STUDY

Requested by the ITRE committee

European Parliament

Moving towards Zero-Emission Steel

Technologies Available, Prospects, Timeline and Costs

Policy Department for Economic, Scientific and Quality of Life Policies
Directorate-General for Internal Policies
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Abstract

This study is assessing the European steel industry's possible decarbonisation pathways in light of the European Commission's "Fit for 55" package, by evaluating available technology options and the adequacy of available funding streams. The paper shows that options based solely on existing production processes have limited potential to achieve the required emission reductions. Full decarbonisation options will require the widespread availability of green electricity, hydrogen and/or CCS/CCUS infrastructure. It is important that flexibility in the choice of technology decarbonisation options is maintained to account for differences in regional characteristics including natural resources and infrastructure.

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LIST OF ABBREVIATIONS

BF	Blast Furnace
BOF	Basic Oxygen Furnace
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CE	Circular Economy
CEAP	Circular Economy Action Plan
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and/or Storage
CCU	Carbon Capture and Utilisation
CSP	Clean Steel Partnership
DG	Directorate General
DPP	Digital Product Passport
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EC	European Commission
ECSC	European Coal and Steel Community
EGD	European Green Deal
EIB	European Investment Bank
EOR	Enhanced Oil Recovery
EP	European Parliament
EC	European Commission
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse Gas
GDP	Gross Domestic Product
GVA	Gross Value Added
ICT	Information and Communication Technologies
IPPU	Industrial Processes and Product Use
JTF	Just Transition Fund
JTM	Just Transition Mechanism

MEA	Monoethanolamine
MS	Member State
Mt	Million tonnes
NGEU	Next Generation EU
OPEX	Operational Expanditure
RD&I	Research, Development and Innovation
RFCS	Research Fund for Coal and Steel
RRF	Recovery and Resilience Facility
SMR	Steam Methane Reforming
SPI	Sustainable Products Initiative
TGR	Top Gas Recycling
TRL	Technology Readiness Level
USA	United States of America

EXECUTIVE SUMMARY

Background

Around the world, economies and industrial sectors are undergoing important transformations driven by the urgency of addressing climate change and meeting Paris Agreement goals. This is also the case for the iron and steel industry. As the European Union is moving towards achieving carbon neutrality by 2050 and reducing its Greenhouse Gas (GHG) emissions by 55% by 2030, decarbonisation of the iron and steel sector must be part of this process. As one of the energy-intensive industries, the iron and steel sector is hard to decarbonise. However, numerous technology options already exist that can support the decarbonisation of the sector in an integrated manner.

Steel is an indispensable material in our everyday lives. It is used in the production of cars, in our buildings and urban infrastructure and to produce the renewable energy technologies required for the energy transition such as wind and solar power. Thus, steel is expected to remain a key material also in the future. The iron and steel sector is a cornerstone of the European economy and industry. In 2020, the sector supported a total of 2.6 million jobs out of which 326,000 were direct. Altogether, the EU steel industry contributes with €132 billion in Gross Value Added (GVA) to our economies. Given its importance for the European citizens and the economy, it is imperative to transform the sector while ensuring that it is retained in Europe.

Aim

The aim of this in-depth analysis is to give an independent assessment of the European steel industry's decarbonisation pathways as well as available technology and funding options in light of the European Commission's Fit-for-55 package proposed in July 2021. To reach -55% emissions by 2030, Europe and its industry must step up its ambitions and channel necessary investments that will determine the future of the industry in the next decades. The paper identifies the most promising technologies in this regard, based on interviews with industry and other stakeholders, and taking into account the currently planned decarbonisation paths of major players.

Key Findings

Besides providing an overview of the policy developments shaping industrial decarbonisation on the European level, the paper discusses trade and competitiveness issues faced by the EU steel sector as well as the societal and economic relevance of the sector. As argued above, the European steel industry is a cornerstone of the European economy and industry. Besides the employment impacts that a transformation of the sector brings, the steel industry is highly exposed to international trade impacts: the bloc's competitive position has deteriorated in recent years due to a downward price-trend partly attributed to global steel overcapacities, with Chinese steel exports ruling the market and making the EU a net importer of finished steel products. Since the steel industry is capital and energy intensive, any required investment into decarbonisation technologies will impact the profitability of EU steelmakers that already operate in highly competitive global markets. Thus, a major challenge for the EU steel industry will be to remain competitive vis-à-vis players based in regions where carbon regulations and costs are non-existent or limited.

In section 2 we describe the conventional production routes of making steel, followed by introducing to the available low carbon technology options proposed for the industry. The Blast Furnace – Basic Oxygen Furnace (BF/BOF) steel-making process is still the most wide-spread method used in the EU (accounting for 60% of steel production in EU) despite it being heavily carbon-intensive, but new ways

of producing steel are starting to enter the market with promising results. Some of these technologies are aimed at optimising the traditional BF route and/or retrofitting plants with CCUS, while others rely on switching to Electric Arc Furnaces (EAF), using increased quantities of scrap steel, often combined with Direct Reduced Iron (DRI) technology powered by natural gas or hydrogen. While we conclude that options based on existing production processes have limited potential to achieve the required CO_2 reduction targets, the more progressive route would require the availability of cheap, renewable energy in the future to become economically viable. The steel industry of the future will most likely follow the hydrogen-based DRI route once hydrogen is widely available at competitive prices to replace natural gas-based processes, but the speed and impact of this route greatly depends on progress regarding the availability of green electricity and hydrogen. At last, the use of CCS/CCUS will likely be needed for a zero-carbon industrial future: the technology doesn't only remove those hard-to-abate GHG units from production that can't be decarbonised further but can also play a role in supporting the large-scale deployment of climate-friendly hydrogen by capturing the CO_2 emitted during the conventional, natural-gas based production as a steppingstone until enough RES and electrolyser capacity is available to produce green hydrogen.

The analysis in section 3 on different public funding instruments at EU-level shows that although these constitute an important support for the sector, they are not enough to fully drive forward the transformation of the sector. The dedicated support instruments for the sector, the Research Fund for Coal and Steel and the new European Clean Steel Partnership (CSP) are crucial for the support of RD&I technologies. The CSP constitutes a good example of public-private cooperation with an EU contribution of €700 million and a private commitment of up to €1 billion[1]. A coordinated approach based on public support and industry investments will be required to arrive to finance the transition. However, there is still a large public funding gap to support scale-up and roll-out at industrial scale of the most mature technologies. Estimates suggest that new, low-CO_2 production technologies will require an investment of approximately €50-60 billion, with €80-120 billion/y capital and operating costs[2]. Given the energy-intensity of the sector, support for financing operational costs (OPEX) will also be important. Furthermore, the study finds that current funding mechanisms could benefit from being less bureaucratic and more flexible.

The full set of conclusions and recommendations focused on funding, regulation and technology and based on the analysis of this study are presented in section 4 of this report.

[1] Eurofer (2021) Launch of the Clean Steel Partnership paves the way for further research and deployment of ground-breaking technology. Available at: https://www.eurofer.eu/news/launch-of-the-clean-steel-partnership-paves-the-way-for-further-research-and-deployment-of-ground-breaking-technology/#:~:text=The%20partnership%20will%20develop%20the,our%20industry's%20overall%20climate%20strategy.

[2] For information on the methodology to calculate the figures cited please see: GreenSteel for Europe (2021)) *Investment Needs*. Available at: https://www.estep.eu/assets/Uploads/GreenSteel-D2.2-Investment-Needs-Publishable-version.pdf.

1. CONTEXT AND SUBJECT OF THE STUDY

1.1. Policy context

In this subsection, we provide a brief summary of some of the main policies, strategies and instruments that shape the industrial decarbonisation transition in the European Union (EU), and which are of particular relevance for the steel industry.

Around the world, economies and industrial sectors are undergoing important transformations driven by the urgency of addressing climate change. In Europe, the European Green Deal (EGD), presented in December 2019, sets out the new growth and decarbonisation vision for the EU. The EGD aims at transforming the EU into a modern, resource-efficient, and competitive economy, where economic growth is decoupled from resource use. It aims at achieving a climate-neutral and prosperous continent by 2050. The European Climate Law, adopted in July 2021, writes into law the targets set out in the European Green Deal for Europe's economy to become a climate neutral continent by 2050. It also sets a transitional target of reducing GHG emissions by 55% in 2030 (compared to 1990 levels).

In July 2021, the European Commission (EC) adopted several proposals to revise the policy instruments for delivering on the transitional targets of reducing GHG emissions by 55% in 2030. Collectively, the updated policies make up the Fit-for-55 package and include[3]:

1. **Revision to the EU Emissions Trading System (ETS) to increase its ambition**
   The EU ETS is considered a key tool to reduce GHG emissions from power and manufacturing sectors[4], including the iron and steel sector. It is based on the 'cap and trade' principle, with a cap set on the total amount of GHG emissions that can be emitted by installations covered under the EU ETS system, where installations can buy or receive emissions allowances that can be traded. Installations must surrender enough allowances that cover their emissions. On the other hand, if an installation reduces its emissions, it can make use of its spare allowances to cover its future needs or trade them with another installation that is short of allowances[5].
   The Fit-for-55 package aims to reduce GHG emissions of sectors covered under the EU ETS by 61% by 2030 compared to 2005 levels. This will be done through a one-off reduction of the overall emissions cap by 117 million allowances, accompanied with a stronger linear reduction factor of 4.2% per year instead of the 2.2% under the current system. Moreover, the allocation of free allowances under the EU ETS will have to reflect technological progress in innovative low-carbon technologies[6]. In addition, strengthening the Market Stability Reserve (MSR)[7] is linked to the review of the EU ETS. Increasing EU ETS ambitions will require MSR rules to remain fit to their purpose to tackle structural imbalances in the allowances throughout the 4th phase of the EU ETS.

[3] EC. (2021). Delivering the European Green Deal: The Decisive Decade – Architecture.
Available at: https://ec.europa.eu/commission/presscorner/detail/en/fs_21_3671.

[4] The scope of coverage of the EU ETS has been expanded in the latest revision to include emissions from the aviation sector. The new legislative proposal would also establish a new emissions trading system for emissions generated from fuels in road transport as well as buildings.

[5] EC. *EU emissions trading system (EU ETS).* Available at: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_en.

[6] EC. (2021). *Increasing the ambition of the EU emissions trading*. Available at: https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/increasing-ambition-eu-emissions_en.

[7] The Market Stability Reserve (MSR) is a system that has been established to address the surplus of allowances included in the EU ETS system since 2009 and to improve the system's resilience to major shocks by adjusting the supply of allowances to be auctioned.

2. Introduction of a Carbon Border Adjustment Mechanism (CBAM)

CBAM was introduced in the Fit-for-55 package as a measure to reduce the risk of carbon leakage[8] as the EU increases its climate mitigation ambition. The mechanism will be designed in compliance with the World Trade Organisation (WTO) rules. The CBAM aims at encouraging producers in non-EU countries to green their production and align it with the EU targets. The proposed system will require EU importers to buy certificates corresponding to the carbon price that would have been paid, had the goods been produced under the EU's carbon pricing rules. The pricing of certificates will depend on the auctioning price of EU ETS allowances. Applying CBAM will ensure that importers pay the same carbon price as EU domestic producers, thereby maintaining the competitiveness of the EU industry9.

3. Revision of the Energy Efficiency Directive (EED)

The revised EED seeks to introduce new EU 2030 binding targets of 36% for final and 39% for primary energy consumption. The revision introduces indicative Member State (MS) contributions to the EU-level target for energy efficiency and increases the annual energy saving obligations of all MS to 1.5%. Furthermore, it states that the 'energy efficiency first' principle should be applied to policy and investment decisions.

4. Revision of Renewable Energy Directive (RED)

Under the proposal the new target for 2030 would consists in 40% of renewable energy as compared to the current target of 32% share of renewable energy in the final energy consumption. In addition, the proposal introduces a 1.1 percentage point annual increase in renewable energy use as indicative target for industry.

5. Alternative Fuels Infrastructure Regulation

Under the Fit-for-55 proposal the current Alternative Fuels Infrastructure Directive would be transformed into a Regulation. The proposal reformulates provisions concerning the deployment of alternative fuels infrastructure, including fleet- and distance-based targets for road vehicles, vessels and stationary aircrafts where currently no mandatory EU-wide targets are set and the reporting on the deployment of such infrastructure, among other aspects.

The EGD objectives towards climate neutrality and green transition also helped shape the new **European Industrial Strategy,** initially launched by the EC in March 2020 and updated in May 2021, with the aim of supporting the achievement of the EGD objectives towards climate neutrality and green transition. The strategy outlines the fundamental points for Europe's industrial transformation while acknowledging that there isn't a standalone solution to strengthen industry's transition, but that rather several key aspects should be considered, interconnected and reinforce each other.

These fundamental include:

1. Creating certainty for industry: A deeper and more digital single market;
2. Upholding a global level playing field;
3. Supporting industry towards climate neutrality;
4. Building a more circular economy;
5. Embedding a spirit of industrial innovation;

[8] Carbon leakage refers to the situation where businesses transfer their production to other countries with laxer GHG emissions constraints that the EU for costs reasons related to climate policies. This could lead at the end to an increase in their total emissions. This risk is usually high in certain energy-intensive industries, including iron and steel industry.

[9] EC. Press corner. Carbon Border Adjustment Mechanism.
Available at: https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661.

6. Skilling and reskilling; and
7. Investing and financing the transition

On supporting industry towards carbon neutrality, the strategy stated that modernisation and decarbonisation of energy-intensive industries is a top priority. It also reaffirmed the role of 'energy efficiency first' principle in reducing emissions across the industries, with secure and sufficient supply of low-carbon energy at competitive prices, which will require planning and investing in low-carbon generation technologies, capacities and infrastructure. It highlighted the importance of carbon border adjustment mechanisms to ensure global level playing field and reduce the risk of carbon leakage.

One year later in May 2021, the industrial strategy was further updated to focus more on proposing actionable measures based on the priorities set out in the March 2020 Communication and addressing the new circumstances resulting from the COVID-19 pandemic[10], in particular:

- Strengthening the resilience of the Single Market;
- Supporting Europe's open strategic autonomy through addressing dependencies; and
- Supporting the business case for the twin green and digital transitions[11].

The **EU Hydrogen Strategy** is also highly relevant for the iron and steel industry given that, as it is explained below, many of the decarbonisation options are based on hydrogen. The Strategy aims to arrive at 40 GW of electrolysers producing renewable (also known as 'green') hydrogen by 2030 capable of producing up to 10 million tonnes (Mt) of renewable hydrogen[12,13]. By 2050, the Strategy envisions large-scale deployment of hydrogen across energy-intensive industry, transport and other hard-to-decarbonise sectors.

Increasing the circularity of the iron and steelmaking processes will be an important aspect of the transition towards decarbonising the iron and steel sector. In this context, the **Circular Economy Action Plan** (CEAP) of 2020 is another key building block of the European Green Deal and the main guidance for transitioning to a circular economy. Measures in the CEAP aim to make sustainable products a norm in the EU, while empowering consumers and ensuring there is less waste. They focus on the sectors that use most resources and where the potential for circularity is high such as: electronics and information and communication technologies (ICT), batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water and nutrients. The following points of the CEAP's policy measures targeting industry and industrial emissions can be relevant for the steel industry:

- **Sustainable Product Initiative (SPI)** on the extension of product scope and of requirements regarding the Eco-design of products, on the introduction of a Digital Product Passport, on economic and reputational incentives for circular products and on support for circular business models;
- Mandatory Green Public Procurement criteria;

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10 The update does not replace the 2020 industrial strategy.

11 EC (2021) Updating the 2020 Industrial Strategy: towards a stronger Single Market for Europe's recovery. Available at: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_1884.

12 EC (2020) COM (2020) 301 final. A hydrogen strategy for a climate-neutral Europe. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301&from=EN.

13 For context, note that decarbonising 94 Mt of steel, which is the amount of steel produced in the EU in 2019 that is suitable for the hydrogen route, would require approximately 37-60 GW of electrolyser capacity according to the following study: Morfeldt, J. et al. (2015) The impact of climate targets on future steel production – an analysis based on global energy system model. Journal of Cleaner Production vol. 105 p. 469. Available at: https://www.sciencedirect.com/science/article/pii/S0959652614004004?via%3Dihub.

- Circularity criteria in the revision of the Industrial Emissions Directive;
- Requirements for recycled material content in products; and
- Restrictions to extra-EU export of waste.

1.2. Trade and competitiveness

The steel industry represents an important economic pillar of the European economy. Crude steel production in the EU represents 7.6% (139.3 Mt in 2020) of the overall production globally (1,828.2 Mt in 2020), with Germany being the leader of steel production in the EU[14]. Nonetheless, Europe's competitive position has deteriorated in recent years as prices globally have been on a downward trend, partly due to global steel overcapacities. Already in 2015, the economic slowdown adversely impacted the global demand for steel, with production in China generating overcapacity and decreasing the price of steel worldwide. At the same time, in the past three years EU imports from China have increased. EU exports of finished steel products shrunk from nearly 25.7 Mt in 2011 to almost 17.7 Mt in 2020, making Europe a net importer of these products, with around 21.1 Mt of finished steel imports into the EU in 2020, mostly coming from Turkey, Russia, South Korea and China as shown in Figure 1-1[15]. It is worth mentioning that the carbon pricing policies adopted in top exporting countries to the EU are currently not as ambitious as in the EU[16]. This results in the European steel industry being both highly exposed to international trade impacts as well as unfair trade practices. Consequently, the EU is looking at policy instruments to account and correct for the unequal environmental requirements of tradable products based on mechanisms such as the CBAM and the SPI.

One of the issues that affected the EU steel exports was the trade dispute that took place in the administration of Donald Trump, former president of the United States of America (USA), who decided in 2018 to add extra tariffs on EU exports of steel and aluminium entering the US, with 25% additional tariffs on steel and 10% on aluminium. This resulted in almost 50% reduction of finished steel exports to the USA between from 2018 to 2020. However, on 31 October 2021, the EU and USA jointly announced an agreement to end the dispute on steel and aluminium and promote low-carbon steel production.[17] The two partners have agreed to reach an arrangement in the framework of the next two years to promote production of low-carbon emissions steel and aluminium through establishing supportive domestic policies. Moreover, they plan to apply measures aimed at ensuring that these policies aimed at promoting green steel are not circumvented by imports from countries producing carbon-intensive steel. The steel arrangement will be open to other countries wishing to join.

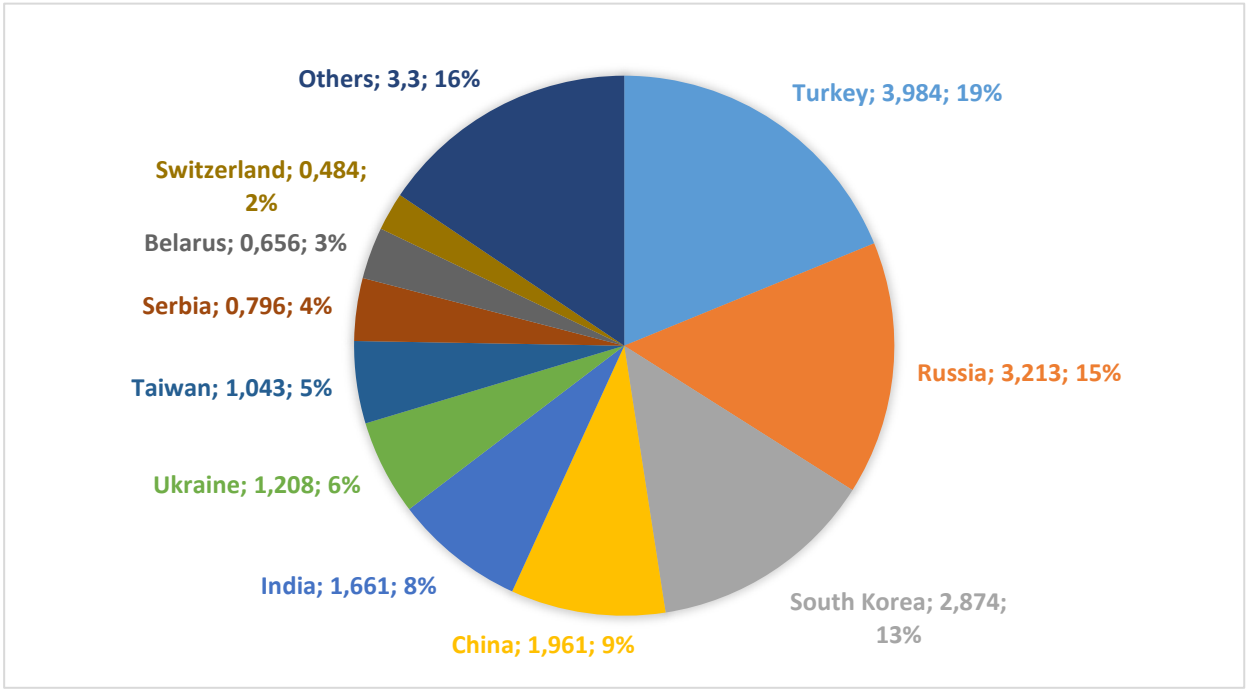
[14] EUROFER (2021) *European Steel in Figures*. Available at: https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2021/European-Steel-in-Figures-2021.pdf.

[15] Ibid.

[16] There are no carbon pricing tools in Russia (e.g., cap and trade, carbon tax). Some regions in China such as Shanghai have launched an ETS system in 2021, covering electricity generation, with an average carbon price of 6.18 USD/ton CO_2 (much cheaper than EU carbon prices) with the aim of further expanding the ETS system to cover heavy industries (e.g. petrochemicals, iron and steel, chemicals). In Turkey, there are no explicit carbon pricing tools, however, fuel excise taxes are an implicit form of carbon pricing covering, CO_2 emissions from energy use.

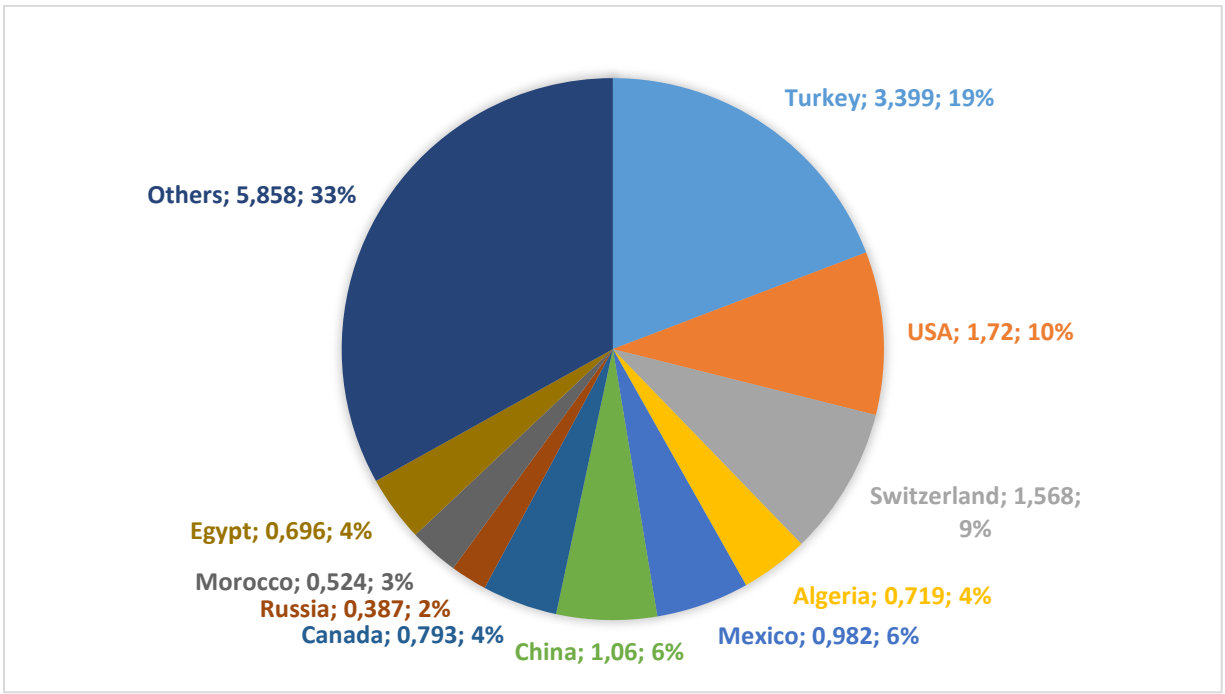
[17] Ammann J. for Euractiv (01/11/2021) EU and US slash tariffs, start cooperating on 'green steel'. Available at: https://www.euractiv.com/section/economy-jobs/news/eu-and-us-slash-tariffs-start-cooperating-on-green-steel/.

Figure 1-1: Imports of finished steel into the EU in 2020 (in Mt) and share of imports by country (%)



Source: Eurofer (2021): European Steel in Figures.

Figure 1-2: EU Exports of finished steel from the EU in 2020 (in Mt) and share of exports by country (%)



Source: Eurofer (2021): European Steel in Figures.

Since the steel industry is capital (high capital expenditure (CAPEX)) and energy intensive (affecting operational expenditure (OPEX)), any required investment to decarbonise its production will impact the profitability of EU steelmakers that already operate in highly competitive global markets.

It is estimated that regulatory costs account for between 20% to 30% of margins and maybe even higher than 100% in some years[18]. Thus, a major challenge for the EU steel industry will be to remain competitive vis-à-vis players based in regions where carbon regulations and costs (see section on the ETS above) are non-existent or limited. EU policies such as the CBAM and SPI are aimed at addressing this issue. This is further complicated by rising energy prices in Europe and the need to employ industrial workforce in 'future-proof' jobs as contribution to a Just Transition[19].

Hence, to decarbonise the European steel-making industry, a supportive EU policy framework is of essence. Such policy should define a proper mix of pull and push measures to incentivise new business models, create markets for climate-neutral, circular economy steel and derived products and close the initial cost gap between conventional and low-carbon steel.

On the other hand, changing customer preferences driven by increased awareness of climate change and a growing demand for low-carbon products are putting pressure on companies to innovate. It is estimated that about 14% of steel companies globally are at risk of losing value if they are unable to address their environmental impact[20,21].

1.3. Societal and economic relevance

Iron and steel are indispensable materials for our everyday lives; they are used as a material input for the automotive industry, energy production and networks, urban and long-distance transport infrastructures, and general mechanical engineering industries. Steel is also expected to be a key material in the future as changing environments will likely require steel to meet infrastructure and construction needs around the world and to build climate-resilient cities and coastal protection. Steel is also a key material to produce renewable energy technologies such as wind and solar energy[22]. For these reasons, and to avoid external dependence on this versatile material, it is in Europe's interest to ensure domestic production is retained as the sector evolves towards new modes of productions compatible with a climate-neutral Europe. In the following sections we present a short overview of the current situation of the EU iron and steel sectors and highlight the important role they play in creating employment for EU citizens both directly and indirectly.

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18 CEPS (2013), Assessment of cumulative cost impact for the steel industry. Available at:, https://www.ceps.eu/ceps-publications/assessment-cumulative-cost-impact-steel-industry/.

19 The decarbonisation process and shifting to non-conventional production route could result in jobs losses, therefore employees previously occupying jobs related to the conventional production value chain might need re-skilling and re-training to be able to maintain their jobs as the industry decarbonises, while according to Just Transition principles, employers should provide them with these opportunities. Investments in clean technologies at the same time are also resulting in the creation of new, 'future-proof' jobs.

20 McKinsey & Co. (2020), Decarbonisation challenge for steel – Hydrogen as a solution in Europe.

21 Crocker, T. et al. for CDP: Disclosure Insight Action (2019) Melting Point: Which steel companies are ready for the low-carbon transition? Available at: https://cdn.cdp.net/cdp-production/cms/reports/documents/000/004/659/original/CDP_Steel_2019_Executive_summary.pdf?1564490803.

Note: The study is based on the evaluation of 20 global steelmakers. The figure represents a weighted average value of all companies where individual results range from 2 to 30%. The study assumes a price of CO_2 of 100 USD. Two companies with headquarters in Europe were considered: SSAB (Sweeden), ArcelorMittal (Luxembourg).

22 "Each new MW of solar power requires between 35 to 45 tons of steel, and each new MW of wind power requires 120 to 180 tons of steel". For more information see: ArcelorMittal (accessed on 20/11/2021) Steel is the power behind renewable energy. Available at: https://corporate.arcelormittal.com/media/case-studies/steel-is-the-power-behind-renewable-energy.

1.3.1. Production and employment in the EU iron and steel sector

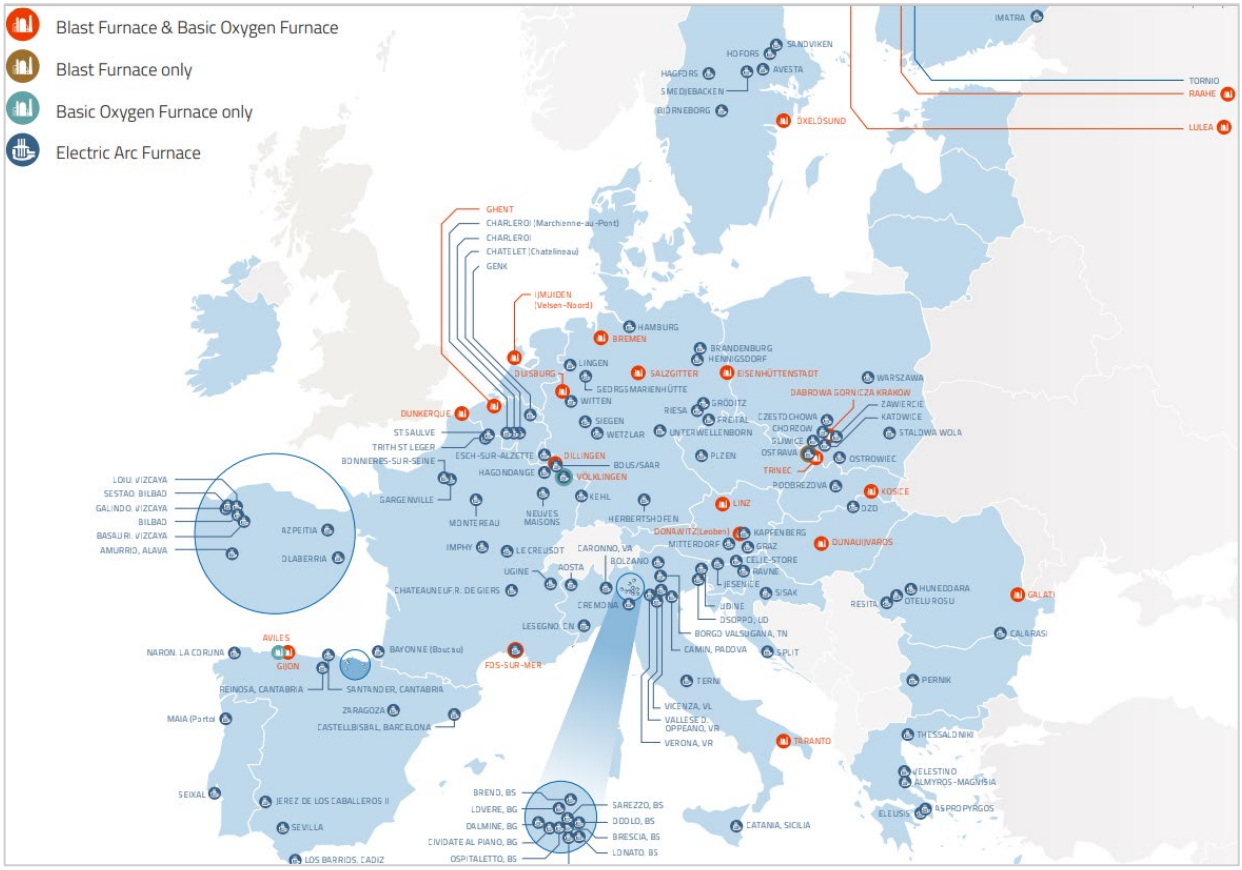
The iron and steel sector is a cornerstone of the European economy and industry. A total of 2.6 million jobs are supported by the steel industry, of which 12.2% are direct jobs and the remaining 87.8% are indirect and induced jobs[23].

Altogether, the EU steel industry contributes with €132 billion in Gross Value Added (GVA) to our economies. During the last decade, the number of direct jobs decreased by almost 40 000, which is similar to the trend observed in total crude steel production over the same period.

Direct employment in the EU steel industry is the highest in Germany (25.5%), followed by Italy (9.3%) and France (8.1%). These shares are also reflected in output figures: Germany produces 25.6% of all steel output in the EU, Italy follows with 14.6% and France with 8.3%. Other big producers are Poland and Spain. The sector produces steel at more than 500 sites across 22 EU Member States, with Figure 1-3 showing the map of production sites and associated production methods.

Recently, investment decisions have become challenging due to the tight investment margins and strong competition, especially on the global level. The economy slowdown during the COVID-19 pandemic has made the situation worse, resulting in a reduction in steel products demand in 2020 and fall in prices of nearly 30% compared to 2018 levels.

Figure 1-3: Map of primary and secondary steel production across the EU



Source: EUROFER (2021). European Steel in Figures.

[23] EUROFER (2021) European Steel in Figures. Available at: https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2021/European-Steel-in-Figures-2021.pdf.

and https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2021/European-Steel-in-Figures-2021.pdf.

Table 1-1 below shows the consumption of steel by different sectors based on 2020 data from EUROFER. Consumption compared to 2019 is lower in all categories, including a -18.18% drop in the automotive sector and -5.68% in construction, due to the COVID-19 pandemic's effects on Europe's economy. Crude steel production was down to 139.3 Mt from 157.5 in 2019, basically halving production volumes in the second quarter of the year. Numbers from 2020 are thus only partly representative of the sector's performance, but indicative of the challenge of the industry to recover and stay competitive while also adapting to newer and cleaner technologies. With time, on the other hand, enhanced circular practices can drive overall crude steel production output down, given steel's 'infinite recyclability[24]' as pointed out by EUROFER; making the steel sector an important player in the circular economy.

Table 1-1: Steel consumption per sector

Sector	% share of steel demand in 2020
Construction	38%
Automotive	15%
Mechanical Engineering	16%
Metalware	15%
Tubes	14%
Domestic appliances	10%
Other Transport	2%
Miscellaneous	2%

Source : EUROFER (2021).

[24] Recycled steel at the time often displays downgraded quality, thus technological and regulatory improvements in this field are necessary.

2. TECHNOLOGIES AVAILABLE, PROSPECTS, TIMELINE AND COSTS

2.1. Low-carbon/carbon neutral technology and options for the steel industry

In the following subsections, we provide a brief description of the currently most wide-spread ways to make steel, followed by a description of the low carbon/carbon neutral technology options[25] proposed for the steel industry.

The technology options currently available and described below can be broadly categorised into those focused on increasing the efficiency of current production methods, including options to retrofit existing plants with Carbon Capture and Storage/Utilisation (CCUS), and those replacing the traditional steelmaking production routes.

2.1.1. Steelmaking – the traditional way (BF/BOF)

Before we introduce the latest technologies in steelmaking, it's worth to take a look at the traditional processes. The most common production route is the Blast Furnace – Basic Oxygen Furnace (BF/BOF) steel-making process, which uses a mix of liquid iron and scrap steel and accounts for close to 60% of the crude steel output in the EU, while the rest is produced in Electric Arc Furnaces (EAF)[26]. These ratios seem to be changing slowly as more producers move to the EAF process due to decarbonisation efforts. EAFs are often dedicated to produce lower quality steel from scrap steel or directly reduced iron (DRI) feedstock, and the process is easier to decarbonise given that most emissions come from the electricity source powering the furnace. Figure 2-1 illustrates both processes including ironmaking.

Steelmaking is still one of the most carbon-intensive industrial processes in the world, the iron and steel sector dominates the industrial emissions in the EU (together with the cement and chemicals sectors)[27], generating around 152 mega tons of CO_2-equivalent ($MtCO_2e$), of which 41% are process-related and 59% are energy related[28]. The process-related GHG emissions represented around 18% of the total Industrial Processes and Product Use (IPPU) GHG emissions. Most of the process-related GHG emissions are attributed to the iron reduction process in the blast furnace (BF/BOF).

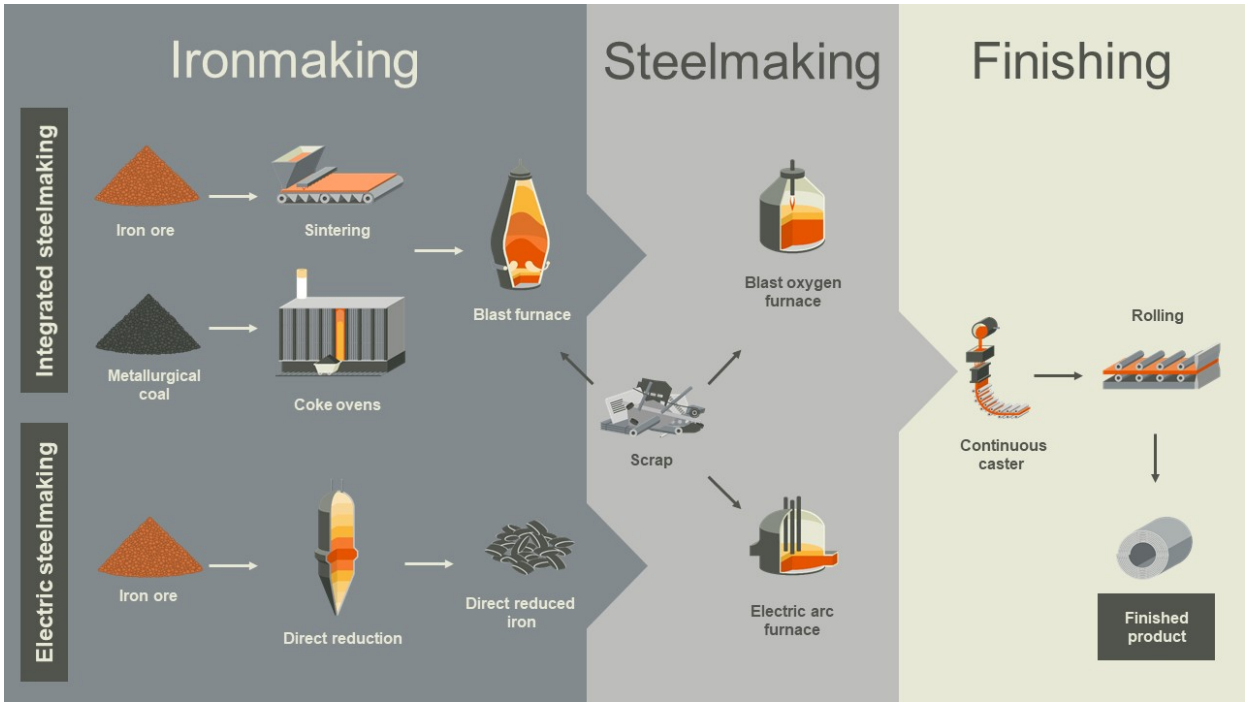
[25] We based our selection of the technologies on the following key factors: i) Technology readiness level ≥ 6; ii) Possible market entry before year 2030; iii) Commercial availability to achieve the accelerated target of the Fit-for-55 package by 2030.

[26] EUROFER (2021) European Steel in Figures. Available at: https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2021/European-Steel-in-Figures-2021.pdf.

[27] Steel, cement and chemicals sectors generate the highest volumes of GHG emissions in the manufacturing sector.

[28] EEA. (2018). Annual European Union greenhouse gas inventory.

Figure 2-1: Iron and steelmaking processes



Source: BHP (2020). Pathways to decarbonisation episode two: steelmaking technologies

2.1.2. Available low-carbon/carbon neutral technology options for the steel industry

As described in the section above, the traditional iron and steelmaking processes are highly carbon-intensive and generate large amounts of GHGs. Nonetheless, steel is and will remain a key commodity in the economy and an important material in the construction sector and for maintaining and developing new infrastructure. Thus, new ways of producing iron and steel are required to reconcile our need for these materials and the urgent task of decarbonising our economy. The alternative, low-carbon and /or carbon neutral steelmaking technologies selected and described below are the ones which are most advanced in terms of Technology Readiness Levels[29] (TRLs) and thus either already being deployed or with the potential for large-scale deployment by 2030. Many of these technologies are based on optimisation of the traditional iron and steelmaking process (BF/BOF) described above, other options rely on transitioning from the BF/BOF process into the EAF or DRI ones. Given that EAF is based on the electrification of the melting process, the availability of cheap, renewable energy in the future will play an important consideration in choosing this option. The hydrogen-based DRI production route will greatly depend on the availability of green electricity and hydrogen. In the next section we provide a comparative analysis of the different available options for producing low-carbon/carbon neutral steel.

[29] Horizon 2020 – *Working Programme 2014 - 2015*. (2014). General Annexes: Annex G: Technology readiness levels (TRL). Available at: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf.

I. Increased use of recycled scrap or steel

Recycling one tonne of steel can save 1.5 tonnes of CO_2, 1.4 tonnes of iron ore, 740 kg of coal and 120 kg of limestone compared to primary steel produced in a traditional blast furnace[30]. However, main challenges to increase the use of recycled scrap are increasing the recycling rate of steel scrap and the quality of recycled steel or scrap, which is often contaminated with other trace elements (mostly with copper). Improving the quality of scrap can take place in the downstream applications in steel value chain by improving dismantling and sorting of end-of-life products. Upstream activities that involve design changes due to reduce copper usage and facilitate the disassembly of end-of-life products can facilitate downstream dismantling processes[31].

Near net shape casting

This process encompasses various technologies that result in significant shortening of the process-chain from liquid steel to final steel product. This process can substitute the conventional hot rolling process[32], which represents around 20% of the steel production process emissions.

Examples of this process include the Castrip® process used for producing flat-rolled, carbon and stainless-steel sheets at very thin gauges. It allows steel makers to produce thin flat-rolled products in far fewer process steps compared to the conventional process, saving money on both capital (CAPEX) and operational (OPEX) costs, with considerable savings of time and energy[33].

Top gas recycling (TGR – BF)

Top gas recycling (TGR) process entails modifications in the existing BF to allow for the re-usage of the reducing agents contained in the blast furnace top gas. In this process, CO_2 is removed from the top gas leaving the BF to recycle the reducing agents: carbon monoxide (CO) and hydrogen (H_2). This modification reduces the demand for coke and hence the energy demand for this step and associated emissions from the coking plant. TGR-BF consists of the following modifications to the conventional BF:

- Injection of CO and H_2 (reducing top gas components) into the shaft and/or hearth tuyeres[34];
- Lower fossil-based carbon input due to lower coke rates;
- Use of pure oxygen in place of hot air blast at the hearth tuyere (elimination of nitrogen);
- Recovery of high-purity CO_2 from the top gas for underground storage or use (CCUS)[35].

Smelting reduction process (in combination with CCS)

Conventional BF production process requires the pre-processing of raw materials, iron ore into sinter and pellets and coal into coke. The smelting reduction process (commonly known as HIsarna process)[36]

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30 Bellona (2021) Climate action in the steel industry.

31 Joint Research Centre, the European Commission's science and knowledge service. (2020). *Decarbonisation of industrial heat: The iron and steel sector*. Available at: https://ee-ip.org/fileadmin/user_upload/DOCUMENTS/Content/JRC119415_-_Iron_and_steel_decarbonisation_brief.pdf.

32 This process results in steel that has been roll-pressed at very high temperatures—over 930 ˚C (1,700˚F), a temperature above the re-crystallization point for most steels types. This makes the steel easier to form and results in products that are easier to work with.

33 Brian Wang. (2017). Article: *New steel process is faster, lower cost, higher quality, uses 5-10 times less energy and enables new thinner sheets*. Available at: https://www.nextbigfuture.com/2017/03/new-steel-process-is-faster-lower-cost.html.

34 A tuyere is a tube or pipe used to air blown air into a furnace or hearth.

35 A. Keys, M. van Hout, B. Daniëls (2019) Decarbonisation options for the Dutch steel industry.

36 Tata Steel (2020) HISARNA: Building a sustainable steel industry.

is considered an innovative process that eliminates the pre-processing steps with iron ore directly undergoing smelting reduction process. In this process, iron ore (which can be mixed up to 50% with scrap) is reduced directly into pig iron in a reactor. This process allows for CO_2 emissions reductions up to 85%. Since the CO_2 exhaust from this process is relatively clean, it is suitable for CCS application. Captured CO_2 can be transported via CO_2 networks and injected into storage locations[37].

Carbon Capture Sequestration and Utilisation

The carbon dioxide produced during the steelmaking process can be captured at all three CO_2 point-sources of the traditional BF/BOF process. Capturing the CO_2 from the BF and coking ovens using carbon capture technologies can reduce emissions by approximately 70%[38]. An important advantage is that carbon capture can be retrofitted to existing assets, maintaining the already purchased equipment without disrupting the BF/BOF process[39].

Research to efficiently capture CO_2 from the blast furnace gas using pre-combustion CO_2 removal technology has received support from the EU through the Horizon 2020 R&I programme. The STEPWISE project focused on developing a CO_2 capture technology based on the Sorption Enhanced Water Gas Shift (SEWGS) process. The process combines CO_2 adsorption[40] and water-gas shift (WGS) reaction into one, with an overall gain in energy efficiency. It is estimated that the technology has the potential to decrease the worldwide CO_2 emissions by 2.1 Gt/yr based on current emission levels.[41] The pilot unit is situated at the Swerea Mefos facilities in Luleå, Sweden and is fed by the adjacent steel plant of SSAB[42].

Many BF/BOF based steel plants combine the gases from the coke oven, the BF and the BOF in a collection system and burn them at once in a combined heat and power (CHP) plant. For the gas stream exiting the CHP plant, the most common capture technology is based on CO_2 separation using a chemical solvent. CO_2 separation with chemical absorption using a monoethanolamine (MEA)-based solvent[43] is well-know and commercially available.

Carbon dioxide can be either stored underground or used to produce other materials via Carbon Capture and Utilisation (CCU)[44]. The Carbon2Chem® project led by Thyssenkrupp aims to use CO_2 and other gases[45] from the steelmaking process to produce valuable chemicals such as ammonia and methanol. The pilot plant in Duisburg which has been operating since March 2018 has been successful in producing ammonia, methanol and higher alcohols from steel mill process gases. In addition to steel mill gases these processes require additional hydrogen, which is being produced using renewable

Available at: https://www.tatasteeleurope.com/sites/default/files/TS%20Factsheet%20Hisarna%20ENG%20jan2020%20Vfinal03%204%20pag%20digital.pdf

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

38 A. Keys, M. van Hout, B. Daniëls (2019) Decarbonisation options for the Dutch steel industry.

39 Global CCS institute (2017) *CCS: a necessary technology for decarbonising the steel sector*.
Available at: https://www.globalccsinstitute.com/news-media/insights/ccs-a-necessary-technology-for-decarbonising-the-steel-sector/.

40 Adsorption refers to the adhesions of atoms or molecules onto a surface. This is to be contrasted with absorption, which is the process by which one material is retained by another one.

41 For the simple integration the CO_2 avoidance costs is 32 €/tonCO_2. For more information see: https://www.stepwise.eu/.

42 STEPWISE project (Accessed on 06/09/2021). Available at: https://www.stepwise.eu/.

43 For environmental and energy-considerations associated with the use of this solvent see: Luis, P. (2015). *Use of monoethanolamine (MEA) for CO2 capture in a global scenario: Consequences and alternatives*.
Available at: https://www.sciencedirect.com/science/article/pii/S001191641500418X#s0005.

44 For a discussion on CCU abatement potential see: *CCUS Projects Network (2020) Feedstock for the process industries and climate action – The potential of CO2 utilisation*. Available at: https://www.ccusnetwork.eu/sites/default/files/TG2_Briefing-Potential-of-CO2-Utilization.pdf.

45 Steel mill gas comprises 44% nitrogen, 23% carbon monoxide, 21% carbon dioxide, 10% hydrogen and 2% methane.

electricity. The pilot plant runs a two-megawatt alkaline water electrolyser. In its second phase, the project will aim to show that the technology can be upscaled, that there can be long-term stability in the interactions between steel production and chemical synthesis and that the Carbon2Chem® approach can be transferable to other industries besides steel. Lastly, the second phase of the project will aim to bring the technology to market readiness. The second phase of the project has received € 75 million funding from the German Federal Ministry of Education and Research until 2024. Carbon2Chem® is expected to help reduce CO_2 emissions at Thyssenkrupp's steel mill by 30% by 2030[46].

The Steelanol project is another example of CCU applied to the steel industry. This concept is based on ethanol production at the steel mill in Ghent, Belgium using a technology developed by LanzaTech®, whereby gases produced during the chemical reactions associated with the steel production process are fermented by microbes that secrete ethanol[47,48].

Currently, the only large-scale CCS project in steel is the Al Reyadah CCS Project in Abu Dhabi. The project has been in operation since 2016 and it captures 0.8 $MtCO_2$/y. The CO_2 is transported via a 43 km pipeline to the Rumaitha oil field for the purpose of Enhanced Oil Recovery (EOR)[49].

II. Options replacing conventional BF production route

Shifting from BF to EAF

Primary steel making is usually carried out in BF and BOF as described previously, while secondary steel making involves direct smelting of steel scrap from recycled steel feedstock from waste streams in EAFs. EAF process requires less energy and the main energy carrier to this process is electricity.

Accordingly, if the electricity used in this process is produced via renewable energy, this production route can have very low CO_2 emissions. This process however depends on the availability and quality of steel scrap within the EU market. This process is readily available on the market. This production route could achieve significant emission reductions compared to the BF production route, depending on the type of electricity used.

Direct reduced iron (DRI) using Natural Gas/Hydrogen

Using Natural Gas

Direct Reduction of Iron for primary steel production can run on natural gas (NG) instead of using coke in a blast furnace, which already results in a reduction of about 66% in GHG emitted compared to the BF route[50] and is thus a key low-carbon technology to consider. RI with NG requires cheap and constantly available natural gas, thus regions with low gas prices have an incentive for choosing this mode of production (big steel producers using the DRI method are in the Middle East and North

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46 Thyssenkrupp (29/10/2020) Carbon2Chem®: *First project phase successfully completed and notice of funding received from federal government for second phase*. Available at: https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/carbon2chem--first-project-phase-successfully-completed-and-notice-of-funding-received-from-federal-government-for-second-phase-88707.

47 Steelanol (Accessed on 16/09/2021)*Steelanol recycles carbon into sustainable, advanced bioethanol.* Available at: http://www.steelanol.eu/en.

48 Steelanol consists of using a microorganism to ferment the carbon monoxide (CO) contained in the exhaust gases. The microorganism can produce both bioethanol and bio-based raw materials. The steel industry exhaust gases present a high concentration of CO (24%-56%).

49 Ibid.

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

America for this reason)[51]. This technology can be used as an intermediate step before transition to hydrogen (due to limited availability of hydrogen markets given high hydrogen production costs).

Using Hydrogen and EAF

In this process, hydrogen will be used instead of NG to extract iron in direct reduction plants, eliminating CO_2 emissions from iron ore reduction process. The product of this step must then be further smelted into crude steel in an electric arc furnace. Scrap steel can be also smelted in the electric arc furnace together with the reduced iron from the DRI process. If hydrogen used in this process is produced from renewable sources, then this production route (DRI + smelting in EAF) can be carbon neutral.

This process can be commercially available before 2025. It can be initiated using natural gas, to be gradually replaced with hydrogen (due to limited availability of hydrogen markets given high hydrogen production costs).

The project HYBRIT (see case study below) is already using this production route at their Lulea pilot plant. The same technology has been selected and will be pursued by Tata Steel in their plant in Ijmuiden, the Netherlands. The plant had original plans to reduce their emissions using CCS, which upon further assessment got replaced with DRI technology to produce iron using natural gas/ hydrogen before being converted to steel in electric furnaces[52].

Biomass cofiring/ use as reductants

This process uses biomass (secondary biomass, e.g., residues from biomass processing) as an alternative reductant or fuel. Biomass is generally characterized by its high moisture and volatile contents; thus, it must undergo preliminary thermal treatments before its utilization. This option is regionally dependent and most relevant in areas where biomass supply is widely available. In Europe, the availability of biomass is likely not enough to reduce carbon emissions on a large scale[53].

2.2. Comparative analysis of clean steel and emission free production technologies and options

In this section, we conducted a comparative analysis of the above mentioned low-carbon/carbon neutral technologies. Table 2-1 includes the latest available information on the following aspects for each technology:

- Examples of technologies: Examples of projects that are currently in place, in pilot or in demonstration phases that apply the given technology;
- Technology readiness level (TRL): which refers to the estimated technical maturity level of a given technology. It follows of a scale from 1 to 9, with TRL 1 being in a very early stage where 'basic principles are observed', and TRL 9 being a 'technology with an actual system proven in operational environment'[54];

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51 McKinsey & Company. (2020). *Decarbonization challenge for steel – Hydrogen as a solution in Europe*.
Available at: https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel

52 Tata Steel. 15 September 2021. *Tata Steel opts for hydrogen route at its IJmuiden steelworks.*
Available at: https://www.tatasteeleurope.com/corporate/news/tata-steel-opts-for-hydrogen-route-at-its-ijmuiden-steelworks.

53 McKinsey & Company. (2020). *Decarbonization challenge for steel – Hydrogen as a solution in Europe*.
Available at: https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel.

54 Horizon 2020 – *Working Programme 2014 - 2015*. (2014). General Annexes: Annex G: Technology readiness levels (TRL). Available at: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf.

- Possible market entry year: possible year of which the given technology can be brought into the market;
- GHG abatement potential: The magnitude of potential GHG reductions that can be realized via the given technology;
- Cost outlook: expected cost of a given technology, mostly indicative of Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) in €/ton of product; and
- Technical, financial and regulatory barriers facing the implementation of the given technologies. Technical barriers refer to obstacles related to the technological development process of a given technology, while regulatory barriers refer to obstacles due to regulations or policies, and financial barriers are those barriers facing a given technology due to economic reasons.

Table 2-1: Analysis of decarbonisation technology options

Technology Option	Examples (developed/under development)	TRL	Possible Market Entry year	GHG abatement potential (%)	Cost (outlook)	Technical barriers	Financial Barriers	Regulatory Barriers
1. Increased use of recycled of scrap steel	Well-developed and used in several EAF steel plants	Technology Readily available	Currently Available	Up to 58%[55]	Technology readily available at competitive cost	N/A (Technology already in place)	N/A (route cheaper than primary steel production)	Concerns about long-term availability of scrap steel for the industry as well as its quality; lack of incentives for material quality improvements and end-of-life dismantling regulations for construction waste and vehicles
2. Near net shape casting	Castrip, Salzgitter, ARVEDI ESP	8-9	Currently available	60%[56] from the emissions related to conventional hot rolling process, which represents around 20% of the process emissions	CAPEX: ≤ 50 €/ton of product[57]	N/A (Technology already in place)	N/A	N/A

[55] Commission staff working document COM (2021) 350 Final – *Towards competitive and clean European steel*.

[56] ICF Consulting Services Limited and Fraunhofer Institute for Systems and Innovation Research (ISI), 2019 *Industrial Innovation: Pathways to deep decarbonisation of Industry, Part 1: Technology Analysis and Part 2: Scenario analysis and pathways to deep decarbonisation.*

[57] European Commission. (2018). *Impact on the Environment and the economy of technological innovations for the Innovation Fund*.

Technology Option	Examples (developed/under development)	TRL	Possible Market Entry year	GHG abatement potential (%)	Cost (outlook)	Technical barriers	Financial Barriers	Regulatory Barriers
3. Top gas recycling	ULCOS-BF, IGAR	7	2025+	Up to 30%[58] Up to 65% in combination with CCUS[59]	CAPEX: 80-110 €/ton of product without CCUS, and €110-150 €on of product with CCUS [60]	R&D needs for the gas injection systems in the BF, processing of top gases (cleaning, separation, compression), and industrial demonstrations to the project.	Funding is mainly related to de-risking of the project	Availability of biogas, green hydrogen and green electricity when needed
4. Smelting reduction process in combination with CCS	HIsarna	5-6	2030 – 2035	Up to 85%[61] [62]	CAPEX: €500 m (for a 1.15 Mt/year plant excluding. O2 plant which is estimated to be around 435 €/ton-capacity)[63] Full investment cost range: 101 –	More industrial testing and demonstration projects are necessary	Very high CAPEX costs. More funding channels are needed	Insufficient availability of CCS infrastructure, to be integrated to the process and achieve high CO_2 emission reductions

[58] European Commission. In-depth analysis in support of the Commission Communication. *A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. European Commission (773 final).

[59] Green Steel for Europe. (2021). *Technology Assessment and Road mapping*. Available at: https://www.estep.eu/assets/Uploads/210308-D1-2-Assessment-and-roadmapping-of-technologies-Publishable-version.pdf.

[60] Green Steel for Europe. (2021). *Technology Assessment and Road mapping*. Available at: https://www.estep.eu/assets/Uploads/210308-D1-2-Assessment-and-roadmapping-of-technologies-Publishable-version.pdf.

[61] Agora Energiewende and Wuppertal Institute (2021): *Breakthrough Strategies for Climate-Neutral Industry in Europe: Policy and Technology Pathways for Raising EU Climate Ambition*.

[62] Green Steel for Europe. (2021). *Technology Assessment and Road mapping*. Available at: https://www.estep.eu/assets/Uploads/210308-D1-2-Assessment-and-roadmapping-of-technologies-Publishable-version.pdf.

[63] Ibid.

Technology Option	Examples (developed/under development)	TRL	Possible Market Entry year	GHG abatement potential (%)	Cost (outlook)	Technical barriers	Financial Barriers	Regulatory Barriers
					500 €/ton of product[64]			
5. Carbon capture and sequestration and/or use	Carbon2Chem, Steelanol STEPWISEEVEREST (currently being discontinued in favour of the DRI H_2 approach)	7-8	2025 – 2030	63% for CCU[65] And up to 90%[66]	Low technology readiness at high cost	Storage sites and chemical recycling routes need to be available for deployment.	More funding channels needed as the technology will become indispensable. Both CAPEX and OPEX	Requires CO_2 transport infrastructure and access to it. Low public support for the technology
6. Shifting from BF to EAF	Swedish steel company SSAB announced plans to replace approx. 1.5 Mt of conventional steelmaking capacity in Oxeloesund with EAF by 2025	Technology Readily available	Currently Available	63%-73%[67]	Technology readily available at competitive cost	EAFs can only process steel that has already been reduced from iron ore to pig iron in blast furnaces or using hydrogen, or scraps	N/A	N/A
7. Direct Reduced Iron (DRI) using Hydrogen and EAF	HYBRIT, GrINHy, H2Future, SuSteel, SALCOS, SIDERWIN, ULCOWIN	DRI – H2: 7 DRI- electrolysis: 6	DRI H2: 2030 – 2035 DRI- electrolysis: 2040 – 2045	87 – 97%[68]	Technology available at high operating cost. Estimated CAPEX: 101 – 500 €/ton of steel[69], with an estimated OPEX	N/A (Technology already in place)	High costs of hydrogen and electrolysers (for DRI and iron electrolysis). Funding mechanisms need	Related to the certification and availability of hydrogen infrastructure as well as renewable electricity

64 European Commission. (2018). Impact on the Environment and the economy of technological innovations for the Innovation Fund.

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

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

67 Ibid.

68 Ibid ref. 12.

69 European Commission. (2018). *Impact on the Environment and the economy of technological innovations for the Innovation Fund*.

Technology Option	Examples (developed/under development)	TRL	Possible Market Entry year	GHG abatement potential (%)	Cost (outlook)	Technical barriers	Financial Barriers	Regulatory Barriers
					ranging from 490 to 590 €/ton steel[70]		to cover OPEX and not only CAPEX	
8. Direct Reduced Iron (DRI) using NG	ArcelorMittal, Hamburg	Technology Readily available	Currently Available, Before 2025	Up to 66%[71]	Technology readily available	N/A, but NG shall be replaced with H_2 as soon as possible	N/A low cost	N/A
9. Biomass cofiring	SHOCOM, GREENEAF2, ACASOS	Between 2 and 7, depending on the method of biomass application	2030[72]	20% – 42%[73] depending on the substitution rate	Not commercially available yet[74] CAPEX values for integration of pre-processing of biomass in steel plants are relatively low, while OPEX depends mainly on the availability of raw material[75]	R&D needs to demonstrate options that focus on pre-processing (e.g., drying) and upgrading of biomass through testing, scaling up and optimisation of processes, while focusing on smart integration in steel plants. Validation tests are also available	Mainly related to the availability and costs of biomass (operating costs)	Uncertainty on whether the use of biomass for industrial applications (alternative fuel or substitute material) will be promoted in the future, which probably affects investments and research decision in this technology option

70 Agora Energiewende and Wuppertal Institute (2021): *Breakthrough Strategies for Climate-Neutral Industry in Europe: Policy and Technology Pathways for Raising EU Climate Ambition*.
71 Ibid ref. 12.
72 Green Steel for Europe. (2021). *Technology Assessment and Road mapping*. Available at: https://www.estep.eu/assets/Uploads/210308-D1-2-Assessment-and-roadmapping-of-technologies-Publishable-version.pdf.
73 H. Mandova et al, Research Paper (2018) *Possibilities for CO2 emission reduction using biomass in European integrated steel plants*, Biomass and Bioenergy 115 (2018) 231 – 243.
74 Ibid.
75 Green Steel for Europe. (2021). *Technology Assessment and Road mapping*. Available at: https://www.estep.eu/assets/Uploads/210308-D1-2-Assessment-and-roadmapping-of-technologies-Publishable-version.pdf.

2.2.1. Discussion on decarbonisation technology options

As described in the introduction, the technologies listed in the table above fall under two broad approaches. The first is focused on optimising existing processes and increasing their circularity through efficiency measures and scrap-based steel production. Studies focused on analysis of national decarbonisation trajectories in the sector have concluded that options based solely on existing production processes have limited potential to achieve the required CO_2 reduction targets[76]. In the case of technology options relying on steel-scrap, sufficient availability of scrap could constitute a bottleneck as accumulation of steel and scrap is subject to a time lag. Another consideration is related to the quality of steel produced, since scrap-based technology pathways lack sufficient quality of the scrap feedstock, since the feedstock is contaminated in most of the cases[77].

In the case of the hydrogen-based decarbonisation solutions for the steel sector, a key consideration is the availability of renewable electricity to produce green hydrogen. Based on estimations reported in previous studies, decarbonising 94 Mt of steel, the amount of steel produced in the EU in 2019 that is suitable for the hydrogen route, would require approximately 37-60 GW of electrolyser capacity[78]. This figure should be contrasted with the 40 GW of electrolyser capacity by 2030 proposed in the EU Hydrogen Strategy[79]. The share of renewables in the electricity grid needs to be considered if positive climate outcomes are to be achieved. Otherwise the risk of shifting process-related emissions in steel industry to combustion-based emissions in the energy supply sectors is likely if electricity generation remains fossil-fuel intensive[80]. At the moment, only a few European countries have an electricity grid with an average carbon intensity low enough to produce hydrogen based on the production emissions specified in the EU Sustainable Taxonomy (3 tCO_2/tH_2)[81, 82]. For example, hydrogen produced via electrolysis with grid electricity based on the current German electricity mix can increase emissions of the BF-BOF route by 36.9%[83]. Lack of sufficient spare renewable energy and consequential limited availability of green hydrogen is also an important barrier for rolling out CCU technologies in large scale[84]. Currently, the volumes of proposed CCU projects are not sufficient to contribute substantially to GHG emission abatement.

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[76] Arnes. M et al. (2017) *Pathways to a low-carbon iron and steel industry in the medium-term- the case of Germany*. Journal of Cleaner Production vol.163, p.84. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0959652615019228?via%3Dihub.
Rootzen.J; Johnsson, F. (2015) *CO2 emissions abatement in the Nordic carbon-intensive industry – An end-game in sight?* Energy vol.80 p.715. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0360544214013875?via%3Dihub.

[77] Morfeldt, J. et al. (2015) The impact of climate targets on future steel production – an analysis based on global energy system model. Journal of Cleaner Production vol. 105 p. 469.
Available at: https://www.sciencedirect.com/science/article/pii/S0959652614004004?via%3Dihub

[78] EP (2021) *Carbon-free steel production: Cost reduction options and usage of existing gas infrastructure*.
Available at: https://www.europarl.europa.eu/RegData/etudes/STUD/2021/690008/EPRS_STU(2021)690008_EN.pdf.

[79] EC (2020) COM(2020) 301 final. *A hydrogen strategy for a climate-neutral Europe*.
Available at: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf.

[80] Mayer, J. et al. (2018) *Macroeconomic implications of switching to process-emission-free iron and steel production in Europe*. Journal of Cleaner Production vol. 210 p. 1517.

[81] Bellona (2021) *Cannibalising the Energiewende?* 27 Shades of Green Hydrogen.
Available at: https://network.bellona.org/content/uploads/sites/3/2021/06/Impact-Assessment-of-REDII-Delegated-Act-on-Electrolytic-Hydrogen-CO2-Intensity.pdf.

[82] Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0852
EC (2021) 2800 final. Available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=PI_COM:C(2021)2800 See Annex I.3.10.

[83] Bellona (2021) *Hydrogen in steel production: What is happening in Europe – part one*. Available at: https://bellona.org/news/climate-change/2021-03-hydrogen-in-steel-production-what-is-happening-in-europe-part-one.

[84] CCUS Projects Network (2020) *Feedstock for the process industries and climate action – The potential of CO2 utilisation*. Available at: https://www.ccusnetwork.eu/sites/default/files/TG2_Briefing-Potential-of-CO2-Utilization.pdf.

In the case of CCS, the option is often seen as medium-term solution to achieving intermediate targets until carbon-free solutions can be upscaled at sufficiently low-costs. Thus, worries about the need for double-investment or the risk of stranded assets are often cited against the deployment of this technology. However, future predictions show that achieving the 2050 targets in the steel industry will not be possible without CCS[85].

Low public acceptance and, in certain Member States, national legislation are additional barriers hampering the deployment of CCS. However, based on the growing urgency to decarbonise EU's economy and its energy-intensive industries, support for CCS has slowly been gaining momentum[86]. CCS, can also play a role in supporting the large-scale deployment of climate-benign hydrogen by capturing the CO_2 emitted during the conventional, natural-gas based production called steam methane reforming (SMR). In this way, low-carbon (blue) hydrogen could serve as a steppingstone until enough renewable electricity and electrolyser capacity is available to produce green hydrogen.

2.2.2. Economic considerations including technology costs

In the case of the steel sector all the options for decarbonising steel, except for recycling, are associated with at least 30% cost increases. However, these numbers are only applicable to bulk steel costs; metal parts will be perhaps 10% more costly, and it will only add €265-353[87] to a car[88].

Green hydrogen combined with renewable electricity represents a promising option for decarbonised steel production, where the cost of hydrogen (and green electricity more generally) represents an important economic factor. Figure 2-2 assesses the competitiveness of hydrogen-based steel making processes against conventional production routes, where it provides an analysis on the prices of carbon and hydrogen needed for hydrogen-based steelmaking to become competitive. Based on the Figure below, at a CO_2 price of 60 €/ton, hydrogen price would need to be 1200 €/ton or lower to make hydrogen-based steelmaking cost competitive. Conversely, at a CO_2 price of 90 €/ton, hydrogen prices could be as high as 2000 €/ton and hydrogen-based steelmaking would still be cost-competitive. Analysis by McKinsey & Co. finds that hydrogen-based steel production is expected to be cost competitive from 2030 onwards in Europe. It is necessary to highlight that the above analysis excludes capex implications (depreciation) given that conventional steel production assets are already largely written off[89].

https://bellona.org/news/climate-change/2021-03-hydrogen-in-steel-production-what-is-happening-in-europe-part-one.

84 CCUS Projects Network (2020) *Feedstock for the process industries and climate action – The potential of CO2 utilisation*. Available at: https://www.ccusnetwork.eu/sites/default/files/TG2_Briefing-Potential-of-CO2-Utilization.pdf.

85 Eurofer (2019) *Low Carbon Roadmap: Pathways to a CO2-neutral European Steel Industry*.
Available at: https://www.eurofer.eu/assets/Uploads/EUROFER-Low-Carbon-Roadmap-Pathways-to-a-CO2-neutrhttps://www.argusmedia.com/en/news/2184819-germany-launches-ccus-supportal-European-Steel-Industry.pdf.

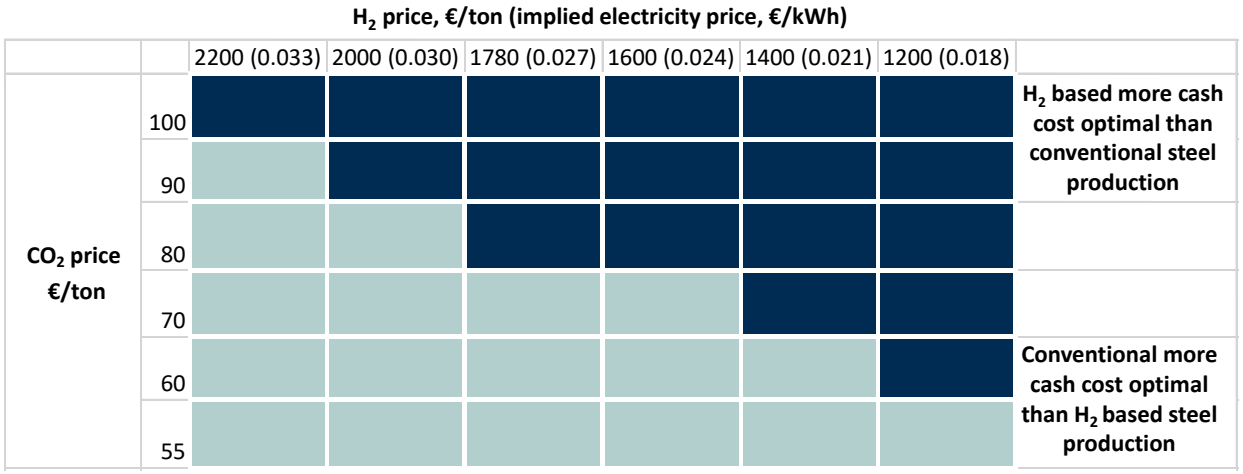
86 Argus media (2021) *Germany launches CCUS support*. Available at: https://www.argusmedia.com/en/news/2184819-germany-launches-ccus-support.

87 Values converted from US dollars to Euros based on the conversion rate on 12/12/2021. Original source cites $300-400.

88 For further discussion on costs please see page 23 of OECD, Financing Climate Futures. (2019). *Low and zero emissions in the steel and cement industries – Barriers, technologies and policies.*

89 McKinsey & Company. (2020). *Decarbonisation challenge for steel – Hydrogen as a solution in Europe*.

Figure 2-2: Cost competitiveness of hydrogen based steel production in comparison to conventional production based on price of CO_2 and H_2[90]



Note: Dark blue: cash cost conventional >/ cash cost H_2-based; Light green: cash cost conventional </ cash cost H_2-based.

CCUS constitutes the other relevant option for the steel industry. The costs of carbon capture vary significantly per sector and are highly dependent on the purity and concentration of the carbon dioxide stream. For the iron and steel sector, the levelised cost of CO_2 capture can range from approximately 27-115 €/ton[91, 92]. Based on existing and planned CCUS projects in Europe, the two main options for CO_2 transport are pipelines and shipping. Costs of offshore CO_2 pipelines range between 2-29 €/ton of CO_2. Costs of shipment vary between 10-20 €/ton of CO_2[93]. The estimated costs of CO_2 storage depend on the formation type and location. Despite the relatively high costs associated with it, CCUS, in certain cases, it can be more cost-effective to retrofit CCUS to existing facilities than building new capacity with alternative technologies[94].

The figure below shows the simplified levelised costs[95] of different low carbon technologies available for decarbonising steel production. The ranges are based on global estimates but nonetheless provide an interesting comparison. The figure shows that the range of levelised costs for BF/BOF is currently the lowest.

The costs for steel production based on innovative smelting technologies combined with CCS (term used by the IEA, in our analysis we use 'smelting reduction processes') follow. The DRI route based on natural gas has a range of levelised costs between 355-633 €/ton[96] (400 – 600 $/ton) and adding CCS to this option increases the costs to a range of ~399-577 €/ton[97] (450 to 650 $/ton).

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90 Own elaboration based on: McKinsey & Company. (2020). *Decarbonization challenge for steel – Hydrogen as a solution in Europe*.

91 IEA (2021) I*s carbon capture too expensive?* Available at: https://www.iea.org/commentaries/is-carbon-capture-too-expensive?utm_content=bufferccd81&utm_medium=social&utm_source=linkedin.com&utm_campaign=buffer.

92 Values converted from US dollars to Euros based on the conversion rate on 12/12/2021. Original source cites $30-130.

93 IOGP. (2019). The Potential for CCS and CCU in Europe. Available at: https://ec.europa.eu/info/sites/default/files/iogp_-_report_-_ccs_ccu.pdf.

94 IEA (2021) *Is carbon capture too expensive*? Available at: https://www.iea.org/commentaries/is-carbon-capture-too-expensive.

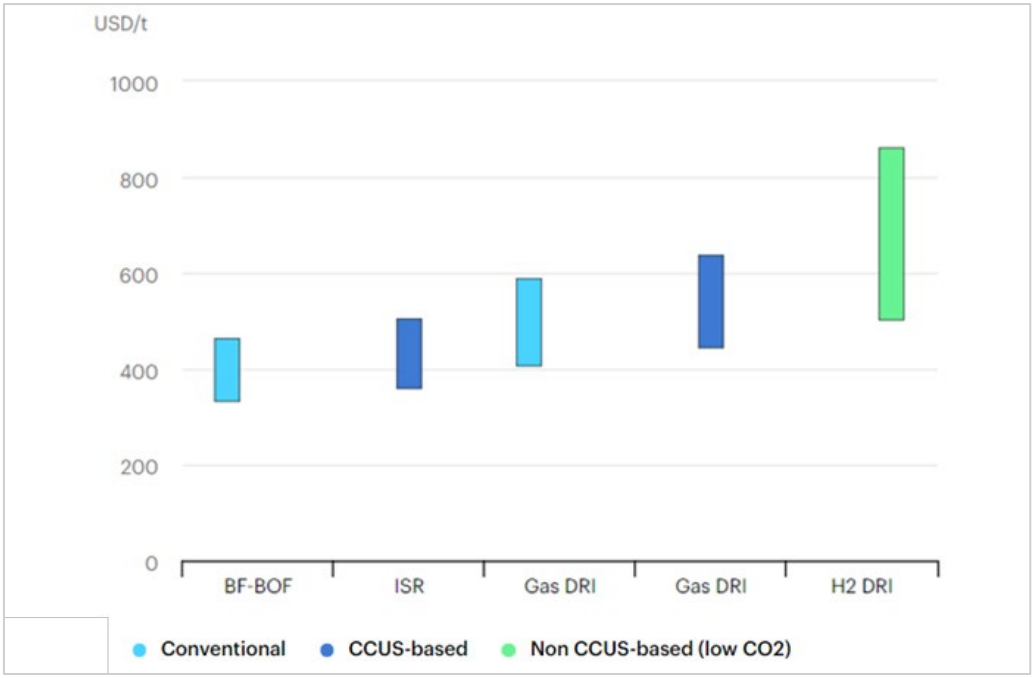
95 The levelised cost of energy (LCOE) measures lifetime costs divided by energy production. It provides the value of the total cost of building and operating a power plant over an assumed lifetime. It facilitates the comparison of different technologies with different life spans, project size, different capital cost etc.

96 Values converted from US dollars to Euros based on the conversion rate on 13/12/2021.

97 Ibid.

Finally, the hydrogen DRI based route have the biggest range of levelised costs, these are estimated to be between ~ 444-754 €/ton[98] (500 and 850 $/ton).

Figure 2-2: Simplified levelised cost ($/ton) of competing low-carbon technologies in steel production[99]



Source : IEA (2020) CCUS in the transition to net-zero emissions.

2.3. Case study

We have selected the **HYBRIT project** as an important example of a successful project for low-carbon/carbon neutral steelmaking. It is important to note that abundant green electricity, good RDI and collaboration with the local university, combined with support from the national government in the form of funding, make the project much more feasible in Sweden at the time then in other Member States. Thus, the conditions that make it successful are not necessarily available and reproducible in other parts of Europe and other technology options might be considered elsewhere.

[98] Ibid.

[99] Note ISR stands for Innovative Smelting Reduction.

Box 1: Case study HYBRIT – Hydrogen Breakthrough Ironmaking Technology

1. The company

HYBRIT Development AB is a research and technology development company set up by steelmaking company SSAB, iron producer LKAB and utility Vattenfall that will deliver innovative technology solutions to their existing iron-and steelmaking facilities in Sweden. These companies aim to produce fossil-free steel, from mining to product on a commercial scale by 2035, by introducing novel technologies to substitute carbon-intensive industrial processes. The project is the first of its kind and an example for industrial decarbonisation Europe-wide.

2. Main characteristics

a. National and regional context

The Swedish region of Norrbotten accounts for ca. 90% of iron ore production in Europe: this production marks the beginning of the steel industry's value chain and is of crucial importance for the industry in the region. The county has few SMEs and is dominated by large companies, thus the fact that the value chain can transform to fossil-free production methods while maintaining competitiveness is crucial for the regional economy and involved companies as well as to maintain competitiveness and sustain the GDP.

b. Technology and emission savings

The HYBRIT project is developing the technology and value-chain to arrive at zero-carbon steel. First, LKAB's iron ore pellets will be made using non-fossil fuels (bio oils), requiring changing the heating technology in the refining process. Trials for other alternative heat sources are being carried out too, e.g. hydrogen combustion and electric heating. For producing iron from the pellets, the blast furnaces used in iron production are replaced with a direct reduction (DRI) process that uses hydrogen instead of coal or natural gas for which the electricity powering the electrolysis is fossil-free. As a result, iron ore is reduced to sponge iron (also known as direct reduced iron). Other processes in steel-making will also be electrified or substituted with biofuels instead of coal, while the use of secondary materials (mostly scrap steel) will increase too. It is estimated that the technological breakthrough in the HYBRIT initiative eliminates around 90% of emissions associated with steelmaking.

c. Project status /TRL

The aim of the project is to reach TRL 9 by 2030-2035. Construction of the first pilot plant started in spring 2018 in June in Luleå, northern Sweden. The first demonstrational plant is planned to operate by 2026 and scaled up commercially by 2035. The first batches of zero-carbon steel have been rolled out for testing by SSAB in July 2021, and are already being delivered to the first customer, the Volvo Group.

3. Main impacts

a. Emission reduction / sustainability

The project has demonstrated that it is possible to produce fossil-free steel. Furthermore, the project has brought together key businesses to cooperate and work towards a fossil-free steel value chain and could have a major effect on the whole steel supply chain in Europe. Using HYBRIT technology, the Swedish steel industry's transition alone is estimated to reduce Sweden's carbon dioxide emissions by about 10%, while contributing to the region's economic development.

b. Employment and growth

Besides reducing industrial emissions and direct environmental impacts of steelmaking, the companies in the Norrbotten region will be able to keep their workers employed. thanks to their novel processes that keep the industry competitive in the long-term. Large capital investments by businesses and the region will flow into infrastructure, buildings and equipment are already ongoing and planned. Collaboration between the research community and businesses is thriving in Luleå, which is Sweden's acclaimed center for research and education focusing on mining (with a strong actor being Luleå University of Technology). The region strives to be an internationally renowned center of excellence in the field.

c. Supply chain impacts

In a national context, iron that will be produced by HYBRIT can be further processed by all Swedish steelmakers and the number of plants and processes involved can thus increase. The sectors downstream using steel worldwide are wide-ranging, including construction, infrastructure, transport, machinery and the automotive industry. Carmakers Volvo and Scania have already signed up as customers for the zero-carbon steel produced by HYBRIT. With zero-carbon production processes like HYBRIT's, supply chains for these sectors can decarbonise from the bottom up.

d. Innovation and technology transfer

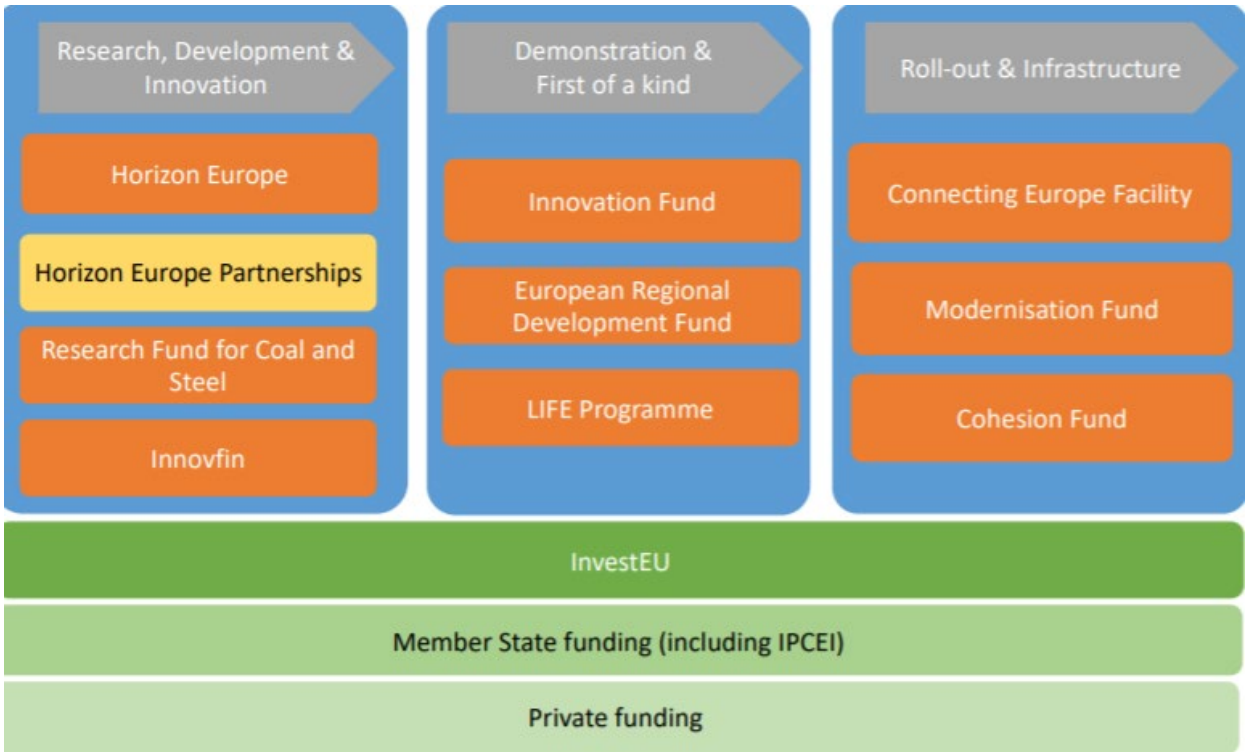
By manufacturing the first fossil-free steel in the world, the three companies prove that it's possible to create a fossil-free steel value chain and significantly reduce the global carbon footprint of the industry. By scaling up this technology and producing sponge iron on an industrial scale, HYBRIT can enable the steel industry to make the transition. Digitization and automation of certain processes will also make the mining and steelmaking methods among the most effective in the world, for others to follow.

3. EU INVESTMENT INSTRUMENTS AND INITIATIVES TO SUPPORT DEPLOYMENT OF ZERO EMISSION STEEL

3.1. Existing funding and budget programmes

Figure 3-1 below provides a good overview of the key funding and support mechanisms at EU-level available for the steel sector. In this section of the report, we provide a brief summary of the key funding instruments available.

Figure 3-3: EU programmes supporting the decarbonisation of the steel industry



Source: ESTEP AISBL (2020) Proposal for a European Partnership under Horizon Europe Clean Steel – Low Carbon Steelmaking.

3.1.1. The Recovery and Resilience Facility

The Recovery and Resilience Facility (RRF) is a key component of the Next Generation EU (NGEU) recovery package which will be made available as part of the long-term budget for 2021-2027 to support EU Member States in their recovery from the coronavirus pandemic. Under the RRF, €723.8 billion will be made available to Member States in the form of loans and grants to support reforms and investments; 37% of total investments will be allocated towards fostering the green transition[100].

The RRF provides a unique opportunity for Member States to invest in the decarbonisation of their energy-intensive industries, including the steel industry. Based on the Commission's analysis of the submitted RRF plans, it is possible to assert that several Member States plan to use a portion of the funds to support the decarbonisation of their steel industry. For example, the Italian RRF plan mentions investments in clean hydrogen production including 5 GW of installed electrolysis capacity by 2030.

[100] European Commission (2021) *Recovery and Resilience Facility*. Available at: https://ec.europa.eu/info/business-economy-euro/recovery-coronavirus/recovery-and-resilience-facility_en.

The plan foresees that at a later stage RRF investments could be complemented by the Just Transition Fund to support areas like Taranto in transitioning towards a hydrogen-based clean steel production and the reskilling of steel workers[101]. Decarbonisation of industry is an important component of the majority of submitted RRF plans, however only a few countries explicitly mention the steel sector.

3.1.2. Just Transition Mechanism

The Just Transition Mechanism (JTM) is a key policy to ensure a fair transition towards a climate-neutral economy. It provides targeted support to help mobilise at least €65-75 billion[102] in the next MFF period of 2021-2027 in the most affected regions, to mitigate the socio-economic and employment impacts of the transition[103]. As part of the JTM, the Just Transition Fund (JTF) will invest €17.5 billion in the territories most negatively affected by the transition, including regions with polluting heavy industry. The steel sector is one of the priorities of JTF support in six Member States[104]. Based on the Territorial Just Transition Plans submitted by Member States, the JTF will support the deployment of new technologies as well as programs for economic diversification, upskilling and reskilling of workers and the decarbonisation of the industry overall. Moreover, grants and loans are also accessible for public and private use under the new InvestEU Just Transition scheme and the new Public Sector Loan Facility.

3.1.3. InvestEU

The InvestEU programme will provide a budgetary guarantee and mobilise €10-15 billion in private sector investments, while the loan facility combines €1.5 billion of grants from the EU budget with €10 billion of loans from the EIB to mobilise between €25 and €30 billion of public investment. Investments in sustainable industrial applications that result in emission reduction are a priority of the Fund, both under the *Sustainable Infrastructure* and the *Research, Innovation and Digitalisation* windows of the InvestEU programme. Financial support under the InvestEU Fund can take various forms of equity or loan finance provided by the European Investment Bank Group or other implementing partners.

Selected projects for funding already include a break-through initiative in steelmaking by Belgian ArcelorMittal, who received €75 million in European Investment Bank (EIB) loans to scale up two projects, of which 'Steelanol', an industrial-scale demonstration plant that captures waste gases (carbon and hydrogen) from the blast furnace used in steelmaking and biologically converts them into recycled-carbon ethanol that can be used in liquid fuel blends[105]. The InvestEU Advisory Hub can support potential project applicants.

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[101] European Commission (2021) SWD(2021) 165 final. *Analysis of the recovery and resilience plan of Italy*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021SC0165&from=EN.

[102] Note: The amount cited is based on 3 different funding mechanisms: the Just Transition Fund (EU budget), a dedicated scheme under InvestEU (private funding) and a public sector loan facility with back up from the EIB. For more information please see: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/finance-and-green-deal/just-transition-mechanism/just-transition-funding-sources_en.

[103] European Commission (2021) https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/finance-and-green-deal/just-transition-mechanism_en.

[104] Belgium (Hainaut), France (Bouches-du-Rhône, Nord), Italy (Taranto), Luxemburg (Esch-sur-Alzette), Slovakia (Košice) and Sweden (Upper Norrland).

[105] EIB (2020) Belgium: EU supports ArcelorMittal with EUR 75m EIB loan to scale up breakthrough technology to reduce carbon emissions. Available at: https://www.eib.org/en/press/all/2020-120-eu-supports-arcelormittal-with-eur-75m-eib-loan-to-scale-up-breakthrough-technology-to-reduce-carbon-emissions#_edn4.

3.1.4. Innovation Fund

Aims at funding innovative low-carbon technologies and processes programmes in the energy-intensive industries with European value added that can bring significant emission reductions. Such programmes include products substituting carbon intensive ones, CCS and CCU, innovative renewable energy generation and energy storage.

The Innovation Fund supports the creation of adequate financial incentives for projects that invest in the next generation of technologies that are necessary to achieve the EU's low-carbon transition[106]. It is funded by auctioning of allowances under the EU ETS. It is estimated that the Innovation Fund will provide around €25 billion of support over the period 2020 – 2030 (depending on the carbon price[107]).

Projects are selected based on effectiveness of GHG emissions avoidance, degree of innovation, project maturity, scalability, and cost efficiency. Innovation Fund grants will pay for up to 60% of project costs, and up to 40% of the grant is paid up front, with additional disbursements paid upon achievement of performance milestones.

3.1.5. Sustainable financing taxonomy

The EU action plan 'Financing Sustainable Growth' describes the EU's strategy in addressing sustainable finance in relation to Paris Agreement. The sustainable finance taxonomy represents a part of this action plan, with the aim of further incentivising and channelling private sector investments in sustainable development. The delegated acts of the sustainable finance taxonomy set criteria for activities that can make substantial contribution to climate change mitigation and adaptation activities[108]. Iron and steel production activities are among the activities listed in the EU taxonomy for sustainable investment[109], with technical screening criteria recognising the most climate-friendly forms of production while ensuring no significant harm to the environment. The technical screening criteria also recognizes the importance of R&D and innovation activities for low-carbon/carbon neutral steel manufacturing. The criteria also encourage investments in breakthrough technologies[110].

[106] European Commission (2021). Available at:) https://ec.europa.eu/clima/policies/innovation-fund_en.

[107] At 50 €//tonCO_2.

[108] EC. (2021). Commission delegated act regulation supplementing regulation 2020/852 of the European Parliament by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to climate change mitigation or climate change adaptation and for determining whether that economic activity causes no significant harm to any of the other environmental objectives. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:d84ec73c-c773-11eb-a925-01aa75ed71a1.0021.02/DOC_1&format=PDF and Annex 1 https://ec.europa.eu/finance/docs/level-2-measures/taxonomy-regulation-delegated-act-2021-2800-annex-1_en.pdf.

[109] Ibid.

[110] EC. (2021). Commission SWD *Towards competitive and clean European Steel*. Available at: https://ec.europa.eu/info/sites/default/files/swd-competitive-clean-european-steel_en.pdf.

Box 2: Technical Screening Criteria for Manufacture of Iron and Steel[111]

Activities with substantial contribution to climate change mitigation in the iron and steel sector shall involve manufacturing one of the following products:

a) iron and steel where GHG emissions reduced by the amount of emissions assigned to the production of waste gases do not exceed the following values applied to the different manufacturing process steps:
   1. hot metal = 1,331 tCO_2e/t product;
   2. sintered ore = 0,163 tCO_2e/t product;
   3. coke (excluding lignite coke) = 0,144 tCO_2e/t product
   4. iron casting = 0,299 tCO_2e/t product;
   5. electric Arc Furnace (EAF) high alloy steel = 0,266 tCO_2e/t product; and
   6. electric Arc Furnace (EAF) carbon steel = 0,2091 tCO_2e/t product.

b) steel in electric arc furnaces (EAFs) producing EAF carbon steel or EAF high alloy steel, where the steel scrap input relative to product output is not lower than:
   i. 70 % for the production of high alloy steel; and
   ii. 90 % for the production of carbon steel.

Where the CO_2 that would otherwise be emitted from the manufacturing process is captured for the purpose of underground storage, the CO_2 is transported and stored underground.

3.2. The revised Research Fund for Coal and Steel and the new European Clean Steel Partnership

The Research Fund for Coal and Steel (RFCS) is an EU funding programme tasked with supporting research in the coal and steel sectors. The funding comes from the revenues resulting from the liquidation assets of the European Coal and Steel Community (ECSC). The RFCS is not part of the Multiannual Financial Framework (MFF) as it has its own legal bases. During the summer of 2020, the Commission adopted a package of proposals to revise the three legal bases regulating the Research Programme of the RFCS. On 19 July 2021, the EU adopted the new RFCS package, with a 2021-2027 annual RFCS allocation of €111 million managed by the EC in cooperation with the Coal and Steel Committee and the Coal and Steel Advisory Groups[112].

The European Partnership for Clean Steel has been officially launched on 24 June 2021. The Clean Steel Partnership (CSP) was established with the aim to support RD&I activities from the pilot to the demonstration phase of breakthrough technologies for low and zero-carbon steelmaking. The Clean Steel Partnership relies on funds' synergies to €700 million coming in equal parts from Horizon Europe and assets of the European Coal and Steel Community in liquidation. However, the expected investment needs from the both the public and private side in the period 2020-2027 are estimated at €2 billion. This public funding for the CSP should be matched by private investment directly linked to

[111] EC. (2021). *Commission delegated act regulation supplementing regulation 2020/852 of the European Parliament by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to climate change mitigation or climate change adaptation and for determining whether that economic activity causes no significant harm to any of the other environmental objectives. Annex 1.* Available at: https://ec.europa.eu/finance/docs/level-2-measures/taxonomy-regulation-delegated-act-2021-2800-annex-1_en.pdf.

[112] European Commission, *The Research Fund for Coal and Steel*, Accessed on 03/09/2021. Available at: https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/research-fund-coal-and-steel-rfcs_en.

the Partnership and additional private investment, which could be complemented by other public sources, such as the EU programmes described in the previous section[113].

The general objective of the CSP is to develop technologies at TRL8 to reduce CO_2 emissions associated with the steelmaking process by 80-95% by 2050 as compared with 1990 levels. The specific and operational objectives are set on the basis of their contribution to achieving the general objective and should be realisable within the next 7 to 10 years. They are[114]:

1) Enable steel production through carbon direct avoidance technologies at demonstration scale;
2) Foster smart carbon utilisation technologies in the steelmaking routs at demonstration scale;
3) Develop deployable technologies to improve energy and resource efficiency;
4) Increase recycling of steel scrap and residues;
5) Demonstrate feasibility of breakthrough technologies for clean steel production; and
6) Strengthen the global competitiveness of the EU steel industry in line with the EU industrial strategy for steel.

The specific and operational objectives are defined in line with the impact pathways of Horizon Europe.

Although the creation of the CSP to accelerate the deployment of technologies to decarbonise the iron and steel sector is an important and necessary step to support the transition of the sector to a green future, interviewed companies have indicated that the funds will not be sufficient in themselves to achieve this transformation. Thus, the CSP should serve as an instrument to advance the RD&I of technologies and bring them to market-maturity. The wide-spread deployment of these technologies will however require additional funding including from private investors. A recent report on investment needs for green steel in Europe estimates that new, low-CO_2 production technologies will require an investment of approximately €50-60 billion, with €80-120 billion/y capital and operating costs[115]. It also estimates that investments in new technologies would increase production costs for the EU steel industry by at least €20 billion/y compared to the retrofitting of existing plants (i.e. the upgrading of existing plants with the best available techniques). Notably, at least 80% of these costs will be related to operational expenditure (OPEX), primarily based on the increased use and higher prices for low-carbon or decarbonised energy[116]. These CAPEX and OPEX figures indicate that support is not only needed on the upfront investment side, but also on the operating costs sides where access and availability to green electricity/hydrogen are crucial. Replacing the EU steel production based on BF/BOF (60% of total EU steel production) with the hydrogen direct route would require more than €180 billion in steel plants, electrolysers and additional renewable capacity[117].

In Germany, the financial support needed for the steel industry to decarbonise are estimated at €13 to 35 billion[118]. Thus, there seems to be a funding gap between developing new technologies (RD&I) and the scale-up and roll-out of technologies at industrial scale.

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[113] ESTE AISBL (2020) *Proposal for Clean Steel Partnership under the Horizon Europe Programme*.

[114] Ibid.

[115] CAPEX cost of approximately €60 billion has also been confirmed by another source: Citi Research Viewpoint, (2021), *European Steel: Decarbonization investments are 'affordable', but re-rating the big upside for equity investors*.

[116] GreenSteel for Europe (2021),) *Investment Needs*. Available at: https://www.estep.eu/assets/Uploads/GreenSteel-D2.2-Investment-Needs-Publishable-version.pdf.

[117] EP (2021),) *Carbon-free steel production*. Available at: https://www.europarl.europa.eu/RegData/etudes/STUD/2021/690008/EPRS_STU(2021)690008_EN.pdf.

[118] Clean Energy Wire (2021) Steel industry needs 13 to 35 billion euros support for climate-neutral transition – analysis. Available at: https://www.cleanenergywire.org/news/steel-industry-needs-13-35-billion-euros-support-climate-neutral-transition-analysis.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

The main output of this study is to provide an in-depth analysis on the decarbonisation pathways and most promising technologies for the European steel industry, in the view of Fit-for-55 package. In this section, we draw conclusions on the options for zero emissions steel processes. We base these conclusions on the findings of the previous sections, in addition to the interviewees' input, with a focus on prospects, timeline, existing barriers and potential financing and investment gaps in the sector.

Funding

Although there are various funding streams to support the green transition, such as the Innovation Fund, the Modernisation Fund, the JTM, InvestEU etc., these are not specific to the iron and steel sector and thus the sector can expect to receive only a small portion from these funds. In addition, these funds can be accessed only through an application by Member State governments, which can constitute a barrier for companies not used to such application processes or wishing for a faster, less-complex application procedure.

The Research Fund for Coal and Steel, the sector-specific funding instrument, will receive €111 million annually. In addition, the Clean Steel Partnership has been allocated €700 million from public funds and is expected to receive up to €2 billion from additional private contributions. This constitutes a large amount of money and is an important stimulus for the development of necessary RD&I activities. Yet the Fund in itself will not be sufficient to pay for necessary investments to decarbonise the European iron and steel sector.

Studies estimate that new low-CO_2 production technologies will require a €50-60 billion investment, with €80-120 billion/y capital and operating costs[119]. Furthermore, the Clean Steel Partnership provides most of its funding for development of technologies that are TRL 6-7, where such projects will take years to be sufficiently scaled and won't be able to contribute to the 2030 goals. Thus, there is a funding gap between developing new technologies (RD&I) and the need to scale-up low carbon technologies to industrial scale and the operation of such plants.

Also, there is often a perception of a long bureaucratic process surrounding the funding mechanisms that needs speeding up. For example, if companies miss a funding cycle, they will have to wait for next funding cycle to reapply (this could take a year), even if the projects they are seeking funds for are ready to be implement. Additionally, lack of knowledge from companies about different funding opportunities based on the instruments mentioned above also constitutes a barrier.

Finally, the funding of operational expenses (OPEX) is also needed in addition to the capital expenditures (CAPEX). The comparative analysis has demonstrated that several financial barriers lie within the OPEX costs. The replacement of fossil fuels by electricity, which is the case for many of the technology options analysed, results in an increased cost of energy supply and can significantly increase the OPEX[120]. It is estimated that production costs based on new, low-carbon technologies could increase by at least €20 billion/y and that operational expenditures would be responsible for at

[119] GreenSteel for Europe (2021),) *Investment Needs*. Available at: https://www.estep.eu/assets/Uploads/GreenSteel-D2.2-Investment-Needs-Publishable-version.pdf.

[120] Green Steel for Europe (2021). *Collection of possible decarbonisation barriers*. Available at: https://www.estep.eu/assets/Uploads/210308-GreenSteel-D1-5-Decarbonisation-Barriers-Publishable-version.pdf.

least 80% of these costs[121]. Thus, energy prices and (taxation/subsidy) policies associated with them do constitute an important factor for the iron and steel industry.

Regulation

EU regulations addressing climate change and industrial decarbonisation need further alignment. Based on interviews, companies have mentioned that policies under the Renewable Energy Directive (RED), the Energy Efficiency Directive (EED), the Energy Taxation Directive and the EU ETS are not always aligned and do not send coherent policy signals. E.g. the revised RED seems to incentivise carbon circularity, but the EU ETS does not. For instance, steel production processes result in process gases (waste gases) which can be used to generate electricity. However, using waste gases are not counted as a mitigation measure according to the EU ETS regulations. It is therefore reasonable to improve alignment of the EU ETS regulation with RED, EED and Energy Taxation directives as well as the Circular Economy Action Plan.

With regards to CBAM, the effects of CBAM on the iron and steel sector have not been assessed yet, and the draft proposal doesn't address exports. The EU industry cannot compete with global prices outside the EU with high production, carbon and energy prices. In general, the industry welcomes the CBAM as a tool to address carbon leakage and push global producers to drive down their emissions to align with the EU climate neutrality targets.

Technology

For technologies relying on electricity and availability of green hydrogen, availability of renewable electricity in sufficient amounts and at low costs, still constitutes a barrier. More investments in renewable energy, storage and infrastructure are required. For companies opting for the DRI option based initially on natural gas, guidelines and further certainty on how to phase out natural gas would be helpful.

The increased use of recycled steel/scrap accompanied with the use of waste (and in limited cases biomass) are promising routes for the steel industry as well; however, availability of raw materials including scrap steel represents a barrier. The use of EAFs depends on the availability and quality of scrap steel, which is still limited, to achieve full circularity. The quality of scrap steel is often not sufficient for re-use, since it is contaminated in many cases, thus yielding lower quality of secondary steel.

Furthermore, more demonstration projects are necessary in most of technologies with low TRLs. De-risking mechanisms are necessary to encourage RD&I and breakthrough technologies.

There is limited infrastructure availability for CCUS and hydrogen. In addition, CCS still faces significant public acceptance issues which need to be tackled by informing the general public on the technology and gain public trust for it.

There is a need for more studies on the social impacts of the low carbon/carbon neutral transitioning in the steel sector. The transition will probably result in laying off people in different production sites and therefore losing their jobs/incomes. More efforts to mitigate undesirable social outcomes of the transition should be taken.

[121] Green Steel for Europe (2021),) *Investment Needs.* Available at: https://www.estep.eu/assets/Uploads/GreenSteel-D2.2-Investment-Needs-Publishable-version.pdf.

4.2. Recommendations

In this subsection, we provide recommendations on the adequacy and consistency of ongoing and future actions proposed at EU level, and how to protect and promote the EU iron and steel industry in its path towards decarbonisation taking into considerations challenges related to globalisation and competition.

We derived the below recommendations based on the findings of the comparative analysis as well as interviews with relevant stakeholders:

1. Market confidence is needed on the long-term, ensuring the stability of the EU regulatory and policy framework to encourage investment decisions and enable financial incentives in green steel. Carbon pricing, renewable energy subsidies and hydrogen market regulations are examples of fields where alignment and complementarity are crucial;
2. Demand for low-carbon/carbon neutral steel should be supported through public procurement initiatives to create a market for these products;
3. Carbon leakage measures (such as CBAM and carbon contracts for differences) need to be in place to ensure level playing field. Measures need to address both imports and exports of steel products;
4. Funding mechanisms need to be less bureaucratic but transparent, and more flexible funding is needed for demonstration projects, with financial de-risking instruments. Funding mechanisms should support the scale-up and roll-out of already commercially available technologies and address both CAPEX and OPEX (especially for first-of-a-kind project);
5. Availability of supporting infrastructure (CCS and Hydrogen networks) needs to be accelerated, especially for industrial clusters, to support the transition to low-carbon/carbon neutral technologies;
6. Supporting the deployment of Digital Product Passports (DPPs) in the downstream products and applications of steel (e.g., in construction and transportation industries) can improve the process of steel recovery and reuse. The design of DPPs usually contains product related information by manufacturers, including instructions on disassembly and dismantling. If followed correctly during the recycling or end-of-life phase of steel products, steel recovery rates can be enhanced; and
7. All suggested technology options should remain open and support to achieve full-market deployment of these technologies should continue. Member States should have the flexibility to choose which technology mix is best suited given their national conditions (renewables in the electricity mix, infrastructure, public acceptance etc.). With sufficient and affordable renewable energy, the hydrogen-based DRI route seems likely to become the main decarbonisation route for the industry, given that it is expected to be cost competitiveness from 2030 onwards. Given the longevity of steel plants already any investments into coal-or coke-based processes should be avoided.

REFERENCES

- Agora Energiewende and Wuppertal Institute, (2021), *Breakthrough Strategies for Climate-Neutral Industry in Europe: Policy and Technology Pathways for Raising EU Climate Ambition*. Available at: https://www.agora-energiewende.de/en/publications/breakthrough-strategies-for-climate-neutral-industry-in-europe-summary/.
- ArcelorMittal, (accessed on 20/11/2021), *Steel is the power behind renewable energy*. Available at:

  https://corporate.arcelormittal.com/media/case-studies/steel-is-the-power-behind-renewable-energy
- Arnes. M et al., (2017), *Pathways to a low-carbon iron and steel industry in the medium-term- the case of Germany*. Journal of Cleaner Production vol.163, p.84. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0959652615019228?via%3Dihub
- Bellona, (2021), *Cannibalising the Energiewende? 27 Shades of Green Hydrogen*. Available at: https://network.bellona.org/content/uploads/sites/3/2021/06/Impact-Assessment-of-REDII-Delegated-Act-on-Electrolytic-Hydrogen-CO2-Intensity.pdf
- Bellona, (2021), *Climate action in the steel industry*.
- Bellona, (2021), *Hydrogen in steel production: What is happening in Europe – part one*. Available at: https://bellona.org/news/climate-change/2021-03-hydrogen-in-steel-production-what-is-happening-in-europe-part-one.
- CCUS Projects Network, (2020), *Feedstock for the process industries and climate action – The potential of CO2 utilisation*. Available at: https://www.ccusnetwork.eu/sites/default/files/TG2_Briefing-Potential-of-CO2-Utilization.pdf.
- CEPS, (2013), *Assessment of cumulative cost impact for the steel industry*. Available at: https://www.ceps.eu/ceps-publications/assessment-cumulative-cost-impact-steel-industry/
- Crocker, T. et al. *for CDP: Disclosure Insight Action, (2019), Melting Point: Which steel companies are ready for the low-carbon transition?* Available at: https://cdn.cdp.net/cdp-production/cms/reports/documents/000/004/659/original/CDP_Steel_2019_Executive_summary.pdf?1564490803.
- ESTE AISBL, (2020), *Proposal for Clean Steel Partnership under the Horizon Europe Programme*.
- Eurofer, (2019), *Low Carbon Roadmap: Pathways to a CO2-neutral European Steel Industry*. Available at: https://www.eurofer.eu/assets/Uploads/EUROFER-Low-Carbon-Roadmap-Pathways-to-a-CO2-neutrhttps://www.argusmedia.com/en/news/2184819-germany-launches-ccus-supportal-European-Steel-Industry.pdf.
- EUROFER, (2021), *European Steel in Figures*. Available at: https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2021/European-Steel-in-Figures-2021.pdf.
- European Commission, (2020), 301 final. *A hydrogen strategy for a climate-neutral Europe*.
- Available at: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf.
- European Commission, (2021), *Recovery and Resilience Facility*. Available at: https://ec.europa.eu/info/business-economy-euro/recovery-coronavirus/recovery-and-resilience-facility_en.

- European Commission, (2021), *Analysis of the recovery and resilience plan of Italy*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021SC0165&from=EN.
- European Commission, (2021), *Updating the 2020 Industrial Strategy: towards a stronger Single Market for Europe's recovery*. Available at: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_1884.
- European Commission, (2021), *Delivering the European Green Deal: The Decisive Decade – Architecture*. Available at: https://ec.europa.eu/commission/presscorner/detail/en/fs_21_3671.
- European Commission, (2021), *Increasing the ambition of the EU emissions trading*. Available at: https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/increasing-ambition-eu-emissions_en.
- European Commission, *EU emissions trading system (EU ETS)*. Available at: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_en.
- European Commission, *The Research Fund for Coal and Steel* (Accessed on 03/09/2021). Available at: https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/research-fund-coal-and-steel-rfcs_en.
- European Commission, (2018), *Impact on the Environment and the economy of technological innovations for the Innovation fund*.
- European Commission. *In-depth analysis in support of the Commission Communication. A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. (773 final).
- European Commission. *Press corner. Carbon Border Adjustment Mechanism*. Available at: https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661
- European Environment Agency, (2018), *Annual European Union greenhouse gas inventory*.
- European Investment Bank, (2020), *Belgium: EU supports ArcelorMittal with EUR 75m EIB loan to scale up breakthrough technology to reduce carbon emissions*. Available at: https://www.eib.org/en/press/all/2020-120-eu-supports-arcelormittal-with-eur-75m-eib-loan-to-scale-up-breakthrough-technology-to-reduce-carbon-emissions#_edn4.
- European Parliament, (2021), *Carbon-free steel production: Cost reduction options and usage of existing gas infrastructure*. Available at: https://www.europarl.europa.eu/RegData/etudes/STUD/2021/690008/EPRS_STU(2021)690008_EN.pdf.
- Global CCS institute, (2017), *CCS: a necessary technology for decarbonising the steel sector*. Available at: https://www.globalccsinstitute.com/news-media/insights/ccs-a-necessary-technology-for-decarbonising-the-steel-sector/.
- Green Steel for Europe, (2021), *Technology Assessment and Road mapping*. Available at: https://www.estep.eu/assets/Uploads/210308-D1-2-Assessment-and-roadmapping-of-technologies-Publishable-version.pdf.
- European Commission, (2020), *Horizon 2020 – Working Programme 2014 – 2015, (2014), General Annexes: Annex G: Technology readiness levels (TRL)*. Available at: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf.

- ICF Consulting Services Limited and Fraunhofer Institute for Systems and Innovation Research (ISI), (2019), Industrial Innovation: *Pathways to deep decarbonisation of Industry, Part 1: Technology Analysis and Part 2: Scenario analysis and pathways to deep decarbonisation.*
- IEA, (2021), Is carbon capture too expensive? Available at: https://www.iea.org/commentaries/is-carbon-capture-too-expensive.
- IOGP, (2019), *The Potential for CCS and CCU in Europe*. Available at: https://ec.europa.eu/info/sites/default/files/iogp_-_report_-_ccs_ccu.pdf.
- Joint Research Centre, the European Commission's science and knowledge service, (2020), *Decarbonisation of industrial heat: The iron and steel sector*. Available at:

  https://ee-ip.org/fileadmin/user_upload/DOCUMENTS/Content/JRC119415_-_Iron_and_steel_decarbonisation_brief.pdf.
- Keys. A. M. van Hout, B. Daniëls, (2019), *Decarbonisation options for the Dutch steel industry*.
- Mandova, H. et al, Research Paper, (2018), *Possibilities for CO2 emission reduction using biomass in European integrated steel plants,* Biomass and Bioenergy 115 (2018) 231 – 243.
- Mayer, J. et al., (2018), *Macroeconomic implications of switching to process-emission-free iron and steel production in Europe*. Journal of Cleaner Production vol. 210 p. 1517.
- McKinsey & Company, (2020), *Decarbonization challenge for steel – Hydrogen as a solution in Europe*. Available at: https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel .
- Morfeldt, J. et al., (2015), *The impact of climate targets on future steel production – an analysis based on global energy system model*. Journal of Cleaner Production vol. 105 p. 469. Available at: https://www.sciencedirect.com/science/article/pii/S0959652614004004?via%3Dihub
- OECD, Financing Climate Futures, (2019), *Low and zero emissions in the steel and cement industries – Barriers, technologies and policies*.
- Rootzen.J; Johnsson, F., (2015), *CO2 emissions abatement in the Nordic carbon-intensive industry – An end-game in sight?*, Energy vol. 80 p.715. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0360544214013875?via%3Dihub
- Steelanol, (Accessed on 16/09/2021), *Steelanol recycles carbon into sustainable, advanced bioethanol*. Available at: http://www.steelanol.eu/en.
- Tata Steel, (2020), HISARNA: *Building a sustainable steel industry*. Available at: https://www.tatasteeleurope.com/sites/default/files/TS%20Factsheet%20Hisarna%20ENG%20jan2020%20Vfinal03%204%20pag%20digital.pdf .
- Tata Steel, (15 September 2021), *Tata Steel opts for hydrogen route at its IJmuiden steelworks*. Available at:

  https://www.tatasteeleurope.com/corporate/news/tata-steel-opts-for-hydrogen-route-at-its-ijmuiden-steelworks.
- Thyssemkrupp, (29/10/2020), *Carbon2Chem®: First project phase successfully completed and notice of funding received from federal government for second phase*. Available at: https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/carbon2chem--

first-project-phase-successfully-completed-and-notice-of-funding-received-from-federal-government-for-second-phase-88707.

- 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*. Available at: https://doi.org/10.3390/en13153840.
- Wang, B., (2017), *New steel process is faster, lower cost, higher quality, uses 5-10 times less energy and enables new thinner sheets*. Available at: https://www.nextbigfuture.com/2017/03/new-steel-process-is-faster-lower-cost.html.

This study is assessing the European steel industry's possible decarbonisation pathways in light of the European Commission's "Fit for 55" package, by evaluating available technology options and the adequacy of available funding streams. The paper shows that options based solely on existing production processes have limited potential to achieve the required emission reductions. Full decarbonisation options will require the widespread availability of green electricity, hydrogen and/or CCS/CCUS infrastructure. It is important that flexibility in the choice of technology decarbonisation options is maintained to account for differences in regional characteristics including natural resources and infrastructure.

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