNEF, 2021a; Energy Transitions Commission, 2018; Fleiter et al., 2019; IEA, 2020; Material Economics, 2019; McKinsey, 2018) have shown that fundamental changes are necessary to the steelmaking process, through breakthrough technologies, if emissions are to be brought in line with the 2050 GHG reduction target. This involves a transformational change of the steel industry's production processes and an increased sense of urgency. Due to the steel industry's long-lasting capital assets, 2050 is just one investment cycle away. Investment decisions made in the next decade will need to be aligned with the EU's climate targets if the industry is to avoid the risk of stranded assets or locking in CO_2 emissions beyond 2050. This urgent need for action is reflected not only in the European Commission's update to the 2020 Industrial Strategy (European Commission, 2021a) and the accompanying Staff Working Document on Steel (European Commission, 2021h), but also in assessments by the steel industry (Eurofer, 2019).

This report provides a snapshot of the current status of the steel sector and presents the main technology options that are being developed by EU steelmakers to decarbonise primary steel production. The industry is focussing on the development of direct reduced iron (DRI) technology. This process currently uses natural gas to reduce iron ore and already accounts for 5% of steel production outside of the EU. European steelmakers are investigating the use of low-CO_2 hydrogen in the DRI process to produce low-CO_2 steel. Other technological routes, including carbon capture and storage/utilisation (CCUS) technologies, are still being investigated by some steelmakers, particularly in partnership with the chemical industry for the reuse of CO_2. Several low-carbon technologies are progressing very rapidly and are close to commercial deployment, while some promising technologies (such as iron ore electrolysis) are not likely to be commercially available before 2050.

While making low-CO_2 primary steel is expected to be more expensive than current steel costs in the short term, by 2050 the picture is less clear. Future costs and investment needs are presented in this report, based on the results of recent external studies, highlighting the considerable variability in these projections. As the recent Staff Working Document on clean steel (European Commission, 2021h) has highlighted, the Commission has a number of policy options in its toolbox to ensure that the right framework conditions are in place to allow industry to bridge the funding gap for industrial deployment of these low-CO_2 technologies. This report provides evidence of the recent global momentum towards low-CO_2 steel and discusses the EU's opportunity to be a frontrunner in creating lead markets for green steel, thereby providing the European steel industry with the opportunity to secure a competitive advantage by becoming the first to decarbonise its processes.

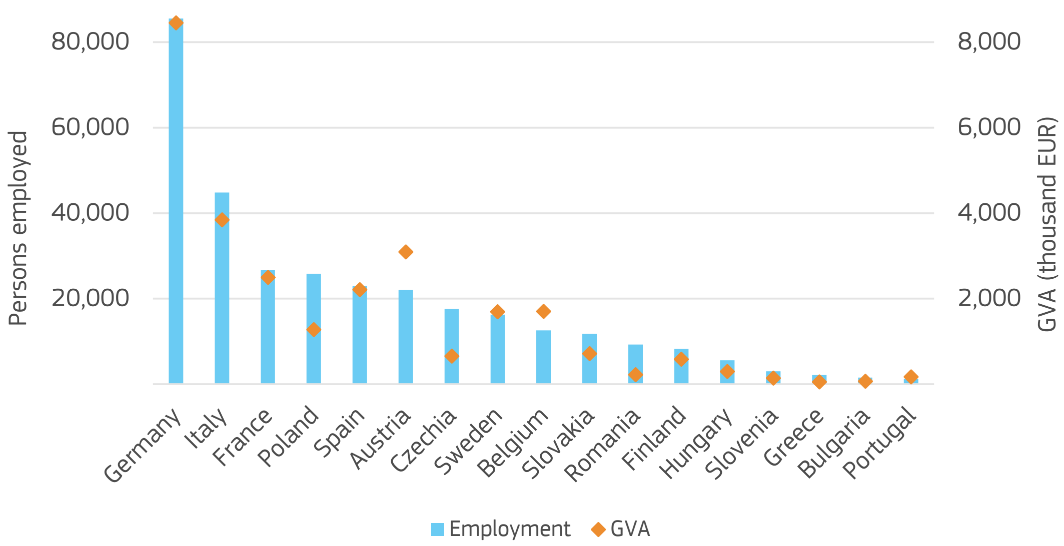
2 The steel decarbonisation challenge

Steel is a hugely important material, both for today's society and for tomorrow's low-carbon economy. However, the European steel industry has been struggling in the face of rising global overcapacity, stagnating internal demand and most recently, a global pandemic. At the same time, deep reductions of emissions are needed from a sector that is one of the biggest industrial emitters of CO_2, as well as a significant source of other pollutants. The EU's policies and the sector's framework conditions have in the past not been sufficient to incentivise deep decarbonisation of the industry. However, recent policy momentum in the EU has put the spotlight on the steel sector, which could be on the brink of deploying breakthrough low-CO_2 technologies.

2.1 Steel's importance in the EU economy

The European steel industry is a historic cornerstone of the EU – the European Coal and Steel Community ultimately led to its creation – and the industry still has a strategic place in the EU economy. According to Eurostat, in 2018 the sector directly employed around 330 000 people and created some EUR 29 billion of direct Gross Value Added (Eurostat, 2021a). Taking into account the indirect impact of the industry through the activities supported by the sector's EU supply chains, the steel sector can be linked to a further 1.6 million jobs and EUR 82 billion of added value in 2019 (Eurofer, 2020). The steel sector has a footprint in many Member States, via the main steel-producing sites and its downstream value chains, however the bulk of activity is located in a handful of countries.

Figure 1 Iron and steel sector (NACE 24.1) employment and GVA per EU Member State, 2018



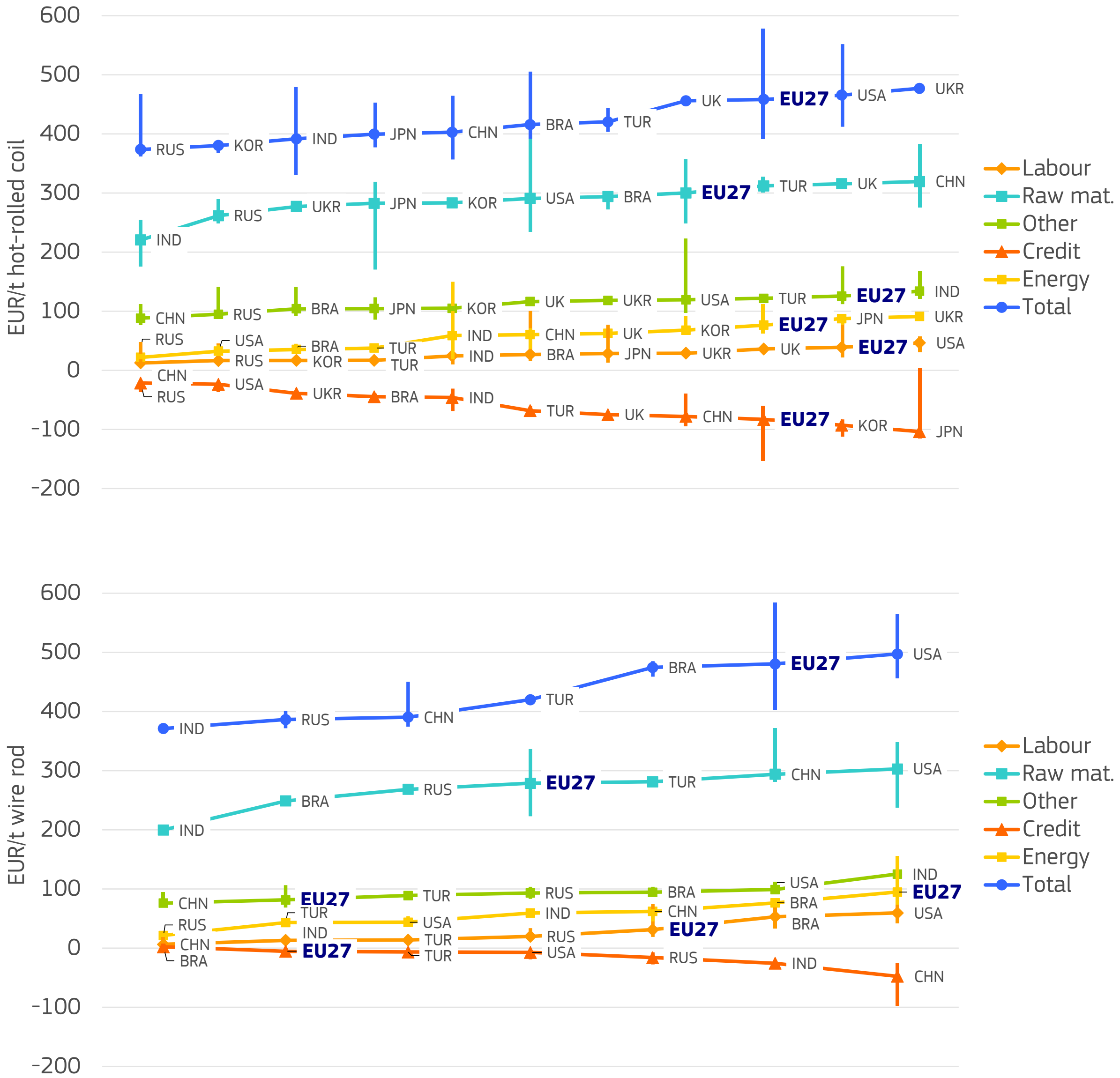
Source: JRC based on Eurostat

Steel is a particularly important material since it is a building block for many strategic EU sectors of the economy, be it construction, transportation, energy or manufacturing and other industry. The sector has, however, struggled in recent decades, suffering a permanent demand drop after the 2008 financial crisis from which it has never recovered. It is additionally facing increasing international competition from both neighbouring countries and overseas – the EU went from being a net exporter historically to being a net importer of finished steel in 2016, and has seen downward pressure on utilisation of production capacity, amounting to structural overcapacity in the sector (McKinsey, 2021c).

EU steelmakers face some of the highest costs of production compared to the other major steel-producing regions. **Figure 2** shows the breakdown of production costs into five components, sorted in increasing order, as well as the range of the corresponding costs in each country (Medarac et al., 2020).

Figure 2 Steelmaking costs in the EU and 3rd countries in 2019

(Top: Hot-rolled coil production costs in BF-BOF process, Bottom: Wire rod production costs in EAF process)



Source: JRC (Medarac et al., 2020) based on (CRU, 2020)

The top figure shows the breakdown of production costs of hot-rolled coil, a proxy for flat products typically produced in the integrated route. The bottom figure shows the breakdown of production costs of wire rod, a proxy for long products produced mainly in the recycling route. The average total production costs in the EU are amongst the highest in the world. It is worth noting that there is a wide range of costs in the EU, showing that some European steelmakers are able to compete with cheaper global production, while others face some of the highest costs worldwide. The higher average production costs of European plants are due to high costs in several cost elements, including energy, raw materials and labour. The European facilities are among world leaders in creating credits in the integrated route, notably from recycling waste gases for power self-generation. This is a reflection of the cumulated effect of the investments in innovation and optimisation in the European steel industry. However, the industry's significant R&D efforts over the last decades are not enough to mitigate the structurally higher costs faced by the sector.

This challenging business environment is combined with the fact that the industry is expected to make major strategic investments to address both economic viability and environmental sustainability in the immediate future.

2.2 The climate and environmental urgency

The steel industry is one of the biggest industrial emitters of greenhouse gases and a significant source of other pollutants. Globally, the sector is responsible for around 7% of CO_2 emissions. In the EU 27, 5% of total emissions, some 190 Mt of CO_2, come from steelmaking alone. Of all energy-intensive industries, the iron and steel sector has the highest total CO_2 emissions. These emissions are currently inherent to the way steel is made in the EU, due to the use of coke and coal in blast furnaces to reduce iron ore, releasing CO_2 in the process. While integrated plants (combining blast furnaces and basic oxygen furnaces) have optimised their material and energy flows over the years and are among the most energy and CO_2 efficient worldwide, they are operating close to optimum levels. The potential to further reduce CO_2 emissions through additional incremental efficiency improvements has been almost fully exploited. Achieving the deep CO_2 emission reductions necessary will require major changes to the industry to deploy new low-CO_2 technologies and circular economy solutions. The urgency of this transition is reinforced by the long investment cycles of steelmaking assets. Blast furnaces, the cornerstone of integrated steelmaking plants, have operating lives of up to 20 years before they need relining[1]. If reinvestment is made in existing infrastructure at the end of its technical life, there is an accrued risk of locking in CO_2 emissions or stranding assets. For the iron and steel industry to successfully transition to net-zero by 2050, decisions on investments will need to be made in the next decade and will need to be aligned with the strategies to decarbonise the sector. Estimates calculate that by 2030, some 50% of today's blast furnace capacity will require major reinvestments, including relining the blast furnace, a major capital investment of several hundred million euros that extends a blast furnace campaign by two decades (Agora Energiewende and Wuppertal Institute, 2021). Reinvestments into the current CO_2-intensive production pathway risks locking in emissions until 2050 and beyond, or creating future stranded assets.

2.3 The policy context

The EU has set clear ambitions for decarbonisation, with a target to reduce GHG emissions by at least 55% by 2030, supported by the comprehensive Fit for 55 legislation package, and the long-term objective to become the first climate-neutral continent by 2050, set out in the European Green Deal policy initiatives and anchored by the European Climate Law (European Parliament and Council of the EU, 2021). For these goals to be reached, the EU's industry, including the iron and steel sector, will need to transform its current highly CO_2-intensive processes. The Commission's 2020 Industrial Strategy and its 2021 update highlights the need to further accelerate the green and digital transition of Europe's industry and increase the resilience of EU industrial ecosystems. Building on the High-Level Group on Energy-Intensive Industries "Masterplan for a competitive transformation of EU energy-intensive industries enabling a climate-neutral, circular economy by 2050" (HLG EII, 2019), several actions have been launched to accelerate the transformation of EU industries. These include the ERA Common Industrial Technologies Roadmaps, launched in 2020 in the New ERA Strategy (European Commission, 2020c), focussing on research and innovation investment agendas which help the development and uptake of innovative technologies, and the co-creation of a transition pathway for the energy-intensive industries ecosystem, in partnership with industry, public authorities, social partners and other stakeholders, (European Commission, 2021g).

A key policy mechanism for reducing industry's emissions is the EU Emissions Trading System (ETS). As a consequence of the EU's increased emissions reduction ambition, the emissions reduction target for ETS sectors, including the iron and steel industry, has increased to 61% by 2030 vs 2005 in the proposed revision of the ETS directive (European Commission, 2021b). Historically, the iron and steel sector and other energy-intensive industries have been shielded from the full carbon price in the ETS via free allocation of emission allowances. While this has effectively protected the industry from carbon leakage risks, it has not provided sufficient incentive for a transition to climate-neutral technologies (Stede et al., 2021). Furthermore, the free allocation rules based on technology-specific product benchmarks in the iron and steel sector (such as the blast furnace-made hot metal benchmark) has incentivised incremental emission reduction improvements over the deployment of new breakthrough technologies. Indeed, as installations deploying innovative technologies can fall out of the specific product benchmark or even out of the EU ETS altogether, they are put at a competitive disadvantage compared to existing technologies, since they are not granted the same level of free allocations. This issue has been identified in the Commission's ETS revision proposal (European Commission, 2021b), which suggests reviewing the benchmark definitions so as to make them technology-neutral, ensuring equal treatment of installations independently of the technology used. Investments in low-

[1] Every 20-25 years, the refractory lining of a blast furnace is renewed to extend its operational life.

carbon technologies have in the past been further economically disincentivised by the low and volatile carbon price in the ETS. The average price in 2020 of 25 €/tCO_2 (icap, 2021) was still far below the current indicative breakeven costs of zero-carbon technologies (Sartor & Bataille, 2019). In 2021, however, ETS prices have soared, climbing over 60 €/tCO_2 in September. The free allocation of allowances currently means that steelmakers are facing a much lower effective carbon rate and are still largely shielded from this surge in CO_2 prices, weakening the price signal that would incentivise investments in deep CO_2 reduction measures.

Figure 3 2021 EU ETS price

Source: JRC based on Ember (Ember, 2021)

As an alternative measure to mitigate carbon leakage risks, the Commission has proposed the introduction of a Carbon Border Adjustment Mechanism (CBAM) on the carbon content of imports (European Commission, 2021c). This would ensure that exporters to the EU face the same carbon prices as EU industry is subject to under the ETS. As the CBAM is considered an alternative to free allocations, free allowances would be phased out gradually, while the CBAM is phased in. The iron and steel sector is one of the selected industrial sectors, which also includes refineries, cement, organic basic chemicals and fertilisers, that will fall under the initial CBAM scope. Addressing free allocations in this way could incentivise investments into low-CO_2 production processes by fully integrating the carbon cost into the production cost of materials.

3 The steel sector today

To understand the decarbonisation challenges faced by the European steel industry, it is first important to understand how steel is currently made, both in the EU and globally. In Europe, just over half of all steel is made in a process that centres on the use of coal in a blast furnace to make new steel from iron ore. This incurs inevitable process emissions, and EU steel mills have more or less optimised this production route already, making the scope for further CO_2 emissions very limited. Steel production from recycled scrap in the electric arc furnace emits a fraction of those CO_2 emissions and is the dominant production route in several third countries. Maximising the share of recycled steel production in the EU is an important lever to reduce emission of the sector, however virgin steel production will continue to be needed.

3.1 How steel is currently made

There are two main ways in which steel is currently produced in the EU: from mined iron ore, involving a series of highly energy-intensive processes centred around the blast furnace or from recycled steel scrap, directly melted into steel in an electric arc furnace. These are two fundamentally different manufacturing routes, with vastly different raw material and energy inputs.

The primary route involves two main stages – making iron, then steel – since the mined iron ore, Fe_2O_3, first needs to be reduced to iron, Fe, in the presence of carbon (coke and coal) in a blast furnace, before being further processed into steel.

In the first step, the iron ore itself is pre-processed into sinter or pellets in dedicated plants, an agglomeration process that requires temperatures of about 1 000ºC from the consumption of coal and natural gas. This step typically requires 1-2 GJ/t of pellets or sinter, noting that sintering usually occurs at the integrated steelmaking site, while pelletising tends to take place upstream at the iron ore mining stage.

In the blast furnace, the reducing gases that bind and remove the oxygen from iron ore are generated from coke and injection coal. Coke is a refined coal derivative, made from heating coking coal (also called metallurgical coal) in a coke oven in the absence of air at around 1 000ºC. This energy-intensive process requires around 6.5 GJ/t coke.

The sinter or pellets and coke are charged into the blast furnace, while hot air and pulverised coal are blown in from the bottom, forming reducing gases from coke which react with iron ore to produce hot metal. This reaction requires extremely hot temperatures of up to 1 400ºC and consumes around 12 GJ/t hot metal. Additionally, limestone is added to the blast furnace as a fluxing agent, facilitating the removal of impurities. The iron and steel industry is a major consumer of lime in the EU, consuming some 40% of total lime demand in the EU (Manocha & Ponchon, 2018).

To make steel, the molten hot metal is poured into the basic oxygen furnace (BOF), where oxygen is blown into the metal to reduce its carbon content (from around 4%) to steel grade levels (below 1%). This is an exothermic process that does not require additional fuel inputs. At this stage, a certain amount of steel scrap can also be fed into the basic oxygen furnace, acting as a coolant.

The crude steel from the BOF is then cast into different intermediary steel products through various hot-and cold-rolling downstream processes.

The primary steelmaking blast furnace – basic oxygen furnace (BF-BOF) route is highly integrated, with all its processes usually located at the same site (except for the pelletising plant, which is usually located by the iron ore mine). The waste gases emitted by the coke oven, blast furnace and basic oxygen furnace form an important part of the energy balance, since they are recovered and reused as fuel to provide process heat or to fire onsite power plants that generate electricity (the gases can also be sold to external power plants that sell electricity to the grid). In total, the primary steel production route requires around 21 GJ/t crude steel and accounted for 73% of global steel production in 2020 and 56% in the EU (World Steel Association, 2021a).

In the secondary steelmaking route, recycled steel scrap is smelted in an electric arc furnace (EAF) at 1 600ºC to produce liquid steel. Electricity is the main energy input to this process, but natural gas from dedicated burners to melt the scrap can represent an additional energy input (Bianco et al., 2013). A small amount of solid carbon, such as coal or coke (some 12kg per tonne of steel) is also used to increase the energy efficiency of the process (through slag foaming) and as a carburising agent (Echterhof, 2021). In terms of direct, the secondary steelmaking route requires around 2.5-3 GJ/t of crude steel.

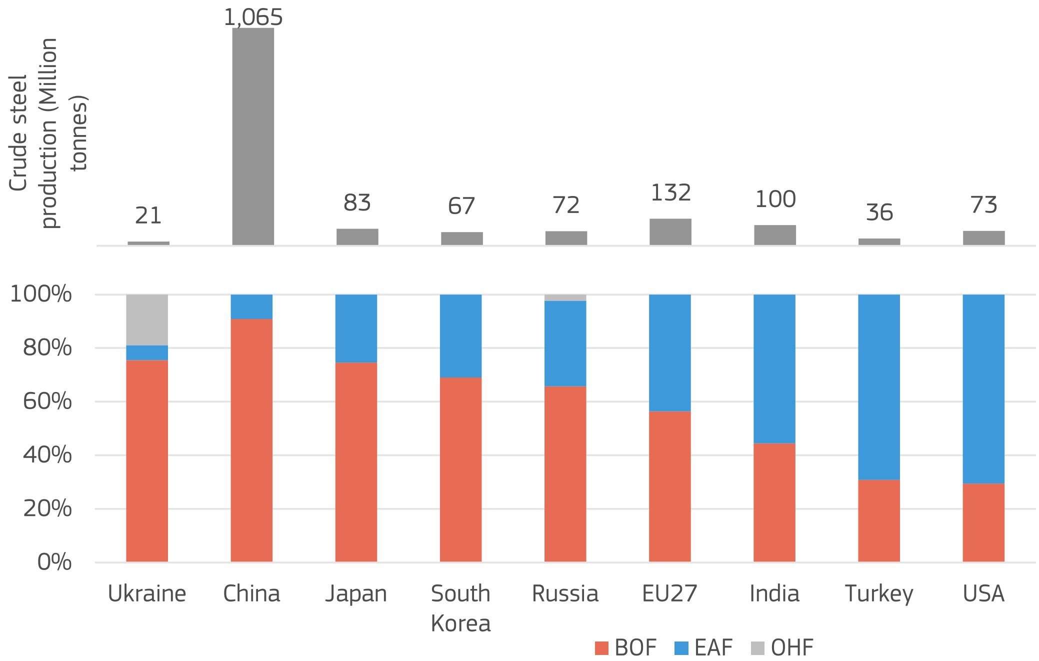
Another commercially deployed method of primary steel production, whereby iron ore is directly reduced in its solid state to produce direct reduced iron (DRI, also called sponge iron), bypasses the need for a blast furnace and coke oven, since the main reduction gases in this process, hydrogen and carbon monoxide syngas, are generated from natural gas or coal. The sponge iron is then melted and refined into steel, often with additional scrap steel, in an electric arc furnace. This production route accounts for a minor share of global steel production (around 5%) (World Steel Association, 2019), although a strong increasing trend can be observed. Between 2015 and 2019, the production of DRI increased by 46%. Of the 111 Mt of direct reduced iron produced globally in 2019, India and Iran accounted for 60% of global production (World Steel Association, 2020). In the EU there is currently only one commercial DRI plant, operated by ArcelorMittal in Hamburg. Built in the 1960s, it produced 47 kt of DRI in 2019 (World Steel Association, 2020).

There are several types of DRI process currently in use globally, which can use different sources of reducing gases (natural gas or coal) and types of iron ore feeds (pellets or fine ores). The most common DRI processes are based on a shaft furnace, where the reduction of iron ore to sponge iron takes place in the presence of gaseous reductants. The two main technology providers of shaft furnaces are Midrex and HYL/Energiron, where Midrex has a dominating market share: it accounts for 80% of world DRI production via the shaft furnace (Midrex, 2020). Around a quarter of global DRI production occurs in rotary kilns. These are coal-fired, smaller plants (they cannot be built larger than about 200 000 tonnes per year (Midrex, 2010)), and are predominantly deployed in India.

Steel made with the DRI-EAF route, using a shaft-furnace (Midrex or Energiron) using natural gas as the reductant, requires around 13 GJ of energy per tonne of steel (10 GJ of natural gas in the DRI and 3 GJ of electricity in the EAF).

It's important to note that the distinction between primary and secondary steel is not clear cut. Basic oxygen furnaces in the integrated steelmaking route use scrap as a coolant in the exothermic BOF process. Up to 30% of the charge can be steel scrap (World Steel Association, 2021b), with the average at slightly below 20% (Wörtler et al., 2013). The steel scrap fed into EAFs in the secondary route can also be 'sweetened' with a metallic charge (pig iron[2] from the BF-BOF route or DRI/HBI) to improve the quality of the resulting steel.

Figure 4 Crude steel production by process, 2020



Note: Ukraine and Russia produced 19% and 2% (respectively) of total crude steel in open hearth furnaces (OHF), an older and less efficient steelmaking process.

Source: JRC based on (World Steel Association, 2021a)

[2] Iron ore reduced in a blast furnace can be cooled and cast into pig iron for use as a metallic feedstock.

3.2 Where steel is made – in the world and in the EU

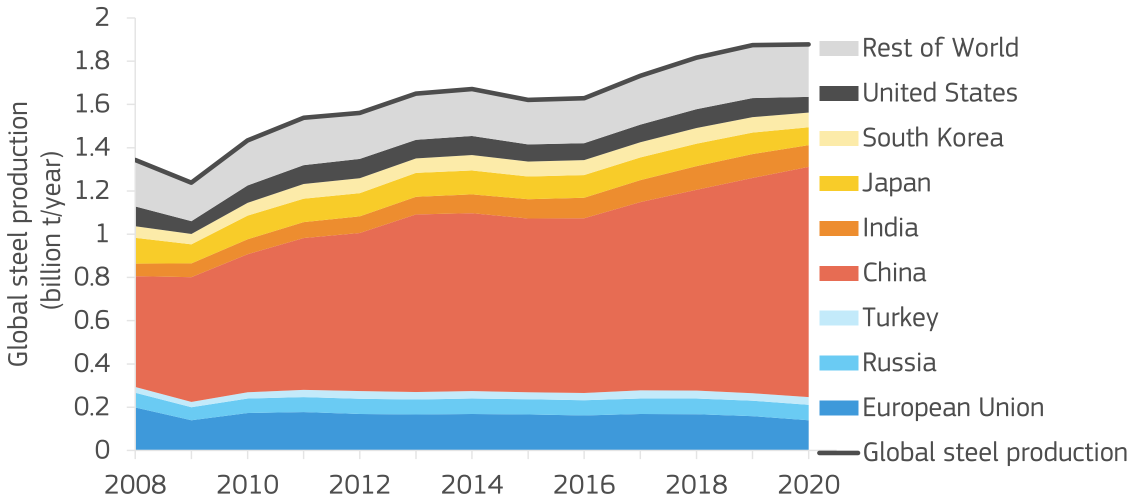
3.2.1 Global crude steel production

Steel is one of building blocks of modern industrialised society, and one of very few materials whose production is measured in billions of tonnes. Global steel production is ever-increasing, and has more than doubled in the last 20 years. The story of steel production in recent decades has been marked by an explosion of production in China. In 2010, China was producing 45% of the world's steel; in 2020 it is responsible for 57%, or 1 billion tonnes, of the world's total. In the same time period, the EU's share of global steel production has diminished, from 12% in 2010 to 7% in 2020.

EU steel production had been relatively constant at around 165 million tonnes since recovering from the 2009 low caused by the financial crisis. The Covid-19 crisis, however, marked a significant downturn for the industry, as production decreased by 12% from 2019 to 139 million tonnes in 2020, a level not seen since 2009. Despite this, the EU as a block remains the second largest steel producer in the world. The only major steel producers that increased production in 2020 compared to 2019 were China (+7%) and Turkey (+6%).

2021 has seen a demand recovery and a steel price surge, allowing European steel producers to generate better margins and bounce back somewhat from the 2020 slump (Fitch Ratings, 2021). However, the EU steel industry continues to face structural challenges, including increasing long-term overcapacity leading to lower utilisation rates, combined with the rising costs and investments required to decarbonise the industry (McKinsey, 2021c).

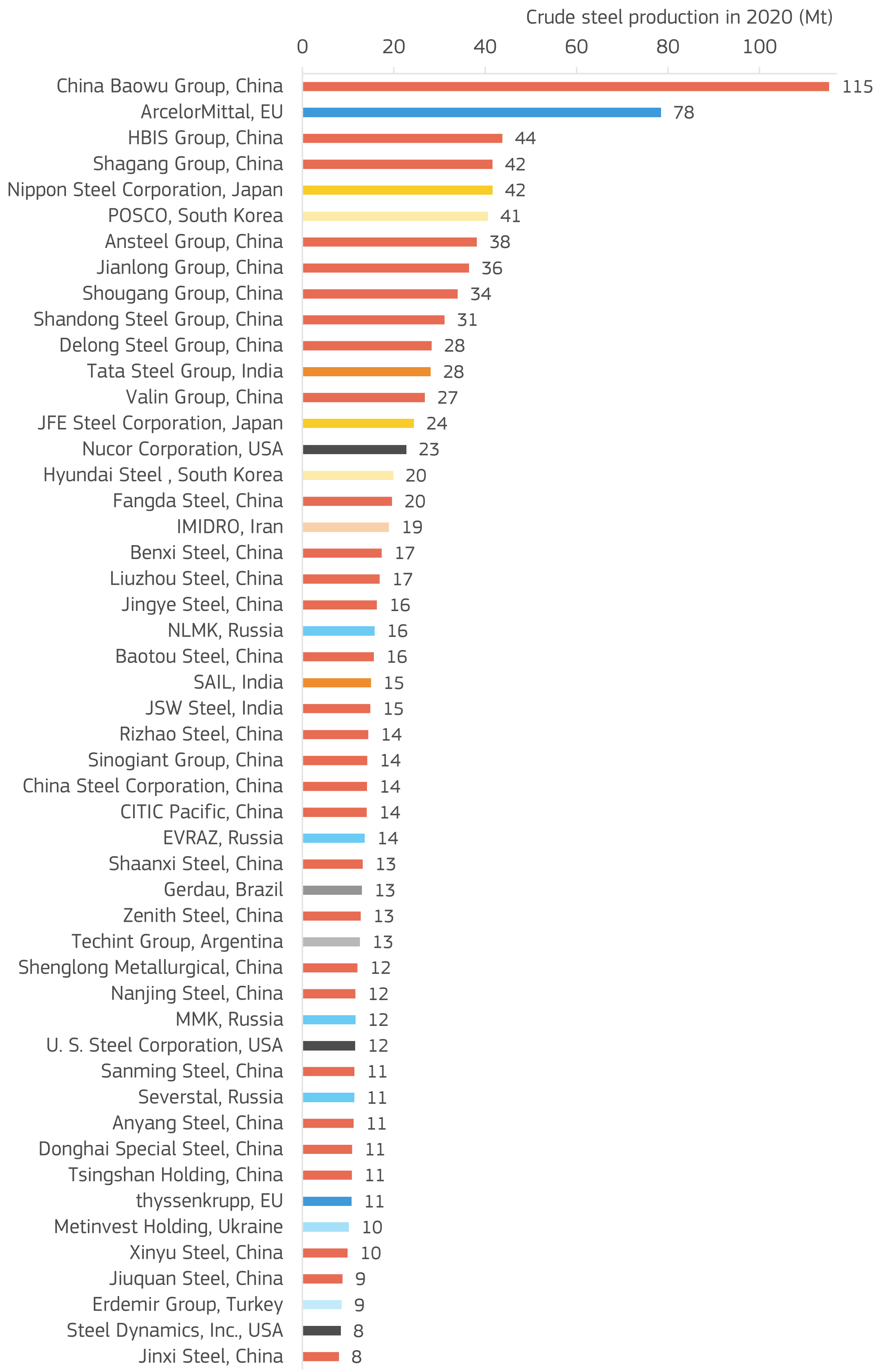
Figure 5 Global steel production, 2008-2020



Source: JRC based on World Steel Association

The Covid-19 crisis also brought about a reshuffling amongst the top steel-producing companies globally. ArcelorMittal, the multinational steel producer headquartered in Luxembourg, had continuously been the biggest steel producer over the last two decades. In 2020, this spot was claimed by Chinese firm Baowu Group, by a considerable margin. Of the top ten global steel producers, seven are now Chinese, and only one other EU company, thyssenkrupp, is in the world's top 50, as shown in **Figure 6**. The steel industry can also be considered to be very fragmented compared to many other global industries.

Figure 6 Top 50 global steel producers, 2020

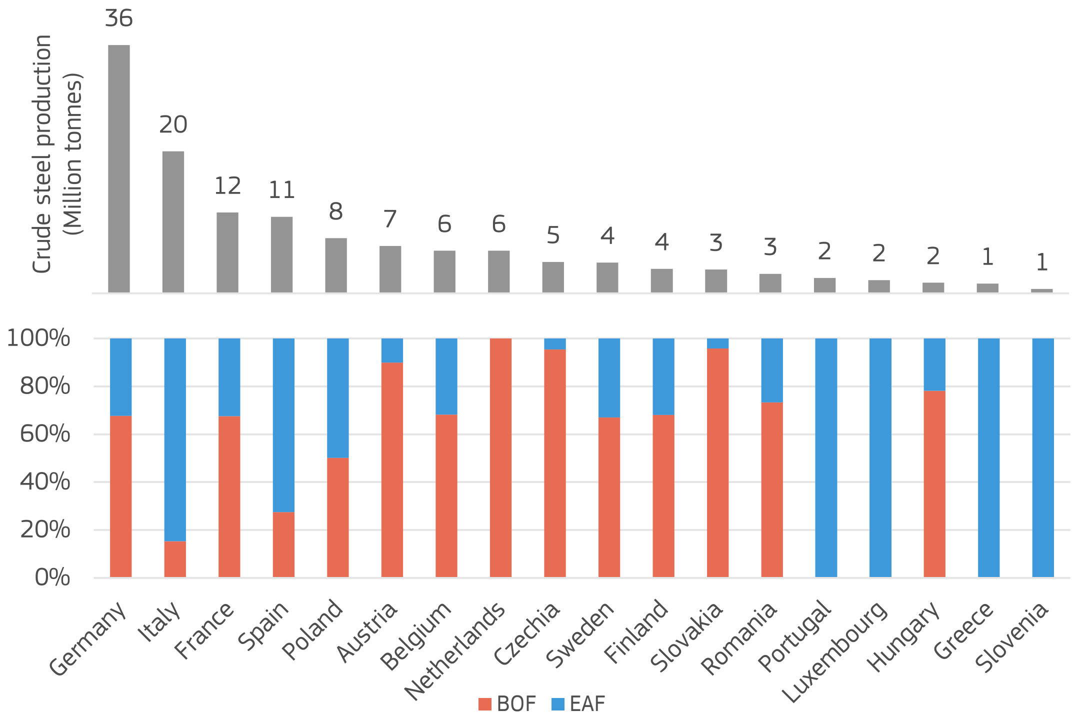


Source: JRC based on (World Steel Association, 2021a)

3.2.2 Steel production in the EU

Steel production in the EU is dominated by a handful of countries. Germany produced 26% of all EU steel in 2020, followed by Italy (15%), France (8%) and Spain (8%). Just over half of all steel produced in the EU in 2020 (56%) was made via the primary route and 44% was made through the recycling route. As **Figure 7** shows, this split varies considerably between Member States. In Germany, two thirds of steel (68%) is made in blast furnaces, while in Italy the vast majority (85%) is made in electric-arc furnace mini mills.

Figure 7 Steel production by Member State in 2020

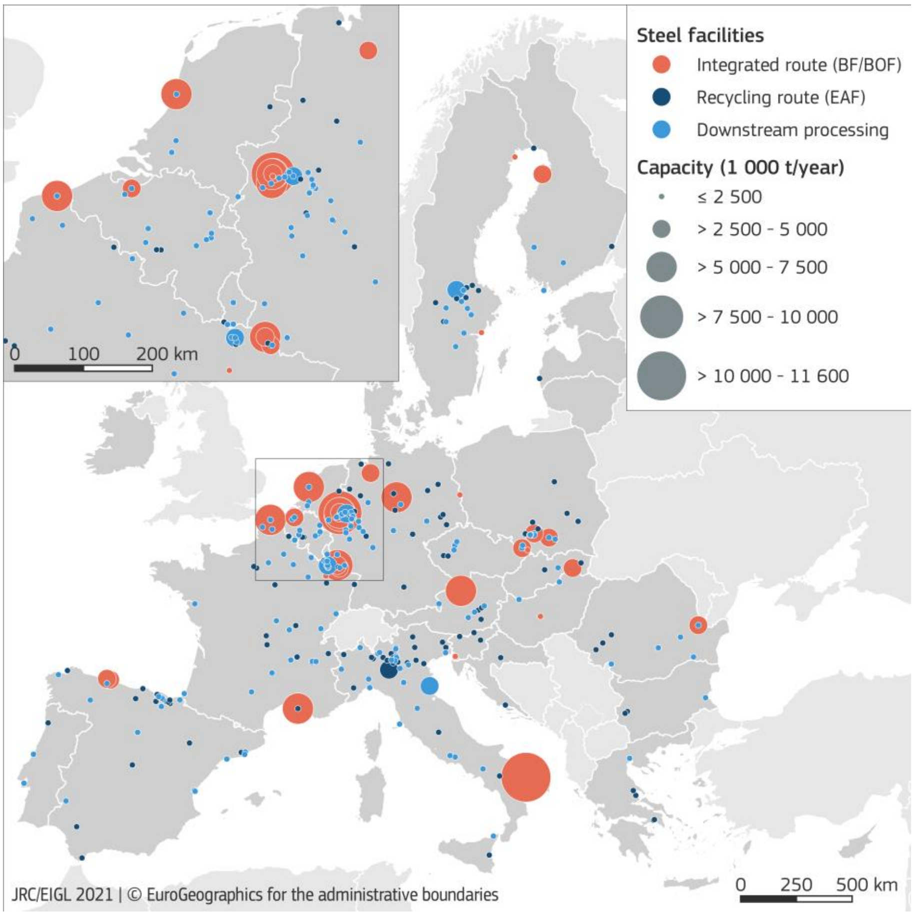


Source JRC based on (World Steel Association, 2021a)

Fourteen countries in the EU have primary steelmaking capacities. Primary steel plants are huge industrial sites which often include multiple blast furnaces in combination with the other necessary up- and downstream processing plants (coke, sinter, BOF, rolling, etc.). The smallest such sites in the EU have crude steelmaking capacities of just above 1 million tonnes per year, while the largest sites have capacities of around 10 Mt/year (Taranto, Italy and Duisburg, Germany). There are 25 such integrated steelmaking sites in the EU, with a high concentration of steelmaking capacity located between the Rhine-Ruhr and Benelux regions, a highly industrialised zone in Europe. There is also a smaller cluster of primary steelmaking capacity in Eastern Europe (Poland, Czechia and Slovakia).

On the other hand, electric arc furnace production sites, sometimes referred to as mini-mills, are typically much smaller installations, with capacities ranging from some 100 000 tons of steel per year, to 2.5 Mt/year at the largest EAF production site in Germany. There are around 120 EAF production sites spread across eighteen countries in the EU.

Figure 8 Steel facilities in the EU

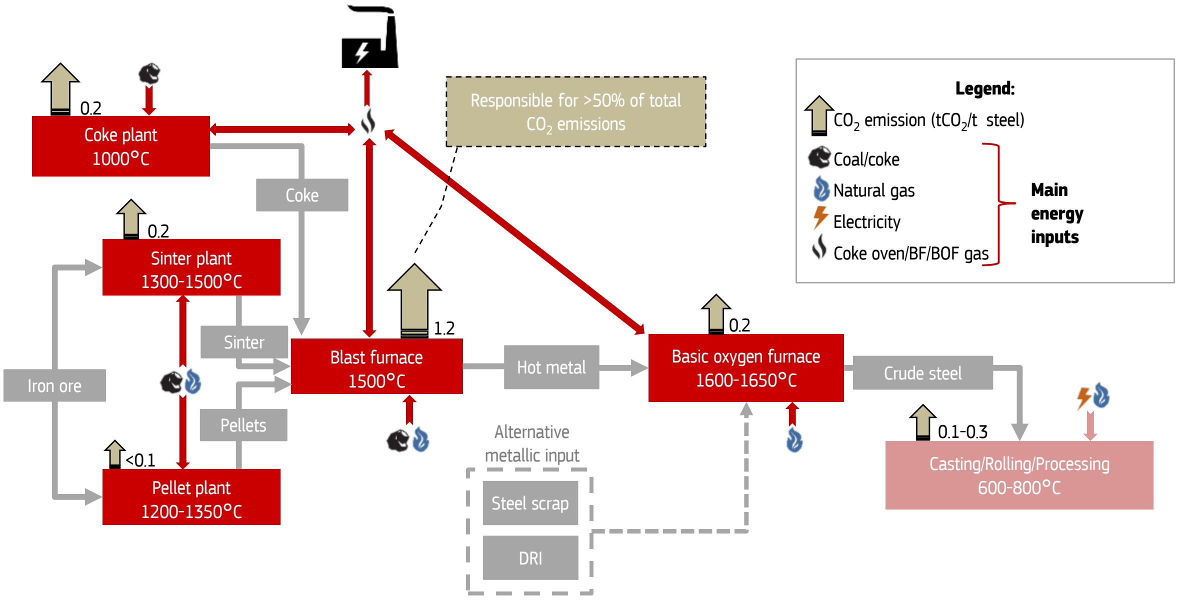


Source: JRC/Energy and Industry Geography Lab based on (Steel Institute VDEh, 2019)

3.2.3 CO_2 emissions of steelmaking routes

While both the primary and secondary steelmaking routes are very energy-intensive industrial processes, they can have vastly different CO_2 emission intensities. In the BF-BOF steelmaking route, carbon is not only an energy input, but also necessary to bind and remove oxygen from iron ore, resulting in process CO_2 emissions. This processing step in the blast furnace is the most CO_2-intensive, responsible for over 50% of the total CO_2 emissions of the final product. All other processing steps in the integrated steelmaking route, from preparing the raw materials in the coke and sinter plants, to producing and rolling the steel products, all emit CO_2 from the combustion of fossil fuels required to reach the high processing temperatures, as shown in **Figure 9**. Attributing emissions to each specific process is not straightforward, since waste gases are recirculated within the steel plant to various sub-processes, including internal power plants, as well as to external power plants. In Figure 9, the emissions of waste gases are allocated to the plant where they originate. Furthermore, steel plants can by input products, such as pellets or coke, which lowers the CO_2 emissions occurring at the specific steelmaking site. On average, the total BF-BOF route emits around 1.9 tCO_2/t crude steel, however there is a wide variability between countries and plants depending on the efficiency of energy and materials use.

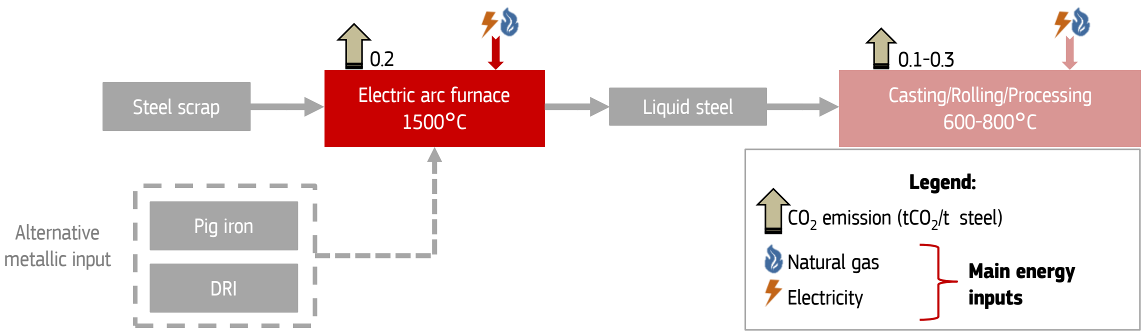
Figure 9 Simplified flow diagram and CO_2 emissions of the BF-BOF route



Source: JRC

The secondary steelmaking route is largely electrified. Small amounts of natural gas and coal are used in the electric arc furnace to provide additional heat and for slag foaming, and an even smaller proportion of CO_2 emissions are due to the consumption of the graphite electrodes in the EAF, which together contribute some 0.06 to 0.1 tCO_2/t steel of direct emissions (Echterhof, 2021). A typical EAF consumes around 500 kWh of electricity per tonne of steel. At the current average CO_2 intensity of electricity in the EU, the total (direct and indirect) emissions from EAF steel melting are around 0.2-0.3 tCO_2/t steel. The indirect emissions from electricity consumption, around 0.1-0.2 tCO_2/t steel, would be avoided if the EAF used renewable electricity.

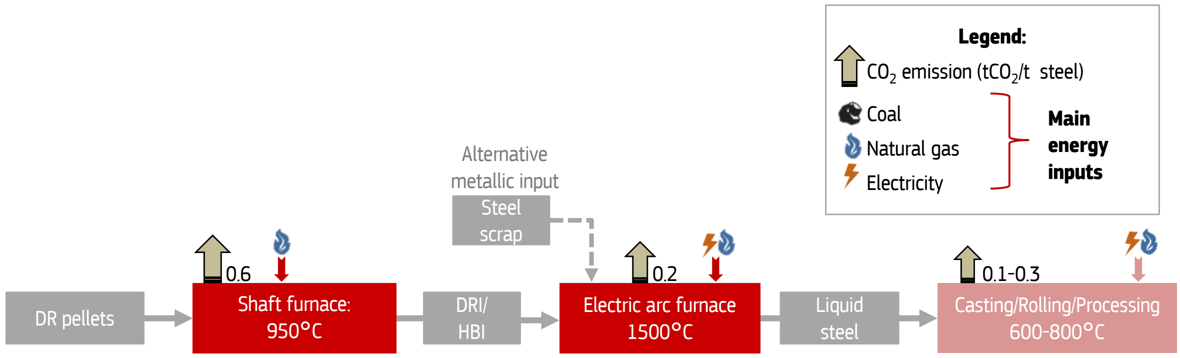
Figure 10 Simplified flow diagram and CO_2 emissions of the EAF route



Source: JRC

A number of different processes have emerged over the past fifty years which achieve the direct reduction of iron ore without the need for blast furnaces or coke (thus dispensing also with the need for coke ovens), referred to as Direct Iron Reduction (DRI). In these processes, iron ore is reduced to metallic iron in its solid state, below the melting temperature of iron, by reduction gases composed of a mixture of CO and H_2. The direct-reduced iron is then generally used as a feedstock for EAFs. The main type of technology that has been commercialised is shaft furnace-type reactors, such as those developed by Midrex and HYL/Energiron. In both cases, the shaft furnace uses reformed natural gas to reduce iron ore pellets. This process emits between 30% and 60% less CO_2 than through the BF-BOF route (Cavaliere, 2019; Sarkar et al., 2018). Due to the need for abundant, cheap natural gas, most shaft furnace DRI plants are situated in natural gas-rich countries. In 2019, global DRI production was 108 Mt, compared to 1 281 Mt of pig iron.

Figure 11 Simplified flow diagram and CO_2 emissions of the direct reduction route



Source: JRC

In India, the number one DRI producer worldwide, a large amount of DRI plants are rotary kilns that use coal instead of natural gas. This coal-based process is around three times as CO_2-intensive as natural gas, making coal-based DRI the most CO_2-intensive steelmaking route (Carpenter, 2012).

Shaft furnace DRI processes use iron ore pellets as feedstock, which are typically higher grade (higher iron content, lower gangue levels) than blast furnace pellets. The supply of DRI grade pellets is limited (Midrex, 2018), and other technologies that can allow the use of lower-quality iron ore are also being considered by industry.

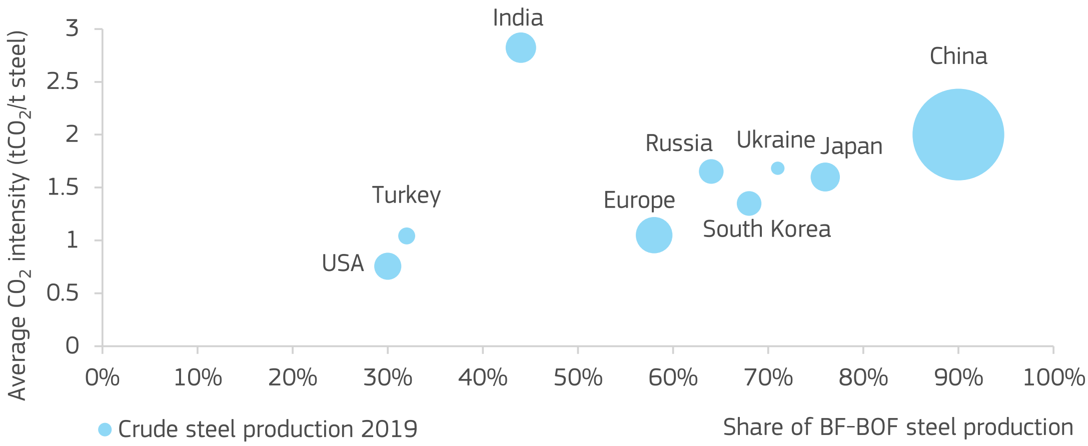
Worth noting also are other upcoming ironmaking technologies, commercially available but deployed at a small scale, which can reduce directly iron ore fines. These processes thereby do not need to agglomerate (by pelletising or sintering) the iron ore. These technologies include two-stage smelting reduction processes (e.g. Finex), where the iron ore is pre-reduced in a fluidised bed, then charged with coal into a melter-gasifier to make hot metal, or two-stage fluidised bed processes which reduce iron ore fines to DRI (e.g. Circored).

3.2.4 CO_2 intensities in the EU and third countries

The CO_2 intensities of steelmaking vary greatly across the globe. The main factor influencing the average CO_2 intensity is the share of steel coming from each production route in every country, i.e. how much steel is made from iron ore via the BF-BOF route versus the share of steel made in EAFs, which primarily use steel scrap. Additionally, the input materials used in each process also affect the average CO_2 intensity. Steelmakers add steel scrap to the BOF to control the reaction temperature, however the amount will vary depending on the availability and price of scrap and the desired characteristics of the final product. Increasing the scrap charge reduces the amount of hot metal (from the blast furnace) needed per final tonne of steel, thus lowering the CO_2 intensity. Similarly, EAFs can also be charged with iron feedstocks in the form of DRI, as well as liquid hot metal or pig iron (from a blast furnace) in addition to scrap, depending again on local availability, economics and desired quality of the crude steel.

Comparing the average CO_2 intensity of steel production (combining all production routes) by country (**Figure 12**), the USA has the lowest CO_2 intensity of the countries shown, followed by Turkey and Europe (EU27, UK and Norway). This is because both countries produce around 70% of their steel via the EAF route. Of the countries with over 50% of BF-BOF steel production, the EU has the lowest CO_2 intensity.

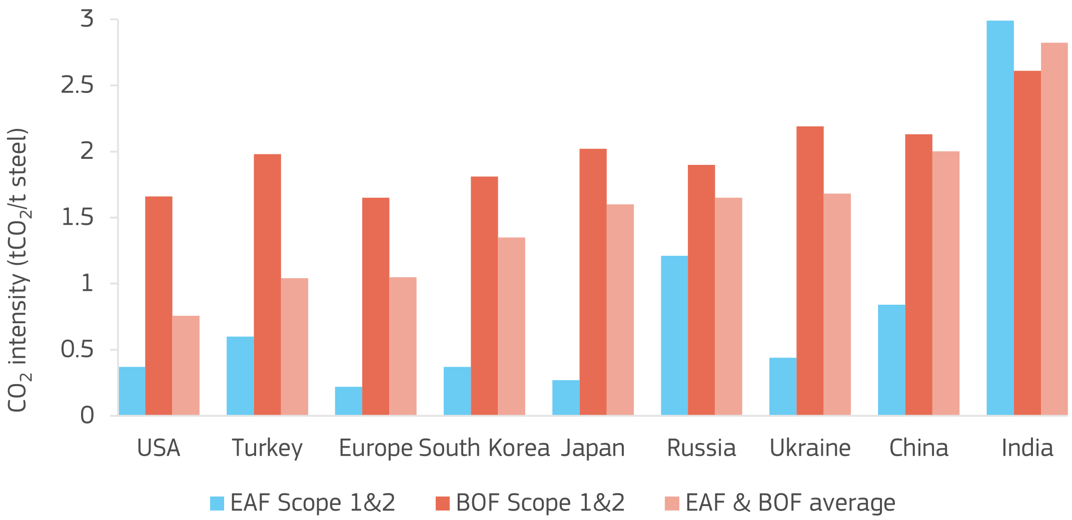
Figure 12 Average CO_2 emission intensity combining all production routes, share of BF-BOF route and total 2019 steel production by country



Source: JRC based on (CRU, 2021) and (World Steel Association, 2020)

Diving deeper into the CO_2 intensities of the different routes in **Figure 13**, of the selected countries, European integrated steel mills have the lowest average CO_2 emission intensities, closely followed by the USA. Blast furnaces in China and India have significantly worse emissions. Even though all blast furnaces rely on coke to operate, the mix of fuels used in the plants can still vary. The fuel mixes used in China and India have some of the highest average CO_2 emission factors, which can explain the high CO_2 intensities of their steel production (A. Hasanbeigi & Springer, 2019). Additionally, the age and efficiency of the steel plants as well as the penetration of energy-efficient technologies (such as coke dry quenching or top gas recovery turbines, which have been adopted in the EU) affect the energy and CO_2 intensity of steel production.

Figure 13 Crude steel emission intensity of BF-BOF, EAF and weighted average



Source: JRC based on (CRU, 2021)

The direct and indirect CO_2 emission of EAF steelmaking presents an even more diverse picture on the global scale. The EU has the lowest CO_2 emission intensity amongst the countries shown, while Russia, China and India have far greater CO_2 emission intensities. For the EU and the USA, the most important factor affecting the CO_2 emissions of EAF mills is the CO_2 intensity of the electricity grid, since the main energy input to the EAF is electricity. However, in other countries, most notably China and India, an additional important factor is the type of metallic feedstocks used to make steel in the EAF. Indeed, while EU EAF mills predominantly use recycled steel scrap, in India and Russia a large amount of DRI is used as feedstock, while in China around

45% of feedstock is pig iron issued from blast furnaces (A. Hasanbeigi & Springer, 2019). DRI in India has a particularly large CO_2 footprint as around 80% of it is made with coal (Ministry of Steel India, 2021), a process that is around three times more CO_2-intensive than DRI made with natural gas (IEA, 2020). In the USA, electric steel mills also use some pig iron and DRI to sweeten the scrap input, allowing them to produce higher quality steel.

3.3 Efficiency and circularity: possible levers towards CO_2 reduction?

3.3.1 Future steel demand and steel in a circular and digital economy

EU steel production saw an unprecedented drop in 2020 of 12% (to 139 Mt) due to the COVID-19 pandemic affecting large steel-using sectors such as the automotive industry particularly strongly. In the short term, steel demand is likely to bounce back somewhat towards pre-crisis levels of 157 Mt in 2019 (Eurofer, 2021). Future EU steel demand is, however, highly uncertain. The industry's growth scenario forecast reaches 200 Mt annual production by 2050 for EU27+UK (Eurofer, 2019). In other external decarbonisation scenarios, a wide range of steel demand is modelled; from 180 Mt in scenarios relying heavily on new technologies (Material Economics, 2019), to 153 Mt (Fleiter et al., 2019) or even 130-140 Mt (IEA, 2020; Material Economics, 2019) in scenarios relying heavily on material efficiency strategies. Considering that EU steel capacity is currently around 213 million tonnes (OECD, 2021), even maintaining relatively constant future steel production would still require a reduction of around 30 Mt of surplus capacity for the steel industry to operate at a sustainable capacity utilisation of 85%.

Those external scenarios modelling a reduction in future steel demand rely on material efficiency and circularity improvements in the use of steel, as well the substitution of steel for other materials. In the automotive sector, substituting steel for cheaper and lighter materials, such as aluminium, plastics and carbon-fibre reinforced polymers, is already an established practice, albeit not driven currently by CO_2 emission considerations. Similarly, lighter materials could benefit the shipping industry, such as aluminium-steel foam or magnesium alloys for ship hulls (Linturi & Kuusi, 2019). Given the lifecycle emissions of those alternative materials, it is not a given that such substitutions are necessarily net-positive in terms of CO_2 emissions. Given the relatively low cost of steel and material properties in terms of strength and durability, a widespread substitution effect is unlikely (IEA, 2020). Another development is the possible return towards the use of wood in the construction industry, replacing steel and concrete. Taking environmental considerations into account, timber is an interesting option, since it can be considered a renewable construction material with, ultimately, net-zero carbon emissions (depending on the end-of-life disposal scenario) (Arup, 2019). Cross-laminated timber, an engineered structural system developed in the 1990s and increasingly used in Europe over the last 20 years, possesses structural and environmental properties that make it an attractive alternative to concrete and steel construction (Espinoza et al., 2016). Several building towers using cross-laminated timber with concrete and steel elements have been built or are under construction, such as the 85-metre Mjøsa Tower in Norway (Industry Europe, 2019) and the 98-metre WoHo tower in Berlin (Bloomberg, 2021). The use of wood to construct wind turbines is also being explored. Vestas and Vattenfall are collaborating with Swedish startup Modvion to deploy wooden wind turbines in the future (Vattenfall, 2020). Despite these efforts, due to the sheer scale at which steel is currently used in the construction industry, these recent developments are unlikely to affect steel demand significantly.

In the future, steel will also play an increasingly important role for the energy transition, as it is a key material for renewable sources like wind and solar. Steel represents about 70%-80% of the total mass of a wind turbine (Moné et al., 2017; World Steel Association, 2012). Overall, existing turbine designs range on average between 107 and 132 tonnes of steel per MW (Carrara et al., 2020). For solar PV, steel is used in the system support structures at an intensity of around 68 tonnes per MW (Carrara et al., 2020). A recent JRC report (Carrara et al., 2020) found that, with average assumptions on demand drivers (technology deployment, plant lifetime, market shares, material intensities) leading to renewable deployment in line with the Commission's 2030 Climate Target Plan Impact Assessment, the demand for steel from wind and solar energy would be around 3.7 Mt/year (wind) and 1.8 Mt/year (solar) by 2030, and by 2050 would reach 7.0 Mt/year (wind) and 3.7 Mt/year (solar). While these are important volumes, as a comparison in 2019, total actual steel consumption in the EU was close to 160 Mt, with the automotive sector alone consuming 28 Mt (Eurofer, 2020). The JRC report notes, however, that there is a wide variability depending on the actual evolution of the abovementioned drivers. For instance, a high demand scenario with more renewable deployment reaches 28 Mt of steel for wind and solar by 2050.

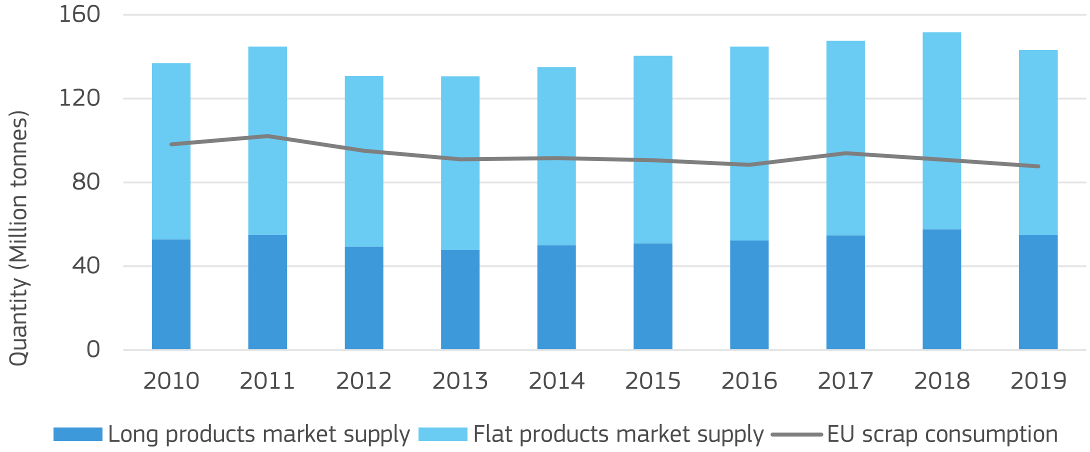
More efficient material use in the design of end-products is another potential lever to reduce future steel demand (IEA, 2020). Current design practices tend to over-dimension structural steel components (Moynihan & Allwood, 2014), leaving some potential to reduce steel use in buildings. Current design (de)construction practices could also be optimised to allow the reuse of some structural components (Bukauskas et al., 2018). In Europe, while recovery of structural steel is around 99%, only about 10% of it is directly re-used instead of recycled into new steel (SteelConstruction.info, 2013). Reducing the demand for steel can further be achieved by extending the lifetime of buildings or transport, and by increasing the intensity of usage through new business models, such as car-sharing or increased public transport.

Digitalisation can also play a potentially important role in reducing final steel demand, by providing tools that can improve yield losses in the manufacturing process and inefficiencies in steel production. Digitalisation can enable new dimensions of data flows between steel producers and customers, optimising yields by pooling demand for final steel shapes at the steel plant, and digital product passports could further enable reuse of structural steel. Beyond improving material efficiency, digitalisation provides a range of opportunities to improve the energy efficiency of steelmaking and increase the quality of finished products; amongst others by optimising process control, limiting unplanned downtime and optimally scheduling planned downtime. While the steel industry is already to a large extent automated, the promise of 'Industry 4.0' is to integrate this digitalisation throughout the entire production chain (and beyond), instead of different parts of the production chain operating in silo (Branca et al., 2020). The European Commission has recognised the importance of digitalisation in the EU industrial strategy, proposing a list of actions to accelerate the green and digital transitions of EU industry (European Commission, 2021a). Industry itself also considers digitalisation as a strategic priority and expects to have a strong positive effect on process efficiency (Fraunhofer, 2018; McKinsey, 2021a). Several digitalisation measures are likely to provide only incremental improvements to the energy and CO_2 efficiency of steel production. The United States Department of Energy, for instance, estimates that data analytics reduce energy intensity by 2% (BloombergNEF, 2021b). It is thus important to note that the potential impact of digitalisation in terms of energy demand and CO_2 emission reduction is difficult to quantify and thus rarely explicitly modelled in long-term decarbonisation scenarios.

3.3.2 Limits to scrap use: quality and availability

Steel made from recycled steel scrap in an electric arc furnace only emits a fraction of the CO_2 emissions associated with primary steel production. Maximising the use of secondary steel thus appears to be an important lever to decarbonise the sector. Currently in the EU, however, only around 40% of steel is made via the EAF route, while 60% is made via the BF-BOF route. Even though some 85% of end-of-life steel is already recycled, significantly increasing the share of secondary steel is currently limited by the quality and quantity of scrap. A lot of steel is used in construction and infrastructure assets with very long lifetimes, which can be considered in-use steel stocks (Pauliuk et al., 2013). As the EU's mature economy will see slower further urbanisation and infrastructure development, the EU steel stock will saturate and increasing amounts of scrap steel will become available. Modelling efforts have shown that by 2050, old scrap supply could come close to, or even exceed, final steel demand (Pauliuk, 2013; Material Economics, 2019). If all scrap were of equal quality, this would nearly fully displace the need for new primary steel production. In reality, however, old scrap is mostly re- or down-cycled into lower quality steel, which cannot be used in applications such as the car industry which mainly need high quality steels. Steel products can broadly be categorised into two types: flat steel products, such as steel sheets used in the automotive sector, and long products, such as beams or rods used for structural applications. End-of-life scrap is often contaminated with tramp elements, of which copper is the most critical. Concentrations over 0.1 wt% of copper leads to surface defects when forming steel into flat products, while long products have a nominal copper tolerance of 0.4 wt% (Daehn et al., 2017). Copper is pervasive in end-of-life scrap, as car and appliances scrapping does not separate the copper wires or motors from steel scrap. Unlike other elements, copper cannot be removed during the steelmaking process. Addressing copper contamination would thus need to occur upstream of the steel plant, by improving the dismantling and sorting of end-of-life products during recycling. Changes in the design of products that reduces the use of copper or facilitates their disassembly can further reduce the need for downstream interventions. Due to these quality constraints, steel made from recycled scrap is currently mostly used in applications that can tolerate lower-quality steel. However, as **Figure 14** shows, the demand for flat products in the EU is far larger than that for long products. Given current recycling practices, a significant amount of steel would thus still need to be made from iron ore in the future.

Figure 14 Scrap, flat and long steel products consumption



Source: JRC based on (Eurofer, 2020)

Drastically increasing the share of scrap input so that EU steel demand is met from recycled steel would require big efforts in increasing the quality of end-of-life scrap, by improving the dismantling and sorting of end-of-life products or designing products with end-of-life dismantling and material recuperation in mind (Daehn et al., 2017). Taking these factors into account, in external decarbonisation scenarios where the potential to increase scrap quality is maximised and overall steel demand is reduced, the share of scrap steel inputs used in EU steelmaking could increase from the current 50% to 60% (IEA, 2020) or even 70% in high recycling scenarios (Fleiter et al., 2019; Material Economics, 2019). An interesting comparison to the EU are the USA, where 70% of steel is made in EAFs, including significant amounts of higher-quality flat steel. Some of the factors explaining how USA steel manufacturers can produce high quality steel in EAF are the deployment of modern mini-mills in the USA with better EAF technology, the use of high-quality prime steel scrap (over recycled shredded scrap) and the addition of metallic raw materials such as pig iron from blast furnaces and direct-reduced iron to “sweeten” the EAF input and dilute impurities (S&P Global Platts, 2019). As has been highlighted in the Commission’s Staff Working Document on steel (European Commission, 2021h), the Commission’s Circular Economy Action Plan (European Commission, 2020e) identifies steel as a priority material and the Commission is developing the Sustainable Products Initiative which will revise and widen the Ecodesign Directive, proposing additional legislative measures to support the recycling and reuse of steel.

4 Decarbonisation options: technologies and costs

While increasing circularity through the use of recycled steel and reducing steel demand are important levers for the decarbonisation of EU steelmaking, virgin steel will continue to be needed in the future. This requires the deployment of new steelmaking technologies to replace the coal-based BF-BOF route.

The steel sector is currently exploring different strategies to reduce CO_2 emissions. In the short term, extensive process modifications and a switch from fossil fuels to low-CO_2 energy sources can enable some limited CO_2 mitigation. Combined with Carbon Capture Utilisation and Storage (CCUS) technologies, deeper emissions cuts can potentially be achieved. Key technologies include:

— Partially replacing coal/coke in the blast furnace with biomass or hydrogen.

— Using a new type of coal-based smelting reactor (the HIsarna process) which replaces several energy-intensive steelmaking processing steps, and can be combined with CCUS.

— Capturing and recycling the emitted CO_2 (CCU) from the current steelmaking route in the production of basic chemicals and synthetic fuels.

A different pathway, which seems to be emerging as the principal strategy for most European steelmakers, is to fully replace existing processes with breakthrough technologies that rely on hydrogen or electricity to reduce iron ore, allowing the production of steel with little-to-no CO_2 emissions. Deploying these technologies would require replacing existing steel processes with new steel plants. Key technologies include:

— The direct reduction of iron ore to iron using hydrogen (H-DRI), which completely avoids the use of fossil fuels. This process could already be deployed by 2030, but relies on low-CO_2 hydrogen and electricity made available in large quantities and at low cost. Several steelmakers are exploring the use of natural gas as a transition fuel until enough hydrogen is available at an acceptable cost.

— Electrolytic processes, whereby iron ore is reduced solely through electricity, at high temperature (molten oxide electrolysis) or low temperature (electrowinning). While these technologies are potential game changers, they are not expected to be deployed before 2040-2050.

— The smelting reduction of iron ore to steel with fossil free inputs, such as using hydrogen plasma in a single reactor. This technology is highly integrated and potentially very efficient, however it is also at an early stage of development and not expected to available before 2040-2050.

The following section will focus on the main decarbonisation technologies that are being pursued by EU steelmakers: Hydrogen DRI, CCUS and iron ore electrolysis.

4.1 Hydrogen DRI

The direct reduction of iron ore using natural gas or coal is already a well-established technology, with 111 million tonnes of DRI produced globally in 2019 (World Steel Association, 2019). DRI (sponge iron) is then processed to steel in an EAF. Various types of DRI technology are currently deployed. The reducing gases used in the DRI process are a mixture of hydrogen and carbon monoxide. The process gas of a typical Midrex plant using natural gas has 1.5 ratio of hydrogen to carbon monoxide (Midrex, 2017). Broadly speaking, there are two reactions occurring in parallel that reduce iron ore to iron in a natural gas based DRI plant:

1) $Fe_2O_3 + 3H_2 \rightarrow 2Fe$ and $3H_2O$
2) $Fe_2O_3 + 3CO \rightarrow 2Fe$ and $3CO_2$

As these reactions show, the reduction reaction with hydrogen produces solely water (H_2O) as a by-product. In fact, using low-CO_2 hydrogen instead of natural gas would nearly entirely eliminate all CO_2 emissions from steelmaking (the direct-reduced iron is fed into an EAF, where it is smelted into steel). However, even if low-CO_2 hydrogen and electricity is used, there are still some small amounts of remaining CO_2 emissions associated with various processes of steelmaking. Since steel is an alloy of iron and carbon (as well as other alloying materials), and H-DRI produces iron in a carbon-free environment, small amounts of carbon need to be added to the EAF to make steel (Vogl et al., 2018). Additionally, in the EAF process, carbon plays an important role as a slag foaming agent. The inevitable consumption of the graphite electrodes of the EAF further contribute to small amounts of CO_2 release (Echterhof, 2021). Lime is another important input into the EAF as a fluxing agent to remove impurities (such as phosphorus, sulphur and silica). Some 40% of the lime produced in the EU is currently used in the iron and steel industry (note that lime is used in many processes, including sintering and hot metal desulphurisation, as well as being a fluxing agent in the BOF and EAF)

(Manocha & Ponchon, 2018). Lime is made from the calcination of limestone, a process that requires very high temperatures and which releases additional CO_2 due to the decomposition of limestone. Reducing CO_2 emissions in lime production would require decarbonisation measures similar to those in the cement industry, such as carbon capture and storage. Finally, the processes upstream of steelmaking, namely the mining of iron ore and its preparation into pellets, currently also have associated CO_2 emissions. If the DRI and EAF process fully relies on zero-CO_2 hydrogen and renewable electricity, those remaining emissions are in the order of 30-70 kg CO_2 per tonne of steel, compared to 1.8 tonne of CO_2 per tonne of steel in the BF-BOF route (ESTEP, 2021b; Vogl et al., 2018).

If the hydrogen used in the DRI is produced in a carbon-free manner, and the electricity in the EAF is also decarbonised, the emissions of the H-DRI+EAF route could be around 98% lower than the conventional BF-BOF route (Vogl et al., 2018). The hydrogen demand for 100% hydrogen use in the DRI process is estimated in academic studies to be around 50-60 kg of hydrogen per tonne of produced steel (Bhaskar et al., 2020; Fischedick et al., 2014; Material Economics, 2019; Rechberger et al., 2020; Vogl et al., 2018). If all current primary production of steel in the EU (92 Mt in 2019) were to be replaced by a 100% H-DRI route, this would represent some 5.5 Mt of annual hydrogen demand. As a comparison, the Commission's Hydrogen Strategy (European Commission, 2020b) foresees the production of up to 10 Mt annually by 2030 and the chemical industry currently already consumes 9 Mt of hydrogen annually, made from fossil fuels, in refineries and fertiliser production.

External decarbonisation studies show a wide range of future hydrogen demand in the steel sector, due to varying assumptions regarding, amongst others, future steel demand, the future share of secondary steel production, the share of scrap used in the process and diffusion of the H-DRI process. For the EU27+UK[3], some indicative figures include 3.7 Mt of hydrogen[4] by 2050 if the recycling route represents 50% of production and a 70/30 hydrogen/natural gas use (Agora Energiewende and AFRY Management Consulting, 2021) or 3.9 Mt of hydrogen by 2050 in a scenario where 36% of all steel is made with 100% H-DRI (Material Economics, 2019).

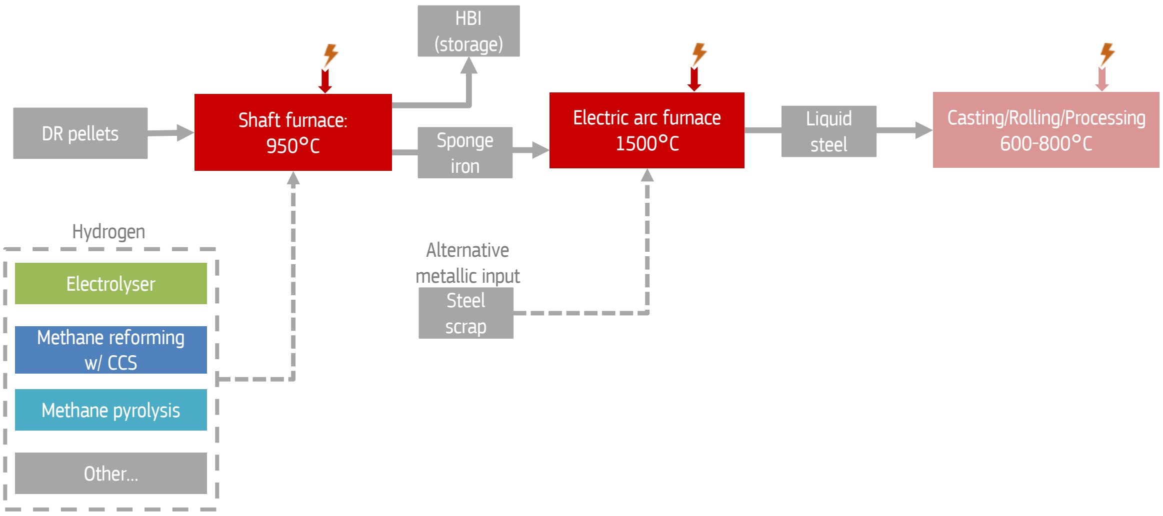
If all the hydrogen is to be produced via water electrolysis using renewable electricity (renewable hydrogen), this hydrogen demand would also represent a substantial additional demand for renewable electricity. The H-DRI+EAF route using renewable hydrogen requires between 3.5 and 3.95 MWh of electricity per tonne of steel, depending partly on electrolyser efficiencies and heat integration options (Bhaskar et al., 2020; Krüger et al., 2020; Vogl et al., 2018). The hydrogen electrolyser represents 75% of that electricity demand. In an extreme scenario, where all 92 Mt of current primary steel production were to be produced with renewable hydrogen in the H-DRI route, over 300 TWh of renewable electricity per year would be required. Taking into account the electricity demand for the additional 65 Mt of secondary steel being produced in the EU, the steel sector could require over 350 TWh of electricity per year. This is a substantial amount of renewable electricity, representing over 35% of the EU's total renewable electricity production in 2019 (Eurostat, 2021b). This can be considered a high demand scenario for hydrogen use in the steel industry, since it is uncertain whether future demand for primary steel will remain at current levels. As with the hydrogen demand projections, external studies find wide ranges of future renewable electricity demand. For instance, the total electricity demand to decarbonise the sector in EU27+UK[3] could be between 214 and 355 TWh of electricity by 2050, depending on circularity measures and shares of H-DRI (Material Economics, 2019), or up to 400 TWh as estimated by the steel industry, of which 60% is needed for the production of hydrogen (Eurofer, 2019).

[3] Original data source refers to the 28 Member States of the EU in 2019.

[4] Calculated from 123 TWh LHV H_2

The H-DRI+EAF steelmaking process itself is technically 'hydrogen colour-blind': that is to say that hydrogen can be used in the process regardless of its source.

Figure 15 Simplified flow diagram of the hydrogen DRI process



Source: JRC

Besides renewable hydrogen from renewable electricity, other low-CO_2 hydrogen sources are being considered to decarbonise steel production. Besides water electrolysis, the main low-CO_2 hydrogen production route being explored is the coupling of CCS technologies with hydrogen made from natural gas, using conventional steam methane reforming or auto thermal reforming. Both H-DRI and hydrogen infrastructure are technically agnostic to the colour of hydrogen. The priority for the EU, as stated in the Commission's Hydrogen Strategy, is to develop and enable renewable hydrogen, while the use of other forms of low-carbon hydrogen can be considered in a transition phase (European Commission, 2020b). At the time of writing, one project in the EU linked to low-CO_2 steelmaking is exploring the use of fossil-based hydrogen with carbon capture (H2morrow, Germany). It is important to note, however, that production and transport infrastructure supporting the development of low carbon hydrogen production does not necessarily benefit the deployment of renewable hydrogen and could lead to stranded assets. Additionally, the use of fossil-based hydrogen with carbon capture requires the development of extensive infrastructure to transport and store the CO_2 emitted during production. Finally, it is important to acknowledge the lifecycle greenhouse gas emissions of fossil-based hydrogen. Over 1 Mt of fugitive or vented methane were emitted in the natural gas supply chain in Europe in 2020, according to estimates by the International Energy Agency (IEA) (IEA, 2021). The full CO_{2e}-footprint of fossil-based hydrogen with carbon capture is one of the crucial aspects to take into account when considering its use to decarbonise the sector. A recent study using current global methane leakage rates and a range of current CO_2 capture rates (80-90%) estimates that fossil-based hydrogen with carbon capture would emit only slightly lower levels of greenhouse gases than unabated hydrogen from natural gas (Howarth & Jacobson, 2021). Another recent study found that if state-of-the-art methane reforming allowing high CO_2 capture rates (>90%) is combined with very low natural gas leakage rates, fossil-based hydrogen with carbon capture could technically come close to renewable hydrogen in terms of CO_2 emissions (Bauer et al., 2022).

The production of hydrogen from methane pyrolysis is also currently being discussed in the context of steelmaking. Thermally decomposing methane (the main component of natural gas) at very high temperatures directly splits it into hydrogen and solid carbon. A techno-economic analysis of pyrolytic and renewable hydrogen DRI steel production found similar levels of emissions and levelised costs of production (Bhaskar et al., 2021). At the time of writing, one pilot project in the EU has been announced that aims to use pyrolytic hydrogen for steelmaking. ArcelorMittal plans to build a pyrolysis plant on the premises of its existing site in Eisenhüttenstadt, Germany, to generate additional hydrogen needed by a new DRI-EAF to be set up by 2026 (ArcelorMittal, 2021b).

A number of H-DRI projects that have been announced in the EU are planning to use natural gas as a transition fuel and to gradually increase the share of hydrogen as it becomes economically available. This would require new steel plants to permit both the use of natural gas and hydrogen, as has been highlighted in the German government's *Steel Action Plan* (BMWi, 2020). Producing steel with natural gas in the DRI-EAF route already provides a significant CO_2 reduction versus the BF-BOF route. If renewable electricity is used in the process, a reduction in CO_2 intensity (tCO_2/t steel) of 67% can be achieved versus the integrated route (Müller et al., 2021), and a 55% reduction with an electricity grid CO_2 intensity of 300 gCO_{2e}/kWh (Duarte et al., 2008) (corresponding to Germany's grid intensity in 2020). Beyond the two possibilities of running the DRI process either entirely with natural gas or with hydrogen, the partial substitution of natural gas with hydrogen and flexible operation of a plant with varying mixtures of hydrogen and natural gas offer another interesting perspective. This would allow the use of natural gas as a bridge technology, as well as the possibility of providing demand-side management services to the electricity grid by allowing more flexible operation of the hydrogen electrolyser (Müller et al., 2021). For DRI plants to operate with varying input gas types, some process adjustments are required, as opposed to a plant using solely reformed natural gas. This is partly due to the thermodynamics of the process, since the reaction with carbon monoxide is exothermic, while the reduction with hydrogen is endothermic. The EnergironZR process by HYL Energiron has been claimed to be able to operate with varying levels of hydrogen in the reducing gas (Lösch et al., 2020).

At the time of writing, 18 projects (**Table 1**) initiated by almost all EU steelmakers, as well as some new entrants to the sector, are developing H-DRI across the EU. These projects are at varying levels of development, from early stage announcements to the operation of pilot plants. Currently the most advanced project developing the use of 100% renewable hydrogen-based DRI is the Hybrit partnership between the steelmaker SSAB, the iron ore miner LKAB and the utility Vattenfall in Sweden, which produced the first batch of fossil-free steel from its pilot plant in 2021 (SSAB, 2021a). The project is aiming to decarbonise the full steel value chain, including iron ore mining, and is also building a pilot hydrogen storage plant.

As mentioned in section 3.2.3, depending on the future deployment of DRI plants worldwide, there could be a potential lack of supply of DRI-grade pellets to satisfy future demand (McKinsey, 2021b), which will require, on the one hand, additional investments into iron ore beneficiating plants, and on the other the development of technologies to make DRI with lower-quality ore. Worth highlighting here are two projects developing hydrogen-reduction technologies that can use iron ore fines directly. Primetals/voestalpine is investing in Hyfor technology, based on its Finex fluidised-bed/smelting-reduction process, at a pilot plant in Austria (Primetals, 2021). The Metso Outotec Circored fluidised bed technology is also 100% hydrogen-based and avoids the need for iron ore pellets. It has already been demonstrated at industrial-scale through a demonstration plant built in 1999 in Trinidad (Outote, 2021).

Another alternative being explored to the hydrogen DRI-EAF route is the combination of DRI technology with a submerged arc furnace. This would allow the DRI to be smelted before being made into steel in a basic oxygen furnace. This route would allow the steelmakers to conserve part of their existing assets, the basic oxygen furnace, which allows different metallurgical processes from those in an EAF. Both ArcelorMittal at its site in Dunkirk (ArcelorMittal, 2021a), and Thyssenkrupp at its Duisburg plant (thyssenkrupp, 2020) have announced plans to integrate a hydrogen-based DRI plant with a smelting furnace to produce low CO_2 steel.

Table 1 Selected hydrogen based steel decarbonisation projects in the EU (as of September 2021)

Country	Project (site)	Company	Reductant/fuel	Technology	Technology description	Timeline	Status
Austria	HYFOR (Donawitz)	voestalpine	H2 (electrolysis)	H-DRI	H-DRI using fine ores	2021: Pilot plant operational	Pilot
Austria	H2Future (Linz)	voestalpine	H2 (electrolysis)	Electrolyser	6 MW H2 electrolyser for steel	2020: PEM 6MW electrolysis plant operational	Pilot
Belgium	(Ghent)	ArcelorMittal	NG, then H2	H-DRI	2.5 Mt DRI plant and two EAFs	2030: Operational 2.3 Mt DRI	Letter of intent signed
France	(Dunkirk)	ArcelorMittal	NG then H2	H-DRI	Initially NG, then H-DRI with submerged arc furnace	2021: MoU signed with Air Liquide	MoU signed
France	(Dunkirk)	Liberty Steel	NG then H2	H-DRI	Initially NG, then H-DRI	2021: MoU signed	MoU signed
Germany	H2Steel (Duisburg)	Thyssenkrupp	H2 (electrolysis)	H-DRI	DRI with submerged arc furnace + BOF	2024: Commission first large-scale DRI 2025: Produce 0.4 Mt green steel with H2 2030: Produce 3 Mt of green steel	Announcement
Germany	H2morrow (Duisburg)	Thyssenkrupp	Fossil H2 + CCS	Fossil H2 +CCS	Supply of fossil H2 + CCS (offshore CCS storage)	2021: Feasibility study completed	Feasibility study
Germany	H2Hamburg	ArcelorMittal	Grey H2 then H2 (electrolysis)	H-DRI	Grey H_2, then renewable H2	2023: Produce 0.1 Mt (grey) H-DRI	Plant design commissioned
Germany	HyBit (Bremen)	ArcelorMittal	NG, then H2 (electrolysis)	Electrolyser + H-DRI	24 MW H2 electrolyser	2026: commercial DRI	MoU signed
Germany	(Eisenhüttenstadt)	ArcelorMittal	NG then H2 (pyrolysis)	H2 pyrolysis + H-DRI	H2 from pyrolysis	2026: pilot innovative DRI	Announcement
Germany	(Wilhelmshaven)	Uniper and Salzgittter	H2 (electrolysis)	Electrolyser + H-DRI	2 Mt DRI plant with upstream electrolyser.	N/A	Feasibility study
Germany	SALCOS (Salzgitter)	Salzgitter	NG then H2	Wind + electrolyser + H-DRI	Wind park, electrolyser and H-DRI	2020: Commissioned 30 MW wind park and electrolyser 2022: DRI plant	Construction started
Netherlands	H2ermes (IJmuiden)	Tata Steel	NG, then H2 (electrolysis)	Electrolyser + H-DRI	H2 production for H-DRI	2021: Final investment decision 2025: Start H2 production	Feasibility study
Romania	(Galati)	Liberty Steel	NG then H2	H-DRI	NG then H-DRI	2023-2025: commercial with NG (2.5 Mt)	MoU signed
Spain	(Gijon)	ArcelorMittal	NG, then H2 (electrolysis)	H-DRI	2.3 Mt DRI plant and 1.1 Mt EAF	2025: Operational 2.3 Mt H-DRI	MoU signed
Sweden	Hybrit (Luleå)	SSAB	H2 (electrolysis)	Electrolyser + H-DRI	Decarbonisation of full steelmaking value chain	2021: pilot plant operational 2026: commercial demonstration plant	Pilot plant
Sweden	LKAB (Kiruna)	LKAB	H2 (electrolysis)	Electrolyser + H-DRI	Ore miner shift to H-DR	2029: DRI plant in Malmberget	Announcement
Sweden	H2green Steel (Svartbyn)	Northvolt team	H2 (electrolysis)	Electrolyser + H-DRI	Greenfield plant	Before 2030: 5 Mt capacity	Announcement

Source: JRC based on company announcements and (Vogl, Sanchez, et al., 2021)

4.2 CCS & CCU

Carbon capture and storage (CCS) technologies have long been considered highly relevant to the decarbonisation of the energy-intensive industries such as iron and steelmaking (Fischedick et al., 2014). The main principle is that CO_2 emissions can be captured at the production site, transported and then stored in geological formations, for instance in depleted oil and gas fields in the North Sea. When the EU's Ultra-Low CO_2 Steelmaking (ULCOS) research programme, a consortium of 48 European companies and organisations from 15 European countries, shortlisted a small number of breakthrough technologies with the potential to reduce steel's CO_2 intensity by at least 50% in 2010, three out of the four breakthrough technologies selected at the time relied on CCS to achieve deep CO_2 reductions (Abdul Quader et al., 2016).

As an alternative to storing CO_2 underground, another possible pathway is to use the captured CO_2 as a raw material, for instance in the production of chemicals. This group of technologies are referred to as carbon capture and utilisation (CCU). The European steel industry itself has identified 'Smart Carbon Usage', encompassing CCS and CCU technologies, as an essential pathway towards CO_2 neutrality in its 2019 roadmap (Eurofer, 2019).

In principle, CCS and CCU refer to a range of possible technologies that in the first instance aim to capture CO_2. These technologies could be retrofitted to existing integrated steelmaking processes or applied to new steelmaking processes. At the time of writing, three EU steelmakers are investigating CCS and CCU projects at pilot or demonstration level.

One of the main challenges in applying CO_2 capture technology as a retrofit to the current BF-BOF steelmaking route is the number of CO_2 emission sources in an integrated steel mill. Complicating the matter, waste gases are recirculated within the plant, meaning that CO_2 is produced in one place but emitted in another. For instance, the most significant emissions of CO_2 come from the onsite power plant which consumes the waste gases coming from the blast furnace, and depending on the configuration of the plant, also from the coke oven and basic oxygen furnace. However, the biggest share of CO_2 actually originates from the blast furnace, where large quantities of carbon in the form of coke and coal are processed as a reductant and a fuel, both of which result in the formation of CO_2 in the resulting blast furnace gas. Of the three waste gases produced in a steel plant (blast furnace, coke oven and basic oxygen furnace gases), the blast furnace gas has the highest CO_2 content and is emitted in the biggest volume, which is why most projects aiming to retrofit CCS and CCU technologies focus on applying them to the blast furnace (Chisalita et al., 2019), or aim to capture the flue gas streams from the power plant and blast furnace hot stoves (Arasto et al., 2013).

Several process modelling studies explore the potential of applying different carbon capture technologies to a steel mill, a selection of which are shown in **Table 2** below. The CO_2 reductions achieved in these models vary depending on the technologies and inputs to the models. In these studies, while CCS technologies can lead to substantial emission reductions, these values are well below the >90% emission reduction theoretically achievable by other breakthrough technologies. Capturing larger amounts of CO_2 emissions would be increasingly technically and economically challenging, due to the many smaller CO_2 sources at a steelmaking site (Arasto et al., 2013). While CO_2 capture rates close to 100% have been shown in theory to be economically feasible for concentrated gas streams (Brandl et al., 2021), in practice the mean capture efficiencies over the long term are likely to be lower.

Table 2 Iron and steelmaking with selected CO_2 capture technologies

Type of CO_2 capture technology	CO_2 reduction vs BF-BOF	Source
TGR-BF+post-combustion CCS	47%	(Hooey et al., 2013)
Post combustion (MEA)	50%-75% 48% - 58% 50%-60%	(Arasto et al., 2013) (Chisalita et al., 2019) (IEAGHG, 2013)
Calcium looping	65%-76% 49%-84%	(Chisalita et al., 2019) (Tian et al., 2018)
STEPWISE (SEWGS)	40%	(Petrescu et al., 2019)

Source : JRC (based on references in table)

ArcelorMittal is pursuing several CCUS options by building pilot plants at its Dunkirk and Ghent steel plants. The IGAR project in Dunkirk builds on the 'top gas recycling blast furnace technology' (TGR-BF), initially developed within the ULCOS consortium, by capturing waste gases from the blast furnace and reforming it to syngas (carbon monoxide and hydrogen), which can be injected back into the blast furnace as reducing gases. The reported CO_2 savings are 0.1-0.3 tCO_2/t steel (IETS, 2020), and ArcelorMittal expects this technology to cut CO_2 emissions by up to 20% (ArcelorMittal, 2021c).

Also at the Dunkirk site, ArcelorMittal is developing the 3D pilot project that will use a new amine-based technology to capture 0.5 t of CO_2 per hour from the blast furnace by 2030 (ArcelorMittal, 2021c). The company aims to build a full-scale CCS plant at Dunkirk that would capture 1 Mt of CO_2 per year by 2025 (IFP Energies nouvelles, 2020). To put this in context, this represents 8% of the estimated 12 Mt of CO_2 emitted by the Dunkirk plant in 2019. The scale-up of this technology will depend on the deployment of CO_2 transport and storage infrastructure. ArcelorMittal is exploring the possibility of linking this project with the Norwegian Northern Lights and the Port of Rotterdam (Porthos) CCS infrastructure networks.

Instead of transporting and storing the captured CO_2 (CCS), current efforts in the EU industry are focussing mostly on pilot projects that capture the CO_2 from existing steel plants and use it as a raw material to produce base materials for the chemical industry (CCU).

ThyssenKrupp's Carbon2Chem pilot project is already synthesising methanol from blast furnace and basic oxygen furnace gas, and aims also to produce ammonia, using the nitrogen by-product from waste separation (De Ras et al., 2019). The production of both methanol and ammonia requires the reaction of CO_2 and CO with hydrogen, which ThyssenKrupp aims to produce by water electrolysis. As with the H-DRI technology route, the renewable hydrogen demand would require substantial amounts of renewable electricity for water electrolysis. According to the Carbon2Chem consortium, this process could reduce the CO_2 intensity of steel production to 0.86 tCO_2/t steel, or some 50% lower than the current BF-BOF route (Agora Energiewende and Wuppertal Institute, 2021). ArcelorMittal has also explored this approach in the H2020-funded Carbon4PUR project (completed in March 2021), a broad consortium led by polymer and polyurethane manufacturers to turn industrial waste gases into intermediates for polyurethane plastics (Carbon4PUR, 2021). Another CCU route is being explored by ArcelorMittal at their Ghent steel mill in the H2020-funded Steelanol project. Using technology developed by the company LanzaTech, ethanol is produced via gas fermentation by reacting the captured CO and hydrogen from the flue gas in the presence of microorganisms. The demonstration plant in Ghent aims to produce 80 million litres of bioethanol annually from 2022 (ArcelorMittal, 2020a). A second such plant is currently being planned for ArcelorMittal's Fos-sur-Mer plant in France. The ethanol obtained from this process is to be sold as a fuel-grade gasoline blending component or chemical intermediate. To assess the full CO_2 reduction benefit of this technology, a full life cycle analysis (LCA) would need to account for the gasoline or chemicals displaced by the products of the steel mill gas. Looking solely at the steel mill, this technology would only achieve a minor CO_2 reduction, as it utilises only a small proportion (around 15%) of the blast furnace off-gas. ArcelorMittal calls the combination of the CCUS technologies described above (as well as the Torero project that converts wood waste to bio-coal for use in blast furnaces), its 'Smart Carbon' route. The company expects this route to contribute to their short term 2030 emission targets, and to deploy hydrogen-based technologies once these become competitive (ArcelorMittal, 2021c).

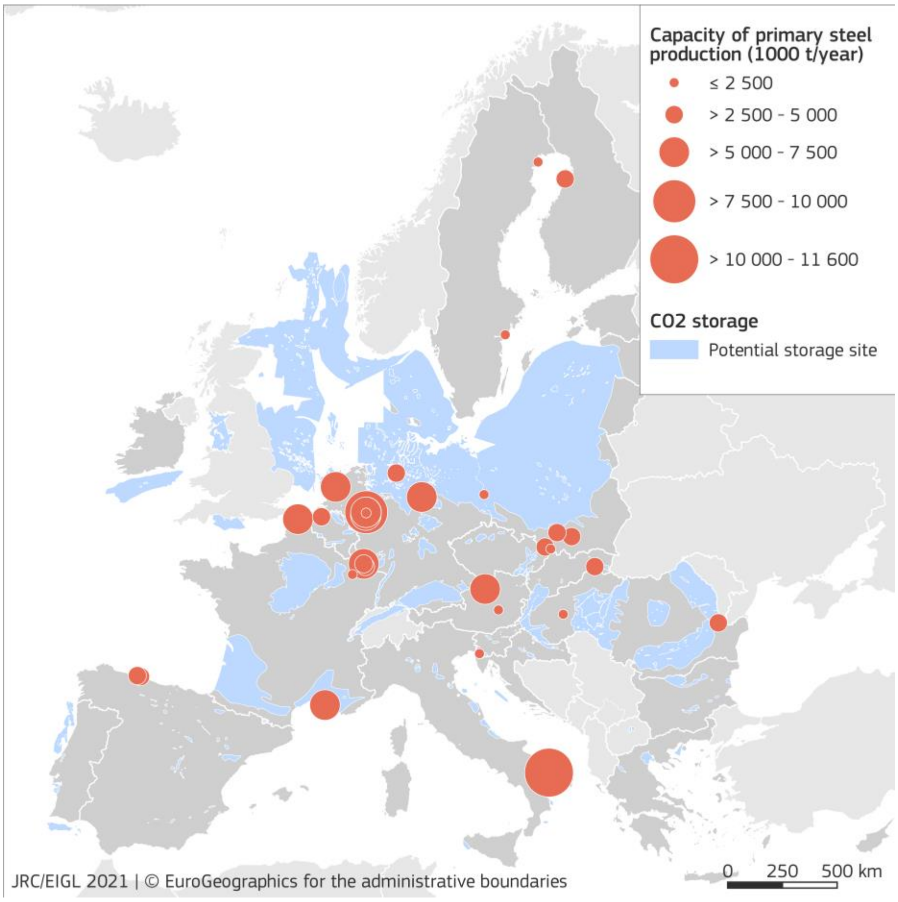
As currently developed, CCU technologies cannot reach full CO_2 emission reduction for two reasons. Firstly, these technologies only capture a small part of the total emissions of a steel mill. Secondly, the captured CO_2 is released during its utilisation, for instance as a fuel or at the end-of-life of the chemical. To be truly low-CO_2, these products would need to form part of a fully closed carbon cycle. ArcelorMittal describe the prospect of 'circular carbon', where plastic waste can be used as an energy source in the steelmaking process, which then captures waste gases to produce new plastic (ArcelorMittal, 2021c).

The steel industry is also investigating alternative steel production technologies to improve the process efficiencies of steelmaking, which can be coupled more efficiently with CCUS processes to achieve deep emissions reductions, such as the HIsarna process being developed by Tata Steel. This technology also has its origins in the EU's ULCOS project, where it was identified as a promising alternative to the blast furnace. The HIsarna process uses a new type of cyclone furnace where powdered iron ore is directly reacted with pulverised coal to make pig iron. This process eliminates the need for coke ovens, sinter and pellet plants, significantly reducing the raw material and energy demand of the process (Tata Steel, 2020b). The H2020-funded LoCO2Fe HIsarna pilot project showed that 50% CO_2 reduction compared to the integrated route is possible by using a substantial amount of steel scrap and replacing part of the coal with biomass. Combined with carbon capture technology, the project estimates that CO_2 emission reductions of 80% are possible (LoCO2Fe, 2021). CCUS could be combined more readily with the HIsarna process as the CO_2 purity of the flue gas is much higher (~95%) and there are fewer emission point sources than in the BF-BOF process (Keys et al., 2019). Tata Steel has been running a pilot plant with a capacity of 0.06 Mt/year at their steel plant site in IJmuiden, Netherlands, since 2010 (as a comparison, Tata Steel's IJmuiden blast furnaces have a capacity of

7.5 Mt/year). To scale up the technology, however, Tata Steel is currently considering building a larger demonstration plant in India and it is not clear whether this technology will be deployed in the EU. Tata Steel Europe was until recently considering using CCUS technologies to reduce the emissions of the IJmuiden plant by 40% by 2030 (Tata Steel, 2020a). To do so, the steelmaker was investigating CO_2 storage options with the Port of Amsterdam (Athos) CO_2 infrastructure partnership, to store CO_2 in the North Sea. Tata Steel Europe has, however, recently announced that the company plans to pursue the hydrogen DRI route to decarbonise the IJmuiden plant (Tata Steel, 2021). This throws the future deployment of HIsarna or other CCUS technologies by Tata Steel in the EU into doubt.

The characterisation of potential CO_2 storage is an important perquisite for the large scale deployment of CCS in Europe. In support of this, the European Commission funded the CO2StoP project (CO_2 Storage Potential in Europe), which made a first assessment of the European CO_2 storage capacity, both onshore and offshore[5]. Mapping the EU's BF-BOF steel plants over potential geological CO_2 storage sites in **Figure 16** shows that 65% of the production capacity is less than 65 km away from a suitable geological formation, and 18% of the capacity (in five steel mills) is located above a possible CO_2 site. Only 12% of the capacity (in four steel mills) is located farther than 100 km from a potential CO_2 storage site. The CO_2 infrastructure is so far non-existent, but two CCS infrastructure projects, Porthos and Northern Lights, are aiming to develop CCS infrastructure to store CO_2 in the North Sea. According to the project owners, the Dutch project Porthos is expected to be operational by 2024 (Porthos, 2021), with a storage capacity of 2.5 Mt of CO_2/year. Project Athos, which was also looking into building CO_2 infrastructure from the Netherlands to the North Sea, has ended after Tata Steel announced its plan to use the DRI technology at IJmuiden (Gasunie, 2021). The Norwegian government is backing Northern Lights, a joint project between Equinor, Shell and Total, which is expected to be completed by mid-2024 with a CO_2 transport and storage capacity of 1.5 Mt per year (Northern Lights, 2021).

Figure 16 Primary steel production and CO_2 storage sites in the EU



Source: JRC/Energy and Industry Geography Lab based on (Steel Institute VDEh, 2019) and CO2StoP[5]

[5] Available at: https://setis.ec.europa.eu/european-co2-storage-database_en

There is also the possibility of applying CCS technologies to natural gas-fuelled DRI plants. While no European steelmakers have announced that they are investigating this option at the time of writing, a DRI steelmaking facility operated by Emirates Steel in the United Arab Emirates has been fitted with carbon capture technology and has been using the CO_2 for enhanced oil recovery (EOR) since 2016. Actual CO_2 capture rates have not been reported, however the planned CO_2 capture rate is 0.8 Mt/year from the DRI plant, which is then transported through a 43 km pipeline for injection into an oil well (Abu Dhabi Carbon Capture Company, 2017). Based on the planned capture rate, and estimating emissions of 3 Mt CO_2/y, given the steel capacity of the plant, this would mean that currently only about 25% of the total CO_2 emissions are captured. While coupling CCS capture with EOR is a mature process deployed in the oil and gas sector, generating revenue for CCS projects, mainly in continental USA, this is not an option for Europe.

The development of CCS projects has historically faced several barriers at national level, including long, unclear permitting processes and a lack of public acceptance. Project experience in Europe has shown that public support is essential. For example, one of the reasons for the cancellation of the Jänschwalde project, which aimed to retrofit CO_2 capture with onshore storage at a power plant in Germany, was public opposition (Kapetaki et al., 2017). For many years the use of CCUS technologies in Germany was not considered, but there are signs that the debate has been revived, as the Government's Climate Action Programme 2030 supports the use of CCUS technologies in primary industries (German Federal Government, 2020). Other barriers to CCS project development are the large up-front capital costs as well as substantial operational expenditure and the high cost of securing the full deployment of this technology. Three out of seven projects selected by the Commission for support in the 2021 Innovation Fund call deploy CCS-technology, which can be expected partly to address this barrier (European Commission, 2021d), however none of these projects are in the iron and steel sector.

While CCUS technologies have in the past been identified as one of the key possible pathways to decarbonise the sector, including in the EU's own ULCOS steel decarbonisation research programme (Abdul Quader et al., 2016) and in external modelling studies (IEA, 2020; Material Economics, 2019), recent announcements and developments by major EU steelmakers seem to indicate that CCUS technologies might play a smaller role compared to hydrogen-based technologies in decarbonising the sector by 2050.

Table 3 Selected CCU- and CCS-based steel decarbonisation projects in the EU (as of September 2021)

Country	Project (site)	Corporate	Technology type	Technology description	Timeline	Development level
Belgium	C4U	Multiple	CCS/U	Advancing two emerging carbon capture technologies (DISPLACE and CASOH) at TRL7. In combination, they aim to capture 90% of the total emission from the steel plant.	Project: 2020-2024.	Demonstration.
Belgium	Carbalyst/Steelanol (Ghent, Fos-sur-Mer)	ArcelorMittal	Biomass + CCU	Capture flue gas and ferment to ethanol. Capture around 15% of available flue gas.	2021: Demonstration plant built. Additional plant in Fos-sur-Mer planned.	Demonstration.
France	3D/DMX (Dunkirk)	ArcelorMittal	CCS	Capture 0.5t CO_2 an hour from steelmaking by 2021. Integrate project with Northern Lights and Porthos CCS cluster projects.	2021-2023: Demonstration plant 2026-2030: Full-scale CCS plant (1 Mt CO_2/y)	Demonstration
France	IGAR (Dunkirk)	ArcelorMittal	CCU	Capture CO_2 and waste H_2 from BF, convert to syngas (dry reforming with plasma torch) and reinject into BF.	Reduce emissions by up to 20%.	Pilot
Germany	Carbon2Chem	Thyssenkrupp	CCU	Produce ammonia and methanol from steel mill gases. Potential to make 20 Mt of annual CO_2 emissions usable.	2025: Industrial scale plant	Pilot
Netherlands	Initiate (former FreSME/Stepwise)	Multiple	CCU	Demonstrate at TRL 7 the generation of urea from steel residual gases.	2025: Demonstrate technology	Pilot/Demonstration.
Germany	Carbon4PUR	Multiple	CCU	Collaboration between steel and chemical industry to use carbon in flue gas as polyurethane building block.	Project: 2017-2021	Pilot
Netherlands	HIsarna (IJmuiden)	Tata Steel	HIsarna smelting + CCS	New smelting technology can reduce CO_2 emissions by 20% vs BF-BOF. Combined with CCS, emissions can be reduced by up to 80%	2011: Pilot plant in IJmuiden	Pilot
Sweden	FreSME/Stepwise	Multiple	CCU	Demonstrating at TRL 6 sorption-enhanced water-gas shift technology to capture CO_2 from blast furnace gas to produce methanol used as marine fuel.	Stepwise: 2015-2019 FreSME: 2017-2021	Pilot/Demonstration.

Source: JRC (based on company announcements)

4.3 Iron ore electrolysis

A promising alternative technology is being developed that uses only electricity to reduce iron ore to iron. It's based on the principle of electrolysis, whereby an electric current is passed through iron ore in an electrolyte, leading to positively charged iron ore ions migrating to the negatively charged cathode to be reduced to iron. Negatively charged oxygen ions move to the anode and are released from the solution (Cavaliere, 2019). Since the electrolysis produces no direct CO_2 emissions, the process could be close to carbon-neutral if the electricity used is CO_2-free.

There are two separate technologies currently under development: in the EU, the focus is on the low-temperature electrolysis of iron ore to iron, referred to as electrowinning. Electrowinning is already commercially used to recover metals such as zinc. In the USA, an alternative process is being investigated where the electrolysis of iron ore at high temperature ('molten oxide electrolysis') can make steel in a single step. Similar high temperature electrolytic processes are already in use to make other metals such as aluminium.

The electrowinning process stems from the ULCOS project, ULCOWIN, developed since 2004, in which iron ore grains are reduced in their solid state at a temperature of 110 °C in an alkaline solution and the metallic iron film is obtained on the surface of the cathode. The iron is then processed to steel in an electric arc furnace. The technology is now being pursued in the H2020-funded Siderwin project, led by ArcelorMittal, with the aim of validating the technology at technology readiness level (TRL) 6 by 2023. The industrial pilot plant of around 100 kg of steel per year was built in 2021. According to the project's development plan, a small-scale 50 kt/y capacity plant in its final form (TRL 9) is expected to be operational in the 2040s, reaching full commercial scale by 2050 (ArcelorMittal, 2019). According to Siderwin project, the technology could reduce direct CO_2 emissions of steelmaking by 87% compared to the BF-BOF route, the residual emissions coming from potential natural gas use in the EAF and finalisation steps. The total steelmaking process would require around 3.6 MWh per tonne of steel, which is comparable to the estimated electricity demand of the H-DRI process with electrolytic hydrogen (3.5-3.95 MWh/t steel). As an indicative figure, to fully replace the 92 Mt of primary steel currently being produced in the EU with this electrolysis technology would require some 330 TWh per year of renewable electricity. While this represents a very important electricity demand, one of the advantages of this technology could be the grid-balancing services it provides through its demand-side response potential. Preliminary modelling exercises of the European power system within the frame of the Siderwin project are investigating the demand side response potential of this technology, indicating that it could provide flexibility capacity with good responsiveness (Barberousse et al., 2020).

Another type of electrolytic steelmaking process, called molten oxide electrolysis (MOE), is being developed by the startup Boston Metals in the USA. In this process, iron ore is dissolved in a liquid oxide electrolyte solvent above the melting point of iron at 1600 °C and reduced into liquid iron. The liquid metal is combined with a carbon source and alloying elements in an electric arc furnace to produce liquid steel. The advantage of this process is that it exhibits a higher productivity compared to other electrolytic processes (Cavaliere, 2019). Although not much information is available at the time of writing, it seems that the MOE process has a slightly higher electricity demand than electrowinning and H-DRI, at 4 MWh/t steel. The development status is also unclear, though it seems that iron production with a pilot-scale MOE-cell was planned for 2021 (U.S. Department of Energy, 2019); one of the main technological barriers to be overcome by full-scale MOE pilots is the performance of an inert anode that can resist the highly corrosive environment and high temperatures of the process. Regarding its grid-balancing potential, the MOE process could be more limited that the electrowinning process. As with the electrolysis of aluminium via the Hall-Héroult process, which operates at 1000 °C, the MOE cells would need to be operated continuously so that the molten material does not solidify. In the case of aluminium, short interruptions are possible due to the thermal mass of the process, allowing a reduction in electricity demand (load shedding) of up to 25% for 4 hours (Shoreh et al., 2016).

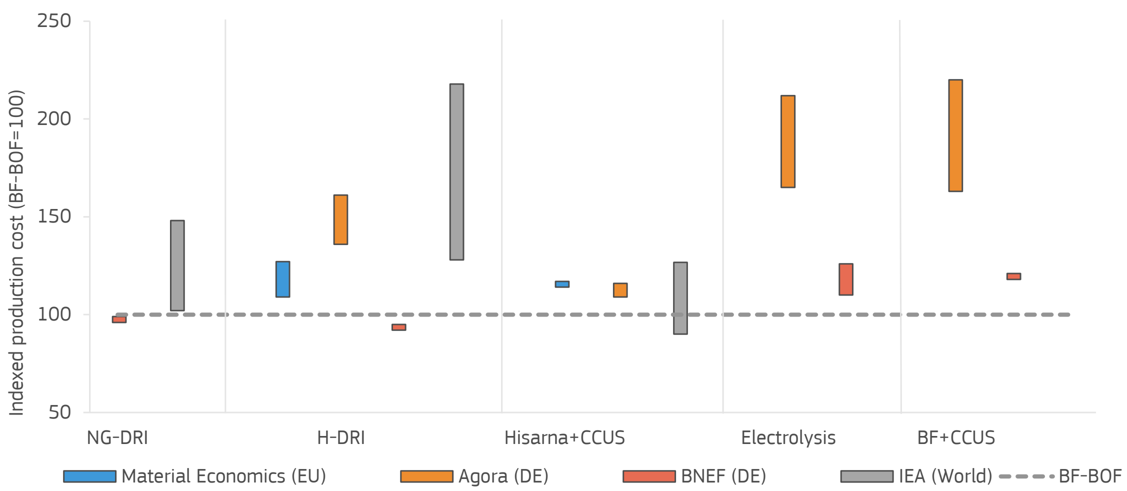
Both electrowinning and MOE would require entirely new types of facility compared to current production processes to reduce iron ore. While the current integrated route relies on large furnaces of multiple million tonnes of capacity, these installations would be modular since they consist of stacked cells, allowing steel production to potentially operate in a smaller, decentralised fashion. However, both technologies are still at an early stage of technological readiness, so that it is unclear what role they can play to decarbonise the EU steel industry before 2050. Recent industry decarbonisation modelling exercises (IEA, 2020; Material Economics, 2019) do not deploy electrolysis at all in their scenarios, while other studies (Agora Energiewende and Wuppertal Institute, 2021; Fleiter et al., 2019) see a possible, but limited, deployment in the EU by 2050.

4.4 The cost of decarbonisation

This section aims to provide an overview of the future costs of producing low-CO_2 steel, compared to today's production costs, as identified in selected external reports. Several technologies are shown via their future levelised cost of steelmaking (LCOS) in €/t steel, a methodology that takes into account the main investment costs (CapEx), discounted over the lifetime of the investment, and the annual raw material and energy costs (OpEx), but do not consider the cost of CO_2 emissions.. LCOS calculations provide a simplified view of future steelmaking costs; they are based on a number of assumptions on techno-economic performance and cannot take into account all possible factors that would affect the cost of technology or energy. Nevertheless, they present a useful methodology for estimating the potential future costs of low-CO_2 steelmaking technologies. It's important to note that these are future costs for nth-of-a-kind commercial plants that have realised cost reductions through economies of scale and efficiency gains.

Figure 17 compares the future LCOS of low-CO_2 technologies compared to the current cost of primary steelmaking from four recent reports (Agora Energiewende and Wuppertal Institute, 2021; BloombergNEF, 2021a; IEA, 2020; Material Economics, 2019). One analysis presents estimates at EU level (Material Economics, 2019), two reports use parameters specific to Germany (Agora Energiewende and Wuppertal Institute, 2021; BloombergNEF, 2021a) and one report provides a wide range of global estimates (IEA, 2020). For each data point, the costs are indexed against the current cost of BF-BOF steel production that is indicated in the respective source, so as to show the relative change in production costs that each publication estimates compared to today's cost of making steel. The parameters used to calculate the production costs all include CapEx estimates (though annualised at varying discount rates and over different lifetimes), raw material costs, and fuel and energy costs. It is important to note that the current unabated BF-BOF production costs do not include CO_2 costs, so this picture does not portray future cost differences. In the future, BF-BOF steel production would be more costly as unabated plants are faced with a rising CO_2 price on their emissions. The estimated carbon price that could make these future technologies competitive with the current production costs can be derived from these LCOS and is presented in **Figure 18** below. This figure shows that depending on the CO_2 price, low-carbon steel technologies can be commercially competitive.

Figure 17 Comparison of future levelised cost of low-CO_2 primary steel production technologies, indexed to current BF-BOF cost, from external sources[1]



Source: JRC based on (Agora Energiewende and Wuppertal Institute, 2021; BloombergNEF, 2021a; IEA, 2020; Material Economics, 2019)

The LCOS results indicate that there is a wide range of uncertainty regarding the future costs of low-CO_2 steelmaking.

In three out of four studies H-DRI steelmaking results in higher production costs compared to today's integrated route: from 10% to 60% more expensive in the studies focussing on Europe, and from around 30%

[1] Note: The data from IEA is based on graph digitisation and the cost of low-CO_2 technologies is indexed to the average cost range of BF-BOF.

to 120% covering production across the world. However, one analysis also estimates H-DRI in 2050 to be cheaper than current steelmaking costs. The main variable driving these differences is the assumed cost of renewable hydrogen, which varies from 1 €/kg to over 5 €/kg, depending on the study. This levelised cost of hydrogen (LCOH) is itself a highly uncertain assumption that depends on its own range of input parameters, including the location of H_2 production (imported or produced locally), the cost and efficiency of electrolysers and the cost of renewable energy. In the selected LCOS, the cost of electricity and hydrogen represent between 27% and 45% of the total cost of H-DRI steel production. The sensitivity to electricity and hydrogen costs is reduced if an increased share of scrap is used in the steelmaking process. Those calculations using the lower range of hydrogen and electricity costs also include hydrogen storage, which would allow steelmakers some flexibility in hydrogen demand. The production cost of the H-DRI route is also dependent on the amount of steel scrap used in the process, and is expected to decrease as the scrap charge increases (Vogl et al., 2018). Finally, the CapEx investments required in this technology route are substantial and can represent a significant part of the total LCOS, depending on the discount rate and plant lifetime used to annualise the CapEx payment. The main installations required are the direct reduction shaft and the electric arc furnace. If the hydrogen is to be produced onsite, then this route also requires electrolysers and possible H_2 storage, depending on the choice of configuration. The Hybrit project, which is the first to produce green steel from H-DRI in its demonstration plant, estimated that the H-DRI technology would represent a 20-30% increase in the cost of producing crude steel (Hybrit, 2018), but would become an attractive investment in the future due to lower electricity costs and higher CO_2 prices (Pei et al., 2020).

The innovative smelting reduction technology being developed by Tata Steel (HIsarna) is analysed in three of the four selected reports and found to increase production costs by 9% to 16% compared to current integrated steelmaking in Europe, and -10% to +30% across the world. This technology path also requires significant CapEx investments, representing between 12% and 21% of the total LCOS in the selected studies. Since the HIsarna process eliminates the need for coke, sintering and pelletizing plants and replaces the blast furnace with a different type of furnace, it could incur significant removal and construction costs to adapt an existing steel plant. Furthermore, this route requires the addition of CO_2 capture technology, as well as CO_2 transport and storage infrastructure. As indicated previously in this report, the total CO_2 abatement potential of this technology is estimated to be limited to a maximum of 80%. It is important to note that a feasibility study on the possible climate neutrality paths of the Tata steel IJmuiden plant – which had been developing the HIsarna project – does not include the HIsarna technology in its two decarbonisation paths (Roland Berger, 2021) and that Tata Steel Europe itself has announced that it plans to pursue the hydrogen route at the IJmuiden site (Tata Steel, 2021). This may indicate that the HIsarna technology is not considered a viable decarbonisation solution for this plant anymore.

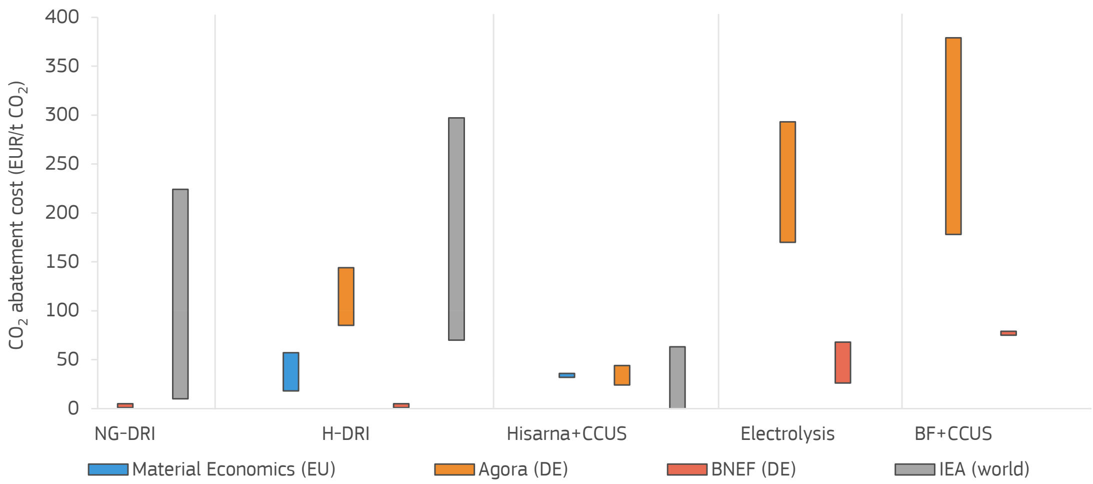
The cost of steel production via direct iron ore electrolysis (both electrowinning and MOE) is highly uncertain, as both processes are still at early stages of development. Two of the four selected reports do not estimate the cost of this technology route due to its low TRL. Early results indicate that steel production would require similar amounts of electricity as the hydrogen DRI route. Since electricity is the only energy input and the process requires a constant supply of power, production costs will be closely linked to the cost of low-CO_2 electricity. As projects are still at pilot stage, it is not clear how capital-intensive the industrial deployment of this technology would be. Lower-cost projections rely on a substantial drop in the CapEx of direct electrolysis equipment due to learning effects for nth-of-a-kind plants, but CapEx costs remain higher than for other decarbonisation technologies. However, since the technology requires comparatively fewer upstream processes (ore beneficiation plants, auxiliary installations such as hydrogen electrolyser, storage, etc.), other analysts expect the nth-of-a-kind CapEx of electrolysis to be lower than for other decarbonisation technologies (Fischedick et al., 2014; Roland Berger, 2020).

Finally, the costs of CCUS technologies applied as a retrofit to the current integrated steelmaking plant are also considered in two studies. These technologies are estimated to have higher costs by 2050 compared to other decarbonisation technologies. As CCUS encompasses several possible implementation options, as described in the previous section, it is not straightforward to isolate the specific cost drivers, since this depends on the chosen configuration. If a substantial amount of carbon (CO and CO_2) is to be captured and converted to chemicals (methanol and ammonia), one significant OpEx driver is the requirement for large amounts of renewable hydrogen. In one analysis, this accounts for 50-60% of the total LCOS (Agora Energiewende and Wuppertal Institute, 2021), which can partly be recouped by the sale of the chemicals produced. However, as previously explained, the sheer amount of available CO_2 is likely to exceed demand. Importantly, achieving a high CO_2 emission reduction rate (>75%) using only CCUS technology becomes technologically and economically less feasible, due to the number of point source emissions of a steel plant (Arasto et al., 2013).

Major CapEx investments are required to replace or retrofit the existing blast furnace-based steelmaking plants. The projected cumulative capital investment needed by 2050 to convert the current integrated route to carbon-neutral production in the EU has been estimated at between EUR 70 billion and around EUR 100 billion (IEA, 2020; Material Economics, 2019; McKinsey, 2021c; Roland Berger, 2020). The largest European steelmaker, ArcelorMittal, has estimated its investment needs for fully implementing its Smart Carbon (CCUS-based) strategy across Europe at EUR 15-25 billion, while pursuing the DRI-based route in Europe would require investment of EUR 30-40 billion (ArcelorMittal, 2020b). These investments do not include the additional infrastructure investments needed in the energy and CCS infrastructure to enable these steelmaking technologies. The German steelmaker thyssenkrupp estimates that EUR 8 billion is needed for the complete transformation of its business towards carbon neutrality (thyssenkrupp, 2021). The German government in its Steel Action Concept roughly estimates investment needs of around EUR 30 billion up to 2050 for the German steel industry alone, of which EUR 10 billion needs to be spent by 2030 (BMWi, 2020).

Using the LCOS and the emissions reduction potential of each low-CO_2 technology, the average abatement costs can be calculated (costs of CO_2 reduction versus current primary steel production, per tonne of CO_2). These values are subject to the same assumptions as described for the LCOS and vary strongly with electricity and hydrogen costs. Nevertheless, they are an indication of the carbon price range that would make low-CO_2 technologies competitive with current BF-BOF production costs. As with the LCOS, the range of estimates is very wide, with some analysts estimating that by 2050, the H-DRI technology could be competitive even without a CO_2 price, in part due to a very low hydrogen price, while in other analysis, a significant CO_2 abatement cost range remains. For studies looking at the cost of H-DRI in Europe, given their input assumptions, estimate a CO_2 abatement cost between 0 and 144 EUR/tCO_2, while globally a much wider range of 70-300 EUR/tCO_2 is determined. It is important to note that much higher CO_2 abatement costs are to be expected before 2050, since the CapEx of technologies reduces over time as the cost of deployment follows learning curves and the OpEx benefits from similar reductions in the cost of renewable electricity and renewable hydrogen, amongst others.

Figure 18 Comparison of CO_2 abatement cost of low-CO_2 primary steel production technologies, from external sources[1]



Source: JRC based on (Agora Energiewende and Wuppertal Institute, 2021; BloombergNEF, 2021a; IEA, 2020; Material Economics, 2019)

To enable the deployment of low-CO_2 technologies, this early-stage cost gap in the CO_2 abatement cost needs to be addressed. While delving deeply into the various policy tools that are available is beyond the scope of this report, Carbon Contracts for Difference (CCfDs) can be highlighted here. The role CCfDs can play in providing certainty and de-risking low-CO_2 investments has been discussed in recent literature (Agora Energiewende and Wuppertal Institute, 2021; Neuhoff et al., 2019; Richstein, 2017; Sartor & Bataille, 2019). The European Commission is considering the development of CCfDs, as announced in the Update to the 2020 New Industrial Strategy (European Commission, 2021a) and the revision to the ETS Directive (European

[1] *Note*: The data from IEA is based on graph digitisation and the cost of low-CO_2 technologies is indexed to the average cost range of BF-BOF. Data from BNEF and IEA is converted at 0.87$/€. CO_2 intensities taken from the respective studies when available.

Commission, 2021b) and the German government is also examining CCfDs to decarbonise energy-intensive industry via the introduction of a pilot CCfD program (BMU, 2021).

Decarbonising primary steel production will also require broad infrastructure investments, be it large-scale renewable (or low-emission) electricity capacity and hydrogen production or transport and storage or CO_2 infrastructure. The increased electricity and hydrogen demand discussed in section 4.1 is likely to occur around the current steel industry clusters, requiring long-range electricity transmission capacities and/or hydrogen pipelines and imports from renewable electricity production sites. Both the EU and national governments will play a key role in planning this infrastructure rollout.

4.5 The role of R&D

The breakthrough technologies needed to decarbonise primary steel production are the results of decades of R&D in the sector. Before this new steel capacity is commercially deployed, the identified decarbonisation technologies still need to be moved up the TRL ladder and will require further R&D investments for pilot, demonstration and first-of-a-kind commercial plants. The different technologies identified in the previous sections have vastly different maturity levels. Some could technically be deployed today (NG-DRI), some still need minor process adjustments (H-DRI, BF-CCU, HIsarna+CCS) and some are still at an early development stage (electrowinning, MOE). Furthermore, the cost trajectory and TRL of many technologies are dependent on progress in auxiliary technologies that are not specific to the steel industry (hydrogen electrolysers, carbon capture technologies).

The European Commission has been instrumental in supporting early-stage (low TRL) R&D projects in the steel sector in the past. Several of the key decarbonisation technologies being considered by the steel industry were developed via the EU's ultra-low CO_2 steelmaking (ULCOS) programme, which was funded through the Commission's 6^{th} Framework Programme. The pan-European ULCOS project brought together 47 partners across the steel industry and research landscape and was instrumental in assessing and developing the low-CO_2 process routes which were then pursued by industry (Abdul Quader et al., 2016).

More broadly, the EU's Horizon Europe funding programme and the Research Fund for Coal and Steel (RFCS) co-finance research and innovation projects in the areas of coal and steel, including projects focussing on CO_2 emissions reduction. The RFCS has in the past financed a smaller number of projects that can be considered to be developing emission reduction technologies, as can be seen in Table 4, and has a lower average funding level of EUR 1.5 million per project. The Research Programme of the RFCS has recently been amended to provide support for clean-steel technologies leading to near-zero-carbon steelmaking projects. (Council of the European Union, 2021)

Horizon Europe, the successor of Horizon 2020, has a budget of EUR 95.5 billion for the period 2021-2027 (30% more than H2020), of which 35% will contribute to climate objectives. Given the breadth and width of the Horizon Europe programme, only a small portion of this overall budget is likely to go to the steel sector.

The Clean Steel Partnership, formally launched in June 2021, aims to bring 12 projects to TRL 8 and four projects to demonstration level. The partnership estimates the R&D investment needs between 2021 and 2030 at around EUR 2.6 billion (ESTEP, 2021a). It will be funded under both Horizon Europe and the RFCS, with the EU contributing EUR 700 million towards this mechanism.

The European Commission is also facilitating action on technology innovation in industry through the Implementation Working Group on energy efficiency in industry (IWG 6) of the European Strategic Energy Technology Plan (SET Plan), which brings together the European Commission, Member States, industry and research representatives to identify priority activities where funding should be targeted and agree on specific targets for technology development (IWG 6, 2021), and through the ERA Common Industrial Technologies Roadmaps focussing on research and innovation investment agendas (European Commission, 2020c).

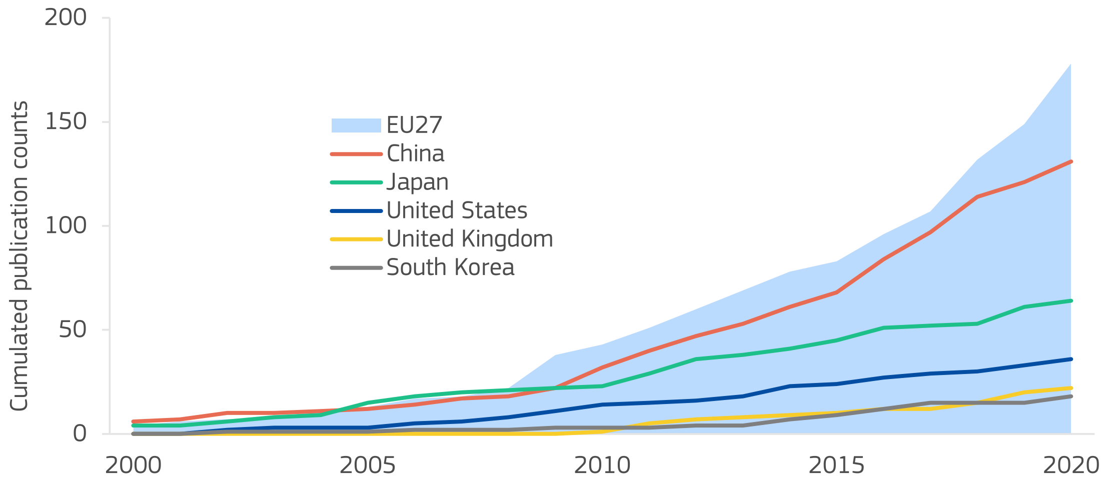
Table 4 Projects in past/ongoing R&D funding programmes for the steel industry focussing on CO_2 emission reduction

Funding programme	Selected funding period	No. of projects	Total budget	EU contribution	TRL levels
ULCOS (FP6)	2004-2010		€ 35 M	€ 20 M	
RFCS	2011-2020	16	€ 24 M	€ 16 M	2-5
H2020	2014-2020	42	€ 331 M	€ 268 M	2-7
Clean Steel Partnership	2021-2030	tbd	€ 1.7 bn	€ 700 M (Horizon Europe + RFCS)	5-8

Source: JRC

To see how the early stage R&D on steel decarbonisation in the EU compares at international level, two knowledge development indicators are reviewed. A broad bibliometric search of scientific papers provides some insight into which regions worldwide have been most active in research supporting low-CO_2 steel manufacturing. General terms such as 'green steel', 'fossil-free steel' and steel decarbonisation' were searched for in the years 2000 to 2020. This publication activity analysis shows EU-27 leading the field, spearheaded by German and more recently Swedish publications, and has steeply increased since 2010. China shows similar levels and a similar trajectory of research activity to the EU, while the remaining countries have not followed this sharp increase in research output.

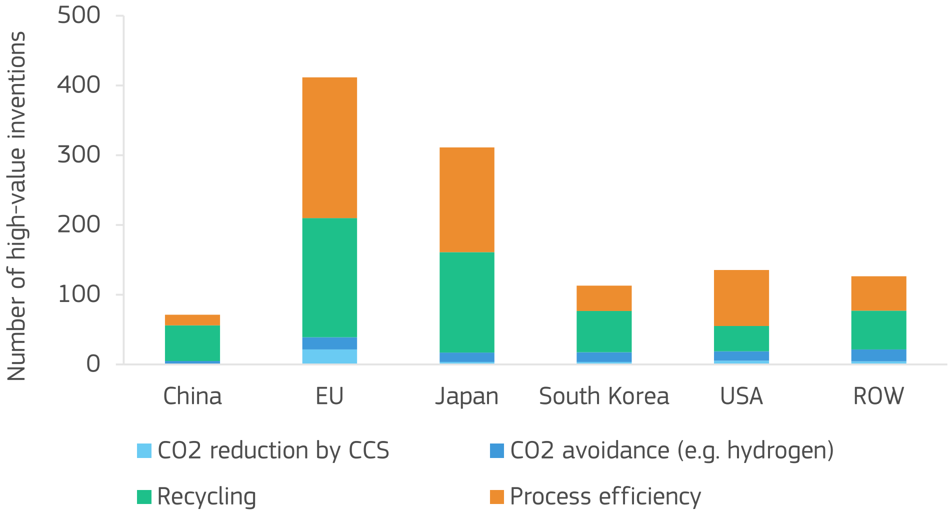
Figure 19 Cumulative publication count on low-CO_2 steelmaking, 2000-2020



Source: JRC base on Scopus

The activity of the EU in developing technologies to decarbonise the steel sector can also be tracked by looking at the high-value patenting activity related to climate change mitigation technologies (CCMT). In the period 2010-2018, the EU has the largest share (35%) of green inventions in the steel sector, followed by Japan (27%). The vast majority of technologies are related to recycling and process efficiency activities, and those linked to the use of hydrogen or CCS in steelmaking represent only a fraction of the total patenting activity. Within that smaller subset, twice as many hydrogen-related patents were filed than for CCS. Inventions on avoiding CO_2 (e.g. through the use of hydrogen) are spread across all countries, while the majority of CCS patents are in the EU.

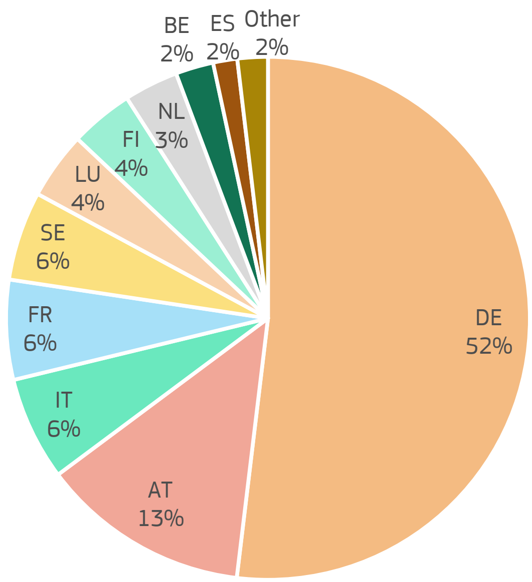
Figure 20 Patenting of climate change mitigation technologies related to metal processing, 2010-2018



Source: JRC based on EPO's PATSTAT[1]

Within the EU, over half of all inventions in climate change mitigation technologies in steel sector are in Germany (52%), followed by Austria (13%). The patenting activity is not led by steelmaking companies, but rather by technology providers or other players along the steel value chain, such as the steel plant supplier SMS Group, the technology company Siemens and the steel plant construction company Primetals Technologies (including its predecessor Siemens VAI; Primetals is now a subsidiary of Mitsubishi Heavy Industries).

Figure 21 Inventions in climate change mitigation technologies for steel, by EU countries, 2010-2018

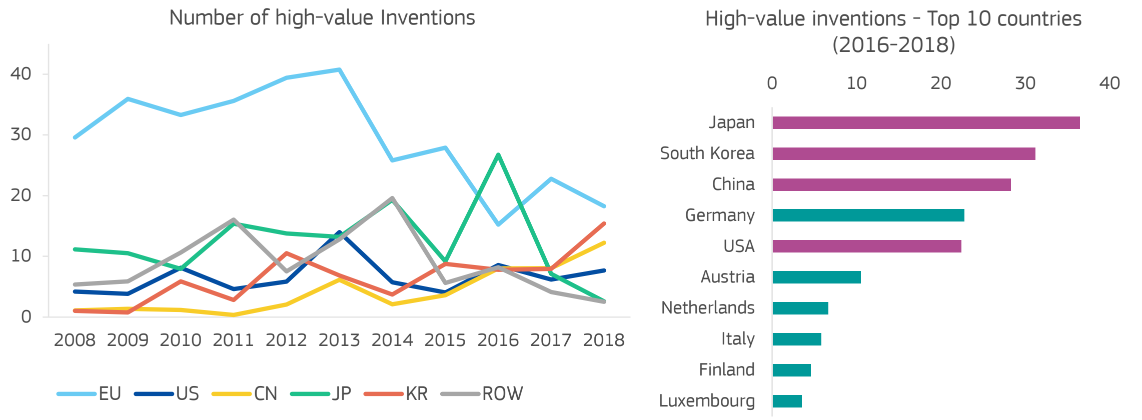


Source: JRC based on EPO's PATSTAT

[1] The European Patenting Office's PATSTAT database

Taking a closer look at inventions that can be linked to climate change mitigation technologies for steelmaking involving hydrogen, electric arc furnaces or electrolysis[1], the patenting activity was also clearly spearheaded by the EU over the last decade. From 2014 onwards however, the yearly number of EU patents has been declining. Since 2016, Japan has been the most prolific country, followed by South Korea. This activity has been driven by South Korea's steelmaking conglomerate, Posco, and Japan's second steel manufacturer, JFE Steel.

Figure 22 Inventions related to CCMT breakthrough steel technologies (2008-2018) and top-10 countries (2016-2018)



Source: JRC based on EPO's PATSTAT

The various metrics indicate that EU companies have been global leaders in the early-stage development of technologies and underline the instrumental role played by public support at EU and national level. EU R&D programmes such as ULCOS have contributed to the development of several important technologies, which are now at varying development levels on the TRL scale. Due to the scale and complexity of the technologies, the maturity of the industry and the high costs associated with innovation, progress has been slow in developing these breakthrough technologies towards demonstration levels and subsequent commercialisation. The Commission's Innovation Fund, one of the world's largest funding programmes targeting the commercial demonstration of innovative low-carbon technologies, is funded by the auctioning revenues of the EU ETS and can provide some EUR 25 billion of support between 2020 and 2030 (at a carbon price of €50/tCO_2), including projects in the steel industry. It will, for example, provide funding for the demonstration plant of the Swedish Hybrit project, whose initial R&D stages were partly funded by the Swedish government. The recently launched public-private Clean Steel Partnership will also provide funding addressing the gap at demonstration stages. A thorough review of funding opportunities for the EU industry (Green Steel for Europe, 2021) identifies around EUR 2 billion in grants for CO_2 emission reduction in the steel sector between 2021 and 2030 from EU support schemes, and concludes that additional support is needed, given the large investments required to decarbonise the steel sector.

[1] Y02P 10/134 ('CCMT related to metal processing by avoiding CO_2, e.g. using hydrogen') where intersecting with (C21B or C21C or C21D) ('manufacture of iron or steel'; 'processing of pig-iron'; 'modifying the physical structure of ferrous metals'); Y02P 10/20 ('CCMT related to metal processing recycling') where intersecting with C21C 5/52 ('manufacture of steel in electric arc furnaces'); Y02P 10 ('CCMT related to metal processing') where intersecting with C25C ('electrolytic production of metals') and (C21B or C21C or C21D).

5 Drive towards decarbonisation

The production of low-CO_2 steel is drawing increasing attention at global level as well as in the EU. Industrial actors are coming forward with targets to achieve climate neutrality by 2050. The EU now has the opportunity to be a frontrunner in helping the industry bridge the ‘green premium’ on low-CO_2 steel by creating lead markets for green steel.

5.1 Global targets and pledges

There is a recent momentum shift among major industry players – globally and especially in the EU – to decarbonise steel production. Over the last year, the five biggest steelmakers (by 2019 steel production volume) have announced that they aim to achieve carbon neutrality, with various intermediary 2030 targets. Together, those five steelmakers accounted for 18% (334 Mt) of global crude steel production in 2019. It is worth noting that while all five steelmakers propose to be carbon neutral by 2050, the intermediary 2030 targets represent varying levels of ambition, with some steelmakers aiming for a 30% reduction in emissions based on future peak emissions (HBIS, Baowu), or setting targets based on CO_2 emission intensity (ArcelorMittal, Baowu).

This picture of global ambition is tempered by the fact that none of the 15 next largest steelmakers have set group-wide 2050 decarbonisation targets at the time of writing. These 15 – mostly Chinese – companies together represent 20% (376 Mt) of global crude steel production in 2019. This illustrates how the high fragmentation of the industry could become an important challenge in galvanising global momentum towards decarbonisation; all top 50 steelmakers together only accounted for 57% (1 060 Mt) of global steel production in 2019.

Table 5 2030 and 2050 targets by top 5 global steelmakers

Company	HQ location	2019 (2020) production (Mt)	2019 (2020) rank	Interim target	2050 target
ArcelorMittal	EU	97 (79)	1 (2)	2030: -25% (Global) 2030: -35% (Europe) ([1])	Net-zero
Baowu	China	95 (115)	2 (1)	2035: -30% vs 2023 peak ([1])	Net-zero
Nippon Steel	Japan	52 (42)	3 (5)	2030: -30% vs 2013	Net-zero
HBIS Group	China	47 (44)	4 (3)	2030: -30% vs 2022 peak	Net-zero
POSCO	South Korea	43 (41)	5 (6)	2030: -20% vs 2017-2019	Net-zero

([1]) Targets relate to CO_2 emissions intensity, not absolute emission reduction.

Source: JRC based on company statements

In the EU, however, the picture is quite different. All the biggest EU steelmakers have set carbon neutrality or close to carbon neutrality (>80% reduction) targets by 2050, underscored by the EU steel association’s targets of 80-95% reduction by 2050 compared to 1990 (Vogl, Sanchez, et al., 2021).

However, while net-zero targets or pledges are clearly an important marker of a company’s ambition, they are in and of themselves non-binding and unenforceable. In the EU context, the European Climate Law (European Commission, 2020d), which sets a legally binding target of net-zero greenhouse gas emissions by 2050, indicates that it is a question of how, not if, EU steelmakers will follow up on their targets. It is therefore not surprising that all major steelmakers, even multinational companies such as Tata Steel and ArcelorMittal, now have low-CO_2 steelmaking projects running at several EU sites, as shown in section 4 of this report. In fact, two thirds of global decarbonisation projects, as identified by the Green Steel Tracker dataset (Vogl, Sanchez, et al., 2021), are based in Europe.

Within the EU, however, strong disparities can be observed between countries and between current plans to decarbonise integrated steel plants. As can be seen in **Table 6**, plants in Czechia and Hungary are not covered by any decarbonisation targets. Additionally, no concrete measures or projects have yet been announced for plants in Italy, Poland, Romania or Slovakia, even though these plants belong to multinational steelmakers that have announced overall decarbonisation targets.

Table 6 Decarbonisation plans at EU integrated steel plants (as of September 2021)

Location	Country	Company	Capacity (Mt)	Company-wide 2050 CO_2 target	Announced low CO_2 project at plant
Donawitz	Austria	voestalpine	1.6	yes	yes
Linz		voestalpine	6	yes	yes
Ghent	Belgium	ArcelorMittal	5	Yes	yes
Ostrava	Czechia	Liberty Steel	3.2	yes	unclear
Trinec		TŽ – MS Group	2.4	no	no
Raahe	Finland	SSAB	2.6	yes	yes
Dunkerque	France	ArcelorMittal	6.8	yes	yes
Fos-Sur-Mer		ArcelorMittal	5.1	yes	yes
Bremen	Germany	ArcelorMittal	4	yes	yes
Dillingen		SHS Group	4.8	yes	yes
Duisburg		ThyssenKrupp	11.6	yes	yes
Eisenhüttenstadt		ArcelorMittal	2.3	yes	yes
Salzgitter		Salzgitter	4.8	yes	yes
Dunaújváros	Hungary	Dunaferr	1.7	no	no
Taranto	Italy	ArcelorMittal Italian Government	11.5	yes	unclear
IJmuiden	Netherlands	Tata Steel	7.5	yes	yes
Dabrowa Gornicza	Poland	ArcelorMittal	5	yes	no
Krakow		ArcelorMittal	2.6	yes	no
Galati	Romania	Liberty Steel	3.2	yes	yes
Kosice	Slovakia	U.S. Steel	4.5	yes	no
Avilés/Gijon	Spain	ArcelorMittal	4.5	yes	yes
Lulea	Sweden	SSAB	2.2	yes	yes
Oxelösund		SSAB	1.7	yes	yes

Source: JRC based on company statements

5.2 New markets for green steel

While the decarbonisation of the steel industry is gaining considerable momentum in the EU and abroad, low-CO_2 steel is likely to be more expensive to produce initially, compared to current steelmaking costs. R&D support in the shape of innovation programmes has been successful in scaling-up new technologies from early development to demonstration stage. Furthermore, the vast infrastructure needs, be it for hydrogen, clean power or CO_2 transport and storage, will require coordinated cross-border planning between Member States and industry. Another important aspect for the commercialisation of low-CO_2 technologies is the creation of markets that can foster demand for low-CO_2 primary steel. This was highlighted in the Master Plan of the High-Level Group on Energy-Intensive Industries (HLG EII, 2019) as well as in the EU's Industrial Strategy (European Commission, 2020a) and its update (European Commission, 2021a), which stressed the importance of creating markets for climate-neutral and circular products.

The first commercial near-zero emission primary steel production will be a niche market with a 'green premium', an additional cost compared to current production cost. Investors and producers aiming to bring these low-CO_2 products to market require certainty about early market demand. As the timelines announced by the steel producers for commercial green steel production are approaching – as early as 2024 for the most ambitious announcements (H2GreenSteel, 2021) – first evidence of a voluntary market willing to pay a green steel premium has started to emerge. To name a few examples, the car and truck maker Daimler Mercedes-Benz has partnered with both Swedish startup H2GreenSteel (Daimler, 2021a) and with Swedish steelmaker SSAB, a member of the Hybrit project (Daimler, 2021b), to introduce green steel into their vehicles; and the first batch of H-DRI steel produced by Hybrit has been delivered to Volvo Group (SSAB, 2021a) in a trial delivery, as part of a wider collaboration between Volvo Group and SSAB on producing cars with fossil-free steel (SSAB, 2021b). The automotive industry could be a natural partner and early adopter of green steel for several reasons:

- It is the second largest user of steel (after the construction sector), with 19% of total finished steel demand in 2019 (Eurofer, 2020);
- While various grades of steel are used in the automotive industry depending on the component's needs, a high proportion of high-quality steel is required, which is currently mainly provided by the primary steelmaking route in the EU; and
- The increased cost of low-CO_2 steel would represent a relatively small increase in the total end-user cost of the final product. Since steel is traded as a B2B[1] product and constitutes a small fraction of the total cost structure of the final good, consumers would be faced with a 1% increase on the price of a car made with green steel (Energy Transitions Commission, 2018; Rootzén & Johnsson, 2016).

As identified in the Master Plan of the High-Level Group on Energy-Intensive Industries, public procurement could also play an important role in generating early demand-pull for climate-neutral products, including steel. Governments purchase large quantities of steel for building and infrastructure construction. Public expenditure on works, goods and services in the EU already represents 14% of GDP, and an estimated 32% of steel consumption in Germany is via public procurement (Ali Hasanbeigi et al., 2021). The European Commission has an existing Green Public Procurement (GPP) procedure in place that develops common GPP criteria, led by the Commission's Joint Research Centre (European Commission, 2021e), to facilitate the inclusion of GPP in public tender documents. The EU's GPP is a voluntary instrument covering only a limited number of products and doesn't include steel or other base materials.

A key aspect of successful GPP and other demand-side market creation measures is the need for standardised methodologies to calculate and share the embodied emissions of steel products, which can constitute an important non-cost barrier to creating markets for climate-neutral products (University of Cambridge Institute for Sustainability Leadership (CISL) & Agora Energiewende, 2021). A standard and certification initiative led by industry, ResponsibleSteel, is developing a product standard based on crude steel GHG emission intensity, similar to a label that can be awarded to products that fulfil their criteria (ResponsibleSteel, 2021). The World Steel Association has published a lifecycle GHG inventory methodology based on ISO standards for calculating steel plant GHG emissions (World Steel Association, 2017). Even though it is beyond the scope of this report, defining the scope and emission thresholds of 'green steel' is a crucial first step, leaving the door otherwise open to opportunities of greenwashing by industry. Producing and

[1] Steel is a commodity traded business-to-business between steel manufacturers and other companies, rather than to individual consumers.

maintaining a third-party verified carbon footprint certification system requires an important administrative effort and suffers from iron and steel's highly complex supply chains. Linking the LCA methodology of a standard or certificate with the Commission's proposed Carbon Border Adjustment Mechanism could reduce the administrative burden.

Another important complication in accounting steel's carbon footprint is the differentiation between primary and secondary steel, which carry vastly different emissions intensities. In an early stage, where only a small percentage of primary steel production has shifted to low-CO_2 technologies, the implementation of low-CO_2 material requirements or quotas could lead to a shift towards the use of recycled steel. This is particularly true in the case of public procurement, since the buildings and infrastructure predominantly use steel produced through the secondary route (Vogl, Åhman, et al., 2021). This would not lead to the desired outcome of GPP supporting the uptake of low-CO_2 primary steelmaking technologies.

The two examples highlighted here, voluntary markets and green public procurement, could be important stepping stones towards the implementation of further demand-pull policy instruments to create a deeper market for green steel.

At the level of international multilateral governance, there are several initiatives that are driving momentum towards reducing CO_2 emissions in the steel industry and catalysing demand for low-CO_2 steel. The Steel Breakthrough was launched at COP26 as part of the Breakthrough Agenda, and endorsed by 25 countries and the European Union, including major steelmaking nations like the USA, India, South Korea, India, Japan, but not China at the time of writing. It aims to catalyse the use of near-zero emission steel in global markets and sets a number of KPIs to track global progress in near-zero emission steel production capacity, investment in R&D and cost (UKCOP26, 2021). This initiative complements a number of other international partnerships between the public and private sectors. A recent example is the Clean Energy Ministerial's Industrial Deep Decarbonisation Initiative (IDDI), launched in 2021 and led by India and the UK, which aims to standardise carbon assessments and reporting practices among governments and to encourage the public and private sectors to establish low-carbon steel procurement targets (Clean Energy Ministerial, 2021). In 2019, Sweden and India launched the Leadership Group for Industry Transition (LeadIT), providing a platform for governments and companies to share knowledge and co-produce pathways to industry transformation (LeadIT, 2021). Considering the globalised nature of the steel industry and its growing importance in developing economies, such international, multi-stakeholder public-private partnerships can play an important role in advancing the decarbonisation of the steel industry by facilitating technology transfer and creating global markets for low-CO_2 steel.

6 Looking ahead

The EU iron and steel sector is faced with transformational challenges if it is to reduce its CO_2 emissions on the way to a carbon-neutral future. Due to the industry's long investment cycles, investment decisions made in the next 5-10 years will lay the groundwork for the trajectory of the industry for the coming decades. The technologies needed to achieve the steel industry's transition are still at various stages of development, but all major EU steelmakers are currently developing pilot and demonstration projects for near-zero emission projects. Hydrogen-based DRI appears to be a particularly promising technology that is close to commercialisation and could account for a significant proportion of primary steelmaking. This would entail a high demand for hydrogen and low-CO_2 electricity, which can act as a strong pull for the development of a hydrogen economy, but will need coordinated action at Member State and EU level to deploy the necessary supporting infrastructure. As the cost of electricity and hydrogen becomes the main variables determining the future cost of production, the regulatory framework supporting the deployment of renewable electricity and hydrogen is increasingly important for the steel sector. While new technologies will be needed to make virgin steel in the future, it is clear that the potential of the recycling route needs to be maximised, as this reduces current and future costs and energy requirements.

All technology options to decarbonise primary steel production currently carry higher costs than today's production routes. Concerted policy action is needed for steelmakers to invest and scale up these technologies. The EU and Member States have a number of demand and supply-side instruments in their policy toolbox that can be deployed to create a supportive regulatory environment, including carbon contracts for difference, green steel standards and green public procurement. The sharply rising CO_2 price of the EU ETS can provide a push towards decarbonisation and reinforce the need for a CBAM to level the global playing field, if steelmakers are facing the full CO_2 price. The Innovation Fund, funded by the EU ETS, can support the commercial demonstration of first-of-a-kind plants. At the same time, R&D support for earlier stage technologies that can be deployed closer to 2050 also needs to be maintained and strengthened to further develop additional promising breakthrough solutions for climate-neutral steel.

There is an increased policy drive towards decarbonisation of the steel industry, and the industry has responded with ambitious decarbonisation pledges. The EU can now build on this momentum and be a frontrunner in the production of CO_2-free steel. The EU steel sector can lead the way in deploying decarbonisation technologies, thereby ensuring that it stays competitive as the world transitions towards climate neutrality.

References

Abdul Quader, M., Ahmed, S., Dawal, S. Z., & Nukman, Y. (2016). Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO 2) Steelmaking (ULCOS) program. *Renewable and Sustainable Energy Reviews*, *55*, 537–549. https://doi.org/10.1016/j.rser.2015.10.101

Abu Dhabi Carbon Capture Company. (2017). *Case Study: Al Reyadah CCUS Project*.

Agora Energiewende and AFRY Management Consulting. (2021). *No-regret hydrogen: Charting early steps for H_2 infrastructure in Europe.* https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_02_EU_H2Grid/A-EW_203_No-regret-hydrogen_WEB.pdf

Agora Energiewende and Wuppertal Institute. (2021). *Breakthrough Strategies for Climate- Neutral Industry in Europe: Policy and Technology Pathways for Raising EU Climate Ambition*. www.agora-energiewende.de

Arasto, A., Tsupari, E., Kärki, J., Pisilä, E., & Sorsamäki, L. (2013). Post-combustion capture of CO2 at an integrated steel mill – Part I: Technical concept analysis. *International Journal of Greenhouse Gas Control*, *16*, 271–277. https://doi.org/10.1016/j.ijggc.2012.08.018

ArcelorMittal. (2019). *Decarbonisation of steel production by electrification*. https://www.siderwin-spire.eu/sites/siderwin.drupal.pulsartecnalia.com/files/documents/9. SET Plan Action 6- Hervé Lavelaine - SIDERWIN.pdf

ArcelorMittal. (2020a). *ArcelorMittal strategy towards low-emissions steelmaking*.

ArcelorMittal. (2020b). *Climate Action in EuropeOur carbon emissions reduction roadmap: 30% by 2030 and carbon neutral by 2050*.

ArcelorMittal. (2021a). *Air Liquide and ArcelorMittal join forces to accelerate the decarbonisation of steel production in the Dunkirk industrial basin*. https://corporate.arcelormittal.com/media/news-articles/air-liquide-and-arcelormittal-join-forces-to-accelerate-the-decarbonisation-of-steel-production-in-the-dunkirk-industrial-basin

ArcelorMittal. (2021b). *ArcelorMittal plans major investment in German sites, to accelerate CO2 emissions reduction strategy and leverage the hydrogen grid*. https://corporate.arcelormittal.com/media/news-articles/arcelormittal-plans-major-investment-in-german-sites-to-accelerate-co2-emissions-reduction-strategy-and-leverage-the-hydrogen-grid

ArcelorMittal. (2021c). *Climate Action Report 2*.

Arens, M., Worrell, E., Eichhammer, W., Hasanbeigi, A., & Zhang, Q. (2017). Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany. *Journal of Cleaner Production*, *163*, 84–98. https://doi.org/10.1016/j.jclepro.2015.12.097

Arup. (2019). *Rethinking Timber Buildings*.

Barberousse, M., Debregeas, A., Apostolou, M., & Bono, C. (2020). Electrification of primary steel production based on ΣIDERWIN process: simulation on the European power system in 2050. *"Proceedings of the '"Industrial Efficiency 2020"' Conference."*

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., & Rahbar, S. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *Journal of Cleaner Production*, *187*, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107

Bauer, C., Treyer, K., Antonini, C., Bergerson, J., Gazzani, M., Gencer, E., Gibbins, J., Mazzotti, M., McCoy, S. T., McKenna, R., Pietzcker, R., Ravikumar, A. P., Romano, M. C., Ueckerdt, F., Vente, J., & van der Spek, M. (2022). On the climate impacts of blue hydrogen production. *Sustainable Energy & Fuels*, 1–9. https://doi.org/10.1039/D1SE01508G

Bhaskar, A., Assadi, M., & Nikpey Somehsaraei, H. (2020). Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen. *Energies*, *13*(3), 758. https://doi.org/10.3390/en13030758

Bhaskar, A., Assadi, M., & Somehsaraei, H. N. (2021). Can methane pyrolysis based hydrogen production lead to the decarbonisation of iron and steel industry? *Energy Conversion and Management: X*, *10*, 100079. https://doi.org/10.1016/j.ecmx.2021.100079

Bianco, L., Baracchini, G., Cirilli, F., Sante, L. Di, Moriconi, A., Moriconi, E., Agorio, M. M., Pfeifer, H., Echterhof, T., Demus, T., Jung, H. P., Beiler, C., & Krassnig, H.-J. (2013). Sustainable Electric Arc Furnace Steel Production: GREENEAF. *BHM Berg- Und Hüttenmännische Monatshefte*, *158*(1), 17–23. https://doi.org/10.1007/s00501-012-0101-0

Bloomberg. (2021). *Berlin's New Timber Tower Comes With Lofty Ambitions*.

BloombergNEF. (2021a). *Decarbonizing Steel: Technologies and Costs*.

BloombergNEF. (2021b). *Digital Strategies for Sustainable Steel*.

BMU. (2021). *Eckpunkte für eine Förderrichtlinie Klimaschutzverträgezur Umsetzung des Pilotprogramms „Carbon Contracts for Difference"*.

BMWi. (2020). *For a strong steel industry in Germany and Europe*.

Branca, T. A., Fornai, B., Colla, V., Murri, M. M., Streppa, E., & Schröder, A. J. (2020). The Challenge of Digitalization in the Steel Sector. *Metals*, *10*(2), 288. https://doi.org/10.3390/met10020288

Brandl, P., Bui, M., Hallett, J. P., & Mac Dowell, N. (2021). Beyond 90% capture: Possible, but at what cost? *International Journal of Greenhouse Gas Control*, *105*, 103239. https://doi.org/10.1016/j.ijggc.2020.103239

Bukauskas, A., Shepherd, P., Walker, P., Sharma, B., & Bregulla, J. (2018). Inventory-Constrained Structural Design: New Objectives and Optimization Techniques. *Proceedings of IASS Annual Symposia, IASS 2018 Boston Symposium*.

Carbon4PUR. (2021). *Carbon4PUR*. https://www.carbon4pur.eu/

Carpenter, A. (2012). *CO2 abatement in the iron and steel industry*.

Carrara, S., Alves Dias, P., Plazzotta, B., & Pavel, C. (2020). *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system*. https://doi.org/10.2760/160859

Cavaliere, P. (2019). Clean Ironmaking and Steelmaking Processes. In *Clean Ironmaking and Steelmaking Processes*. Springer International Publishing. https://doi.org/10.1007/978-3-030-21209-4

Chisalita, D.-A., Petrescu, L., Cobden, P., van Dijk, H. A. . (Eric), Cormos, A.-M., & Cormos, C.-C. (2019). Assessing the environmental impact of an integrated steel mill with post-combustion CO2 capture and storage using the LCA methodology. *Journal of Cleaner Production*, *211*, 1015–1025. https://doi.org/10.1016/j.jclepro.2018.11.256

Clean Energy Ministerial. (2021). *Industrial Deep Decarbonisation Initiative*. https://www.cleanenergyministerial.org/initiative-clean-energy-ministerial/industrial-deep-decarbonisation-initiative

Council of the European Union. (2021). *COUNCIL DECISION (EU) 2021/1094*.

CRU. (2020). *CRU Steel Cost Model 2019*.

CRU. (2021). *CRU Steel Cost Model 2021*.

Daehn, K. E., Cabrera Serrenho, A., & Allwood, J. M. (2017). How Will Copper Contamination Constrain Future Global Steel Recycling? *Environmental Science & Technology*, *51*(11), 6599–6606. https://doi.org/10.1021/acs.est.7b00997

Daimler. (2021a). *From 2025: "Green" steel for Mercedes-Benz*.

Daimler. (2021b). *Mercedes-Benz Takes the Next Step on the Road to Green Steel*. https://media.daimler.com/marsMediaSite/instance/ko.xhtml?oid=51167747&filename=Mercedes-Benz-Takes-the-Next-Step-on-the-Road-to-Green-Steel

De Ras, K., Van de Vijver, R., Galvita, V. V, Marin, G. B., & Van Geem, K. M. (2019). Carbon capture and utilization in the steel industry: challenges and opportunities for chemical engineering. *Current Opinion in Chemical Engineering*, *26*, 81–87. https://doi.org/10.1016/j.coche.2019.09.001

Duarte, P., Scarnati, T., & Becerra, J. (2008). *ENERGIRON Direct Reduction Technology - Economical, Flexible,* *Environmentally Friendly*.

Echterhof, T. (2021). Review on the use of alternative carbon sources in EAF steelmaking. *Metals*, *11*(2), 1–16. https://doi.org/10.3390/met11020222

Ember. (2021). *Daily Carbon Prices*. https://ember-climate.org/data/carbon-price-viewer/

Energy Transitions Commission. (2018). *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors*.

Espinoza, O., Trujillo, V. R., Fernanda, M., Mallo, L., & Buehlmann, U. (2016). Cross-Laminated Timber: Status and Research Needs in Europe. *BioResources*, *11*, 281–295.

ESTEP. (2021a). *Clean Steel Partnership (CSP)*. https://www.estep.eu/clean-steel-roadmap/

ESTEP. (2021b). *Improve the EAF scrap route for a sustainable value chain in the EU Circular Economy scenario*. https://www.estep.eu/assets/Uploads/Improve-the-EAF-scrap-route-Roadmap-Final-V2-3.pdf

Eurofer. (2019). *Low Carbon Roadmap*.

Eurofer. (2020). *European Steel in Figures*.

Eurofer. (2021). *Annual Report 2021*.

European Commission. (2020a). *COM(2020) 102 final*.

European Commission. (2020b). *COM(2020) 301 final*.

European Commission. (2020c). *COM(2020) 628 final*.

European Commission. (2020d). *COM(2020) 80 final*.

European Commission. (2020e). *COM(2020) 98 final*.

European Commission. (2021a). *COM(2021) 350 final*.

European Commission. (2021b). *COM(2021) 551 final*.

European Commission. (2021c). *COM(2021) 564 final*.

European Commission. (2021d). *EU invests over €1 billion in innovative projects to decarbonise the economy*. https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6042

European Commission. (2021e). *Green Public Procurement*.

European Commission. (2021f). *Regulation (EU) 2021/1119: European Climate Law*.

European Commission. (2021g). *SWD(2021) 277 final*.

European Commission. (2021h). *SWD(2021) 353 final*.

European Parliament and Council of the EU. (2021). *Regulation (EU) 2021/1119*.

Eurostat. (2021a). *Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E) [sbs_na_ind_r2]*.

Eurostat. (2021b). *SHARES (Renewables)*. https://ec.europa.eu/eurostat/web/energy/data/shares

Fischedick, M., Marzinkowski, J., Winzer, P., & Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Cleaner Production*, *84*, 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063

Fitch Ratings. (2021). *High EU Carbon Prices to Weigh on Steelmakers' Profitability*.

Fleiter, T., Herbst, A., Rehfeldt, M., & Arens, M. (2019). *Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation*. https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/industrial_innovation_part_1_en.pdf

Fraunhofer. (2018). *Industry 4.0 in the European Iron and Steel Industry: Towards an Overview of Implementations and Perspectives*. 32.

Gasunie. (2021). *Athos-project ends after Tata Steel decision*.

German Federal Government. (2020). *Climate Action Programme 2030 - Lower CO2 emissions from production*. https://www.bundesregierung.de/breg-en/issues/climate-action/innovations-for-climateprotection-1795848

Green Steel for Europe. (2021). *Report on funding opportunities to decarbonise the EU steel industry*.

H2GreenSteel. (2021). *H2GreenSteel*. https://www.h2greensteel.com/green-steel

Hasanbeigi, A., & Springer, C. (2019). *How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO2 Intensities*.

Hasanbeigi, Ali, Nilsson, A., Gökce, M., Fontenit, G., & Shi, D. (2021). *Fostering industry transition through green public procurement : A " How to " guide for the cement & steel sectors* (Issue June). https://www.industrytransition.org/content/uploads/2021/08/1-fostering-industry-transition-through-green-public-procurement.pdf

HLG EII. (2019). *Masterplan for a competitive transformation of EU energy-intensive industries enabling a climate-neutral, circular economy by 2050*.

Hooey, L., Tobiesen, A., Johns, J., & Santos, S. (2013). Techno-economic Study of an Integrated Steelworks Equipped with Oxygen Blast Furnace and CO2 Capture. *Energy Procedia*, *37*, 7139–7151. https://doi.org/10.1016/j.egypro.2013.06.651

Howarth, R. W., & Jacobson, M. Z. (2021). How green is blue hydrogen? *Energy Science & Engineering*, ese3.956. https://doi.org/10.1002/ese3.956

Hybrit. (2018). *Summary of findings from HYBRIT Pre-Feasibility Study 2016–2017*.

icap. (2021). *EU Emissions Trading System (EU ETS)*.

IEA. (2020). *Iron and Steel Technology Roadmap*.

IEA. (2021). *Methane Tracker Database*. https://www.iea.org/articles/methane-tracker-database

IEAGHG. (2013). *Iron and Steel CCS study (Techno-Economics Integrated Steel Mill)*.

IETS. (2020). *SURVEY OF CURRENT PROJECTS AND NOVEL TECHNOLOGIES IN THE STEEL INDUSTRY*.

IFP Energies nouvelles. (2020). *DMX Demonstration in Dunkirk*. CORDIS.

Industry Europe. (2019). *Mjøsa Tower - world's tallest wooden building - completed in Norway*. https://industryeurope.com/mjosa-tower-worlds-tallest-wooden-building-completed-in-norway/

IWG 6. (2021). *SET Plan Action 6 on Energy Efficiency in Industry Implementation Plan*. https://setis.ec.europa.eu/system/files/2021-12/SET Plan Action6 on EE in industry-Implementation Plan-Rev2021-final-endorsed.pdf

Kapetaki, Z., Hetland, J., Le Guenan, T., Mikunda, T., & Scowcroft, J. (2017). Highlights and Lessons from the EU CCS Demonstration Project Network. *Energy Procedia*, *114*, 5562–5569. https://doi.org/10.1016/j.egypro.2017.03.1696

Keys, A., van Hout, M., & Daniels, B. (2019). *Decarbonisation options for the Dutch steel industry*.

Krüger, A., Andersson, J., Grönkvist, S., & Cornell, A. (2020). Integration of water electrolysis for fossil-free steel production. *International Journal of Hydrogen Energy*, *45*(55), 29966–29977. https://doi.org/10.1016/j.ijhydene.2020.08.116

LeadIT. (2021). *Leadership Group for Industry Transition*.

Linturi, R., & Kuusi, O. (2019). *Societal Transformation 2018–2037*. Committee for the Future. https://www.eduskunta.fi/FI/naineduskuntatoimii/julkaisut/Documents/NETTI_TUVJ_10_2018_Societal_transformation_UUSI.pdf

LoCO2Fe. (2021). *Development of a Low CO2 Iron and Steelmaking Integrated Process Route for a Sustainable European Steel Industry*. https://cordis.europa.eu/project/id/654013/reporting

Lösch, O., Jochem, E., Ashley-Belbin, N., & Zesch, G. (2020). *Bewertung der Direktreduktion von Eisenerz mittels Elektrolyse-Wasserstoff*. *September*. https://irees.de/wp-content/uploads/2020/10/200918_IREES_EDUARD-Bewertung-Direktreduktion_final_korrektur.pdf

Manocha, S., & Ponchon, F. (2018). Management of Lime in Steel. *Metals*, *8*(9), 686. https://doi.org/10.3390/met8090686

Material Economics. (2019). *Industrial Transformation 2050 Industrial Transformation 2050*.

McKinsey. (2018). *Decarbonization of industrial sectors: the next frontier*.

McKinsey. (2021a). *How digital and analytics can unlock full potential in steel*. *January*.

McKinsey. (2021b). *The DRI dilemma: Could raw material shortages hinder the steel industry's green transition?*

McKinsey. (2021c). *The future of the European steel industry*.

Medarac, H., Somers, J., & Moya, J. (2020). Production costs from iron and steel industry in the EU and third countries. In *Publications Office of the European Union*. https://doi.org/10.2760/705636

Midrex. (2010). Coal Gasification Based DRI Solution for Indian Ironmaking. *17th Annual International Steel Seminar and Exhibition*.

Midrex. (2017). *MIDREX H2: Ultimate Low CO2 Ironmaking and its place in the new Hydrogen Economy*. https://www.midrex.com/tech-article/midrex-h2-ultimate-low-co2-ironmaking-and-its-place-in-the-new-hydrogen-economy/

Midrex. (2018). *DR-Grade Iron Ore Pellets – A Supply Overview*.

Midrex. (2020). *2019 World Direct Reduction Statistics*.

Ministry of Steel India. (2021). *Annual Report 2020-2021*.

Moné, C., Hand, M., Bolinger, M., Rand, J., Heimiller, D., & Ho, J. (2017). *2015 cost of wind energy review*.

Moynihan, M. C., & Allwood, J. M. (2014). Utilization of structural steel in buildings. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *470*(2168), 20140170. https://doi.org/10.1098/rspa.2014.0170

Müller, N., Herz, G., Reichelt, E., Jahn, M., & Michaelis, A. (2021). Assessment of fossil-free steelmaking based on direct reduction applying high-temperature electrolysis. *Cleaner Engineering and Technology*, *4*. https://doi.org/10.1016/j.clet.2021.100158

Neuhoff, K., Chiappinelli, O., Gerres, T., Haussner, M., Ismer, R., May, N., Pirlot, A., & Richstein, J. (2019). *Building blocks for a climate-neutral European industrial sectorNo Title*.

Northern Lights. (2021). *Northern Lights*. https://northernlightsccs.com/

OECD. (2021). *Latest developments in steelmaking capacity, 2021*. https://www.oecd.org/industry/ind/latest-developments-in-steelmaking-capacity-2021.pdf

Outote, M. (2021). *Metso Outotec Circored™ process*. https://www.mogroup.com/portfolio/circored-hydrogen-based-reduction/

Pauliuk, S., Milford, R. L., Müller, D. B., & Allwood, J. M. (2013). The Steel Scrap Age. *Environmental Science & Technology*, *47*(7), 3448–3454. https://doi.org/10.1021/es303149z

Pei, M., Petäjäniemi, M., Regnell, A., & Wijk, O. (2020). Toward a Fossil Free Future with HYBRIT: Development of Iron and Steelmaking Technology in Sweden and Finland. *Metals*, *10*(7), 972. https://doi.org/10.3390/met10070972

Petrescu, L., Chisalita, D.-A., Cormos, C.-C., Manzolini, G., Cobden, P., & van Dijk, H. (2019). Life Cycle Assessment of SEWGS Technology Applied to Integrated Steel Plants. *Sustainability*, *11*(7), 1825. https://doi.org/10.3390/su11071825

Porthos. (2021). *Porthos*.

Primetals. (2021). *HYFOR pilot plant under operation – the next step for carbon free, hydrogen-based direct reduction is done*.

Rechberger, K., Spanlang, A., Sasiain Conde, A., Wolfmeir, H., & Harris, C. (2020). Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking. *Steel Research International*, *91*(11), 2000110. https://doi.org/10.1002/srin.202000110

ResponsibleSteel. (2021). *Responsible Steel*. https://www.responsiblesteel.org/

Richstein, J. (2017). *Discussion PapersProject-Based Carbon Contracts: A Way to Finance Innovative Low-*

Carbon InvestmentsNo Title.

Roland Berger. (2020). *The future of steelmaking*.

Roland Berger. (2021). *Haalbaarheidsstudie klimaatneutrale paden TSN IJmuiden - Tussentijdse parlementaire memo*. https://omgeving.tatasteel.nl/assets/user/Publicaties/publicaties map/210902_TSN_FNV_Klimaat_neutrale_paden_Tussentijdse_Parlementaire_Memo_Final.pdf

Rootzén, J., & Johnsson, F. (2016). Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry. *Energy Policy*, *98*, 459–469. https://doi.org/10.1016/j.enpol.2016.09.021

S&P Global Platts. (2019). *US steel sector thrives as mills move up quality ladder*. https://www.spglobal.com/platts/en/market-insights/blogs/metals/050919-us-steel-sector-thrives-as-mills-move-up-quality-ladder

Sarkar, S., Bhattacharya, R., Roy, G. G., & Sen, P. K. (2018). Modeling MIDREX Based Process Configurations for Energy and Emission Analysis. *Steel Research International*, *89*(2), 1700248. https://doi.org/10.1002/srin.201700248

Sartor, O., & Bataille, C. (2019). *Decarbonising Basic Materials in Europe: How Carbon Contracts-for-Difference Could Help Bring Breakthrough Technologies to Market*.

Shoreh, M. H., Siano, P., Shafie-khah, M., Loia, V., & Catalão, J. P. S. (2016). A survey of industrial applications of Demand Response. *Electric Power Systems Research*, *141*, 31–49. https://doi.org/10.1016/j.epsr.2016.07.008

Somers, J., & Moya, J. (2020). *Decarbonisation of industrial heat: The iron and steel sector*.

SSAB. (2021a). *The world's first fossil-free steel ready for delivery*. https://www.ssab.com/news/2021/08/the-worlds-first-fossilfree-steel-ready-for-delivery

SSAB. (2021b). *Volvo Group and SSAB to collaborate on the world's first vehicles of fossil-free steel*. https://www.ssab.com/news/2021/04/volvo-group-and-ssab-to-collaborate-on-the-worlds-first-vehicles-of-fossilfree-steel

Stede, J., Pauliuk, S., Hardadi, G., & Neuhoff, K. (2021). *Carbon pricing of basic materials: Incentives and risks for the value chain and consumers*. *DIWDiscuss*.

Steel Institute VDEh. (2019). *Plantfacts Capacity Database*.

SteelConstruction.info. (2013). *The recycling and reuse survey*.

Tata Steel. (2020a). *Carbon neutral steelmaking is a major challenge for the steel industry worldwide*. https://www.tatasteeleurope.com/sustainability/carbon-neutral-steel

Tata Steel. (2020b). *HIsarna factsheet*.

Tata Steel. (2021). *Tata Steel opts for hydrogen route at its IJmuiden steelworks*. https://www.tatasteeleurope.com/corporate/news/tata-steel-opts-for-hydrogen-route-at-its-ijmuiden-steelworks

thyssenkrupp. (2020). *Elektro-Roheisen aus Hochofen 2.0*. https://www.thyssenkrupp.com/de/newsroom/pressemeldungen/pressedetailseite/elektro-roheisen-aus-hochofen-20--thyssenkrupp-stellt-bundeswirtschaftsminister-altmaier-und-ministerprasident-laschet-innovatives-konzept-zur-grunen-transformation-der-stahlhutte-

thyssenkrupp. (2021). *Transformation of the steel industry can become a successful model for the transition to climate neutrality*. Press Release. https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/transformation-of-the-steel-industry-can-become-a-successful-model-for-the-transition-to-climate-neutrality-113235

Tian, S., Jiang, J., Zhang, Z., & Manovic, V. (2018). Inherent potential of steelmaking to contribute to decarbonisation targets via industrial carbon capture and storage. *Nature Communications*, *9*(1), 4422. https://doi.org/10.1038/s41467-018-06886-8

Toktarova, A., Karlsson, I., Rootzén, J., Göransson, L., Odenberger, M., & Johnsson, F. (2020). Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study. *Energies*, *13*(15), 3840. https://doi.org/10.3390/en13153840

U.S. Department of Energy. (2019). *Carbon-Free Iron for a Sustainable Future*.

UKCOP26. (2021). *COP26 world leaders summit - statement on the breakthrough agenda*.

University of Cambridge Institute for Sustainability Leadership (CISL), & Agora Energiewende. (2021). *Tomorrow's markets today: Scaling up demand for climate neutral basic materials and products*.

Vattenfall. (2020). *Wooden tower set to reduce carbon dioxide footprint from future wind turbines*.

Vogl, V., Åhman, M., & Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, *203*, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279

Vogl, V., Åhman, M., & Nilsson, L. J. (2021). The making of green steel in the EU: a policy evaluation for the early commercialization phase. *Climate Policy*, *21*(1), 78–92. https://doi.org/10.1080/14693062.2020.1803040

Vogl, V., Sanchez, F., Gerres, T., Lettow, F., Bhaskar, A., Swalec, C., Mete, G., Åhman, M., Lehne, J., Schenk, S., Witecka, W., Olsson, O., & Rootzén, J. (2021). *Green Steel Tracker*. www.industrytransition.org/green-steel-tracker

World Steel Association. (2012). *Steel Solutions in the Green Economy – wind turbines*.

World Steel Association. (2017). *LIFE CYCLE INVENTORY METHODOLOGY REPORT*.

World Steel Association. (2019). Total Production of crude steel. *Steel Statistical Yearbook 2019*, *1*. https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html

World Steel Association. (2020). *Steel Statistical Yearbook: 2020 concise version*. https://www.worldsteel.org/en/dam/jcr:5001dac8-0083-46f3-aadd-35aa357acbcc/Steel%2520Statistical%2520Yearbook%25202020%2520%2528concise%2520version%2529.pdf

World Steel Association. (2021a). *2021 World Steel in Figures*.

World Steel Association. (2021b). *Steel and raw materials factsheet*. http://www.worldsteel.org/dms/internetDocumentList/fact-sheets/Fact-sheet_Raw-materials2011/document/Fact sheet_Raw materials2011.pdf

Wörtler, M., Schuler, F., Voigt, N., Schmidt, T., Dahlmann, P., Lüngen, H. B., & Ghenda, J.-T. (2013). *Steel's contribution to a low car-bon Europe 2050. Technical and economic analysis of the sectors CO2 abatement potential.*

List of abbreviations

BF	Blast furnace
BOF	Basic oxygen furnace
CaPex	Capital cost
CBAM	Carbon border adjustment mechanism
CCfD	Carbon contract for difference
CCMT	Climate change mitigation technologies
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
DRI	Direct reduced iron
EAF	Electric arc furnace
ETS	Emissions trading system
GPP	Green public procurement
H2020	Horizon 2020
H-DRI	Hydrogen direct reduced iron
KPI	Key performance indicator
LOCS	Levelised cost of steel
MOE	Molten oxide electrolysis
OHF	Open hearth furnace
OpEx	Operating cost
R&D	Research and development
RFCS	Research fund for coal and steel
TRL	Technology readiness level

List of figures

List of tables

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