Decarbonisation Pathways 2030 and 2050

(Deliverable D1.7)

Tobias Kempken, Thorsten Hauck (BFI)
Chuan Wang (Swerim)
Michele De Santis (CSM)
Wojciech Szulc (IMZ)
Monika Draxler, Axel Sormann (K1-MET)
Paula Queipo, Manuel Miranda (Idonial)
Danny Croon, Jean-Theo Ghenda (EUROFER)
Jean Borlee, Jean-Christophe Pierret (CRM)
Klaus Peters (ESTEP)

June 2021

This project has received funding from the European Union under grant agreement NUMBER — 882151 — GREENSTEEL

Table of contents

List of Figures

List of Tables

List of acronyms and abbreviations

ACS	Alternative Carbon Sources
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CAPEX	Capital Expenditures
CBA	Carbon Border Adjustment
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon Capture Usage and Storage
CO_2	Carbon Dioxide
CSCF	Cross Sectoral Correction Factor
DR	Direct Reduction
EAF	Electric Arc Furnace
EU	European Union
ETS	Emissions Trading System
GHG	Greenhouse Gas
H_2	Hydrogen
HPSR	Hydrogen Plasma Smelting Reduction
HQ	High Quality
IBRSR	Iron Bath Reactor Smelting Reduction
IPCEI	Important Project of Common European Interest
LULUCF	Land Use, Land-Use Change and Forestry
LQ	Low Quality
MSR	Market Stability Reserve
NDC	Nationally Determined Contributions
NG	Natural Gas
OPEX	Operational Expenditures
OA	Other Actions
PC	Pulverized Coal
REN	Renewable Energy

Executive Summary

Based on the decarbonisation technologies (so called “decarbonisation pathways”) assessed and presented in a separate report (D1.2, “Technology Assessment and Roadmapping”), this report analyses the industrial deployment of decarbonisation technologies in the European steel industry along the time scale. It considers the progress of technological maturities in combination with the different framework conditions of different sites and regions across Europe. As result the increasing industrial deployment of decarbonisation technologies in the European steel industry is prognosed and **6 probable decarbonisation pathway scenarios** are identified.

For 2030, an industrial pathway scenario for the use of **mixed technological implementation** in primary steel production is presented, and this reaches the decarbonisation targets set at European level. The consequences of **slower industrial deployment** of decarbonisation technologies or **additional hydrogen availability** are presented in additional 2030 pathway scenarios.

For 2050, the approach of **mixed technologies** is extrapolated. An additional pathway considers the availability of **additional decarbonisation technologies** by 2050. The third 2050 decarbonisation pathway is based on **increased availability of steel scrap** leading to a larger share of secondary steel production.

The **availability of energy and material flows** required for steel production are assessed as external framework conditions needed for industrial decarbonisation. In this context, eight availabilities and their probable future developments are assessed:

- Renewable Electricity
- Green Hydrogen
- Natural Gas
- Alternative Carbon Sources
- Iron Ore & Pellets
- Steel Scrap
- CO_2 Storage
- CCU Products

These elaborations are complemented by assessments of other framework conditions: Technological maturity, plant specific investment cycles as well as financial and legislative conditions including EU Emission Trading System (ETS) and Cross Border Adjustment Mechanism (CBAM) are the most important framework conditions that need to be considered.

As far as industrial deployment of decarbonisation technologies in primary steel production is concerned, the availabilities of green hydrogen, alternative carbon sources and steel scrap were found to differ across Europe and thus are exploited to estimate the **distribution** of technology routes in the different member states. The technological maturity and the investment cycles are interpreted as defining the **timing** of industrial deployment.

The conclusion of the Green Steel for Europe report D1.5 (“Decarbonisation barriers”) and the projects’ consultation activities was, that the most important barriers for decarbonisation are all related to financial conditions. Financial conditions were consistently found to be the dominant background for the development of industrial deployment scenarios. In this sense, the availability of energy and materials flows must always be linked to the respective costs, respectively to the operational expenditures (OPEX). The OPEX must either themselves enable profitable steel production or the financial and legislative framework conditions must achieve appropriate compensation. The policy options to adapt the financial and legislative framework conditions to enable industrial decarbonisation are highlighted in the Green Steel for Europe D3.2 report – “Impact Assessment Report”.

In the report “Technology Assessment and Roadmapping” (Deliverable D1.2 of the Green Steel for Europe project), the most important decarbonisation technologies were completed to full process chains, so called “technology routes”. These technology routes are considered and further distinguished in this report. They are summarised as **technology route factsheets** in the Annexes A-G. These factsheets give a simplified but transparent overview of technological development and specific requirements of the different options with regard to framework conditions. The technology routes were categorised into four main groups:

- **Optimised Blast Furnace-Basic Oxygen Furnace (BF-BOF) route (Route 1)**
- **Direct Reduction (DR) based route (Route 2)**
- Smelting Reduction (Route 3)
- Iron Ore Electrolysis (Route 4)

The optimised BF-BOF route is further distinguished into utilisation of alternative carbon sources, CCUS and other actions (Route 1A/B/C). The direct reduction-based route is divided into natural gas based direct reduction (Route 2A) and hydrogen based direct reduction (Route 2B).

Based on this information, the optimised BF-BOF routes (Routes 1A/B/C) and the direct reduction-based routes (Routes 2A/B) were considered to reach TRL 9 by 2030-2035 and to start its industrial deployments, whereas Smelting Reduction (Route 3) and Iron Ore Electrolysis (Route 4) might just become options for later industrial deployment by 2050. This is reflected in the pathway scenarios elaborated.

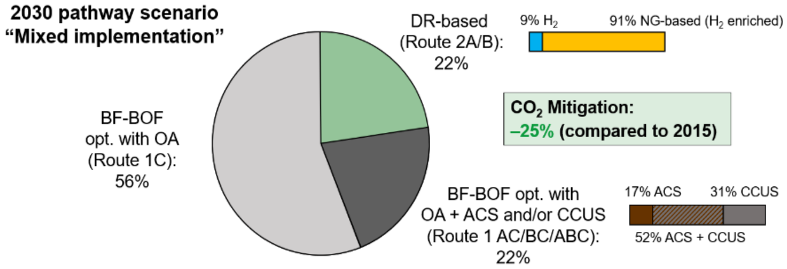
The pathway scenarios show the shares of the considered **primary steel production routes in the EU-27**. The pathway scenarios focus on primary steel production, as this is responsible for an estimated 87% of current CO_2 emissions of the European Steel Industry. This is consistent with the scope of this project: to consider at least 80% of CO_2 emissions from steelmaking. Due to its high share of CO_2 emissions, primary steel production provides huge mitigation potential, however, significant investments and changes of technology routes are needed, and this would obviously be a time-consuming transition. Thus, the demands to enable and start this technology leap in primary steel production are assessed as most urgent with respect to the policy options needed.

The aspects of secondary steel production are also covered in the analyses. The most important framework condition needed to mitigate CO_2 in secondary steel production is the availability of huge amounts of renewable electricity at competitive prices. This demand is consistent with the main demand of primary steel production.

For the first 2030 scenario of “**Mixed implementation**” of decarbonisation technologies, the assessment of national and/or regional framework conditions was utilised to differentiate the EU member states with primary steel production into four groups.

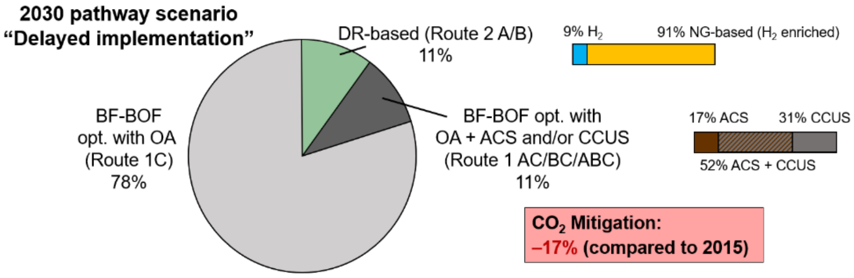
This assessment of national / regional framework conditions was fused with estimations of blast furnace relinings in the EU-27 by 2030. It was estimated that **at least 46%** of primary steel production capacity in the EU-27 will **not** be subject to major technology **switches by 2030** based on their **investment cycles**. The other 54% (i.e. with upcoming BF relinings) were assigned to the four groups of national and/or regional framework conditions. For all scenarios it was assumed that the total annual steel production capacity in the EU-27 remains constant at 160 million tonnes per year.

Based on these assumptions, the **2030 scenario "Mixed implementation"** leads to a production share of 56% being subject to gradual improvements to the BF-BOF route by other actions (Route 1C). Furthermore, 22% of production capacities are expected to utilise alternative carbon sources and/or CCUS measures. Another 22% of production capacities are shifted towards direct reduction-based production (Route 2), with an average share of 9% reduced by hydrogen. Such industrial deployment of decarbonisation technologies by 2030 would meet the targets set by the EU (a 25% reduction in CO_2 emissions compared to 2015). However, as the lead times (~5 years) between investment decisions and industrial implementation are significant, this 2030 scenario can be rated as quite ambitious: 44% of the capacities would need significant investment decisions before 2025 to ensure industrial implementation before 2030.



The **2030 scenario "Delayed implementation"** assumes that 50% of major technology switches to alternative carbon sources, CCUS or Direct Reduction are delayed and realised after 2030. This leads to 78% of primary production capacities being subject to only gradual improvements by "Other actions" (Route 1C); 11% are subject to major utilisation of alternative carbon sources and/or CCUS and a further 11% are estimated to be shifted towards direct reduction-based production. Overall, this pathway scenario results in a 17% reduction of CO_2 emissions compared to 2015, missing the target set by the EU by eight percentage points (+14 Mt CO_2 /a).

However, if the investments cycles and lead times (as discussed above) are considered, the assumptions for this scenario may be rated as more realistic. Several solutions can be discussed to close the gap to emission targets set for the EU-27.

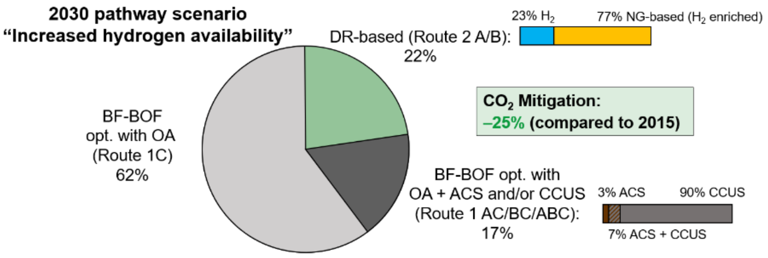


Main examples are:

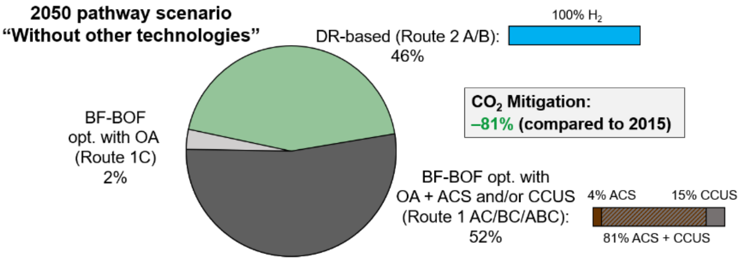
1. Significantly decreasing CO_2 emissions in secondary steel production by extensive use of renewable power. This can be rated as a preferable option since no adaption of steel production sites needing costly investments and involving technical risks is necessary.
2. Increasing hydrogen enrichment for new direct reduction plants.

3. Decreasing energy demand and emissions by increased use of scrap. This approach is however strongly limited for 2030 by the shortage of scrap of sufficient quality.
4. Another option is that primary steel production sites are shut down. However, due to the most probable consequences of carbon leakage and steel quality issues this option can be rated as the worst-case scenario for the European steel industry, for the European economy and for the global climate.

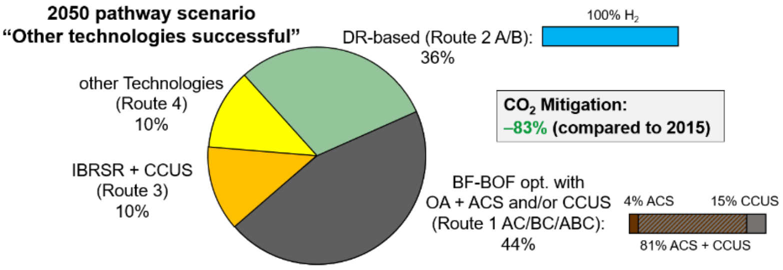
The third **2030 scenario “Increased hydrogen availability”** reflects the more extensive use of hydrogen in the steel industry by 2030 (+0.2 million tons resp. +25% was assumed to be utilised). Since the availability of alternative carbon sources in 2030 is not yet clear, it was also assumed that fewer alternative carbon sources would be utilised. The specific CO_2 mitigation in the BF-BOF-route optimised by “other measures” (Route 1C) and direct reduction-based capacities was increased to reflect higher hydrogen usage. Overall, this pathway scenario needs 39% of primary production capacity to be substantially changed (compared to 44% for the “mixed implementation” scenario) and can be rated as ambitious but viable. This pathway scenario meets the EU target of 25% CO_2 mitigation compared to 2015 and thus reflects an alternative hydrogen-focused way to reach the target.



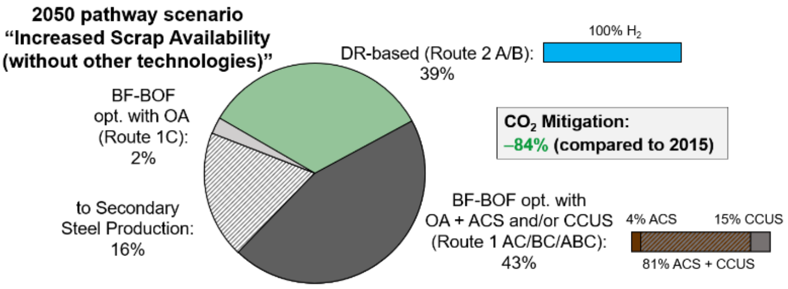
Analyses covering a forecast of almost 30 years obviously include huge uncertainties and a large variance of possible framework conditions and resulting industrial scenarios. To illustrate the range of options three 2050 scenarios were selected which all realise the targeted CO_2 mitigation of >80% but with different technologies. The **2050 scenario “Without other technologies”** extrapolates the 2030 “Mixed implementation” pathway scenario to 2050. It assumes that no other breakthrough decarbonisation technologies will be industrially successful by 2050, so that the decarbonisation process needs to be based on alternative carbon sources, CCUS and hydrogen based direct reduction. In this pathway scenario, 46% of primary steel production is covered by direct reduction-based processes utilising 100% hydrogen; 52% of primary production capacities operate the BF-BOF route improved with significant alternative carbon source and/or CCUS utilisation. However, only 2% of the BF-BOF capacities face gradual improvements. This technology distribution would lead to an 81% reduction in CO_2 emissions compared to 2015, thus building a strong basis for reaching the EU target of climate neutrality.



In the **2050 scenario "Other technologies successful"** two additional decarbonisation technology routes are assumed to be industrially established. This pathway scenario reflects an industrial deployment of iron bath reactor smelting reduction including CCUS measures (Route 3) and other technologies such as, for example, iron ore electrolysis (Route 4) in 10% of primary steel production capacities each; 36% of capacities would be covered by hydrogen-based direct reduction. The remaining share of 44% of primary production capacities is covered by the BF-BOF route adjusted to significant alternative carbon source and CCUS utilisation. This technology distribution would increase the CO_2 mitigation to 83% compared to 2015.



The **2050 pathway scenario "Increased Scrap Availability"** reflects a partial switch of primary steel production capacities towards secondary steel production due to higher availability of steel scrap. In this scenario 15 million tonnes of annual steel production are shifted towards secondary steel production. The distribution of the remaining primary steel production capacities reflects the other two 2050 pathway scenarios with either other technologies being successful or not. Both cases lead to a slight increase of CO_2 mitigation to 84% compared to 2015.



It can be concluded that:

- **framework conditions** such as production costs as well as the availability of resources and infrastructure **dominate** the industrial implementation of breakthrough decarbonisation technologies;
- the framework conditions are currently far from positive for decarbonisation investments;
- **policy actions are needed** to make the framework conditions better suited to promoting investments in breakthrough decarbonisation technologies;
- considering the long investment cycles and the significant lead times, the time pressure for these policy actions is extremely high, particularly for fulfilment of the **2030 targets**;
- actions to safeguard positive decarbonisation investment conditions both in the short term and the long term must be **taken now.**

The next few years will be decisive in achieving the European CO_2 mitigation targets with many influential factors also changing in an unpredictable fashion. The Green Steel for Europe consortium is thus strongly in favour of continuing **the interdisciplinary roadmapping and assessment work** in a follow-up project with consideration to the actual framework conditions and targets and to provide a deeper investigation of aspects which have only been touched upon in this project: secondary steel production including downstream processes and decarbonisation during the decisive years 2030-2040.

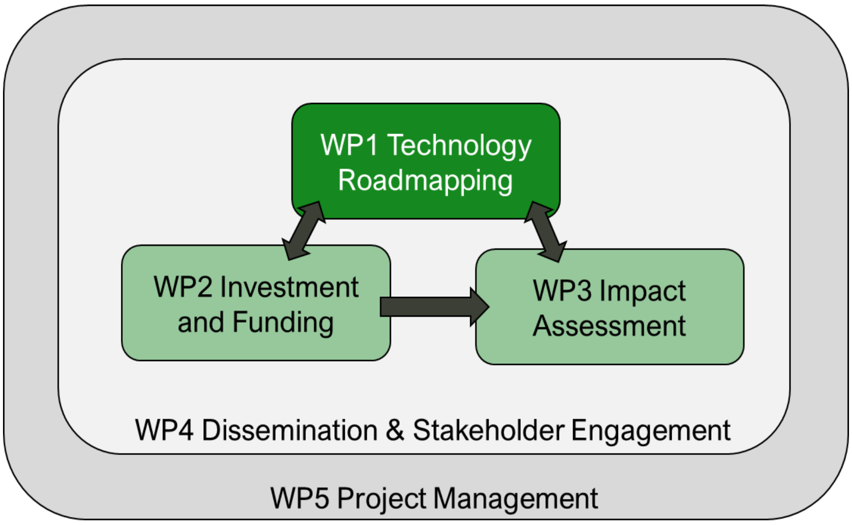
1 Introduction

In line with the Paris Agreement, the European Union (EU) set out to achieve ambitious climate and energy goals, aiming to reduce the net emissions of greenhouse gases to 0% by 2050 (EC, 2019). One further step towards this aim was taken in 2020 when the European Commission presented a legislative proposal for a European Climate Law (Council of the European Union, 2021).

The iron and steel industry is among the largest carbon dioxide (CO_2) emitters and is responsible for 5% (2016) of total CO_2 emissions in Europe and 4-7% of global anthropogenic CO_2 emissions. To meet the EU-27 targets of a 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels and climate neutrality by 2050, it is essential to establish adequate and innovative solutions for transitioning current processes towards carbon-lean production (Green Steel for Europe, 2021c).

The Green Steel for Europe project aims to provide transparency concerning technologies, their implementation and impact, possible barriers and remedies to support the initiation of the crucial next steps. Work package 1 (WP1) is focused on technological aspects, work package 2 (WP2) on financial aspects, work package 3 (WP3) on policy aspects and work package 4 (WP4) on stakeholder engagement (see Figure 1).

Figure 1: GREENSTEEL Work Package Structure

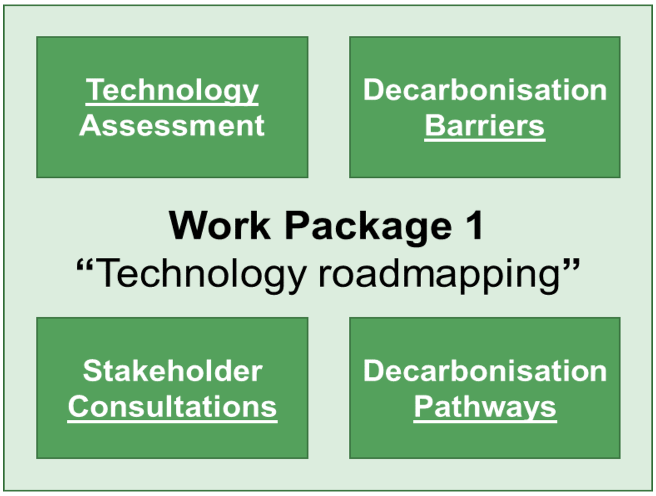


Source: Compiled by the authors.

This deliverable 1.5 – “Decarbonisation Pathways 2030 and 2050” – synthesises all the results of the “Technology Roadmapping” in WP1. The following Figure 2 shows the structure of the “Technology roadmapping” work: It started with the assessment of technologies including a roadmap describing their planned further development and including their combination to complete process chains. The results have been reported in deliverable D1.2 “Technology Assessment and Roadmapping”.

The work continued with an assessment of decarbonisation barriers, already reported in deliverable D1.5 “Collection of possible decarbonisation barriers”. The results for both deliverables were a combination of desk research and stakeholder consultations. The stakeholder consultations have been reported in deliverable D1.6 “Synopsis report of consultation activities”.

Figure 2: GREENSTEEL Work Package 1 contents

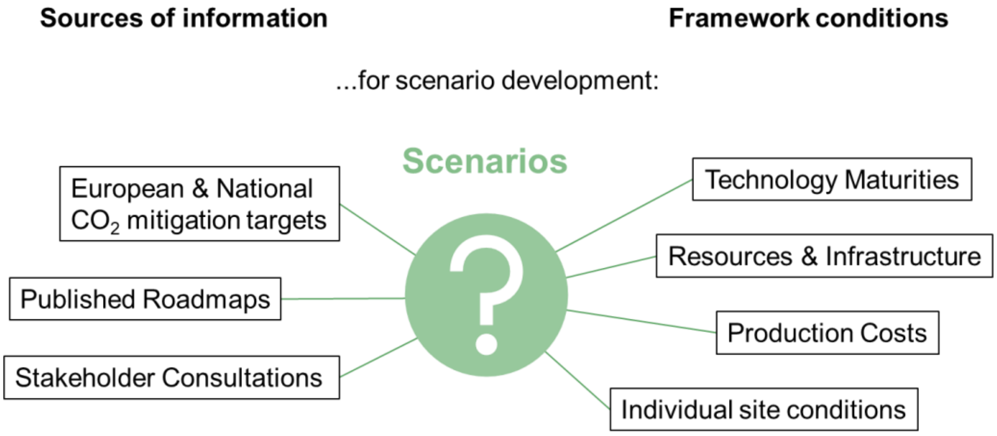


Source: Compiled by the authors.

Continuing the sound basis on technologies and barriers achieved from the deliverables mentioned above, this D1.7 “Decarbonisation Pathways 2030 and 2050” presents pathways for the implementation of decarbonisation technologies in the European steel industry. This industrial implementation is obviously the crucial step to mitigate CO_2 emissions.

The following Figure 3 shows the sources of information which were used – beyond the mentioned deliverables of the Green Steel for Europe project – to develop these industrial decarbonisation pathways: European and national CO_2 mitigation targets and previously published industrial roadmaps were used in the analysis. These sources were fused with the results of the stakeholder consultations carried out by the Green Steel for Europe project to ensure consistency between the expectations of governances, external experts and steel producers.

Figure 3: Sources of information and framework conditions for scenario development



Source: Compiled by the authors.

Decarbonisation of steel production requires substantial changes to the most relevant supply and productions chains of the steel industry. Consequently, the challenge could be compared to a (fifth) industrial revolution, in terms of both complexity and duration. Several framework conditions will influence this process. These can be grouped into:

- technical aspects, in particular with regard to the maturity and progress of the decarbonisation technologies,
- supply aspects, mainly related to availability of infrastructure, energy and feedstocks,
- financial aspects, covering operational and capital expenditures (OPEX, CAPEX) as well as funding and other market framework conditions,
- individual site conditions, covering external local conditions such as national legislative framework conditions with regard to taxation and funding and internal local conditions such as structure and investment cycles of existing brownfield plants.

Chapters 2 and 3 of this report analyse these framework conditions in detail. Chapter 4 summarises the main relevant technology routes which were derived from the technology assessment and which are the basis of the decarbonisation pathways.

Chapter 5 considers that the industrial implementation of decarbonisation technologies depends on successful investment decisions. Consequently, it defines an investment pathway along the timeline of increasing production capacities, from first industrial demos until complete industrial decarbonisation of steel production. It also describes the assumptions and the modelling approach which are used to develop the different implementation scenarios.

Finally, Chapter 6 describes three decarbonisation scenarios for 2030 and 2050 including the assumed implemented decarbonisation technology routes and the resulting CO_2 emissions.

2 External Framework Conditions

The decarbonisation pathway scenarios to be developed for both 2030 and 2050 aim to reflect plausible future pathways for the decarbonisation of the European iron and steel industry. Thus, the definitions of these pathway scenarios were subject to reasonable assumptions to be met for the definitions. In a first step, relevant influencing framework conditions were identified for use as boundary conditions for formulating the pathway scenario (see chapters 6 & 7). These include:

- Availability of (green) Electricity,
- Availability of (green) Hydrogen,
- Utilisation of CCU Products,
- Availability of CO_2 storage,
- Availability of Natural Gas,
- Availability of Alternative Carbon Sources,
- Availability of Iron Ore & Pellets, and
- Availability of Steel Scrap.

Figure 4: Primary steel production countries and sites in EU-27

Source: Authors' composition based on (EUROFER, 2019c)

Availabilities refer to not only general availabilities, but also to economic viability, infrastructural supply and sufficient qualities. These availabilities were assessed in two different scopes. First, their principal availability in terms of production capacities or reserves were assessed. In terms of hydrogen and electricity, the production capacity developments over the next decades were taken into account along with the development of green or CO_2-lean technologies. This assessment led to 'hard constraints' for the developed decarbonisation pathway scenarios, as these strictly limit the implementation potential for decarbonisation technologies.

Additionally, the correlated prices and/or economic consequences of these framework conditions were assessed. Due to the correlated cost, the economic operation of certain decarbonisation pathways could not be realised, which also limits their implementation potential. These effects were considered as 'soft constraints' for development of the decarbonisation pathway scenario.

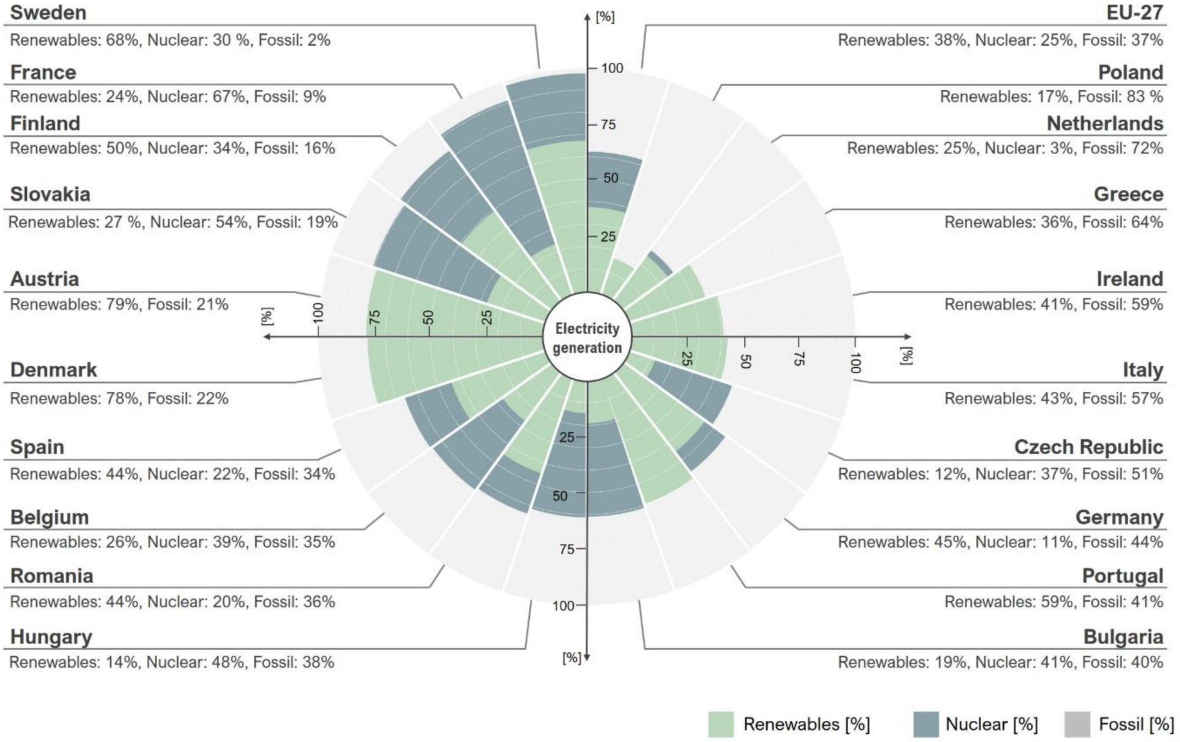
Within the collection of possible decarbonisation barriers (D1.5) and the conducted stakeholder consultation (D1.6), the barriers for decarbonisation (and thus the constraints for specific decarbonisation technologies) were found to differ significantly both nationally and regionally. This will most likely influence local transformation processes to decarbonised industrial steel production. Against this background, the assessment of external framework conditions was conducted on a national level with a focus on EU-27 member states with primary steel production. Figure 4 gives an overview of primary steel production countries (in light green) and sites (in strong green, size correlating to their production capacities) within the EU-27.

2.1 Electricity

The transition towards CO_2-lean technologies within energy-intensive industries such as the iron and steel industry will significantly enhance the need for electricity. In order to be compatible with the goal of overall economic climate neutrality, the electricity needed must be generated without CO_2 emissions, thus demanding decarbonisation of the energy sector. In addition to the increased need for affordable and clean electricity, strengthening the high voltage networks close to industrial consumers and thereby providing an adequate infrastructure for a low-CO_2 iron and steel industry will be inevitable (Wyns et al., 2018).

In 2020, overall European electricity production was 2760 TWh, of which 38% were generated from renewable sources, 25% from nuclear power and 37% from fossil fuels. Figure 5 shows the share of electricity generation by type in 2020, with the percentages decreasing from the inside (0%) to the outside (100%). Grey areas represent the production of electricity through fossil fuels, blue areas indicate the production through nuclear power and the green colour reflects the share of energy produced through renewable energy (EMBER, 2021).

Figure 5: Share of electricity generation in Europe in 2020



Source: EMBER, 2021.

Most of the energy generated in the past was based on fossil fuels. This is particularly true of countries without hydraulic resources and nuclear power plants. Over the last few years, the share of electricity generation from fossil fuels has decreased in all European countries, due to the development and expansion of renewable energy generation as well as the decommissioning of several thermal power plants (ENTSO-E, 2017).

As cross-border flows of electricity account for less than 10% of total electricity production in the EU-27, (European Commission, DG Energy, 2021) electricity generation was assessed on a national level. The countries with the largest share of fossil power generation in Europe are Poland (83%), the Netherlands (72%) and Greece (64%). The Netherlands, Greece, Ireland and Italy will gradually phase out coal-fired power generation over the next few years, but continue to rely on gas generation, which will lead to carbon-based power generation. Sweden (2%), France (8%) and Finland (16%) have the lowest share of fossil power generation and are considerably below the European average see Figure 5 (EMBER, 2021).

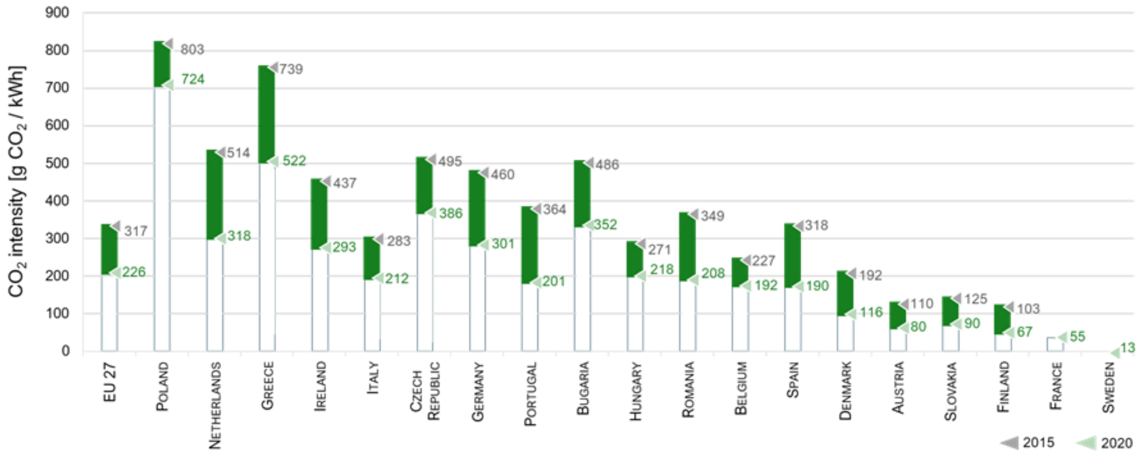
Nuclear power generation in Europe has declined in recent years. This decrease can be linked to several factors, including policy decisions leading to the decommissioning of plants International Energy Agency, 2020). It is likely that this share will continue to decline, as e.g. Germany has announced the phasing-out of nuclear energy by 2022, Belgium by 2025 and Spain by 2030. France has also announced a reduction of the use of nuclear energy by 2035 to half of its electricity mix. Of the EU-27 only Poland, Greece, Ireland, Italy, Portugal, Denmark and Austria do not have nuclear power (EMBER, 2021).

Over the last 10 years, the share of renewable energy (bioenergy, hydropower, solar, wind and other renewables) in electricity generation within Europe has increased. In particular, the share of wind and solar-based electricity has risen significantly over the last few years with Austria (79%), Denmark (78%) and Sweden (68%) using the largest share of renewable energy for electricity generation (Ember, 2021). The distribution of the different types of renewable energies in Europe depend on geographical conditions and possibilities. For example, hydropower plants are mainly found in the Alpine region, the Carpathians and the Scandinavian countries (Nordic regions) (ENTSO-E, 2017), whereas Denmark, Ireland and Germany have the highest share of wind and solar energy in electricity production (EMBER, 2021).

In recent years, the use of bioenergy in electricity generation has been increasing relatively slowly and has remained almost unchanged since 2018. Electricity generation through hydro power has also shown little growth. In 2010-2020, the average annual growth of wind and solar energy was 38 TWh, which means that the annual increase would need to almost triple between 2020 and 2030 to reach the European Green Deal target for 2030. According to the literature, national energy and climate plans currently reach about 72 TWh/year, which would mean that the required increase of 100 TWh/year and the associated energy targets would not be met (EMBER, 2021).

Along with the increase in electricity generation from renewables, carbon intensity has fallen from an EU average of 317 g of CO_2/kWh in 2015 to 226 g in 2020 (Figure 6). This corresponds to a decrease of 29% from 2015-2020. As this value defines Scope 2 CO_2 emissions, it is a key figure for decarbonisation measures relying on increasing electrification. Despite the fact that coal-fired power generation has declined within the last few years, part of it has been replaced by increased use of gas-fired power generation, thereby slowing down the reduction in carbon intensity (EMBER, 2021).

Figure 6: CO₂ carbon intensity in Europe in 2015 and 2020



Source: EMBER, 2021.

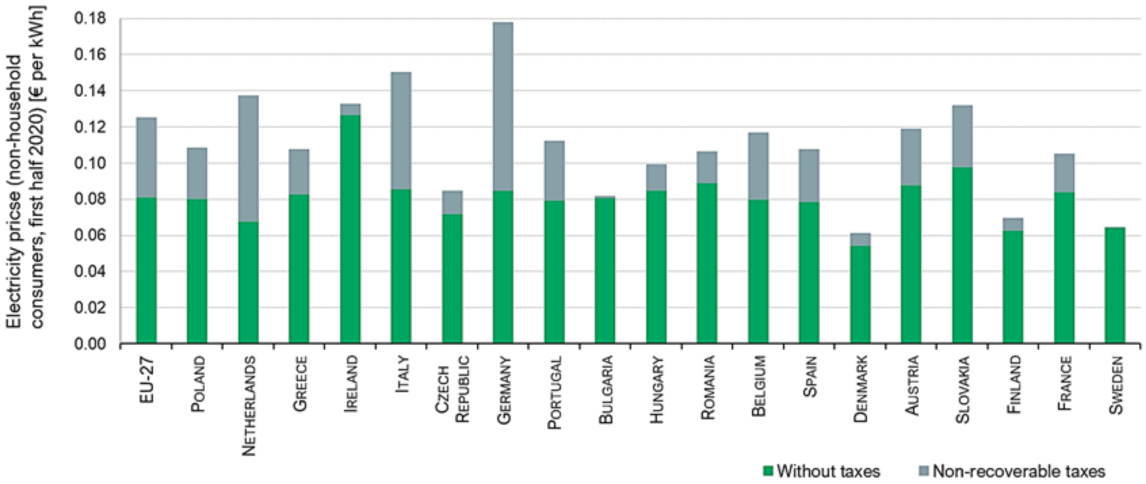
The price of electricity alters over time and shows country-specific differences. Electricity prices differ significantly between the wholesale price (electricity price excluding additional charges) and the retail price (electricity price including additional charges). The final electricity prices for end consumers (retail price) comprise electricity generation prices, grid costs (network costs), taxes, fees and surcharges, resulting in national price differences as well as fluctuations over time. (Eurostat, 2018a; Fraunhofe-ISI and Ecofys, 2015).

Figure 7 shows electricity prices for non-households (medium consumers whose consumption lies between 500 and 2000 MWh/year) in the first half of 2020 without taxes (green) and including non-refundable taxes (blue). The average European price for electricity at the beginning of 2020 amounts to € 0.1254/kWh (including non-recoverable taxes). On a national level, Germany has the highest electricity price (€ 0.1781/kWh) due to the comparatively high share of taxes and levies (EUROSTAT data browser, 20201).

Internationally, European prices are comparable to those in China and lower than in Japan, Australia and Brazil, but higher than in Canada and Russia and almost twice as high as in the USA (European Commission, DG Energy, 2021; Rademakers et al., 2020).

Besides considering the CO_2 intensity of electricity production and electricity price, the overall availability of electricity is relevant to the European industry sector. Annual electricity production in the EU-27 is 2,800 TWh (European Commission -DG Energy-, 2020). Forecasts for the year 2050 estimate an electricity demand of about 400 TWh/year of (CO_2-free) electricity for the European iron and steel industry only. This amount also includes the production and use of hydrogen (EUROFER, 2021) and translates to 15% of current overall electricity production in the EU-27.

Figure 7: Electricity prices for non-household consumers (first half 2020)



Source: Eurostat Statistics Explained, "Electricity prices for non-household consumers, first half 2020 (EUR per kWh)."

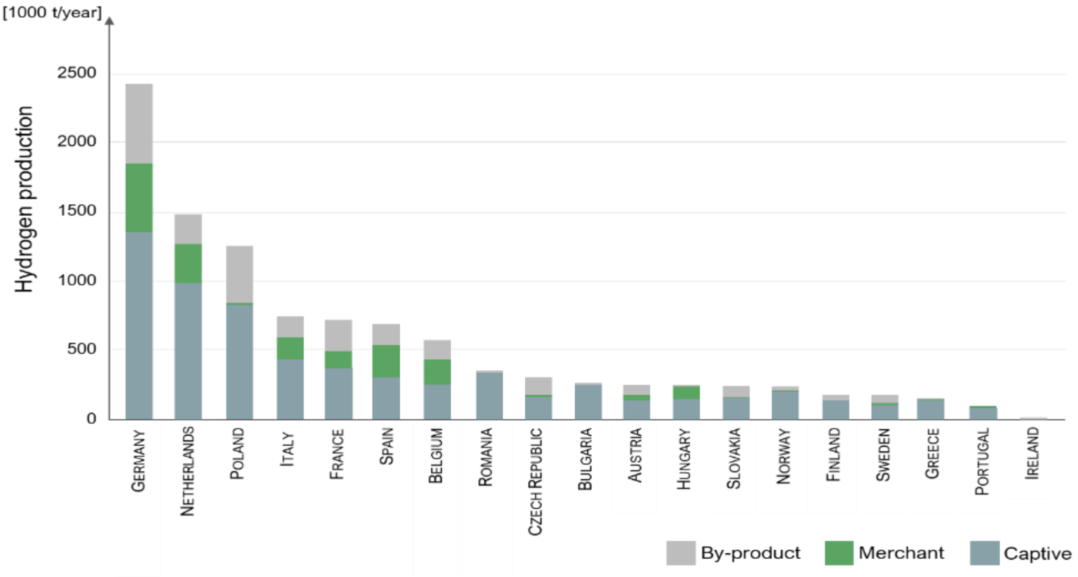
2.2 Hydrogen

In 2018, Europe had a total annual hydrogen production capacity of 11.5 million tons of hydrogen. Assuming a hydrogen demand of 60 t H_2 / t crude steel (via hydrogen-based direct reduction), this production capacity translates to 0.2% of primary steel production demand. The current hydrogen production capacities are either on site for own consumption (= captive production facilities), in merchant production facilities or in plants where the production of hydrogen is a by-product of other processes. The distribution of production capacities differs among individual countries (Figure 8). In a national comparison, Germany is the country where most hydrogen is produced, followed by the Netherlands, Poland and Italy. Up to now, most of the hydrogen produced is utilised within oil refineries and ammonia production; only a minor share (about 2%) is used by the remaining industries (Pawelec et al., 2020; Kakoulaki et al., 2020).

There are several ways to produce hydrogen; these differ in technology as well as in the energy carrier used and thus in their related CO_2 emissions. Depending on which method is chosen, the label of the hydrogen produced changes. 'Fossil-based hydrogen' is generated by thermochemical conversion of fossil fuels (European Commission, 2020a). If no further carbon capture is applied, this is indicated as 'grey hydrogen'. If additional carbon capture and storage is applied to a fossil-based hydrogen production, it is called 'blue hydrogen'. The term 'green hydrogen' or 'renewable hydrogen' refers to hydrogen that is produced e.g. by water electrolysis using renewable energy, so that no CO_2 is generated in its production process (Wouters et al., 2020; Peters et al., 2020; European Commission, 2020a).

Currently, the EU generates mostly grey hydrogen, with the methane steam reforming process route being the most common production process (Pawelec et al.,2020; Peters et al., 2020). Depending on the technology and feedstock, the fossil-based process results in between 100 and 240 g CO_2-eq./MJ (12-30 t CO_2- eq./t H_2) (Wouters et al., 2020). Grey hydrogen production costs are currently in the range of €1 to 2/kg H_2 (28/MWh) (Pawelec et al., 2020; Peters et al.,2020).

Figure 8: Hydrogen production capacity per country



Source: G. Pawelec, M. Muron, J. Bracht, B. Bonnet-Cantalloube, A. Floristean and N. Brahy, "Hydrogen Europe Clean Hydrogen Monitor 2020," Hydrogen Europe.

The price is influenced by various technical and economic factors such as the gas price and capital expenditure (Wyns et al., 2018). Estimated costs for blue hydrogen are around €2 (between €35 - 45/MWh), depending on the technology used and production scales (Pawelec et al., 2020; Wouters et al., 2020; Peters et al., 2020). In Europe, the production of green hydrogen is currently limited to small pilot plants (Pawelec et al., 2020; Peters et al., 2020). As described in Deliverable 1.2, there are several possibilities regarding CO_2-lean hydrogen production. Hydrogen production by water electrolysis would lead to emissions of 14.8 kg CO_2/kg H_2 assuming the average EU-27 electricity mix (Pawelec et al., 2020). In terms of CO_2 mitigation, the electricity used to produce hydrogen should ideally be CO_2-free.

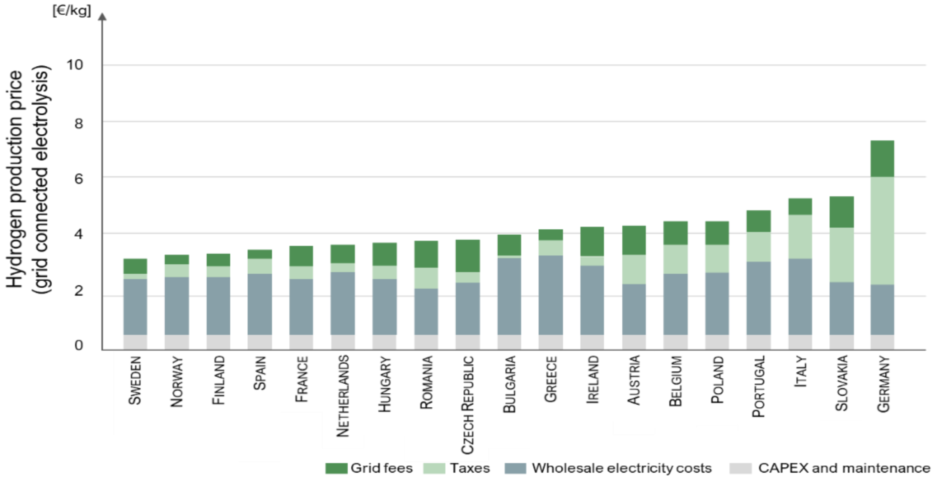
The cost of producing green hydrogen by means of electrolysers with grid electricity varies between about €2.5 and 9.5/kg (€70/MWh to €130/MWh). The main drivers influencing price are the CAPEX of the electrolyser, the utilisation factor (operating hours) and the electricity price as well as the parameters of the electrolyser (Kakoulaki et al., 2020; Wouters et al., 2020).

In 2021, the costs are considerably higher than those of grey or blue hydrogen, but it is expected that the costs will decrease in the common decades and achieve a similar order of magnitude as grey or blue hydrogen (Wouters et al., 2020).

Over the last decade the production costs for green hydrogen have declined by 60% (Kurrer, 2020). Production costs are expected to continue to fall as the investment costs for mass production plants decrease and the prices for electricity from renewable energies, such as wind and solar, continue to decline. In the period between 2016 and 2019, electrolyser capacities have been increased by an annual average of 20% and the development continues (Wouters et al., 2020).

Country-specific differences for the production costs of hydrogen are shown in Figure 9. The differing wholesale prices as well as the different taxes and fees account for the big differences in costs.

Figure 9: Grid connected electrolysis hydrogen production costs (EU-28, 2019)

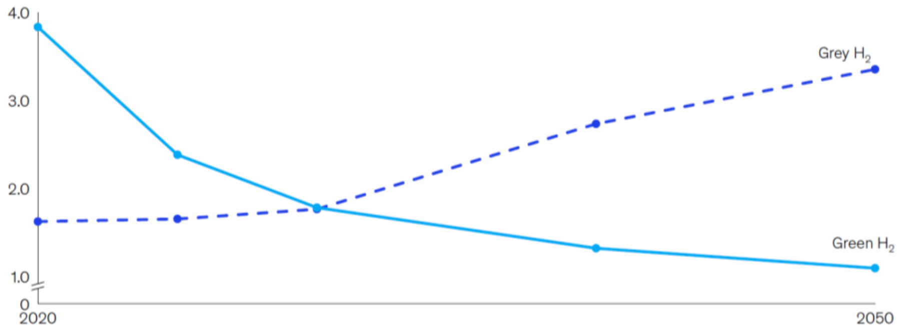


Source: Pawelec et al., 2020.

The International Energy Agency estimates a future global economic potential of 19 EJ (5,277 TWh or 135 Mt) of hydrogen from renewable electricity in total final energy consumption by 2050, while others, (e.g. the Hydrogen Council) see this figure rising to around 80 EJ (22,222 TWh or 568 Mt, not necessarily all from renewables) (Kakoulaki, 2020). In its "Hydrogen strategy" the European Commission set the target of erecting 80 GW of water electrolyser capacity by 2030 (EC, 2020b). Assuming 3 000 annual full load hours and an energy demand of 4 kWh_{el} / m^3 H_2 (Green Steel for Europe, 2021c), this translates to 5.4 million tons of annual hydrogen production. The demand for hydrogen in the EU will increase to between 23 million tons (780 TWh) in a "Business as usual case" and 68 million tons (2.250 TWh) in an "ambitious case" by 2050 (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019).

Figure 10 shows the projected price development of green and grey hydrogen for Germany between 2020 and 2050. Prices for grey hydrogen will rise due to the increasing penalties for carbon dioxide emissions, while the price perspectives for blue hydrogen (not in the figure) will be rather stable. Green hydrogen prices are expected to halve within the next ten years and to fall below grey hydrogen prices from around 2030 onwards (Hoffmann et al., 2020).

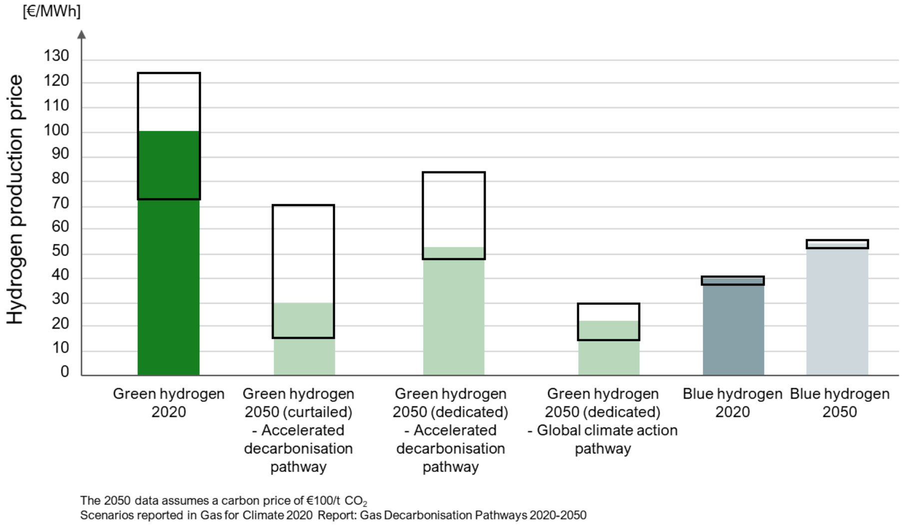
Figure 10: Price development over time for green and grey hydrogen in €/kg H_2 (Germany)



Source: Hoffmann et al., 2020.

Conservative assumptions suggest that by 2030 the price of green hydrogen might fall to €1.8/kg (Kurrer, 2020). Estimates about the production costs of green hydrogen for the year 2050 range between €17/MWh and €84/MWh (Wouters et al., 2020). The figure below (Figure 11) shows different scenarios of price development for hydrogen production costs in 2050 compared to 2020.

Figure 11: Hydrogen production costs (2020, 2050)



Source: Wouters et al., 2020.

In addition to hydrogen production, transport and storage of hydrogen as well as the corresponding infrastructure are essential for the successful deployment of hydrogen-based technologies. Assuming a sufficiently strong grid connection to provide the required electricity, it is possible for steel producers to produce hydrogen in the immediate proximity of the plant, thus reducing transport costs significantly. Further options regarding hydrogen production are at sites with easy access to large amounts of comparatively low-priced electricity, i.e. at major nodes of the electricity grid or at sites where the availability of electricity changes drastically and hydrogen production can be used for grid balancing (large offshore wind parks linked to the national electricity grid) (Kurrer, 2020).

For consumers who cannot generate hydrogen on site, hydrogen can be transported by pipelines. Hydrogen can be injected into the natural gas grid up to a certain percentage, which varies between countries. There are currently approximately 1 500 km of hydrogen pipelines in operation in Europe, but most hydrogen is currently produced at the point of demand (Kurrer, 2020). According to the Hydrogen Backbone Initiative, a 6 800 km hydrogen network would be in place by 2030 and 22 900 km by 2040 (Wang et al., 2020).

The EU and several individual countries (Germany, France, Spain, Portugal, Norway) have recently released hydrogen strategies to promote the development of hydrogen towards 2050. Other national strategies, i.e. Austria, Estonia, Luxembourg, Poland, Slovakia, are currently being developed (Pawelec et al., 2020).

2.3 CCU products

CO_2 mitigation via the pathway of “Carbon Capture and Usage” (CCU) utilises the approach of using CO and/or CO_2 as feedstocks for other valuable products instead of emitting it to the atmosphere. This includes separating it from waste gas streams (“carbon capture”) and its subsequent conversion into other products. A conversion of CO and/or CO_2 can be achieved by chemical or biological processes. Regarding the European iron and steel industry, both approaches are currently being developed and utilised. Below, two reference projects of Carbon2Chem developed by ThyssenKrupp Steel Europe and Carbalyst® by ArcelorMittal will be looked at in more detail.

The Carbon2Chem approach is based on chemical conversion of CO and/or CO_2 into methanol or other higher alcohols as the basis for fuels, plastics or fertilisers. Methanol is the simplest alcohol with the formula CH_3OH. The catalytic reactions of converting CO and CO_2 into methanol can be described as follows:

$$CO + 2\,H_2 \leftrightarrow CH_3OH$$

$$CO_2 + 3\,H_2 \leftrightarrow CH_3OH + H_2O$$

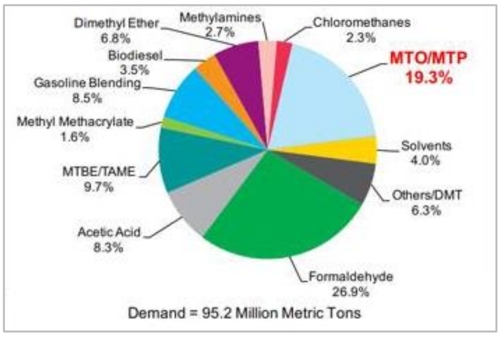
Both reactions are coupled by the water-gas shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

Based on these reactions, the conversion of one mole of carbon dioxide CO_2 requires three moles of hydrogen H_2 for its conversion into methanol CH_3OH. To achieve a maximum CO_2 mitigation potential, the production of hydrogen must not cause additional CO_2 emissions (so-called green hydrogen).

Methanol is used as a feedstock for a wide range of applications in the chemical industry and can be utilised as synthetic fuel for the transport sector. The annual global demand for methanol in 2021 is estimated to be 95 million tons (Avarado, 2017). In 2017, the demand for methanol in the EU-28 was 7.9 million tons (Avarado, 2017). Assuming an integrated steel plant with 1 Mt annual crude steel production, a CO_2 intensity of primary steel production of 1.9 t CO_2 / t CS and CO_2 mitigation of 30% by CCU in terms of methanol production, this plant would be producing 0.4 million tons of methanol. This value corresponds to 5% of 2017 methanol demand in the EU-28. The subsequent use of methanol is illustrated in Figure 12.

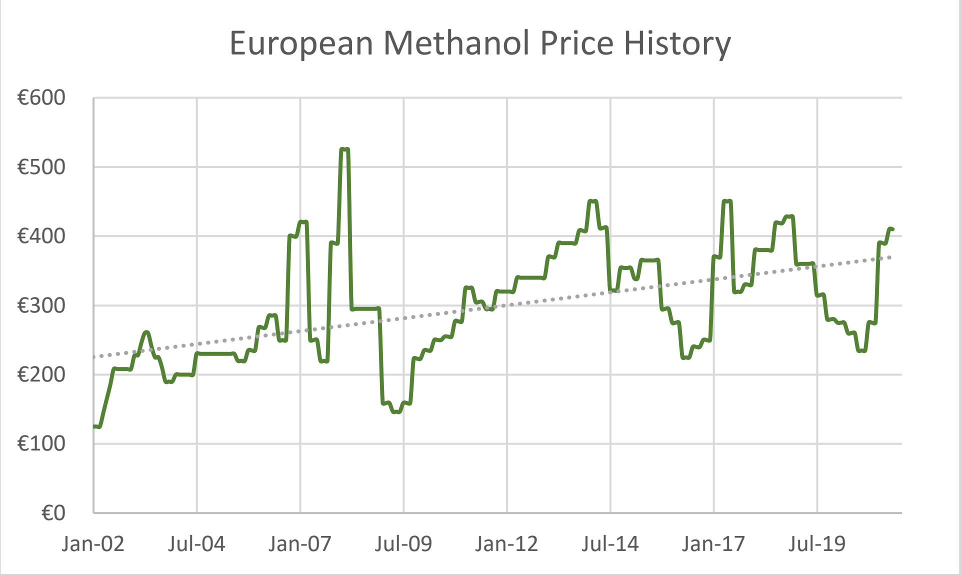
Figure 12: Methanol Demand and Utilisation in 2021



Source: Avarado, 2017.

Due to its widespread use and storability under ambient conditions, methanol is a tradeable product. In the period 2015-2020, the average price of methanol was €325 per metric ton varying between €225 and €450 per metric ton. In the first half of 2021, the average price is €400 per metric ton with fluctuations between €390 and €410 per metric ton. The price history of European methanol is indicated in Figure 13.

Figure 13: European Methanol Price History



Source: Authors' composition based on (Methanex, 2021)

It can be seen that the average price of methanol is increasing over the year, but this development is overlapped by significant fluctuations on a quarterly basis. The European market value of methanol can be estimated based on its demand of 7.9 million tons (2017) and an average price of €368 in 2017, leading to a market value of €2.9 billion per year (EU-28).

In addition to the production of methanol by chemical CCU measures, there is a biological approach of converting CO and/or CO_2 streams into valuable products. ArcelorMittal is following this path within its Carbalyst® approach together with its partner LanzaTech. Within this approach, CO and/or CO_2 is converted biologically to ethanol. Ethanol is a simple alcohol with the chemical formula C_2H_6O. Its production from CO and/or CO_2 can be expressed by the following chemical reaction equations:

$$2\,CO + 4\,H_2 \leftrightarrow C_2H_6O$$

$$2\,CO_2 + 6\,H_2 \leftrightarrow C_2H_6O + 3\,H_2O$$

Based on these reactions, the conversion of one mole of carbon dioxide CO_2 requires three moles of hydrogen H_2 for its conversion into ethanol C_2H_6O. In the biological application developed by LanzaTech, hydrogen is also provided by the water-gas shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

2.4 CO_2 Storage

Carbon Capture and Storage (CCS) refers to the separation of CO_2 from waste gas streams ("carbon capture") and its underground storage instead of its emission to the atmosphere. The underground storage is limited as regards storage capacity and its regional distribution throughout Europe. Additionally, permanent CO_2 storage is subject to national and regional policy decisions and correlated social acceptability (see Deliverable 1.5 “Collection of possible decarbonisation barriers” for more details).

Based on multiple projects detailing CO_2 storage capacity throughout Europe (Holloway et al.,1996; Christensen and Holloway, 2003; Scholtz et al., 2006; Vangkilde-Pedersen et al., 2009), three general types of CO_2 storage reservoirs were identified: Saline aquifers, oil and gas reservoirs and coal fields (Anthonsen et al., 2009). Saline aquifers consist of large storage volumes with largely unknown geology, leading to uncertainties regarding reservoir integrity and properties (Anthonsen et al., 2009). Oil and gas reservoirs are also referred to as “hydrocarbon fields” and have limited storage capacity with a well-known geology and proven capability to retain hydrocarbons (Anthonsen et al., 2009). Additionally, these offer the possibility to use CO_2 for enhanced oil or gas recovery (Anthonsen et al., 2009). Coal fields have very limited storage capacity and injection rates (Anthonsen et al., 2009), and are thus neglected in the following. The availability of saline aquifers throughout Europe is indicated in Figure 14, and the availability of hydrocarbon fields is illustrated in Figure 15.

Figure 14: Saline aquifers in Europe

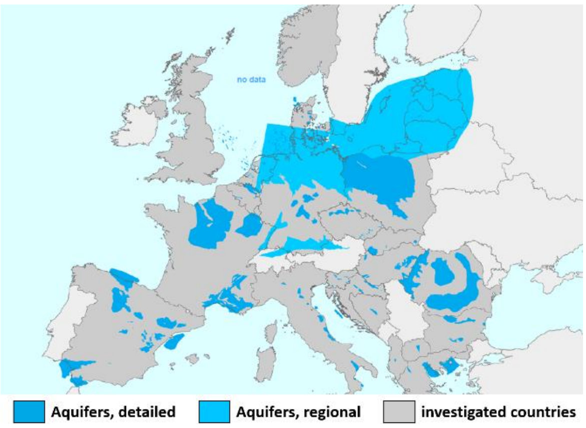
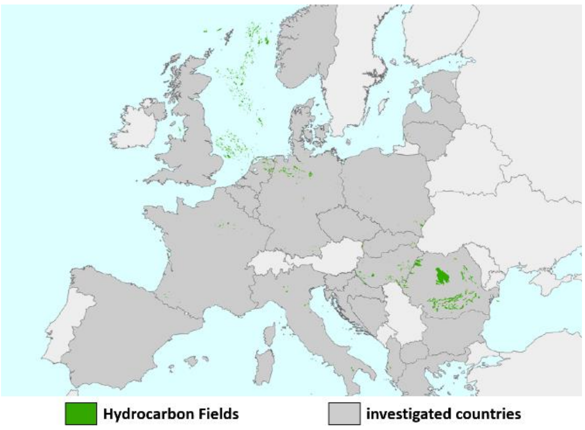


Figure 15: Hydrocarbon fields in Europe

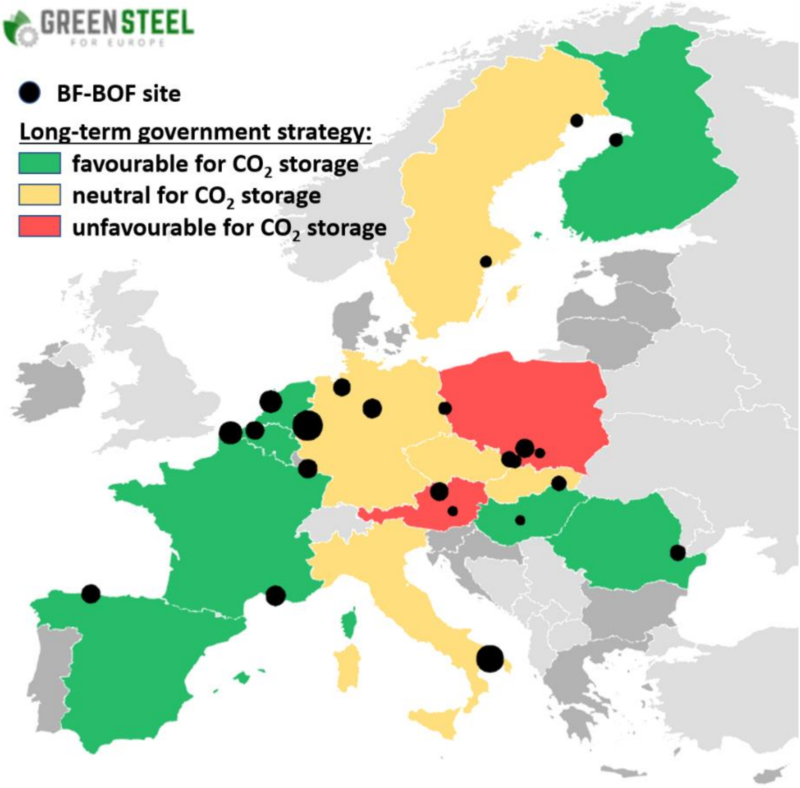


Source: Anthonsen et al., 2009.

It can be seen that saline aquifers are available in each European steel producing country. Regional aquifers are available particularly in the North Sea and the Baltic Sea, while large, detailed aquifers are located throughout Poland, in the north and south of France and Spain as well as throughout Romania. Larger capacity hydrocarbon fields are located in the North Sea, throughout the Netherlands and the north of Germany as well as in Hungary and Romania. If all types of storage reservoirs are considered, CO_2 storage potential in the EU-27 amounts to 104 Gigatons CO_2. If the capacities of Norway are also considered, this potential increases to 134 Gigatons CO_2. The costs for CO_2 storage are estimated to be €1-13 per ton of CO_2 for onshore storage and €2-22 per ton of CO_2 for offshore storage. (Navigant, 2018)

In addition to the technical availability of CO_2 storage reservoirs, Carbon Capture and Storage (CCS) is subject to policy decisions and social acceptability. Thus, existing legislative restrictions reduce CO_2 storage potential to 77 Gigatons CO_2 (Navigant, 2018). The most significant limitations arise in Germany and Poland. An assessment of the current public attitude and legislative restrictions in each EU-27 country was conducted (Navigant, 2018). Based on this assessment, Figure 16 indicates the long-term government strategy (as of 2019) based on a traffic light system.

Figure 16: Graphical indication of long-term government strategy for CCS



Source: Authors' composition based on Navigant, "Gas for Climate. The optimal role for gas in a net-zero emissions energy system", 2019.

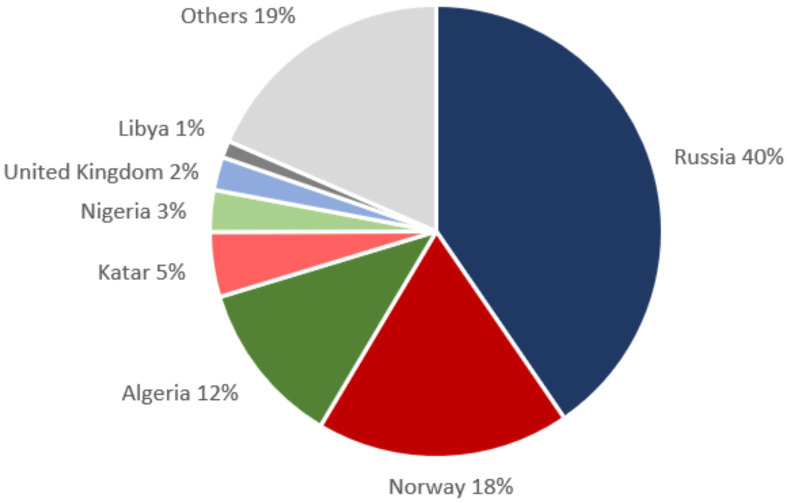
In this figure, countries with a long-term government strategy favourable for permanent CO_2 storage are indicated in green, whereas countries with an unfavourable stance are indicated in red. Neutral long-term government strategies are indicated in yellow. The locations of integrated steel plants are displayed as black dots; the size of the dots reflect the annual steel production capacities. It can be seen that there are favourable long-term government strategies throughout Western Europe (Spain, France, Belgium, Netherlands) as well as in North-eastern (Finland) and South-eastern (Hungary, Romania) EU-27 countries. In Central European countries there is less support for CO_2 storage based on the long-term governmental strategies. It has to be noted that these strategies reflect the situation in 2019 and could change in the future. Additionally, the possibility of storing CO_2 in a country other than its country of origin (cross-border cooperation) is not reflected by this figure.

As CO_2 storage technologies are cross sectoral and the storage sites and their capacities are naturally limited, it is expected that the iron and steel industry will be competing for these CO_2 storage possibilities with other sectors.

2.5 Natural gas

Annual natural gas consumption in the EU-27 amounts to 15 EJ[1] per year (EUROSTAT Data Browser, 2018a). In 2018, 17% of this was produced within the EU-27, whereas 83% was imported from outside the EU-27 (EUROSTAT, 2018). The main partners for natural gas imports are the Russian Federation and Norway. In 2018, 40% of natural gas imports into EU-27 were from Russia and 18% from Norway (EUROSTAT Data Browser, 2018a). The sources of natural gas imports into the EU-27 are illustrated in Figure 17.

Figure 17: Imports of natural gas by partner country (2018)



Source: EUROSTAT Data Explorer, “Imports of natural gas by partner country”, 2018.

As there is already a high import rate of natural gas into the EU-27, the global reserves of natural gas were considered in the following rather than the reserves within the EU-27. The global reserves of conventional natural gas are estimated to be more than 7 000 EJ (Federal Institute for Geosciences and Natural Resources (BGR), 2013). Global annual natural gas consumption amounts to 140 EJ per year. Based on these values, the current global reserves of natural gas are expected to be able to supply the global demand for the next 50 years. Thus, no principal limitations or shortages of natural gas supply into EU-27 were assumed within the considered time horizons until 2030 and 2050. In terms of different classifications of constraints for the following pathway scenarios, no hard constraints (see chapter 2 External Framework Conditions) for natural gas utilisation were considered.

In addition to the general availability, limitations regarding natural gas utilisation could stem from the correlated costs. These would fall into the category of soft constraints in the classification used and described in chapter 2 External Framework Conditions. These prices differ significantly throughout the EU-27 member states. Because of this the costs have to be considered. Table 1 summarises the prices of industrial natural gas prices in EU-27 member states with primary steel

---

[1] 1 EJ = 10^{18} J

production in 2020. It can be seen that the industrial prices range from €17.4 per MWh (Belgium) to €45.2per MWh (Finland) by a factor of 2.6. Natural Gas utilisation is therefore connected to substantially different costs throughout Europe. To identify soft constraints on a national basis, the EU-27 countries with primary steel production were categorised into three groups of high, medium and low natural gas prices in the following.

Table 1: Industrial Natural Gas prices in EU-27 primary steel producing countries in 2020

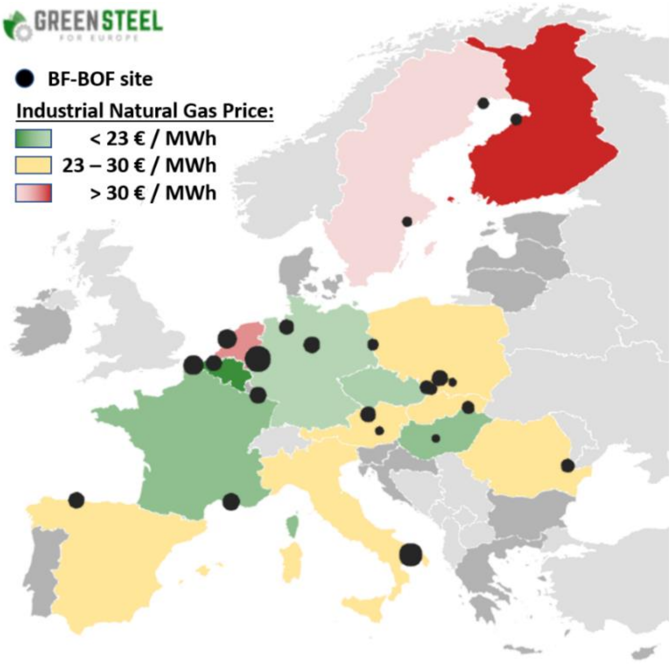
Country	NG Price [€ / MWh]
Austria	24.9
Belgium	17.4
Czech Republic	22.6
Finland	45.2 *
France	21.3
Germany	23.0
Hungary	21.4
Italy	23.6
Netherlands	36.9
Poland	26.1
Romania	24.5
Slovakia	25.6
Spain	23.6
Sweden	34.9

* price in 2017 (latest data available)

Source: Eurostat Data Browser, “Gas prices for non-household consumers - bi-annual data (from 2007 onwards)”, 2020.

The industrial natural gas prices were categorised into three groups: Countries with a high natural gas price above €30/MWh (Finland, Netherlands, Sweden), with a low natural gas price of €23/MWh or lower (Belgium, Czech Republic, France, Germany, Hungary) and those with a medium natural gas price of more than 23 but less than €30/MWh (all others). This categorisation is visualised in Figure 18. Low natural gas prices are indicated in green, medium prices in yellow and high prices in red. The strong the green or red colour is, the more extreme the natural gas price is: Strong green refers to very low prices, whereas strong red refers to very high prices.

Figure 18: Categorisation of EU-27 countries based on industrial natural gas prices



Source: Authors' composition based on Eurostat Data Browser, "Gas prices for non-household consumers - bi-annual data (from 2007 onwards)", 2020.

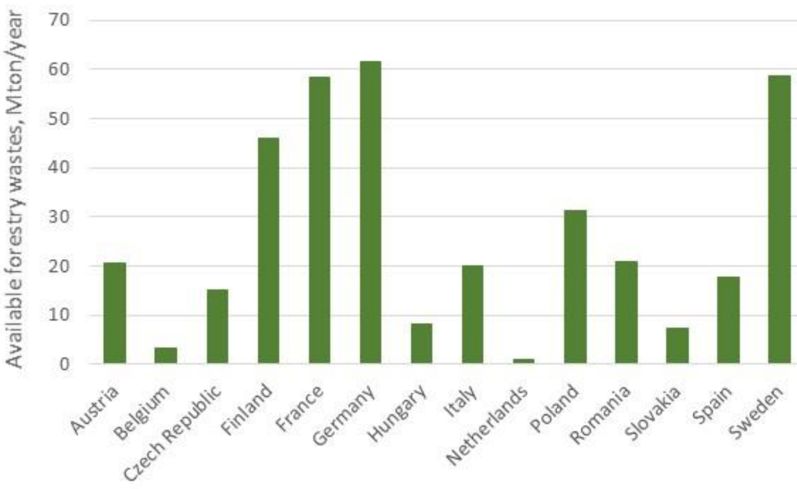
2.6 Alternative carbon sources

Alternative carbon sources, especially renewable energy sources, (e.g. biomass materials) are important for the steel industry to achieve fossil-free steelmaking process towards the green steel products. Biomass fuels are renewable and do not contribute to the greenhouse effect by net CO_2-emissions during thermal conversion since biomass binds CO_2 when it grows. Hence, biomass offers possibilities to produce carbon neutral fuels.

The main source of emissions in iron and steelmaking is caused by coke and pulverized coal (PC) utilisation as reducing agents and energy carriers. The majority of blast furnaces are working at coke rates in the range of 286-320 kg/t_{HM} and pulverized coal injection (PCI) at 170-220 kg/t_{HM} (Wang et al., 2015). In principle, there are two ways of using biomass products in the BF to replace the fossil carbon in the form of PC and coke: by injection via tuyeres or by top charging. To use biomass in ironmaking is not a new topic. In Brazil, biomass has been widely used in the blast furnaces, but limited to small blast furnaces. The injection is understood as the easiest way to introduce biomass for replacing fossil fuels in the BF, a lot of research work has been carried in this area (Suopajärvia et al., 2018; Orre et al., 2021), some pilot or industrial trials have also been performed. In recent years, some research efforts have been put on developing bio-agglomerates by briquetting biocarbon and in-plant fines, and then top-charging to the blast furnaces. Both experimental and pilot trials have been conducted, and the idea is to improve the BF performance by reducing the thermal reserve zone temperature as the biocarbon is more reactive than coke (Mousa et al., 2017; Mousa et al., 2019). Furthermore, the biocarbon is also needed even in the future ironmaking, e.g. hydrogen DR-EAF based process, as carburizing agents. Therefore, to develop biocarbon for the steelmaking is of great importance both in short-term and long-term perspectives. The core knowledge is that the blast furnaces cannot function properly with raw biomass. The biomass has to be upgraded to have similar (although not identical) characteristics to PC In order to use biomass in the iron- and steelmaking process.

So far, the focus has mainly been on forestry wood for different biomass products, such as wood charcoal, torrefied biomass (Wang et al., 2015). However, there are large variations about the forest biomass resources, as shown in Figure 19. The countries with abundant forestry residues are for instance Finland, France, Germany and Sweden.

Figure 19: Total available forestry residues in different EU countries (Mton per year)



The category "Forestry" contains

- Stumps from final fellings originating from nonconifer and conifer trees
- Stemwood from final fellings originating from nonconifer and conifer trees
- Stemwood from thinnings originating from nonconifer and conifer trees
- Logging residues from final fellings originating from nonconifer and conifer trees
- Logging residues from thinnings from nonconifer and conifer trees

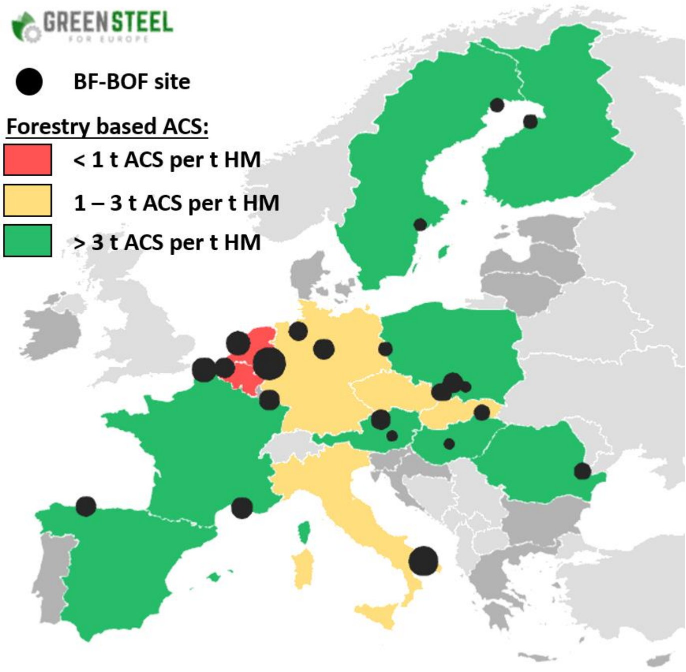
Source: Authors' composition based on (Mandova et al., 2018).

Assuming a replacement of 100 kg/t_{HM} PCI, it requires about 300 kg forestry biomass residues for the slow pyrolysis process in order to produce the biocarbon with high fixed carbon content. Figure 20 illustrates the availability of forestry resides and the locations of integrated steel plants in EU countries. The map indicates green as <10% and red as >35% of waste available to be required for primary steel production. It shows that Austria, Finland, France, Hungary, Poland, Romania, Spain and Sweden have sufficient forestry wastes to replace pulverized coal in BFs, while Belgium and Netherlands have lower availability of forestry wastes for blast furnace application.

However, there is a large concern about the forest biomass availability for the biochar production due the increasing competitions of end-users in other sectors, therefore, other it is of great significance to investigate other types of biomass residues, such as organic sludge, municipal organic waste, industrial food waste and green waste. Compared to the forest biomass, these biomass residues are locally available with a large potential as stated in (Dees et al., 2017; Camia et al., 2018), but usually with high moisture content. Figure 21 shows that Germany, France, Italy, Spain and Netherlands are top five countries with large amount of bio-waste. In contrast with the high forestry resources, the bio-wastes in Finland and Sweden are relatively low.

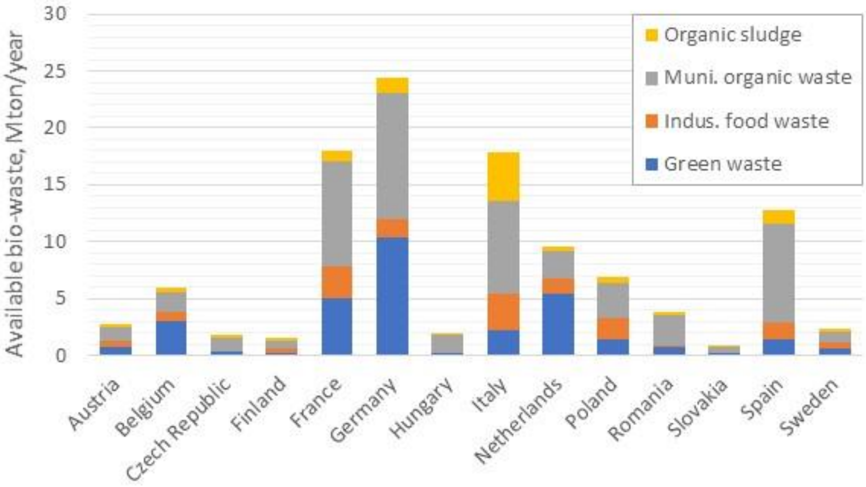
The issue related to the wet organic waste disposal influences the economy, and the environment of European countries, as well as of any other world region. With some new updating processes, for instance the hydrothermal carbonization (HTC) process, these biomass residues can be upgraded to biochar (or so-called hydrochar). The produced biochar can be either injected to BF in the form of powder or top-charged to BF in the form of bio-agglomerates (Mandova et al., 2018; Wang et al., 2020). Compared to other carbonization process (e.g. pyrolysis, torrefaction, etc.), some unwanted elements e.g. P, S, N and alkali (K, Na) can be removed from the biochar as they will be dissolved into the liquid/water, in which liquid fraction representing a high value organic bio-fertilizer is crucial, leading to a circular economy towards a green steelmaking.

Figure 20: Available forestry residues and location of integrated steel plants in EU countries



Source: Authors' composition based on (Mandova et al., 2018).

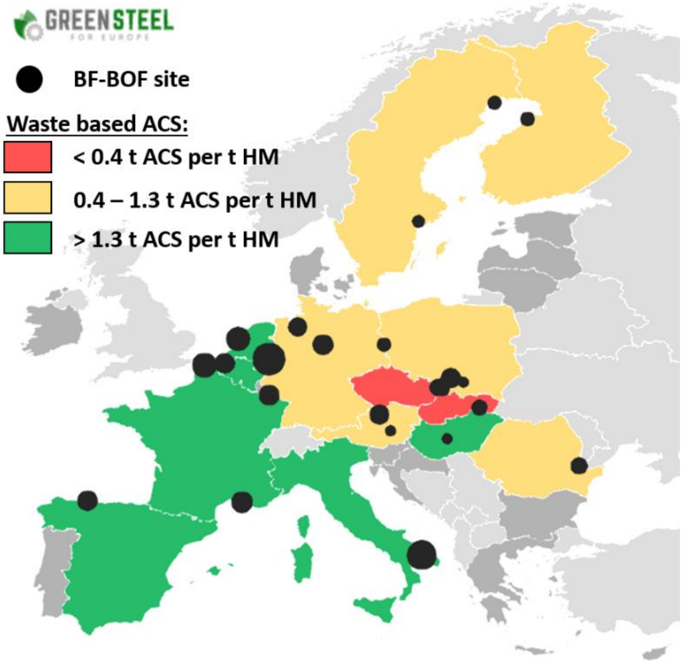
Figure 21: Total available bio-waste in different EU countries (Mton per year)



Source: Authors' composition based on (Mandova et al., 2018).

Figure 22 illustrates the available bio-wastes to the integrated steel plants in different EU countries. In the map, the green colour indicates that bio-wastes required at steel plants is less than 50% of total amount of bio-wastes, indicating that bio-wastes might be sufficient to the integrated steel plants in countries such as Belgium, Netherlands, Spain, Italy, etc. Meantime, the red colour means that available bio-wastes are not sufficient to the steel plants in those countries such as Czech Republic and Slovakia. The yellow colour means that available bio-wastes for applications in the steel plants are medium level in these countries. The assumptions for the calculations are to replace 100 kg/t_{HM} pulverised coal in BFs, and the bio-wastes are updated via two steps, i.e. firstly via HTC to produce hydrochar, and then via slow pyrolysis to get high quality biocarbon with high fixed carbon content.

Figure 22: Available bio-wastes and location of integrated steel plants in different EU countries



Source: Authors' composition based on (Mandova et al., 2018).

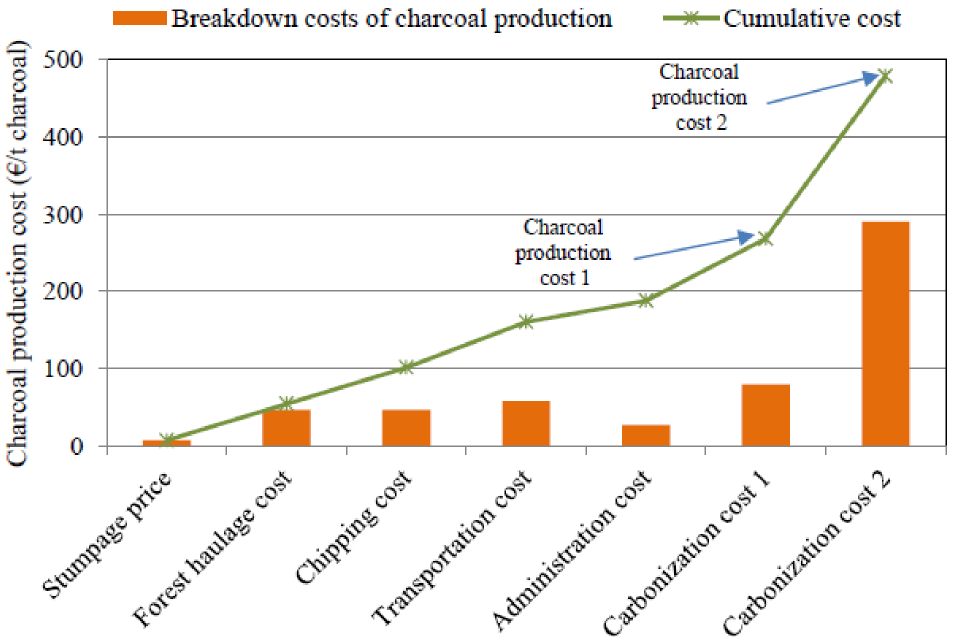
The price of biochar is a challenge for the iron- and steelmaking. For instance, compared to PCI, the wood charcoal price can be 4-5 times higher (Soupojärvi and Fabritius, 2013). The main affecting factors for the biochar price are for example the price of feedstocks, investment (CAPEX) and operation (OPEX) cost. A production cost is listed in Table 2 as one example. More updating steps will require additional CAPEX and cause increased OPEX, leading to high production cost. In addition, extra cost such as harvesting, material handling, transportation, drying, etc. make the biomass products not economic competitive to fossil fuels like coal, which is visualized in Figure 23 for wood charcoal production as an example in Finland.

Table 2: Production cost of bioproducts

	Charcoal	Wood pellets	Hydrochar	Torrefied material
Upgrading process	Slow pyrolysis	Pelletisation	HTC	Torrefaction
Investment cost, €/ton	72.6	39.1	71.4	55.2
Operation and Maintenance, €/ton·year	3.63	1.95	3.57	2.76
Average cost of the final bioproduct, €/ton	255	111	120	147

Source: Authors' composition based on Mandova et al., 2018.

Figure 23: An example of charcoal production



Source: Authors' composition based on Soupojärvi and Fabritius, 2013.

2.7 Iron ore & pellets

Iron ore is raw Fe-containing mineral. The material is a rock which contains Fe in sufficient quantities that make it economically viable to process the ore. The iron is usually found in the form of magnetite (Fe_3O_4, Fe content 72.4%), hematite (Fe_2O_3, Fe content 69.9%), goethite (FeO(OH), Fe content 62.9%), limonite (FeO(OH)·n(H_2O), Fe content 55%) or siderite ($FeCO_3$, Fe content 48.2%). Raw iron ore is prepared (e.g. by sintering or pelletising) for further processing into pig iron, direct reduction iron (DRI, sponge iron) and ferroalloys.

- The methods for preparing iron ore are aimed at improving the quality of the ore, thus facilitating their further processing, as well as increasing Fe content. The preparation of iron ore can be divided into two groups. First mechanical methods of preparation, based on the physical properties of materials:

- gravitational, magnetic and electrostatic enrichment,
- flotation,
- briquetting and pelletising.

Secondly, methods of preparing iron ore for chemical processing:

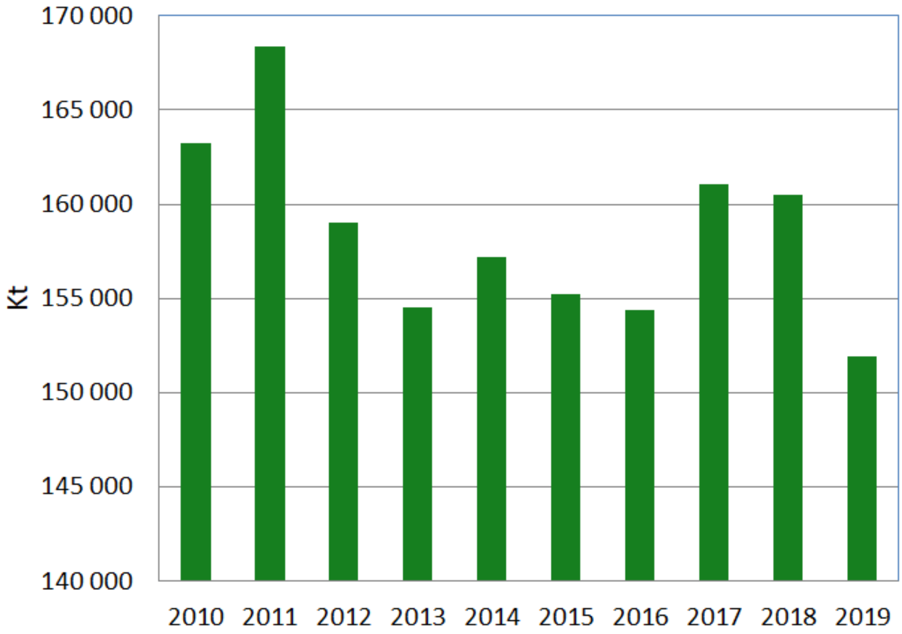
- material compacting by the sintering process,
- roasting the iron ore and concentrates in a suitable atmosphere (removal of: carbon dioxide from ores containing carbonates, chemically-associated water from ores containing hydrated iron oxides).

In metallurgical practice the iron ore is used in one of the following three forms:

- Iron ore concentrate
  An enriched product, whose elements and mineralogical composition meet the requirements of further metallurgical processing. The concentrate is supplied as a commercial product and used as a semi-finished product to make blast furnace pellets and pellets for metallisation and can also be used to make iron-containing briquettes. Iron ore concentrate is produced from magnetite iron ore in the beneficiation process and is used for the production of pellets for blast furnaces and sinter.
- Iron ore pellets
  A material generated from fine (powdered) ore and finely ground concentrates by pelletising and hardening through induration or an unfired method. Blast furnace pellets with at least 62% Fe are used in blast furnaces to make hot metal. Pellets for metallisation made from an upgraded concentrate have at least 66% Fe and are used primarily to produce direct reduction iron (DRI, HBI).
- Iron ore sinter
  A bulk material for blast furnace smelting, which is made by sintering ore, limestone, fine coke, screened sinter and blast furnace dust on special belt sintering machines. Sinter quality is determined by the Fe content of iron ore, strength, destruction during heating and reduction in a blast furnace. Not used in DR processes.

The demand for iron and pellets is closely related to the production of steel and the technology used (BF+BOF or EAF). In 2010-2019, steel production ranged from 168 million tonnes in 2011 to 152 million tonnes in 2019 (King, 2020). The average for the last 5 years is about 156.5 million tons as indicated in Figure 24.

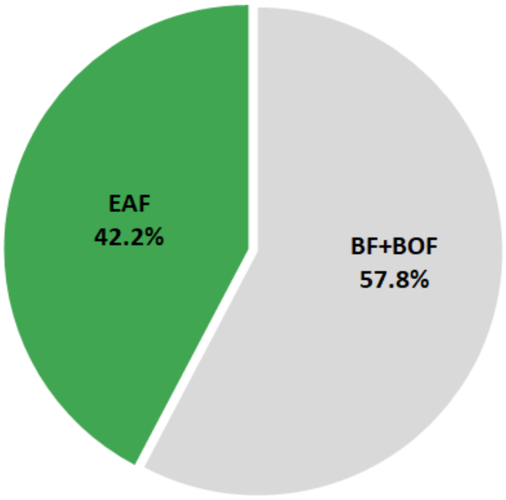
Figure 24: Crude steel production in EU-27 in recent years



Source: King, "EU (27) Europe-demand-forecasts-20-Dec-20.xlsx", [Online].

Of the 152 million tonnes of steel produced in the EU-27 in 2019, 88 million tonnes (57.8%) were produced in the integrated process BF+BOF, and 64 million tonnes (42.2%) in the electrical process EAF (worldsteel, 2018). This is also illustrated in Figure 25.

Figure 25: Share of steelmaking processes in EU-27 in 2019



Source: worldsteel "Steel industry role in future development path", 2018.

The EAF process can operate without liquid hot iron. The feed may only comply with scrap or partially contain pig iron or products from DRI/HBI. The demand for iron ore generates processes in which primary metallic iron is used. Currently in the EU, the BOF process is used to generate iron demand, in which 70%-80% of the charge is a hot metal and the rest is scrap. The hot iron is produced in a blast furnace process, which in the EU is based on sinter, pellets and to a small extent on the lump iron ore. A second technology that can generate iron ore demand is direct reduction (DR) processes. Currently, this technology is not much used in the production of iron in the EU.

In the EU-27 in 2019, about 88 million tonnes of scrap and approx. 130 million tonnes of iron ore were used to produce 152 million tonnes of steel (King, 2020; Polish Steel Association, n.d.). Ore is used in various forms: lump (> 6.3mm), fine (0.15-6.3 mm) and concentrates (< 0.15mm). Lumps and, in some cases, fines can be introduced directly into the blast furnace. Usually, fines are sintered and concentrates are pelletised before introduction to the blast furnace. The consumption of individual forms of iron ore in 2010-2019 is summarised in Table 3 (King, 2019).

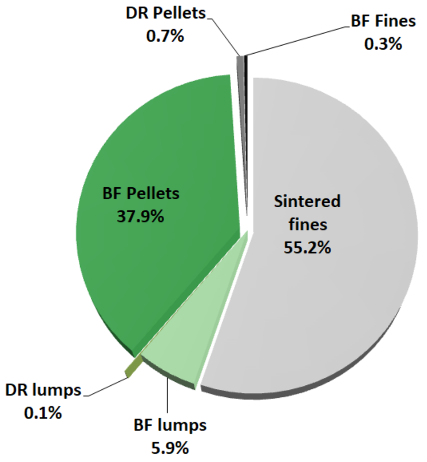
Table 3: The consumption of individual forms of iron ore in 2010-2019 (in kilotonnes)

Form of iron	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Sintered fines	81 463	82 131	77 808	76 623	80 925	77 603	78 560	78 253	75 151	**71 194**
BF lumps	10 663	10 450	9 424	8 139	8 113	9 082	8 590	9 196	8 215	**7 569**
DR lumps	63	56	78	70	120	116	127	127	119	**127**
BF Pellets	45 370	45 505	45 927	46 509	45 804	46 612	46 869	49 162	50 309	**48 839**
DR Pellets	734	668	849	787	823	809	859	861	821	**869**
BF fines	427	419	403	405	407	415	405	414	406	**378**
Total	**128 057**	**139 229**	**134 489**	**132 533**	**136 192**	**134 637**	**135 410**	**138 013**	**135 021**	**128 976**

Source: King, "EU (27) Europe-demand-forecasts-20-Dec-20.xlsx", [Online]. Available: Steelonthenet.com.

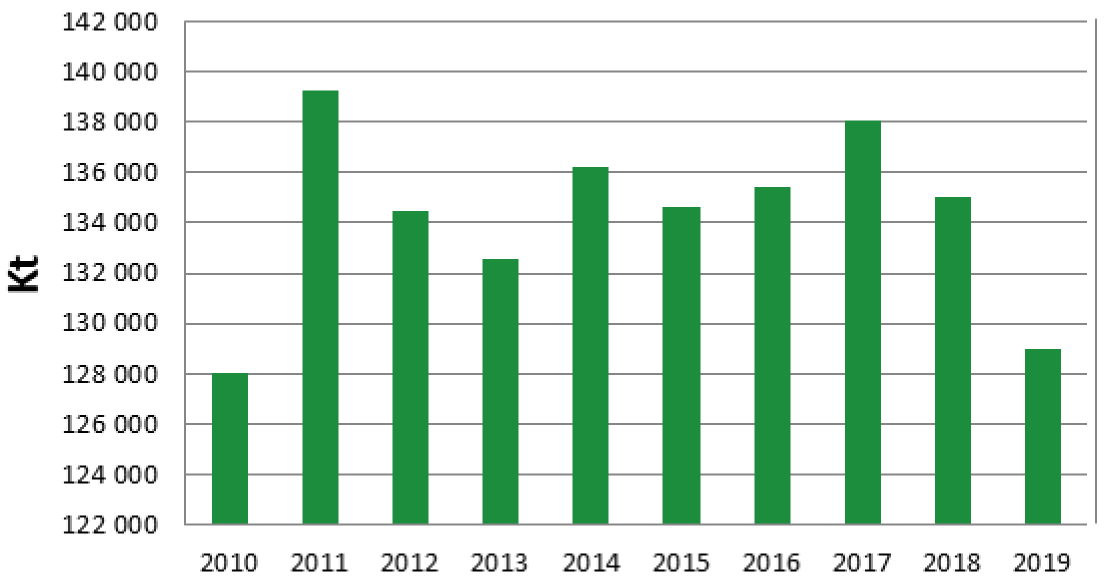
The share of individual forms of iron ore in 2019 is presented in Figure 26, and total consumption in recent years is presented in Figure 27.

Figure 26: The consumption of individual forms of iron ore in 2019



Source: King, "EU (27) Europe-demand-forecasts-20-Dec-20.xlsx," [Online].

Figure 27: Total consumption of iron ore in EU-27 in 2010-2019



Source: King, "EU (27) Europe-demand-forecasts-20-Dec-20.xlsx," [Online].

There are a number of forecasts for steel production in the EU up to 2050. These forecasts have mainly been made by analysts and researchers from various scientific sources in different years. Most forecasts were prepared with the assumption of an annual growth rate of 0.6% to 0.8% (Wörtler, 2013; Ghenda, 2013; Material Economics, 2019). The steel stock will saturate by 2050 at a level of 13.7 tonnes steel per capita in the European Union. So, EU steel production could increase by 20% to 35% by 2050, to between 183 and 219 or even 236 Mt (see Table 4). There is also another approach that takes into account demand side reductions – Circular scenario for steel in 2050 (Material Economics, 2019). The EU steel stock is already close to 12 tonnes per person, and the population level is flattening and expected to decrease. Once a saturation point is reached, EU steel demand would be driven almost entirely by the need to replace products and structures as they reach the end of their life, about 2-3% of the total stock each year. In this scenario, EU demand would fall at first, then stabilise at replacement levels of around 150 million tonnes per year. Production by the EU steel industry could of course still increase but would have to be driven by increasing exports.

Fulfilling the requirements of the CO_2 emission reduction policy with the achievement of neutrality of the steel manufacturing process in 2050 requires a drastic change of the production mix. During the period, primary BF-BOF production should be completely phased out by 2050 and replaced by hydrogen-DR as the production route for the remaining virgin steel. The introduction of hydrogen-DR will take place in 2030, with its first small commercial plant. The production volumes will thereafter increase substantially until 2050. The share of recycled steel will increase linearly with the result that most of the steel will be produced through the EAF route. The detailed share of individual low-emission and zero-emission technologies will depend on many factors, including: the speed of development and implementation of new steel technologies, availability and quality of scrap and DRI, the availability of cheap renewable energy and cheap hydrogen as a reducer and fuel.

Table 4: Forecasted steel production according to various scenarios

2015	2019	2020	2030	2040	2050	Source of information
-	-	191	204	222	236	Estimated in 2010
-	-	-	-	-	219	The European Steel Association (EUROFER) 2013
155	-	-	169	190	193	CISL 2019
-	-	-	176	194	193	Scenario A[1] and B[2]
-	-	-	162	-	141	Scenario C[3]
155	**152**		**182**		**183**	

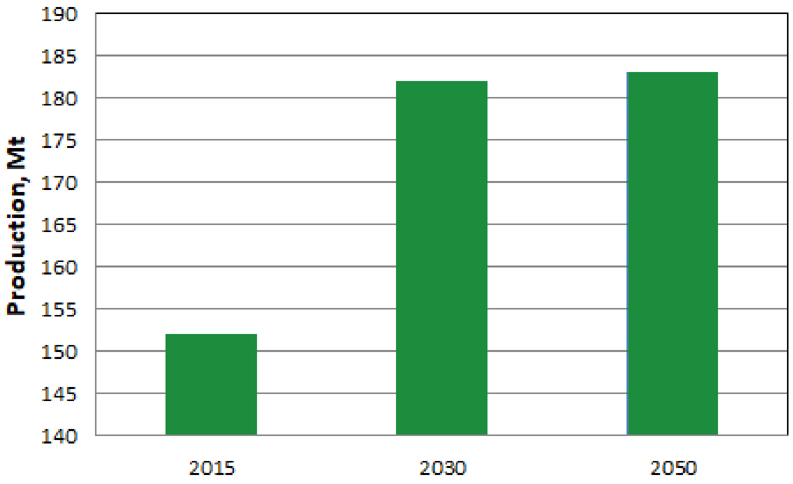
1) - Scenario A is a current trends scenario that illustrates the effect of demand changes on the emissions trajectory, with incremental efficiency improvements and growth rates of EAF steel production.

2) - Scenario B is a decarbonisation scenario that evaluates the impact of the same demand changes as Scenario A, coupled with decarbonisation of electricity production. This scenario also assumes that the direct energy intensity and electricity intensity of steel production of the BF-BOF and EAF routes are equivalent to estimates of the technical minimum intensities (WWF & Ecofys 2011).

3) - Scenario C is a scenario with steps towards circularity that takes Scenario B a step further, with a maximum shift towards EAF steel production that takes into account scrap availability constraints. Such constraints exist despite the increase in scrap availability, as overall demand for steel grows more rapidly.

Source: worldsteel ASSOCIATION, 2018; Material economics, 2019; Wörtler, 2013; Ghenda, 2013; Material Econimics, 2018; Fivel, 2019.

Figure 28: Crude steel production predicted by EUROFER



Source: King, "EU (27) Europe-demand-forecasts-20-Dec-20.xlsx", [Online]. Available: Steelonthenet.com.

The demand for iron and pellets in 2030 and 2050 results from the forecasted steel production level during this period. Projected steel production in 2030 will amount to 182 million tonnes, and in 2050 183 million tonnes. The projected reduction in the amount of iron ore consumed result from the projected increase in the share of steel produced in the EAF process to about 48% in 2030 and even 60% in 2050 and consequently the increase in scrap consumption (King, 2019). For these conditions, the estimated use of iron ore in 2030 is about 140 million tonnes and 100 million tonnes in 2050. The projected consumption of specific forms of iron ore is indicated in Table 5 (King, 2020).

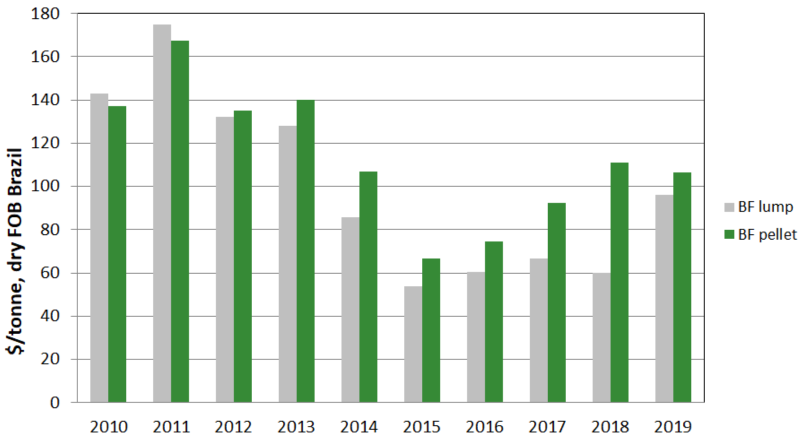
Table 5: The projected consumption of specific forms of iron ore

Form of iron	**2030**	**2050**
	1000 wet metric tonnes	
Sintered fines	70 569	42 094
BF lumps	7 919	5 172
DR lumps	178	253
BF pellets	57 417	50 181
DR pellets	1 175	2 559
BF fines	439	330
Total	**137 697**	**100 589**

Source: King, "EU (27) Europe-demand-forecasts-20-Dec-20.xlsx," [Online].

These prices are influenced by many factors that are difficult to predict: for example how the current state of the global economy, and thus demand and supply, customs policy, political situation in the areas of extraction, freight costs, as well as exchange rates will evolve.

Figure 29: Price of iron ore and pellets FOB Brazil in the years 2010-2019

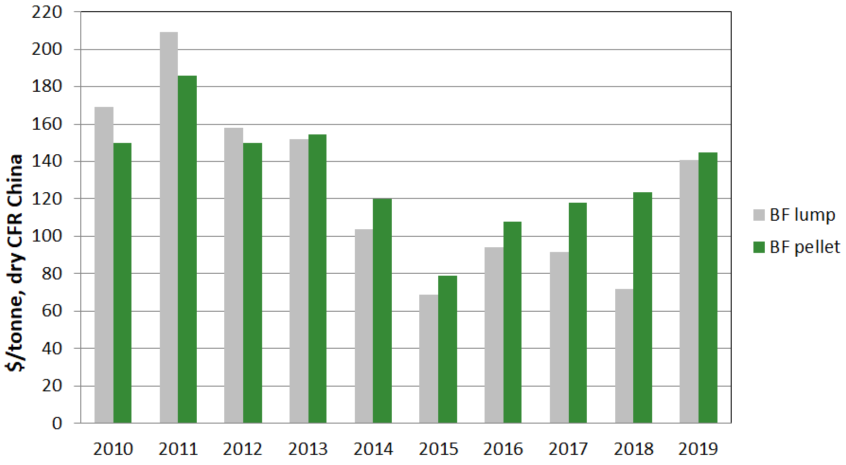


Source: King, "EU (27) Europe-demand-forecasts-20-Dec-20.xlsx", [Online].

Figure 29 and Figure 30 show the prices of iron ore and pellets from Brazil and China (King, 2020). A significant price variability of both raw materials can be observed. Fluctuations are rather independent of the source of origin, and the prices of pellets and a lump ore are clearly linked. In 2012 and 2013, for Brazil and for China there is a noticeable change in relative prices of iron ore and pellets, with the latter becoming more expensive.

Table 6 shows forecasted prices of iron ore and pellets according to King (n.d.). These prices are expressed in USD (adjusted for inflation on 2020 levels). As can be seen from the forecast for 2030 and 2050, the price of pellets will remain significantly higher than iron ore.

Figure 30: Price of iron ore and pellets CFR China in the years 2010-2019



Source: International Energy Agency, "Electricity Market Report, December 2020", IEA Publications, Paris, 2020.

Table 6: The projected raw materials prices in 2030 and 2050

Raw material		**2030**	**2050**
		$/tonne, dry	
Iron ore fines for sinter	CFR China	85.04	67.08
Iron ore fines for sinter	FOB Brazil	60.12	51.36
Iron ore pellet fines	FOB Brazil	76.60	66.55
Iron ore BF lump	FOB Brazil	77.03	69.24
Iron ore DR lump	FOB Brazil	108.42	97.57
Iron ore BF pellet	FOB Brazil	95.98	83.75
Iron ore DR pellet	FOB Brazil	118.66	117.3

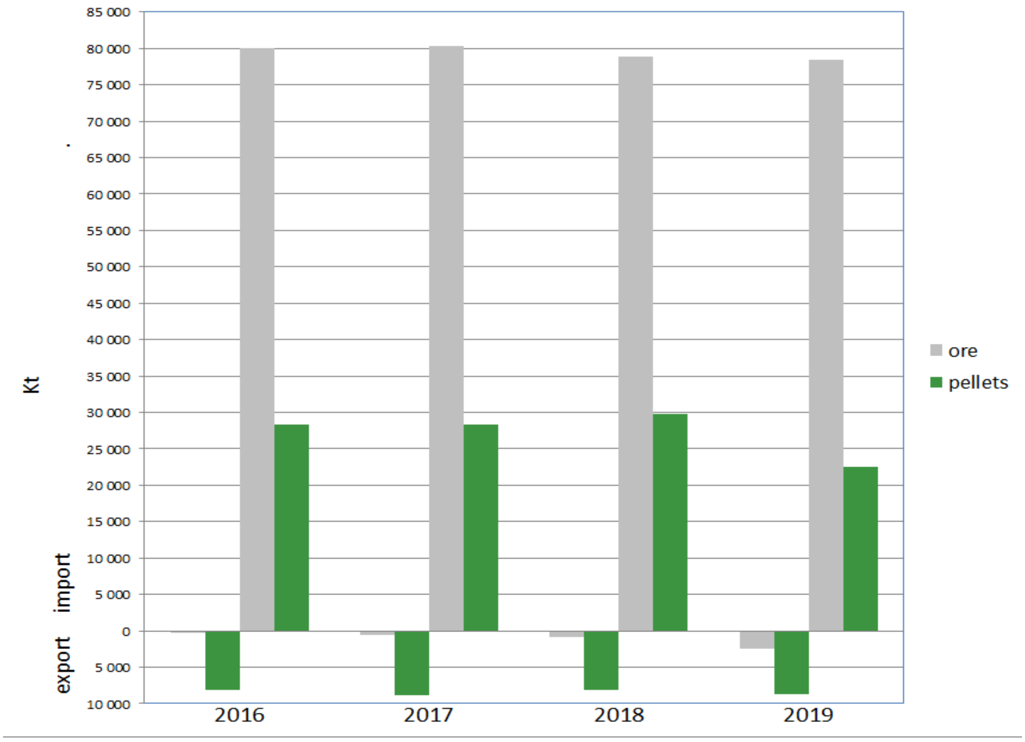
Source: International Energy Agency, "Electricity Market Report, December 2020", IEA Publications, Paris, 2020.

About 80% of the iron ore consumed in the EU-27 comes from imports. Iron ore exports outside the EU are very small, and pellets are a little larger, about 7-8 million tonnes as indicated in Figure 31 (EUROSTAT Data Browser, 2020).

Table 7 shows the world's major iron ore producers along with their production capacities. Among them is one EU country (Sweden) with a production capacity of around 33 million tonnes of ore per year. This translates to 56% of projected 2030 demand (see Table 5).

Determination of the availability of ores and pellets in amounts determined for the estimated demand are based on the available literature data. The availability of raw materials for the forecast steel production volumes does not seem to be a problem for iron ore and its various forms used in metallurgical processes. The forecasted level of ore consumption is significantly below the historical consumption of this raw material, e.g. 175 million tonnes in 1997 or 168 million tonnes in 2007. About 35 million tonnes of iron ore are mined in the EU-27 – Sweden, Austria and Germany. The world's iron ore resources are significant: 230 Gt of which 80 Gt could be economically extracted (reserve) (Morfeldt, 2013).

Figure 31: Exports and imports of iron ore and pellets in EU-27



Source: Green Steel for Europe "Report_GreeSteelProject_WP1_IronOre_EUROFER-Contribution.xlsx", 2020.

Table 7: National iron ore production capacities

Country	Production capacity in kt - Average value from 2012-2016
China	1 387 414
Australia	707 335
Brazil	375 309
India	153 662
Russian Federation	102 040
South Africa	71 816
Ukraine	67 935
United States	49 960
Iran, Islamic Rep.	46 838
Kazakhstan	45 720
Canada	44 413
Sweden	33 414
Mexico	23 427
Chile	16 674
Other countries	103 105
Total	**3 229 062**

Source: Green Steel for Europe "Report_GreeSteelProject_WP1_IronOre_EUROFER-Contribution.xlsx", 2020.

Two EU member states countries produce iron ore pellets: Sweden (LKAB Kiruna, Malmberget, Svappavaara) and Netherlands (Tata Steel Ijmuiden). Total production of iron ore pellets is around 25 million tonnes (2015).

Figure 31 shows that fewer than 10 million tonnes are exported outside EU-27. The remaining demand is to be covered by imports. Based on the high availability of iron ore this is assumed to be possible. Due to the further development of direct reduction technology and the growth of pellets demand, it is expected that new pelletising plants will be installed in the EU-27 in the next decades.

The demand for iron ore and pellets between 2030 and 2050 will result from the amount of steel produced in EU and the applied feedstock structure. It is predicted that in 2030 the production of steel will be about 182 million tonnes and production in 2050 will remain at a similar level reaching 183 million tonnes. At the same time, an increase in the share of the EAF process in relation to BF + BOF will be observed. It is predicted that in 2030 the share of the EAF route will amount to 48%, and in 2050 it could reach 60%. This will increase the share of steel produced from the charge based on the scrap. Only steel with high requirements, mainly for flat products, will be produced with a large share of pig or DR iron. Therefore, after 2030, the demand for iron ore will decrease, while demand for pellets will increase due to the development of DRI. Estimates indicate that the need for all forms of primary iron means fines, lumps and pellets will increase from about 129 million tonnes in 2019 to about 138 million tonnes in 2030, of which about 59 million tonnes will be pellets. However, in 2050, the demand for ore is estimated at approx. 101 million tonnes, of which about 53 million tonnes will be pellets. These raw materials will mostly come from imports (considering its availability), and their price will fall, especially later, when the demand for ore and pellets in connection with the development of scrap processes will decrease. It is anticipated pellets will cost more than iron ore.

2.8 Steel scrap

Thanks to the fact that steel is a 100% recycled material, it is possible to remelt used steel products, i.e. steel scrap, in electric furnaces (EAF) to steel, from which new steel products are produced. Furthermore, around 20-30% of the charge is steel scrap in the BF-BOF route. The increase in the availability of scrap could promote the increase in the share of the EAF process to as much as over 50% after 2050 (Xylia et al., 2017). The amount of home scrap, i.e. scrap created in steel production processes, differs in different steelworks, but usually constitutes about 10% of the total steel production. The new scrap post-production includes scrap generated in steel processing processes for finished products. Both types of scrap are recognised as high-quality scrap with well-known chemicals. The estimated amount is about 13-16% of the total amount of steel that flows through the manufacturing industry, with a slightly higher 20% for the automotive industry. Just like self-scrap, new scrap requires only a small amount of processing and can be quickly used in production processes minimising storage costs.

The old scrap comes from used steel products that have completed their service life. This scrap is considered to be low-quality scrap. Typical sources of old scrap are, for example, cars, rail scrap and steel structures. The recycling industry is essential for the supply of old scrap. It consists of intermediaries, pickers and scrap processors. Scrap, which before re-melting requires processing, is collected by scrap processors or through a municipal waste disposal system. The scrap is then processed to a physical form and chemical composition, according to the requirements of steel producers. Scrap brokers organise transactions between buyers and sellers and receive a fee for this service. A particularly important source of old scrap is scrapped cars that require significant processing before re-melting scrap for new steel. Cars are processed in shredders that shred the vehicle into fist-size pieces, which are then ideal for direct feeding to the furnace. Estimating the availability of old scrap is difficult, as steel products can be in circulation for many years before they are available for recycling. Thus, the overall steel recycling rate is also difficult to estimate, but previous studies suggest that it is between 60-70% of total steel production (Söderholm and Ejdemo, 2008).

High-quality scrap (HQ) is essential for the production of high-quality products – mainly flat products, which are currently mainly produced in integrated processes. If high-quality scrap is not available, low-quality scrap (LQ) can be mixed with DRI to provide a high-quality batch to EAF. Increasing the share of EAF-based steel production will play a key role in the decarbonisation of the steel industry. However, this role will depend on the regional availability of high-quality scrap and therefore can be limited in regions with insufficient supply of high-quality scrap, which will make other technologies obligatory. The growing demand for high-quality scrap will also lead to additional steel production costs in the EAF process.

In 2010-2019, steel production ranged from 168 million tonnes in 2011 to 152 million tonnes in 2019 (King, 2020), as indicated in Figure 24. The demand for steel scrap is closely related to the production of steel and technology used (BF+BOF or EAF). Table 8 presents crude steel production and steel scrap use in the EU-27 in the period 2015-2019.

Table 8: Crude steel production and steel scrap use in EU-27 (in million tonnes, 2015-2019)

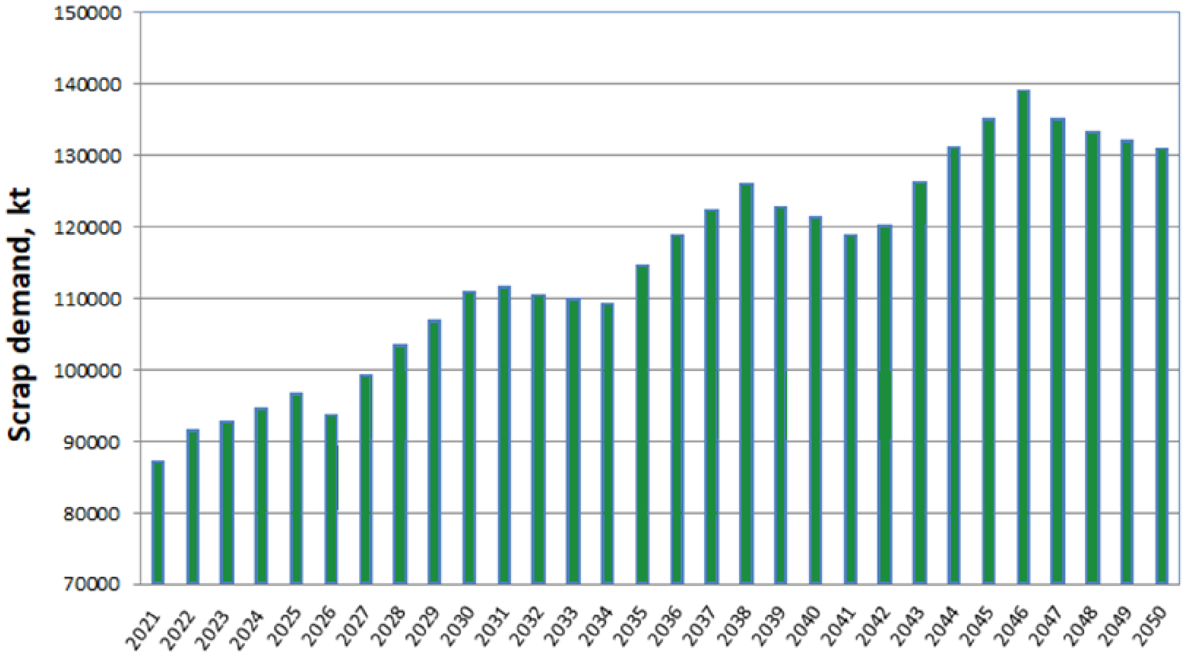
Parameter	**2015**	**2016**	**2017**	**2018**	**2019**
Crude steel production	166.1	162.0	168.5	167.7	159.4
Share of BF-BOF process, %	60.7	60.5	59.6	58.5	59.6
Share of EAF process, %	39.3	39.5	40.4	41.5	40.4
Total scrap consumption	88.4	93.6	93.8	90.9	87.5
Share of scrap in steel production, %	54.6	54.6	55.5	55.9	54.8

Source: World Steel Recycling in Figures 2015-2019, “Steel Scrap – a Raw Material for Steelmaking”.

Steel scrap is not only used in the EAF route. Forecasts for steel production by 2030 and 2050 are described in chapter 2.7 in detail.

To produce this amount of steel, it is estimated that 111 million tonnes of scrap will be needed in 2030 and 131 million tonnes in 2050 (King, 2020). The projected increase in scrap consumption results from the projected increase in the share of steel produced in the EAF process to about 48% in 2030 and even 60% in 2050. The demand for scrap in the years 2021-2050 is shown in Figure 32. It is correlated with forecasted steel production indicated in Table 8.

Figure 32: Predicted demand for scrap in EU-27 in the years 2021 - 2050



Source: King, "EU (27) Europe-demand-forecasts-20-Dec-20.xlsx," [Online].

This is a total demand covering both low quality (LQ) and high quality (HQ) scrap. Separation of these two types of scrap is very difficult, because it is difficult to predict how many flat products will be produced from the steel obtained in the integrated process and how much in the EAF process using the scrap of HQ. The scrap prices in 2019 and the projected scrap prices in 2030 and 2050 are given in Table 9 (King, 2021).

Table 9: Actual and projected scrap prices in 2019, 2030 and 2050 ($/tonne, in 2020 USD)

Location	2019	2030 (proj.)	2050 (proj.)
Scrap delivered to steelworks, USA Midwest	245	247	179
Scrap FOB port, Europe	257	253	183

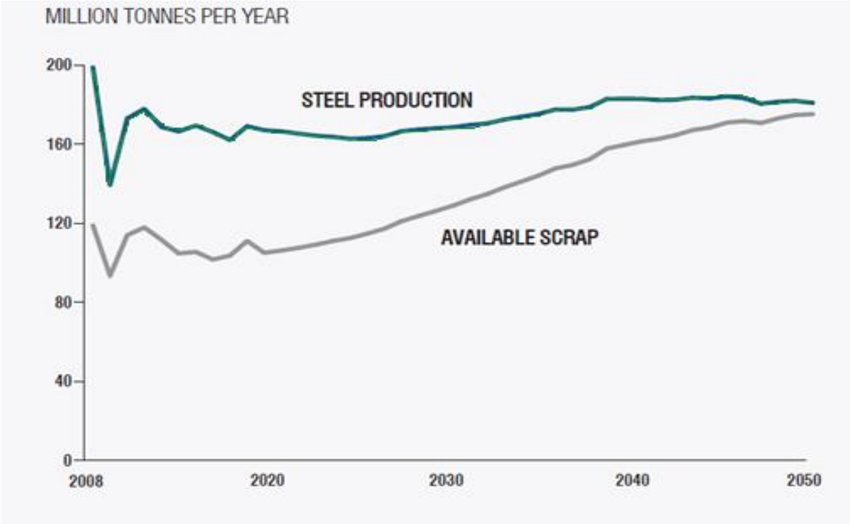
Source: Green Steel for Europe, "Synopsis report of consultation activities (WP1) (Deliverable 1.6)", 2021.

Forecasted scrap prices concern t total scrap and are not developed separately for LQ and HQ scrap. The predicted prices show a decrease from the year 2030 to 2050.

Scrap consumption peaked in 2007 at 111 million tonnes, and this corresponds to the forecast for 2030. Global steel recovery rates are estimated at 85% for construction, 90% for the automotive industry, 90% for machinery and 50% for electrical and domestic appliances (European Union, 2020). Morfeldt et al. (2013) concluded that 90% of scrap recycling is theoretically possible and that home scrap from steelmaking will show stable growth till 2035, growth of prompt scrap will be a little faster and there will be significant growth of obsolete scrap. The total increase of available scrap will rise from about 750 million tonnes in 2019 to around 1 100 million tonnes in 2035. The consumption level is still lower over this period by about several dozen million tonnes.

The amount of available scrap should suffice for the total required steel production in the EU up to 2050 see Figure 33. This might make it possible to satisfy the required steel production in the EU by recycling scrap made of steel previously produced.

Figure 33: Steel scrap availability and steel production



Source: Material Economics, "Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry", University of Cambridge Institute for Sustainability Leadership (CISL).

The assessment of scrap availability is subject to high uncertainty (Pauliuk et al., 2013). This is caused by many factors, such as the size of the demand for steel, the development of technology based on scrap, the actual life expectancy of steel products. Based on data available in the literature (King, 2020; Söderholm and T. Ejdemo, 2008; Xylia et al., 2016), the demand and availability of LQ and HQ scrap in the years 2030 and 2050 were estimated. The results are summarised in Table 10.

The scenario presented above is very optimistic and shows that the availability of both LQ and HQ scrap will be sufficient to meet the decarbonisation goals by 2050. However, there are other forecasts according to which the availability of HQ scrap may not be sufficient. For the EU, the most likely prediction seems to be sufficient scrap availability of around 110 million tonnes by 2050 (Pauliuk et al., 2013). This will ensure that the demand for post-consumer LQ scrap (Pauliuk et al., 2013; Xylia et al., 2016) will be met, while the shortages may be related to own and pre-consumer HQ scrap (Pauliuk et al., 2013; Xylia et al., 2016). The relatively stable projected production and consumption of steel in the EU will result in a decreasing amount of HQ scrap due to the increasing efficiency of metallurgical (own scrap) and processing (pre-consumer scrap) processes (Xylia et al., 2016). The expected increase (23%) in the share of flat products by 2050 (in 2050, the expected share of flat steel production will reach 67%) will increase the demand for HQ scrap in cases where this increase will be realised in the EAF route (Xylia et al., 2016). Long steel production seems to be safe from the point of view of the supply of LQ scrap (Pauliuk et al., 2013; Xylia et al., 2016).

Table 10: Forecasted availability and scrap demand in 2030 and 2050

#	Item	2030 (EAF-48%) million tonnes	2050 (EAF-60%) million tonnes
1	Crude steel production	182	183
2	Scrap consumption	111	131
3	Flat products production	70	106
4	Flat products production	88	53
5	Availability of scrap in total	165	166
6	Availability of home scrap (HQ), 10% x (# 1)	18	18
7	Availability of new scrap (HQ), 16% x (#1)	29	29
8	Availability of old scrap (LQ), 65% x (#1)	118	119
9	Minimal HQ scrap demand	15	47
10	Surplus HQ scrap	32	0
11	Surplus scrap in total	54	35

Source: King, 2020; P. Söderholm and T. Ejdemo, 2008; Xylia et al., 2016.

The following measures could be taken to meet the demand for HQ scrap if a sufficient amount were not available:

- limiting EU scrap exports, especially HQ scrap,
- imports of HQ scrap (mainly from China, which according to Xylia et al. (2016) is to become a significant exporter of this scrap),
- purification of domestic and/or imported LQ scrap (Xylia et al., 2016),
- iron addition from DRI (based on H_2) processes to EAF melts,
- primary steel additions to EAF melts (sweetening) (Pauliuk et al., 2013).

The scrap exports from the EU-28 amounted to 22 Mt in 2019 (Entzian, 2021). Overall, scrap is a significant raw material in steel production, both in the EAF route and BF + BOF route. It is also important to divide scrap into two quality classes: high quality (HQ), i.e. scrap produced during steel manufacturing (home scrap) and during steel product processing (new scrap) and low-quality scrap (LQ) obtained from products that have completed the period of use (old scrap).

The demand for scrap in future will depend not only on the level of steel production, but also on shares of individual steel production processes using scrap as a feedstock. The expected significant increase in the share of the EAF process will increase the demand for scrap, in particular HQ scrap, as part of the products (mainly flat) usually produced from steel manufactured in the integrated process, will be produced from steel from the EAF process using HQ scrap.

There seems to be no threat to the availability of scrap until 2050 in relation to the needs, although views on the availability of HQ scrap are divided. According to one, it will be available in the required quantities, but others claim that this will not be the case. In the event of this second scenario, several recommendations are presented.

3 Other Framework Conditions

Beyond the external framework conditions described in the foregoing chapter which are mainly related to the supply chains, other framework conditions must also be considered as highly relevant for industrial decarbonisation.

3.1 Industrial maturity of technologies

First, the technical maturity of decarbonisation techniques must be taken into account. As reported in deliverable D1.2 “Assessment and roadmapping of technologies (Green Steel for Europe, 2021c) the most relevant technologies are not yet fully industrially established but are expected to reach full industrial maturity in the mid-term, i.e. after 2030. Industrial maturity in this sense has to consider competition to the conventional aggregates such as the BF which profit from age-long optimisation. Due to the huge scale-up effort and complexity in the steel industry, the broad roll-out of new technologies seems unrealistic before their industrial maturity has been proven for several years and under different boundary conditions. Furthermore, as there is usually a time delay between an investment decision and plant start-up of approximately 5 years (Green Steel for Europe, 2021b; Hoffmann et al., 2020) most technologies cannot be estimated to be relevant for industrial steel production in 2030.

However, some technologies summarised under the technology route “Optimised BF-BOF” (Green Steel for Europe, 2021c) have advantageous conditions due to rather high TRL and limited changes needed within the existing plants. This decreases the investment costs and risks as well as the time delay to plant start-up due to approval procedures and implementation.

Furthermore, the “direct reduction” route has advantageous conditions with regard to 2030 since it is already industrially established, being based on natural gas and can be optimised with raising hydrogen contents in a flexible way. This clearly decreases the investment risks and can boost a fast implementation. However, with regard to the long-term target of carbon neutral production, technical risks exist even for this technology. For instance, large-scale production of hydrogen is still not industrially established on the large scale needed for steel production; demonstration projects on small industrial scale have only just been started (Bone, 2021; Midrex, 2019).

3.2 Investment cycles

The largest plants within current integrated steel plants are the blast furnaces. The main factor which contributes to lifetime and maintenance costs is the refractory wear, in particular in the hearth. A so-called relining of a BF usually extends the lifetime by 15-25 years, depending on individual conditions. Since the BFs are central to the operations of integrated plants, BF stoppages due to relining have a major impact on operations. The stoppages usually last 2-3 months and thus the direct costs of the maintenance itself which are in the two-digit-million-euro range (EUROMETAL, 2021) are further significantly increased due to the corresponding production losses.

Large integrated plants operating several BFs can compensate planned BF stoppages by increasing the production of the remaining BFs to some degree. Thus, the BF relinings in these cases are usually carefully coordinated to avoid simultaneous stoppages. Integrated plants with several BFs are consequently more flexible in this sense compared to smaller sites with just one BF.

Due to the large costs/losses associated with relinings, the BFs are usually operated as long as possible with respect to safety. Likewise, the shutdown of a recently relined BF would have financial implications. Since many BFs in Europe have recently been or will be relined over the next couple of years (Thyssenkrupp-Steel, 2014; Salzgitter Flachstahl GmbH, 2015; ArcelorMittal, 2017; Villa, 2021) the corresponding plants are not suitable for short-term industrial implementation of decarbonisation technologies which do not rely on a BF like the direct reduction route.

3.3 Financial conditions

Financial conditions are considerably important for the industrial deployment of decarbonisation technologies. “Financial barriers” were rated by steel producing companies as the most severe barriers hindering decarbonisation (Kempken et al., 2021).

Different aspects of financial conditions have to be considered:

1. **Higher OPEX of decarbonisation technologies compared to conventional technologies:** The OPEX to produce green steel will be clearly higher at least for the upcoming years. Higher OPEX of decarbonisation technologies are mainly related to the supply chains as discussed in detail in the sub-chapters of chapter 2.

   Renewable energy sources lag significantly behind in meeting the required price points compared to coke (excl. carbon tax) and will take time to develop, e.g. with respect to hydrogen production and infrastructure (Ito et al., 2020), energy costs are a substantial part of OPEX, this will obviously cause higher OPEX.

2. **Higher costs for research and development:**

   Higher costs for research and development will occur for large demonstrators (Ito et al., 2020). The rather low maturity of the decarbonisation technologies compared to the centuries-old conventional processes will also increase the need for research and development for a long time after industrial implementation. These costs may be decreased by appropriate funding of research and development.

3. **Higher CAPEX for new plants and for significant adaptions of existing assets:**

   CAPEX implications (depreciation) are highly significant for economic viability, in particular since costs for new or adapted plants will have to compete against largely written-off existing assets (Ito et al., 2020; Hoffmann et al., 2020). These costs may be decreased by appropriate funding, e.g. by tools like IPCEI.

4. **Market context of steel produced with much lower or even without CO_2 emissions** (further named “green steel”):

   This context is not clear since these products and markets do not yet exist. Appropriate standardisation of green steel could help to separate them, and the creation of new key markets for higher priced green steel products could compensate higher OPEX. The end-user industries seem increasingly interested and willing to pay premium prices for green steel, however, it is still not possible to quantify possible prices and additional regulatory initiatives may be needed (Ito et al., 2020; Hoffmann et al., 2020).

5. **The general market context in the steel sector:**

   Over the last few years, the steel sector has faced severe competition and massive global overcapacities. This difficult market context minimised margins or even led to losses for many companies (EUROFER, n.d.).
   This difficult market context also created disputes in global steel trade policies. On the one hand common measures were discussed to decrease overcapacities (Wang and Wong, 2016; Miles and Angel, 2017).

   On the other hand, disputed measures were taken inside and outside Europe to protect own steel markets (Hanlon, 2020; Steil and Della Rocca, 2021). Overcapacities and low margins obviously set difficult conditions for any investment in Europe's steel sector. Furthermore, disputes in recent years regarding global steel trade policies already set sensible conditions for possible measures to compensate higher OPEX for green steel (Thompson, 2021).

In addition to the difficult general market context of the steel sector in Europe, the issues related to decarbonisation discussed above can make the investment decisions even more difficult. On the other hand, as mentioned above, several policy options exist to counteract the financial issues. These options will be assessed in detail in deliverable D3.2 "Impact assessment report" of this project. Examples of important legislative aspects particularly relevant for the economic viability of decarbonisation investments are discussed in the following chapter.

3.4 Legislative framework conditions

The legislative framework conditions consist of regulations regarding European Climate and Energy Policy, the EU Emission Trading System (ETS) as well as possible Carbon Border Adjustment Mechanism (CBAM). These issues are presented in more detail below.

3.4.1 European Climate and Energy Policy

Climate protection is a central element of European Union policy. The Paris Agreement of 2015 is one of the most recent and significant milestones. The agreement calls for zero net anthropogenic greenhouse gas emissions to be reached during the second half of the 21st century. The parties to this agreement also undertook to "pursue efforts to" limit the temperature increase to 1.5 C. Prior to the conference, 146 national climate panels publicly presented a draft of national climate contributions (called "Nationally Determined Contributions", NDCs). The European Union suggested NDC is a commitment to a 40% reduction in emissions by 2030 compared to 1990.

The NDC of the European Union is derived from the European Union's official internal targets for 2030 on reducing greenhouse gas emissions by at least 55%, increasing the share of renewable energy to at least 33.7%, and achieving an energy efficiency improvement of at least 27%. This legislation provisionally agreed in September 2020 revises two targets upwards to at least 32.5% for energy efficiency and at least 32% for renewables. These targets spawned a wide range of regulations.

Governance Regulation is used by the EU as an instrument to ensure coherent long-term energy and climate policy planning. The legislative framework for implementing the current 2030 climate target reduction has been established by the revised Emission Trading System Directive (European Parliament, 2018c), which sets up a cap and trade system for large industrial and power sector installations and the aviation sector to reduce emissions by 43% by 2030 compared to 2005, the Effort Sharing Regulation (European Parliament 2018d), with binding greenhouse gas emission' pathways at member state level for the remaining emissions, adding up to a reduction of 30% by 2030 compared to 2005 for non-ETS sectors and the LULUCF Regulation (European Parliament, 2018g), which obliges member states to ensure that the net carbon sink from land use does not deteriorate compared to how it would have evolved if existing land use management practices were continued. To support the renewable and energy efficiency targets, the European Parliament, Council of the European Union and the European Commission achieved agreement on adoption of the Clean Energy for All Europeans package in May 2020, which consists of four Directives and four Regulations: a Directive on Renewable Energy (European Parliament, 2018b) (that sets a binding target of 32% for renewable energy sources (RES) in the EU's energy mix by 2030. It also includes provisions for mainstreaming RES in the transport and heating & cooling sectors), a Directive on Energy Efficiency (European Parliament, 2018a) that sets a target of 32.5% for energy efficiency for 2030. It also includes provisions extending energy savings obligation and heat meters remote reading, a Directive on Energy Performance in Buildings (European Parliament, 2018e), which sets specific provisions for better and more energy–efficient buildings, an Electricity Regulation (European Parliament, 2019d) that sets principles for the internal EU electricity market. It focuses mainly on the wholesale market as well as network operation, an Electricity Directive (European Parliament, 2019e), which defines rules for the generation, transmission, distribution, supply and storage of electricity. It also includes consumer empowerment and protection aspects, a Regulation on Risk Preparedness (European Parliament, 2019b) that requires member states to prepare plans on how to deal with potential future electricity crises, the Agency for the Cooperation of Energy Regulators (ACER) Regulation (European parliament, 2019c) that updates the role and functioning of the European Union Agency for the Cooperation of Energy Regulators and the Governance of the Energy Union (European Parliament, 2018f), a Regulation that sets a new governance system for the Energy Union. Each member state is requested to establish an integrated 10-year National Energy and Climate Plan for 2021-2030, with a longer-term view towards 2050. Inspired and guided by the above are three climate and energy targets of legislative and political initiatives for the mobility sector (three "mobility packages" consisting of 16 initiatives[2]) on circular economy, the Common Agriculture Policy, the Cohesion Policy, Waste Policy, the European Union's Multiannual Financial Framework and climate mainstreaming in financing and special initiatives for the aviation and maritime sectors. All of these

---

[2] Access to the road haulage market and access to the profession for passenger & freight transport operators, hired freight transport vehicles, road charging and electronic tolling, driving & rest time rules, posting of workers, enforcement, vehicle taxation, CO2 monitoring and reporting of heavy duty vehicles, access to the bus and coach market, Clean Vehicles Directive, Combined Transport Directive, CO2 standards for cars & vans, Battery initiative, CO_2 standards for heavy duty vehicles, digitalisation of freight transport documents (all modes), deployment of advanced vehicle technology and infrastructure safety management.

interact either directly with the steel industry or indirectly with its markets and steel product end users, with the objective to propel these sectors and markets towards the 2030 targets.

On 11 December 2019, the Commission published a proposal on how to intensify the European Union's climate policies. This is called the "European Green Deal Communication" (European Commission, 2019c) and is designed to support increased ambitions for 2030 as well as a proposal for the target of "climate neutrality" in 2050, together with a bundle of measures to advance towards this new 2050 target. One day later, the European Council approved the target and tasked the Commission to immediately commence with the deliberation and publication of the proposed measures.

The Conclusions of the European Council (General Secretariat of the Council, 2019) on the Communication on a European Green Deal and the content of this communication specifically consider the carbon-intensive sectors and energy-intensive industries, notably steel: Because they are deemed indispensable for the supply of key value chains, an enabling framework is to be put in place, which will allow their modernisation and thereby their transformation to carbon neutrality via integrated evolution.

The core of the implementation activities of the European Green Deal are a proposal on a 'European Climate Law' legally enshrining a 2050 climate neutrality target and a plan to increase the EU 2030 climate target to at least 50% and towards 55%. As announced in its communication 'The European Green Deal', the Commission conducted an impact assessment of the Union's 2030 climate ambition (European Commission, DG Climate action, 2020) and published a new proposal on 17 September 2020 to increase the EU 2030 climate target to at least 55% (European Commission, 2018b). The proposal foresees that by 30 June 2021, the Commission shall review relevant Union legislation to enable the achievement of this new target and the climate neutrality objective and consider taking the necessary measures, including the adoption of legislative proposals.

Hence, as announced in its Work Programme for 2021 published on 19 October 2020, the Commission has started working on the so-called Fit for 55 Package, which includes initiatives and revisions of existing directives to be aligned with the new 2030 target and ultimately with climate neutrality by 2050.

The initiatives directly relevant to the manufacturing industry, the Green Deal Communication announces, are: a review of the Emissions Trading System Directive; a review of the Effort Sharing Regulation; a review of the Land use, land use change and forestry Regulation (LULUCF); a review of the Energy Efficiency Directive; a review of the Renewable Energy Directive; CO_2 emissions performance standards for cars and vans, a proposal for a revision of the Energy Taxation Directive; a proposal for a carbon border adjustment mechanism for selected sectors; a new EU Strategy on Adaptation to Climate Change; a strategy for smart sector integration; a 'Renovation wave' initiative for the building sector; an evaluation and review of the Trans-European Network – Energy Regulation; Strategy on offshore wind; an EU Industrial strategy; a Circular Economy Action Plan; initiatives to stimulate lead markets for climate neutral and circular products in energy-intensive industrial sectors; a proposal to support zero carbon steel-making processes by 2030; legislation on batteries; legislative waste reforms; a strategy for sustainable and smart mobility; a revised proposal for a Directive on Combined Transport; a review of the Alternative Fuels Infrastructure Directive; and the Trans European Network – Transport Regulation; a proposal for more stringent air pollutant emissions standards for combustion-engine vehicles; a chemicals strategy for sustainability; a zero pollution action plan for water air and soil; a revision of measures to address pollution from large industrial installations; a proposal for a Just Transition Mechanism, including a Just Transition Fund, and a Sustainable Europe Investment Plan; a renewed sustainable finance strategy; a review of the Non-Financial Reporting Directive; a review of the relevant State aid guidelines, including the environment and energy State aid guidelines and the Proposal for an 8th Environmental Action Programme. Again, all of these will interact either directly with the steel industry or indirectly with its markets and steel product end users, this time with the objective to propel these sectors and markets towards the 2050 target.

3.4.2 Emission Trading System

The European Union Emissions Trading System (EU ETS) is a major pillar of European climate policy[3]. Since its launch in 2005, the EU ETS has been through four phases so far and was subject to several updates, changes and improvements[4] (The first phase ran from 2005-2007, the second phase from 2008 to 2012 and the third from 2013 to 2020).

The fourth phase has just started in 2021 and will run until 2030. The legislative framework of the EU ETS for its current trading period (phase 4) was revised in early 2018 (European Parliament, 2018c) in view of the EU's 2030 emission reduction target and as part of the EU’s contribution to the Paris Agreement. Key elements of the revision include:

- Strengthening the EU ETS via reduction of the maximum amount of allowances (the so-called cap) by increasing the pace of annual reductions in allowances to 2.2% as of 2021 (Figure 34) and reinforcing the Market Stability Reserve (mechanism established by the EU in 2015 to reduce the surplus of emission allowances in the carbon market and to improve the EU ETS's resilience to future shocks)

---

[3] The ETS is the first large greenhouse gas emissions trading scheme in the world. It operates in all EU countries plus Iceland, Liechtenstein and Norway. It limits emissions from more than 11 000 heavy energy-using installations (power stations & industrial plants) and airlines operating between these countries and covers around 40% of the EU's greenhouse gas emissions. It is a cap-and-trade mechanism where an annual maximum amount of greenhouse gas emissions (the so-called cap) - defined by the legislation and reduced every year by a “linear reduction factor (LRF) – can be emitted by the participating sectors. Within this cap, operators need an allowance for each tonne of carbon dioxide equivalent emitted. These allowances are obtained either through auctions or for free. They can also buy allowances on specialised markets, and from each other – so that market is created, where the limit to the total number of allowances creates their monetary value.

[4] The first phase – 2005-2007 – was a pilot phase aimed at putting the system in place and helping market participant to become familiar with this market.

The second phase – 2008-2012 – saw improvements concentrated on the possibility for member states to now use the verified data from phase I to set their caps based on actual emission while developing their own National Allocation Plan (NAP). The economic crisis of 2008 led to severe reductions of productions and consequently to a surplus of allowances, which in return resulted in the fall of the EU allowance price.

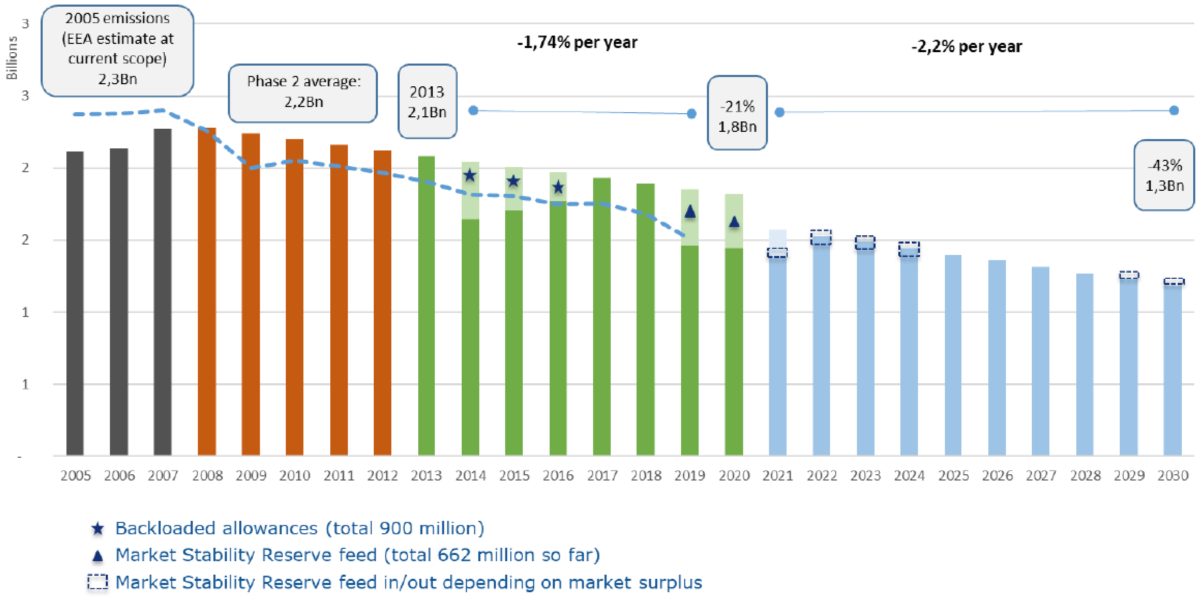
The third phase –2013-2020 – was subject to substantial changes compared to phase I and phase II, including among others: a single, EU-wide cap on emissions set to decrease following a Linear Reduction Factor of 1.74% annually; the establishment of auctioning as the default method for allocating allowances (instead of free allocation); the establishment of EU-wide harmonised rules and benchmarks for free allocation of allowances; the establishment of the Market Stability Reserve to address the surplus of allowances and improve the system’s resilience to shocks by adjusting the volume of allowances to be auctioned.

The fourth phase started has just started in 2021 and will run until 2030.

- Continuing the free allocation of allowances as a safeguard for the international competitiveness of industrial sectors at risk of carbon leakage, while ensuring that the rules for determining free allocation are focused and reflect technological progress.
- Providing several low carbon funding mechanisms to support industry and the power sector to meet the innovation and investment challenges of the low carbon transition

Further pieces of legislation for implementation of the phase 4 ETS Directive have been adopted, including the delegated regulation on free allocation of allowances for 2021-2030 adopted in December 2018 (European Commission, 2019a), the Carbon Leakage List for ETS phase adopted in February 2019 (European Parliament, 2019a), the delegated regulation on the operation of the Innovation Fund and the implementing regulation on benchmark values for the period 2021-2025 European Commission, *Report from the Commission to the European Parliament and the Council – Report on the functioning of the European carbon market,* Brussels, 2020 published in March 2021(European Commission, 2021a).

Figure 34: Cap reduction with increase of the Linear Reduction Factor to 2.2% as of 2021



Source: European Commission, Report from the Commission to the European Parliament and the Council – Report on the functioning of the European carbon market, Brussels, 2020.

3.4.2.1 EU ETS allowances

The demand for free allocation depends on the benchmark values, the historical activity levels of each benchmark, the carbon leakage exposure factor and the cross sectoral correction factor (CSCF). According to the current ETS Directive, the benchmarks for the period 2021-2025 have been updated on the basis of 2016-2017 data (European commission, 2021a) while those for the period 2026-2030 period will be based on 2021-2022. With regards to activity levels, the allocation for the period 2021-2025 will be based on average 2014-2018 activity levels, while the one for the period 2026-2030 will be based on the average for 2019-2023.

On the basis of these rules and the currently available information, the steel sector will need around 1.5 billion allowances in the fourth trading period, while the entire industry will need around 6.3 billion.

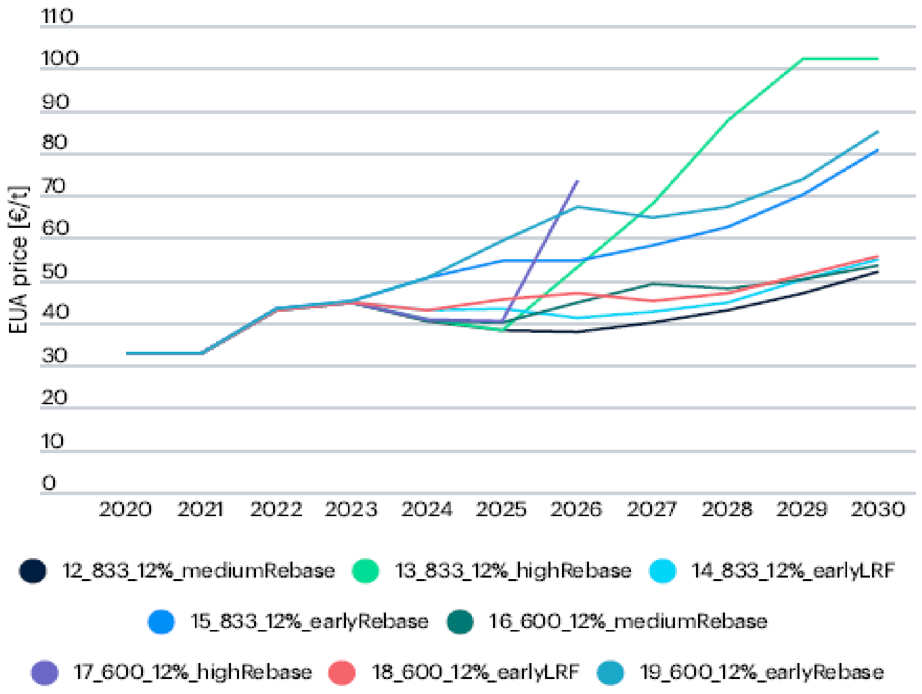
The supply of free allocation is linked to the overall ETS cap, which is defined by the relevant target for 2030. At this stage, the EU has agreed on an overall emissions reduction target of 55% by 2030 compared to 1990, but there is no decision yet on the ETS target. The Commission Impact assessment envisages an ETS target of an around 65% reduction in emissions compared to 2005. In addition, the document considers a possible one-off cancellation of allowances (the so-called rebasing of allowance supply trajectory). In the first case, the free allocation supply would be around 5.4 billion, while in the second case it would be around 5 billion. Since in both cases the free allocation supply is lower than the demand, the cross sectoral correction factor would apply in the last years of the trading period, reaching even 100% in 2030. This indicates that the revision of the EU ETS Directive will need to rebalance the distribution between free allocation and auctioning in order to avoid CSCF.

(Note: The above figures on ETS supply and demand include the UK)

3.4.2.2 Carbon prices

Carbon price forecasts vary significantly among analysts. They see carbon prices ranging from €50 to 100 /t CO_2 and even more by 2030 (Watson, 2020; Ferdinand and Petersen, 2021). In particular, they stress the interplay between the Market Stability Reserve (MSR) review (MSR parameters) and the ETS reform (cap trajectories, potential rebasing). Figure 35 shows examples of projected price developments.

Figure 35: EU Allowance price trajectory Rebasing/MSR interplay - assuming a net CO2 reduction target of 55% by 2030



Source: Ferdinand and Petersen, 2021.

3.4.3 Carbon Border Adjustment Mechanism

The European Commission is working on a proposal for a Carbon Border Adjustment Mechanism (CBAM), for selected sectors, which belongs to the key measures envisaged by the European Green Deal. The proposal for CBAM is expected to ensure that the price of imports reflects more accurately their carbon content to reduce the risk of carbon leakage, as differences in levels of ambition worldwide persist, while the EU increases its climate ambition. Key discussions focused on aspects relating to the design and scope of a CBAM, its connection with the EU Emission Trading Scheme (EU ETS) to ensure complementarity and consistency, the inclusion of indirect costs, the compatibility with World Trade Organization (WTO) rules and the EU's free trade agreements (FTAs), recycling of revenues to support energy efficient and low-CO_2 technologies, and the possible contribution of CBAM to the financing of the EU budget. The adoption of the CBAM proposal is scheduled for the second quarter of 2021.

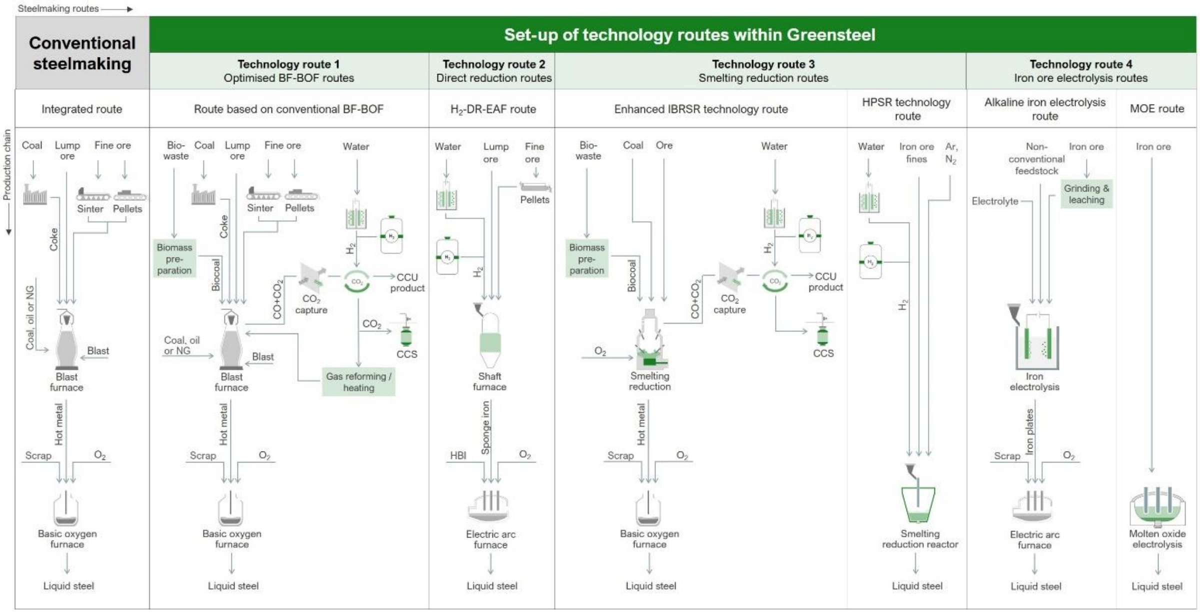
On 5 February 2021 the Parliament's Committee on the Environment, Public Health and Food Safety (ENVI) adopted the Jadot report (2020) which calls for the introduction of a CBAM as part of a broader EU industrial strategy. On 10 March 2021, Parliament adopted the resolution on a WTO-compatible CBAM.

The EU steel industry is in favour of a CBAM or any other measure that will improve the level playing field and is calling for a mechanism that allows a fair transition with the current leakage protection and CBAM as a complementary measure, taking into consideration the risk a sudden removal of free allocation bears for this industry (EUROFER, 2021). With the new climate target of 55% CO_2 reduction, under normal market conditions, the industry estimates a net annual shortage of around 50 Mt CO_2 equivalent. At current CO_2 prices of €55/t this would correspond to €2.75 billion direct and indirect costs per year – which constitute a big disadvantage vis-à-vis competitors exporting into the EU which do not bear such costs.

4 Technology Routes considered for Pathways

Four promising technology routes were identified within the project work as highly relevant (but non-exclusive) examples. These are illustrated in Figure 36. The decarbonisation technology implementations are displayed in green whereas components of the integrated primary steel production route are indicated in grey.

Figure 36: Technology Routes selected within "Green Steel for Europe"



Source: Green Steel for Europe, "Technology Assessment and Roadmapping (Deliverable 1.2)," 2021.

The first technology route consists of measures that further optimise the BF-BOF production route by implementation of add-on technologies. It is differentiated into three sub-routes: 1A – alternative carbon source utilisation, 1B -–carbon capture and usage or storage, 1C – other actions. The second technology route is based on the utilisation of direct reduction technology. It is differentiated into 2 sub-routes, in which the iron and steelmaking units are replaced by new production methods: 2A – based on natural gas and 2B – based on hydrogen. The third technology route comprises technologies based on smelting reduction. This includes the iron bath reactor smelting reduction (IBRSR) option which replaces conventional ironmaking and hydrogen plasma smelting reduction (HPSR) which enables the direct transformation of iron ore into liquid steel. The fourth technology route refers to electricity-based steelmaking by iron ore electrolysis.

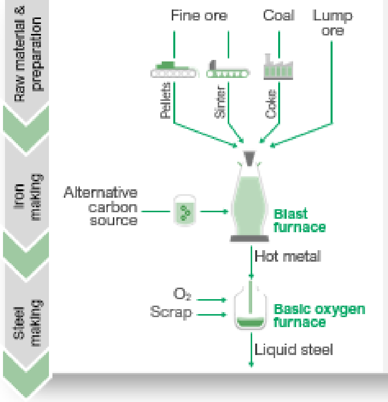
The main information regarding these technology routes and selected sub-routes are summarised below as one-page factsheets. These cover one technology (sub-)route each and contain information regarding technical description (including a process flowsheet), framework conditions, economic assessment, feedstock, CO_2 mitigation potential, TRL development and geographical information.

4.1.1 Optimised BF-BOF with alternative carbon sources (Route 1A)

TECHNOLOGY ROUTES BASED ON OPTIMISED BF-BOF UTILISATION OF ALTERNATIVE CARBON SOURCES

DEVELOPMENT OF EFFECTIVE SOLUTIONS TOWARDS A LOW-CO_2 STEEL PRODUCTION

FACT SHEET



Technical description

The foundation of the technology route is for the blast furnace (BF) and the basic oxygen furnace (BOF). Fossil carbon (in the form of coal and coke) can be substituted by **alternative carbon** such as torrefied material or charcoal by upgrading various carbon containing feed stocks such secondary wood, forest biomass/agricultural residues. In addition, other types of **spent carbon streams** such as the fractions of plastic, paper and biogenic materials in waste societal streams can also be used as potential carbon sources, enabling the increase of the circularity of carbon use and sparing natural resources. This developed technology route can further be combined with carbon capture and usage or other additional mitigation technologies applied upstream and downstream the blast furnace.

Framework conditions

- ☐ Technologies to upgrade alternative carbon sources (e.g. torrefaction or carbonisation)
- ☐ Transportation, storage, price and availability of alternative carbon sources
- ☐ Possibility of integrating upgrading technologies at the steelmaking sites

Feedstock

Beyond usual blast furnace feedstock, various types of alternative carbon sources such as secondary biomass, agricultural residues, sewage sludge or mixed waste streams containing plastics and biogenic materials can be utilised.

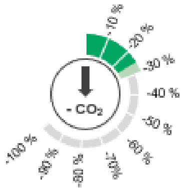
Iron ore

Coal

Alternative carbon source

CO_2 mitigation potential

The mitigation potential of this option compared to conventional BF-BOF route is 25 % to 30 % (on full steel plant emissions) and can be combined with other mitigation routes (such as gas injections in the blast furnace etc.) to reach higher mitigation.



TRL development

TRL 2 - 7	**2020**	🟩🟩▨▨▨▨▨⬜⬜
TRL 8 (TRL 9 is expected in 2035)	**2030**	🟩🟩🟩🟩🟩🟩🟩🟩⬜
Industrially deployed	**2050**	🟩🟩🟩🟩🟩🟩🟩🟩🟩

Economic assessment*

Cost for development up to **TRL 8**	From 5 to 150 M€
Cost for **first industrial deployment**	From 15 to 500 M€
Cost for **production plants**	From 15 up to 500 M€

** min with only alternative carbon source, max with all the others enhancement actions implemented*

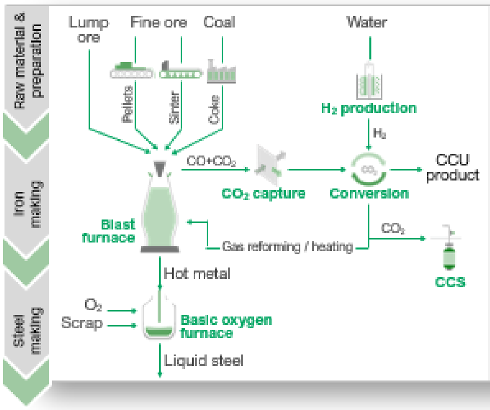
Geographical information

- ☐ Key projects for utilisation of alternative carbon sources in primary steel production in:
  - ☐ Ghent (Belgium)
  - ☐ Dunkerque, Fos-sur-Mer (France)
  - ☐ Bremen (Germany)
  - ☐ Dabrowa Gornicza (Poland)

4.1.2 *Optimised BF-BOF with CCUS (Route 1B)*

TECHNOLOGY ROUTES BASED ON OPTIMISED BF-BOF UTILISATION OF CARBON CAPTURE, USAGE & STORAGE

DEVELOPMENT OF EFFECTIVE SOLUTIONS TOWARDS A LOW-CO_2 STEEL PRODUCTION **FACT SHEET**



Technical description

Carbon capture and usage (CCU) in the iron and steel industry consists of the **capture of CO_2 or CO** from relevant process gases and their **conversion** into other valuable products. Therefore, a typical CCU process consists of multiple components: First, the carbon oxides are captured in a separation unit, and then converted into more valuable products in a biological or chemical reactor and finally the products are refined in a processing unit. If not all the captured CO_2 can be converted, CCU can be complemented by **carbon capture and storage** (CCS). This technology route can be combined with further mitigation technologies such as the utilisation of alternative carbon sources.

Framework conditions

- ☐ Energy efficient separation and purification technologies
- ☐ Availability and price of low-CO_2 hydrogen production
- ☐ Availability and volatility of renewable energy
- ☐ CO_2 and hydrogen transport system
- ☐ Marketability and price CCU products
- ☐ Social acceptance

Feedstock

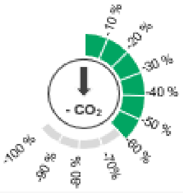
As CCU is an extension of the conventional blast furnace – basic oxygen furnace (BF-BOF) route usual blast furnace feedstock (ores, coke, lime…) is utilised within this technology route. The conversion process further requires hydrogen. In addition, the replacement of certain amounts of coal with alternative sources of carbon is feasible.

Iron ore

Coal

CO_2 mitigation potential

The overall CCU mitigation potential by carbon oxide conversion is estimated to up to 60 % compared to the BF-BOF route. CCU concepts can generally be combined with other CO_2 mitigation technologies



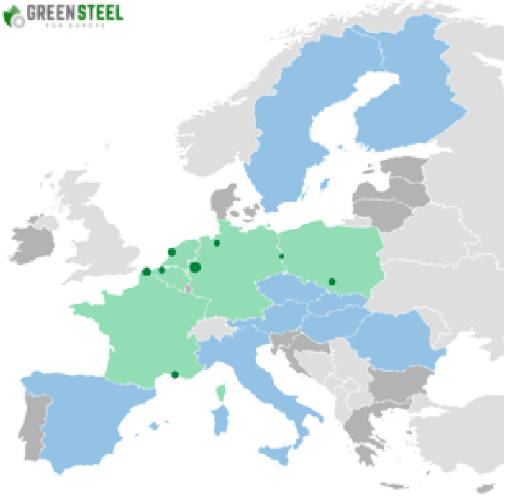
TRL development

TRL 4 - 8	**2020**	🟩🟩🟩🟩▨▨▨▨☐
TRL 9	**2030**	🟩🟩🟩🟩🟩🟩🟩🟩🟩
Industrially deployed	**2050**	🟩🟩🟩🟩🟩🟩🟩🟩🟩

Economic assessment*

Cost for development up to **TRL 8**	1000 M€
Cost for **first industrial deployment** (greenfield)	2000 M€
Cost for **production plants**	4000 M€

* Including all costs for H_2 infrastructures, greenfield; brownfield, costs are 40%



Geographical information

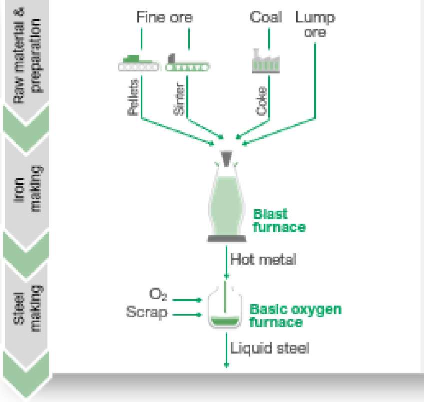
- ☐ CCU projects in primary steel production as indicated in the map in France, Belgium, Netherlands, Germany and Poland
- ☐ CCS projects in primary steel production: Ghent (Belgium), Dabrowa Gornicza (Poland), Bremen (Germany), Eisenhüttenstadt (Germany), Dunkerque (France), Fos-sur-Mer (France)

4.1.3 Optimised BF-BOF with other actions (Route 1C)

TECHNOLOGY ROUTES BASED ON OPTIMISED BF-BOF OTHER ACTIONS (GAS INJECTION, SINTER PLANT,…)

DEVELOPMENT OF EFFECTIVE SOLUTIONS TOWARDS A LOW-CO_2 STEEL PRODUCTION

FACT SHEET



Technical description

The foundation of the technology route is for the blast furnace (BF) and the basic oxygen furnace (BOF). In addition to the use of alternative carbon sources, the application of CCUS and the recycling of spent carbon streams, further CO_2 mitigation technologies are available within the conventional blast furnace route. Examples of these are **gas injection into the blast furnace** (usually of hydrogen-rich gases to minimise or to avoid CO_2 formation), the **waste gas recirculation** and **use of low-CO_2 fuels** at the sinter plant as well as **the increased scrap usage** (mainly at the basic oxygen furnace plant) or the operation of **new heating applications** on hydrogen/internally generated gases (provided these gases replace natural gas imported in the steel plant).

Framework conditions

- ☐ Availability and price of low-CO_2 hydrogen production
- ☐ Availability of volatility of renewable energy for plasma torches
- ☐ Social acceptance
- ☐ Energy efficient separation and purification technologies
- ☐ CO_2 and process gases transport system

Economic assessment

Cost for development up to **TRL 8**	200 M€
Cost for **first industrial deployment**	400 M€
Cost for **production plants**	650 M€

Feedstock

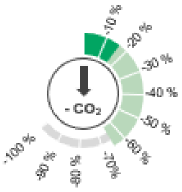
Beyond usual blast furnace feedstock (ores, coke, lime…), gases have to be injected. Either external (hydrogen or natural gas) either process gases, even BF ones after reforming and reheating.

Iron ore

Coal

CO_2 mitigation potential

The savings potential of TGR-blast furnace in combination with CCUS is up to 65 %, even when calculated on a full production perimeter, from raw materials to hot rolled coil. Without CCUS, it is limited to 35 % at blast furnace level and to 15 to 20 % on a full production perimeter.



TRL development

TRL 2 - 7	**2020**	🟩🟩▨▨▨▨▨⬜⬜
TRL 8 (TRL 9 is expected in 2035)	**2030**	🟩🟩🟩🟩🟩🟩🟩🟩⬜
Industrially deployed	**2050**	🟩🟩🟩🟩🟩🟩🟩🟩🟩

Geographical information

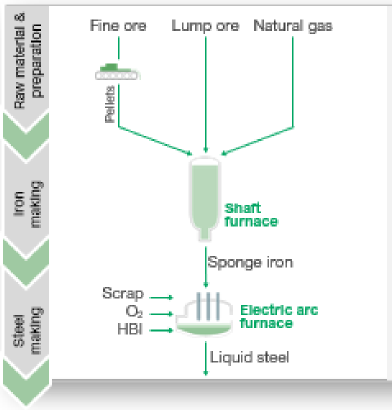
- ☐ Projects of further optimisation of BF-BOF routes are planned in
  - ☐ France (Dunkerque, For-sur-Mer)
  - ☐ Belgium (Ghent)
  - ☐ Netherlands (IJmuiden)
  - ☐ Germany (Duisburg, Bremen, Eisenhüttenstadt)
  - ☐ Poland (Dabrowa Gornicza)

4.1.4 Natural Gas based Direct Reduction (Route 2A)

TECHNOLOGY ROUTES BASED ON DIRECT REDUCTION
DR-EAF BASED ON (H_2-ENRICHED) NATURAL GAS

DEVELOPMENT OF EFFECTIVE SOLUTIONS TOWARDS A LOW-CO_2 STEEL PRODUCTION

FACT SHEET



Technical description

This technology route consists of a **direct reduction** (DR) process utilising **natural gas** or coal to produce sponge iron in the form of direct reduced iron (DRI) or hot briquetted iron (HBI) from iron ore. The sponge iron is subsequently processed into crude steel in an electric arc furnace (EAF). The liquid steel will be processed in secondary metallurgy, then casted and rolled in similar steps as in the current integrated steelmaking route. Natural gas based direct reduction can be complemented by carbon capture and usage (CCU) and/or carbon capture and storage (CCS). Furthermore, the operating gas mixture could be gradually enriched with hydrogen and therefore, this technology route could be considered as an entry point to a technology route based on hydrogen-based direct reduction.

Framework conditions

- ☐ Price and availability of natural gas
- ☐ Process gases transport system

Economic assessment

Cost for development up to **TRL 8**	▶ 50 M€
Cost for **first industrial deployment**	▶ 150 M€
Cost for **production plants**	▶ 500 M€

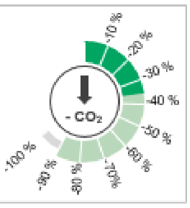
Feedstock

This technology route uses iron oxide pellets and lump ore. The reducing gas, which mainly consists of CO and hydrogen, can be generated by natural gas, coal or coke oven gas.

Iron ore
Natural gas
Hydrogen

CO_2 mitigation potential

Depending on the share of hydrogen in the reduction gas, a CO_2 mitigation potential between 35 % to 90 % compared to the blast furnace – basic oxygen furnace route is estimated. To further enhance the CO_2 mitigation potential, it is possible to supplement this route with CCU or CCS.

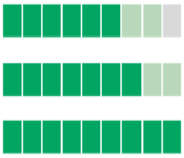


TRL development

TRL 6 - 8 ◀ **2020** ▶

TRL 7 - 9 ◀ **2030** ▶

Industrially deployed ◀ **2050** ▶



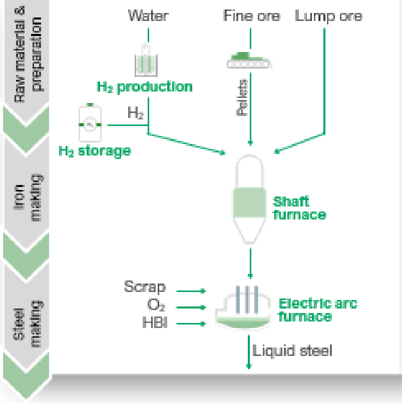
Geographical information

- ☐ As most planned Direct Reduction projects include the utilisation of (H2-enriched) Natural Gas as a bridge technology, all current key Direct Reduction projects are included in the map
- ☐ Direct Reduction Plants in primary steel production are planned in Austria, Belgium, France, Germany, Poland and Sweden

4.1.5 *Hydrogen-based Direct Reduction (Route 2B)*

TECHNOLOGY ROUTES BASED ON DIRECT REDUCTION
DR-EAF BASED ON HYDROGEN

DEVELOPMENT OF EFFECTIVE SOLUTIONS TOWARDS A LOW-CO_2 STEEL PRODUCTION **FACT SHEET**



Technical description

The technology route based on **hydrogen-based direct reduction** (H_2-DR) is derived from the already industrially established direct reduction route, which is usually operated with natural gas or coal. Natural gas based direct reduction could therefore be utilised as an entry point to H_2-DR. There are different technological approaches to the hydrogen-based direct reduction process: The most common approach is the direct reduction of iron ore pellets in a shaft furnace by hydrogen gas. The product of this process is called sponge iron in form of direct reduced iron or hot briquetted iron (HBI). In a next step, the produced sponge iron is further processed in an electric arc furnace (EAF) to liquid steel. The rest of the downstream production will remain, and the liquid steel will be processed in secondary metallurgy, then casted and rolled in similar steps as in the current integrated steelmaking.

Framework conditions

- ☐ Availability and price of low-CO_2 hydrogen production
- ☐ Energy system without (or with minimum) carbon input
- ☐ Strengthening of high-voltage grids
- ☐ Hydrogen transport and storage infrastructure must be provided

Economic assessment

Cost for development up to **TRL 8**	▸ 100 M€
Cost for **first industrial deployment**	▸ 300 M€
Cost for **production plants**	▸ 700 M€

Feedstock

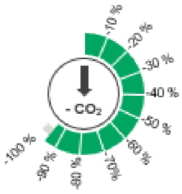
Depending on the technological approach, either iron ore pellets (shaft furnace), or iron fines (fluidised bed reactor) are used within the direct reduction process step. The reducing agent is hydrogen, generated by low-CO_2 processes (e.g. water electrolysis).

Iron ore

Hydrogen

CO_2 mitigation potential

This technology route utilising 100 % hydrogen in combination with renewable energy has a high CO_2 mitigation potential and a CO_2 mitigation of up to 95 % can be reached compared to the integrated steelmaking route.

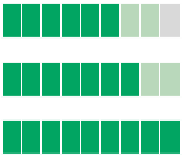


TRL development

TRL 6 - 8 ◂ **2020** ▸

TRL 7 - 9 ◂ **2030** ▸

Industrially deployed ◂ **2050** ▸



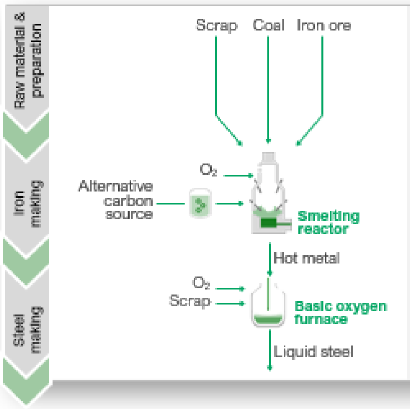
Geographical information

- ☐ As most planned Direct Reduction projects target the utilisation of hydrogen in the future, all current key Direct Reduction projects are included in the map
- ☐ Direct Reduction Plants in primary steel production are planned in Austria, Belgium, France, Germany, Poland and Sweden

4.1.6 *Smelting Reduction (Route 3)*

TECHNOLOGY ROUTES BASED ON SMELTING REDUCTION
IRON BATH REACTOR SMELTING REDUCTION

DEVELOPMENT OF EFFECTIVE SOLUTIONS TOWARDS A LOW-CO_2 STEEL PRODUCTION **FACT SHEET**



Technical description

The **iron bath reactor smelting reduction** (IBRSR) is an ironmaking process that eliminates the coke making and ore agglomeration steps. The ore is liquified in a high-temperature cyclone and drips to the bottom of the reactor where powder coal is injected. The powder coal reacts with the molten ore to produce liquid iron, which will be processed in secondary metallurgy, then casted and rolled in similar steps as in the current integrated steelmaking route.

Framework conditions

- ☐ Carbon capture, usage and storage technologies have to be used in combination with IBSR to attain sufficient mitigation
- ☐ Pre-treatment processes for alternative carbon sources
- ☐ Price and availability of alternative carbon sources
- ☐ O_2 production and CO_2 capture and compression
- ☐ Social acceptance

Economic assessment

Cost for development up to **TRL 8**	▶	400 M€
Cost for **first industrial deployment**	▶	500 M€
Cost for **production plants**	▶	850 M€

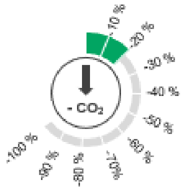
Feedstock

This technology route produces liquid hot metal directly from the raw materials, iron ore fines and coal. Several pre-processing steps are removed requirements about ores quality are less stringent. In addition, the replacement of certain amounts of coal with alternative sources of carbon is feasible.

Iron ore
Coal
Alternative carbon source
Scrap

CO_2 mitigation potential

This technology reduces CO_2 emissions by 20% and reduces the emissions of fine particles, sulphur dioxide and nitrogen oxide between 60 to 80%. Due to the full O_2 operation, the off-gases are concentrated on CO_2 and well-fitted for CCUS.



TRL development

TRL 6	◀	**2020**	▶	🟩🟩🟩🟩🟩🟩⬜⬜⬜
TRL 8	◀	**2030**	▶	🟩🟩🟩🟩🟩🟩🟩🟩⬜
Industrially deployed	◀	**2050**	▶	🟩🟩🟩🟩🟩🟩🟩🟩🟩

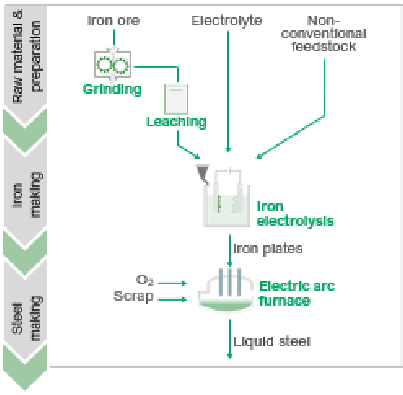
Geographical information

- ☐ This technology route (HISARNA) is developed at Tata Steel Europe Ijmuiden plant. All the related investment, energy, feedstock and infrastructures are therefore to be addressed first in the Netherlands.

4.1.7 *Iron Ore Electrolysis (Route 4)*

TECHNOLOGY ROUTES BASED ON ORE ELECTROLYSIS
ALKALINE IRON ELECTROLYSIS

DEVELOPMENT OF EFFECTIVE SOLUTIONS TOWARDS A LOW-CO_2 STEEL PRODUCTION **FACT SHEET**



Technical description

In the technology route based on iron ore electrolysis, iron oxides are converted into iron plates, which in a subsequent step are further melted in an electric arc furnace. **Low temperature alkaline iron ore electrolysis**, or electrowinning, is the direct deposition of iron from its ores on an electrode. During the electrolysis step, the released gas is almost pure oxygen, which can be recovered, compressed and used at electric arc furnace and downstream processes. The remaining downstream processes are similar to those of the current integrated steelmaking route and the liquid steel will be processed in secondary metallurgy, then casted and rolled.

Framework conditions

- ☐ Energy system without (or with minimum) carbon input
- ☐ Strengthening of high-voltage grids

Economic assessment

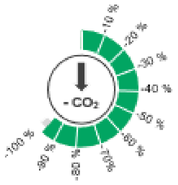
Cost for development up to **TRL 8**	M€ 250
Cost for **first industrial deployment**	M€ 500

Feedstock

This technology route requires preliminary grinding steps of iron ores and leaching out part of its gangue before electrical reduction. Non-conventional feedstock (i.e. by-products from non-ferrous metallurgy residues) can also be used in this process.

CO_2 mitigation potential

The mitigation potential of this option compared to conventional integrated steelmaking route is almost 100 %, without any need of carbon capture and usage or storage.



TRL development

TRL 5 - 6	**2020**	🟩🟩🟩🟩🟩▨⬜⬜⬜
TRL 6 - 8	**2030**	🟩🟩🟩🟩🟩🟩▨▨⬜
Industrially deployed	**2050**	🟩🟩🟩🟩🟩🟩🟩🟩🟩

Geographical information

- ☐ In scope of the SIDERWIN project, a pilot plant is being erected in Maizieres (France).
- ☐ This is not a BF-BOF site.

5 Investment phases and roadmapping approach

Regarding the framework conditions discussed in chapters 2 and 3 it can be concluded that all of them are directly related to the possible decarbonisation barriers discussed in deliverable D1.5 ("Collection of possible decarbonisation barriers"). Extending the focus beyond the R&D effort needed for further technical development of the decarbonisation technologies, the industrial roll-out of decarbonisation technologies which is the focus of this deliverable depends on investment decisions and the corresponding investment framework conditions.

It is obvious that hitherto the current investment framework conditions do not favour investment in extensive decarbonisation of industrial steel production. The generally difficult market and financial conditions of the steel sector in recent years have already caused a general underinvestment with regard to the maintenance of assets, in particular subsequent to the financial crisis (Skanberg and Shields, 2018). The industrial deployment of decarbonisation techniques obviously needs massive investments. Roland Berger estimates this investment need at €100 billion just to replace Europe's approximately 100 million tons of primary crude steel production by hydrogen-based direct reduction by 2050 (Ito et al., 2020).

Despite the high interest of investors in sustainability (Hoffmann et al., 2020), many issues still exist, most of which are financial. Regarding hydrogen, this situation is not expected to change before 2030 or 2040, thus, successful decarbonisation of the European steel industry strongly depends on appropriate policy actions. Hoffmann et al. (2020) and Ito et al.,(2020) conclude: "Without such support, there is a high risk that large parts of the steelmaking value chain will be moved out of Europe to countries with cheap access to energy, and fewer regulations. This would damage not just the European steel industry, but also the chances of a global carbon-neutral future."

Considering the long investment cycles and the significant lead times, the time pressure for these policy actions is extremely high: Actions to safeguard positive decarbonisation investment conditions in the short term and also to safeguard new investments in the long term have to be taken now (Hoffmann et al., 2020; Ito et al., 2020). A large variety of policy options exist; this will be discussed in detail in deliverable D3.2 "Impact assessment report" of the project.

In summary, the framework conditions for decarbonisation investments in the European steel industry are currently not encouraging and it is not possible to predict the timing or the degree of changes, either with regard to trends regarding the barriers or with regard to policy actions which may be taken. The actual industrial deployment of decarbonisation technologies will existentially depend on those investment framework conditions and consequently cannot be predicted in a reliable fashion.

Therefore, the pathways presented for 2030 and 2050 in the following chapters must not be regarded as a reliable prognosis but they are scenarios which can be expected for certain framework conditions. The aim of these scenarios is to make transparent the influences of framework conditions and related policy actions on the industrial roll-out of decarbonisation in the steel industry to provide the technical background for the impact assessment in work package 3 and deliverable D3.2 of the project Green Steel for Europe (Ito et al., 2020).

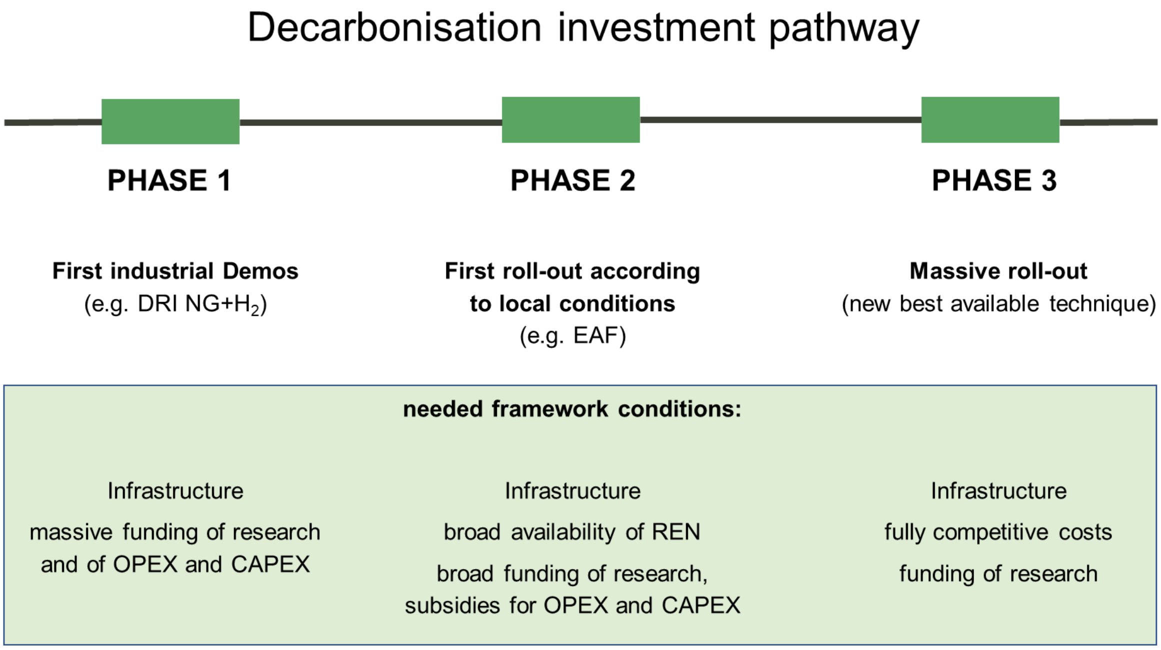
5.1 Investment phases

Key criteria influencing investment decisions are technical readiness, development, operating costs and CAPEX requirements (Ito et al., 2020). It should also be noted that new technologies and new plants usually need several years to reach full productivity and a significant increase of the development effort is needed in these years (up to decades) compared to conventional technologies and existing assets.

Due to the high pressure to significantly and quickly mitigate CO_2 emissions, the industrial processes in the steel industry must be adapted and/or even completely exchanged quickly and extensively. Since this is far beyond the speed and degree of replacement and exceeds innovation investments in the steel industry in the last 50 or more years, different phases of the investment pathway to decarbonisation should be considered in order to set appropriate priorities.

Figure 37 sketches the main aspects of a decarbonisation investment pathway. In the first phase of the investment pathway, which can roughly be assigned to 2030, the first industrial-scale demonstration plants will be built. In this phase, as renewable energy sources will not yet be competitive, the technical risks are still high and new premium markets may not yet be fully developed, investments will rely on massive OPEX and CAPEX funding.

Figure 37: Decarbonisation investment pathway



Source: Compiled by the authors.

Once first full-scale industrial demonstration plants have been successfully operating for some years, the second investment phase will begin. In this second phase local framework conditions will dominate further investments and roll-out of technologies in sites which have advantageous conditions for these investments due to internal or external reasons. This phase could roughly be assigned to 2035-2040.

The third and final decarbonisation investment phase can be identified by a massive roll-out of decarbonisation technologies which then become the new best available technologies and which must be fully economically competitive. This third phase obviously brings with it the highest CO_2 mitigation potential up to carbon neutral steel production. This phase could roughly be assigned to 2045.

The first decades of the final investment phase (Massive roll-out) will still be accompanied by increased need for research and (in particular) development. The completely renewed supply and production chains will still have lower maturity compared to the conventional technologies with which they will have to compete worldwide (assuming that decarbonisation in Europe will be faster than in other regions of the world). However, this increased need for further improvement will also proceed in parallel with the increased optimisation potential of the emerging technologies (Rogers, 1962). The dominant framework condition which will enable the start of this third phase is the full availability of huge amounts of renewable energy at costs which are fully competitive with a global level playing field.

The decarbonisation investment pathway presented in Figure 37 must be interpreted as the technological and financial background to the policy actions which are analysed in deliverable D3.2 “Impact assessment report” of the Green Steel for Europe project. The investment pathway is directly linked to policy actions through the framework conditions required for each investment phase. It illustrates that different priorities exist along the timeline. An appropriate policy roadmap must combine “quick wins” allowing for a fast gradual shift towards decarbonisation but also ensure appropriate long-term conditions to safeguard the long-term investments of the steel industry (Hoffmann et al., 2020).

5.2 Assumptions and modelling approach

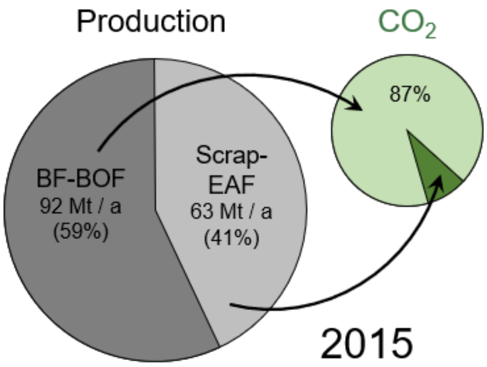
The main target for the development of pathway scenarios is to illustrate plausible distributions of decarbonisation technology implementations in 2030 and 2050. Thus, the pathway scenarios reflect specific distributions of technology routes.

5.2.1 General assumptions

The general scope of the Green Steel for Europe project is to analyse the main steel plants covering at least 80% of the CO_2 emissions. Considering this scope, the analyses were focused on primary steel production (mainly via the BF-BOF route using virgin iron ores). Primary steel production is quite energy intensive due to the effort needed to reduce the iron ores. This effort is not needed in secondary steel production (via EAF based mainly on scrap). In Europe, 59% of the overall steel production in 2015 was via primary steel production, however, due to the high energy intensity primary steel production is responsible for 87% of the CO_2 emissions (Figure 38). Thus, decarbonisation of the primary steel production would obviously also provide the largest potential for CO_2 mitigation. Thus, the focus of the project on primary production ensures maximum mitigation efficiency. This approach is in line with recent studies such as that of Ito et al. (2020).

Due to the large difference in energy intensity between primary and secondary steel production, increasing the share of secondary steel production at the expense of primary production could theoretically also mitigate CO_2 emissions. However, this is greatly limited due to limited availability of scrap with sufficient quality and no significant increase in scrap availability is expected by 2030 (see also section 2.8).

Figure 38: Primary and secondary steel production shares and CO_2 emissions in 2015



Source: Author's composition based on (EUROFER, 2019b)

5.2.2 Technology route-specific assumptions

Based on their technological maturity (and their estimated development) as explained within this project's technology assessment and roadmapping, (Green Steel for Europe, 2021c) five possible technology sub-routes were taken into consideration for 2030 pathway scenarios:

- Route 1A: Optimised BF-BOF by utilisation of alternative carbon sources (see section 4.1.1)
- Route 1B: Optimised BF-BOF by CCUS measures (see section 4.1.2)
- Route 1C: Optimised BF-BOF by other actions (see section 4.1.3)
- Route 2A: Natural Gas based Direct Reduction (see section 4.1.4)
- Route 2B: Hydrogen-based Direct Reduction (see section 4.1.5)

Additionally, any combinations between routes 1A, 1B and 1C into 1AB, 1AC or 1ABC were considered. The corresponding CO_2 mitigation potential of both the single routes (1A, 1B, 1C, 2A, 2B) and combinations (1AB, 1AC, 1ABC) are given in Table 11.

Table 11: Technology specific assumptions for 2030

Year	Route	Technology	CO_2 mitigation	Specific CO_2 emissions
2015	**Ref.**	BF-BOF (Reference)	Reference	1800 kg CO_2 / t CS
2030	**1A**	BF-BOF util. alternative carbon sources (=100 kg/t_{HM} PCI)	–17%	1494 kg CO_2 / t CS
	1B	BF-BOF + CCUS	–30%	1260 kg CO_2 / t CS
	1C	BF-BOF other actions (OA)	–8%	1656 kg CO_2 / t CS
	1AC	BF-BOF util. sec. biomass + OA	–25%	1345 kg CO_2 / t CS
	1BC	BF-BOF + CCUS + OA	–37%	1134 kg CO_2 / t CS
	1ABC	BF-BOF util. alternative carbon sources + CCUS + OA	–48%	941 kg CO_2 / t CS
	2A	NG-based DR (H_2 enriched)	–50%	900 kg CO_2 / t CS
	2B	H2-DR	–90%	180 kg CO_2 / t CS

Source: Compiled by the authors.

The assumed values for CO_2 mitigation reflect an average value over all assumed technology implementations in the EU-27 by 2030. It is expected that due to local or site-specific limitations the full technological CO_2 mitigation potential (as indicated during the technology assessment and roadmapping (Green Steel for Europe, 2021c) cannot be reached in all assumed implementation cases by 2030. Thus, the assumed CO_2 mitigations for these technology routes are lower than the full CO_2 mitigation potential stated in Deliverable 1.2 and in chapter 4 of this report.

Instead, the values stated in Table 11 were extensively discussed in this project's stakeholder consultations and confirmed by the most relevant stakeholders of the European iron and steel industry Green Steel for Europe, 2021b). CO_2 mitigation of the NG-based H_2-enriched Direct Reduction (Route 2A) was estimated on a basis of 25 vol-% H_2 and 75 vol-% natural gas. For pellet production the corresponding CO_2 loads and for EAF power supply estimations for CO_2 loads for electricity prognosed in the EU-27 in 2030 (200 g CO_2 / kWh) were taken into account Green Steel for Europe, 2021c).

In the long-term perspective additional technology routes as well as higher CO_2 mitigation for the already considered technology routes come into play as result of further development and of extensive implementation of all mitigation options of the corresponding route. The assumptions for 2050 are summarised in Table 12.

Table 12: Technology specific assumptions for 2050

Year	Route	Technology	CO_2 mitigation	Specific CO_2 emissions
2015	**Ref.**	BF-BOF (Reference)	Reference	1800 kg CO_2 / t CS
2050	**1A**	BF-BOF util. alternative carbon sources (=150 kg/t_{HM} PCI)	–25%	1350 kg CO_2 / t CS
	1B	BF-BOF + CCUS	–60%	720 kg CO_2 / t CS
	1C	BF-BOF other actions	–15%	1530 kg CO_2 / t CS
	1AC	BF-BOF util. alternative carbon sources + OA	–36%	1148 kg CO_2 / t CS
	1BC	BF-BOF + CCUS + OA	–66%	612 kg CO_2 / t CS
	1ABC	BF-BOF util. alternative carbon sources + CCUS + OA	–75%	459 kg CO_2 / t CS
	2B	H2-DR	–95%	90 kg CO_2 / t CS
	3	IBRSR + CCUS	–80%	360 kg CO_2 / t CS
	4	other technologies	–95%	90 kg CO_2 / t CS

Source: Compiled by the authors.

Additional technology routes being considered for implementation by 2050 are the IBRSR + CCUS route with a CO_2 mitigation of 80% and a combined category "other technologies" (e.g. Alkaline Oxide Electrolysis, Molten Oxide Electrolysis, HPSR) with a lump-sum CO_2 mitigation of 95% compared to 2015.

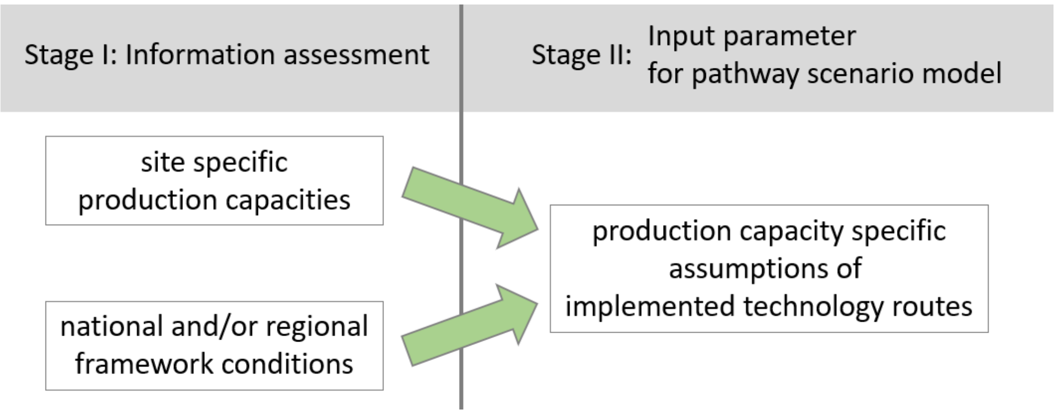
5.2.3 Modelling approach

The overarching target for the elaboration of decarbonisation pathway scenarios is to reflect plausible “what-if” cases of industrial implementation of decarbonisation technologies. Against this background, the modelling approach used is based on assumptions regarding several regional and/or national framework conditions (see chapters 2 & 3). These framework conditions were combined in order to deliver an overall assessment of which technology route(s) may be preferable in the corresponding context.

It was assumed that each primary steel production site in the EU-27 faces challenges in the transition to decarbonisation over the next decades and will be implementing some decarbonisation technology at some point in the future. In the modelling approach, the structure and specific production capacity of each existing primary steel production plant was considered. The site-specific production capacities were extracted from EUROFER’s “Map of EU steel production sites” (EUROFER, 2019c).

The result of this model is a summarised production capacity of each technology route all-over the European steel industry. Figure 39 illustrates this approach.

Figure 39: Principal approach for pathway scenario assumptions



Source: Compiled by the authors.

This approach was combined (refer to Figure 3) with the results of the stakeholder consultations carried out within the project (Deliverable 1.5) and with further published roadmaps e.g. Wyns et al., (2016), Dahlmann et al., (2019), Joas et al., (2019). The assumptions with regard to the technology route for the specific sites were checked for consistency with the results of the statements of the corresponding stakeholders. The summarised European/national production capacity derived for each technology route was checked for consistency with existing roadmap publications and the results were found to be generally consistent. However, compared to existing roadmaps, the approach used within this project, the versatile sources of information and the most up-to-date information which result in more reliable pathways can be rated as added value.

As for each technology route, a corresponding CO_2 mitigation degree was defined (see Table 11 & Table 12) the total CO_2 mitigation of a pathway scenario could be calculated and compared with the CO_2 mitigation targets for the EU-27.

6 Decarbonisation Pathways 2030

Three 2030 decarbonisation pathway scenarios were developed in the scope of the Green Steel for Europe project. The pathway scenario “Mixed implementation” is used as a reference scenario for 2030 and illustrates to what extent technology switches and further incremental optimisation measures are required to meet the set EU-27 targets. The pathway scenario “Delayed implementation” represents a negative case to indicate consequences of a partial delay of decarbonisation measures after 2030. The third pathway scenario “Increased hydrogen availability” illustrates an alternative technology distribution meeting the EU-27 CO_2 mitigation targets based on lower availability of alternative carbon sources but higher hydrogen availability. These pathway scenarios are described in detail below. As a basis for evaluating these scenarios, the emission targets of the European Commission are used. These targets are described in the following section.

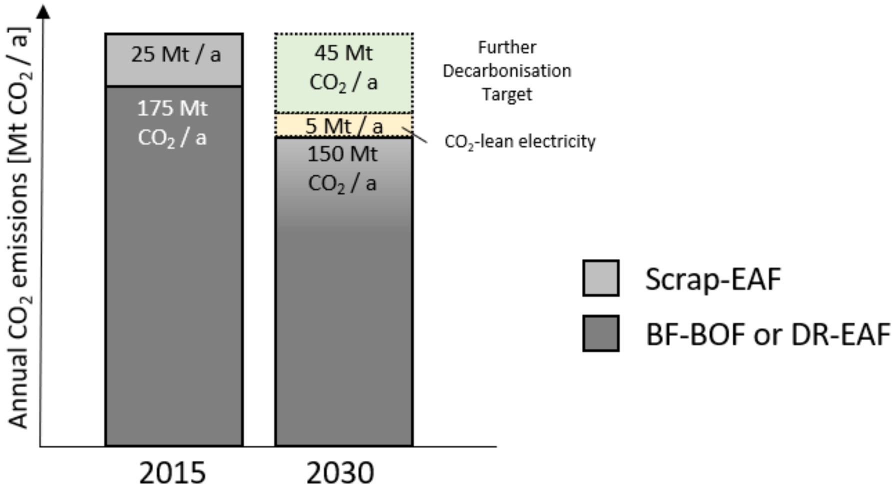
6.1 EU targets for 2030

The existing regulation at the start of this project was the 2030 climate and energy framework, in which the European Commission set the target of a 40% reduction in greenhouse gas emissions by 2030 compared to 1990 levels. This target was implemented in the EU Emissions Trading Systems (see section 3.4.2), the Efforts Sharing Regulation with member states’ emissions reduction targets and the LULUCF Regulation (European Commission, 2019c).

During this project, the European Commission stepped up its ambitions and proposed a target of a 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels in its “2030 Climate Target Plan” (European Commission, DG Climate Action, 2020). This target corresponds to roughly a 25% reduction in greenhouse gas emissions by 2030 compared to 2015 levels (European Commission, DG Climate Action, 2020). The pathway scenario assessments were based on these new 2030 CO_2 mitigation targets for the EU-27 iron and steel industry.

In 2015, 155 Mt of crude steel were produced in EU-27 member states (EUROFER, 2019b; UK Steel, 2019). A total 92 Mt of crude steel (59%) were produced on the primary steel production route (BF-BOF or DR-EAF), whereas 63 Mt of crude steel (41%) were produced in the secondary steel production route (EUROFER, 2019; UK Steel, 2019). Assuming average values of 1.9t CO_2 per ton of crude steel on the primary steel production route and 0.4t CO_2 per ton of crude steel in the secondary steel production route in 2015 Green /steel for Europe, 2021c), this leads to a total CO_2 emission of 200 Mt CO_2 in 2015 by the EU-27 iron and steel industry: 175 Mt originates from the primary steel production route and 25 Mt stem from the secondary steel production route. A 25% cut as targeted by the European Commission by 2030 (European Commission, 2020d) translates to a CO_2 mitigation of 50 Mt annually. Thus, the 2030 target for the EU-27 iron and steel industry is 150 Mt CO_2 annually. These values are visualised in Figure 40.

Figure 40: Visualisation of EU 2030 Targets



Source: Authors' composition based on European Commission's "Stepping up Europe's 2030 climate ambition: Investing in a climate-neutral future for the benefit of our people", European Commission, Brussels, 2020.

As the specific CO_2 emissions of the secondary steel producing route account for a high share of scope 2 emissions due to the consumption of electrical energy from the grid, these are significantly influenced by the CO_2 intensity of electricity production. A decrease of the CO_2 load from 317 g CO_2 / kWh electricity in 2015 (see section 2.1) to 200 g CO_2 / kWh electricity in 2030 would lead to an annual CO_2 mitigation of 5 Mt in the secondary steel production route. This share is visualised by the yellow box in

. To reach the targeted 55% cuts of greenhouse gas emissions proposed by the European Commission, an additional CO_2 mitigation of 45 Mt in CO_2 annual emissions is required by the EU-27 iron and steel industry. This is indicated by the green box in

.

This targeted CO_2 mitigation can be achieved by an unlimited number of combinations of decarbonisation technology implementations throughout the EU-27 iron and steel industry. The following pathway scenarios show three plausible pathways for decarbonisation of the EU-27 iron and steel industry by 2030. These scenarios are evaluated against the presented target value of 150 Mt of annual CO_2 emission.

6.2 Pathway 2030 scenario "Mixed Implementation"

This pathway scenario considers only technology routes which are assumed to be technically available on a full industrial scale by 2030 (see Table 11). The scenario reflects a mixed implementation of the technology routes with the most plausible share of production. The distribution of these technology routes was modelled on national and regional framework conditions as described above and furthermore take into account the investment cycles (see section 5.1) of the primary steel production plants. In the following subsection the basis for the scenario assumptions is explained. In the subsequent subsection the results of the pathway scenario are shown.

6.2.1 Basis for scenario assumptions

Based on the 2015 iron and steel production in EU-27 countries, 87.5% of CO_2 emissions are related to the primary steel production route (see Figure 38). This led to the basic assumption that the most significant part of CO_2 mitigation by 2030 will be covered by the share of primary steel production. Thus, primary steel production is the focus in this pathway scenario. Four available technology routes for primary steel production with high CO_2 mitigation potentials of up to 90% were identified in the technology assessment and roadmapping (Green Steel for Europe, 2021c).These technology routes were summarised in Table 11.

In developing a pathway scenario, plausible shares of production of the decarbonisation technology routes along the primary steel production capacities had to be identified. Based on the assessed national and regional framework conditions (see chapters 2 and 3), it was expected that different technology routes could be preferred in the various EU-27 regions. Thus, national and regional framework conditions can be used to estimate the preferred technology route which could be implemented in which region (and at which site) in the EU-27.

In addition, site-specific framework conditions such as investment cycles define the timing of technology route implementations (see section 5.1). Against this background, only a share of EU-27 production capacities is facing investment decisions. This share can be interpreted as possibly available for a substantial technology switch before 2030.

For the modelling of the "Mixed implementation" pathway scenario, both the national and regional framework conditions and the timing of investment cycles were utilised in a two-step approach:

In the first step, the framework conditions were utilised to estimate the technology route(s) which may have favourable conditions in the different regional areas throughout Europe. Based on the production capacities of existing primary steel production sites, the areas can be assigned to production capacities.

In a second step, the investment cycles were used to define the share of production capacities that are subject to a possible implementation of decarbonisation technologies. The combination of both steps allowed us to estimate a plausible share of the production of technology routes along the EU-27 primary steel production capacities by 2030.

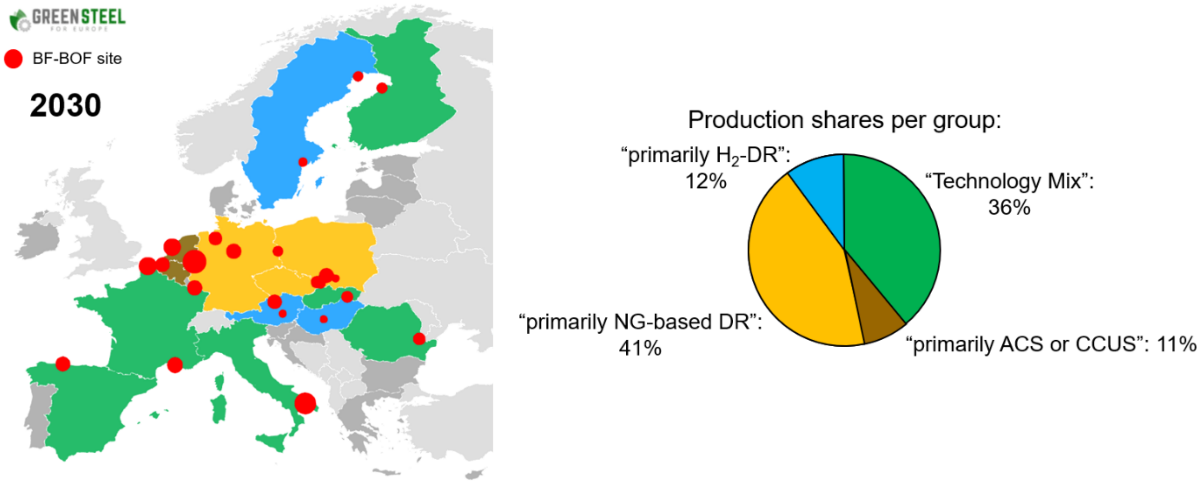
Based on the national and regional framework conditions, the EU-27 member states with primary steel production plants were categorised into four groups:

- Framework conditions favouring the utilisation of alternative carbon sources (Route 1A) or CCUS (Route 1B) by 2030
- Framework conditions favouring H_2-DR (Route 2B) by 2030
- Framework conditions favouring NG-based DR (Route 2A) by 2030
- Framework conditions indicating a diverse technology mix by 2030

A graphical representation of this categorisation is given in the left side of Figure 41. In this map, the primary steel production sites are indicated as red dots with their size directly correlated to their production capacities. The four groups of national framework conditions are displayed in brown, blue, yellow or green colour.

The first group of framework conditions favouring the utilisation of alternative carbon sources (Route 1A) and/or CCUS (Route 1B) by 2030 is displayed in brown and comprises of Belgium and the Netherlands. These countries account for 11% of primary steel production capacity in the EU-27.

Figure 41: Framework conditions grouping for "Mixed implementation" scenario



Source: Compiled by the authors.

Framework conditions favouring H_2-DR are displayed in blue and are assumed to be present in Austria, Sweden and Hungary. This group reflects 12% of primary steel production capacity in EU-27. In Czechia, Germany and Poland framework conditions preferably enabling NG-based and H_2-enriched Direct Reduction were identified. These countries account for 41% of primary steel production capacities in the EU-27.

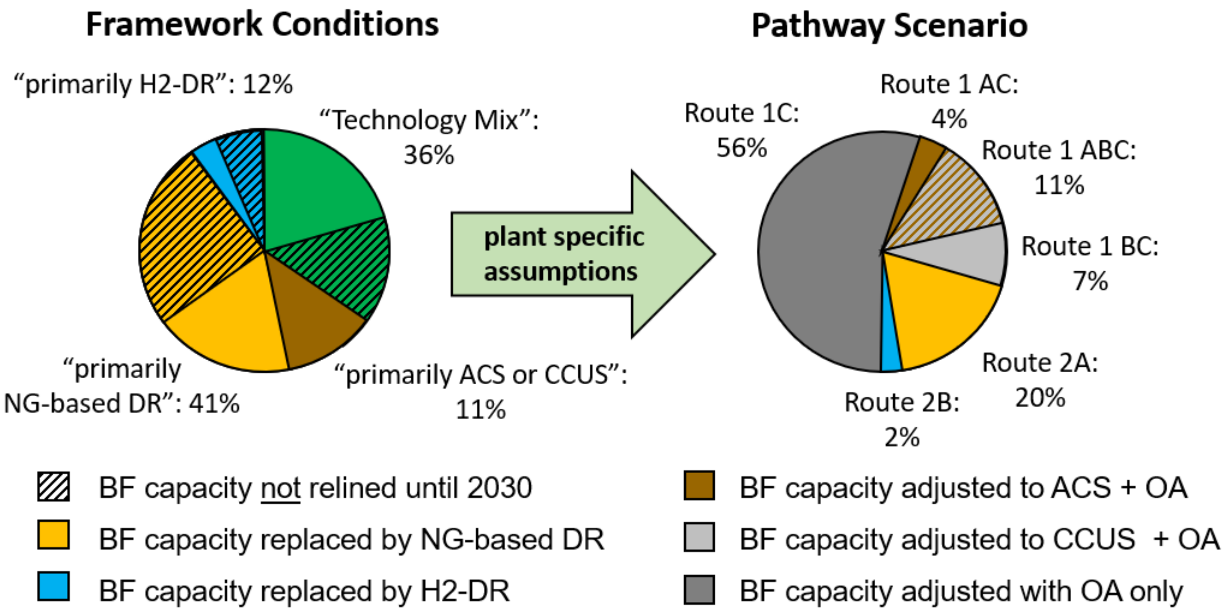
The remaining countries (Finland, France, Italy, Romania, Slovakia, Spain) reflect 36% of primary steel production capacities in the EU-27. For this share, a mixed implementation of all available technology routes (see Table 11) was assumed.

As a second step, the investment cycles of primary steel production plants were analysed, to deduce which sites might generally change their technology route (due to upcoming investment need). During this project's stakeholder consultation activities, the steel producers confirmed that the relining dates of their blast furnaces play an important role in terms of their investment cycles. (Green Steel, 2021b). The consultations revealed that blast furnace journeys usually differ between 15-25 years depending on individual conditions (Green Steel, 2021b). A study conducted by Agora Energiewende regarding the transition towards a climate-neutral industry in the EU-27 (Joas et al., 2019) assumes an average blast furnace journey of 20 years.

Based on this simplified assumption and on publications of past blast furnace relinings, the share of capacities facing blast furnace relinings in the EU-27 until 2030 were estimated. Thus, it was assumed that 46% of primary steel production capacity in the EU-27 will probably not face major technology switches by 2030 based on their investment cycles. The other 54% (i.e. with upcoming BF relinings) were assigned to the four groups of national or regional framework conditions. This is a very ambitious approach since, in fact, just 29-36% of the BF relinings are expected between 2025 and 2030 and any change of production route before 2025 seems impossible considering the long lead times of such large investments.

The two-step approach to estimate the general share of technologies for 2030 is visualised by the left diagram in Figure 42. This left diagram combines the results referring to framework conditions as shown in Figure 41 with the investment cycles: It shows that 46% of primary production capacities in the EU-27 would not be subject to substantial technology switches by 2030 according to the general analysis. This 46% share, depicted as shaded areas in the left diagram, is assumed to implement incremental optimisation measures on the existing BF-BOF route (Route 1C). The other share of 54% (i.e. with BF relining until 2030) faces different conditions as indicated by the colours also used in Figure 41 and is distributed in the further procedure to all options available in full industrial scale by 2030 (see Table 11).

Figure 42: Conversion of National Framework Conditions and Relined Capacities into "Mixed implementation" scenario



Source: Compiled by the authors.

The general analysis (shown in the left diagram) was completed by an individual assessment of all existing primary steel production sites in the EU-27: The most plausible solution was selected for each site as the best result considering the general analysis of framework conditions, the results from stakeholder consultations and the knowledge of the authors about individual conditions, investment cycles and preferences of the sites. The resulting shares of technologies throughout the EU-27 primary steel production are visualised in the right diagram of Figure 42.

A share of 56% stays on the BF-BOF route and implements incremental process optimisation measures (Route 1C). A share of 22% of primary steel production capacities is expected to also still be based on the BF-BOF route but to be significantly optimised by utilisation of alternative carbon sources (Route 1A) and/or CCUS (Route 1B). It is expected that this share is additionally subject to incremental process optimisation as reflected by Route 1C. This share of 22% is further differentiated into Routes 1AC/AB/ABC as follows:

- Route 1AC 17% (corresponding to 4% of total primary steel production): utilising alternative carbon sources without additional CCUS implementation.

- Route 1ABC 52% (corresponding to 11% of total primary steel production): utilising both, alternative carbon sources and CCUS measures.
- Route 1BC 31% (corresponding to 7% of total primary steel production): implementing CCUS measures without an additional implementation of alternative carbon sources.

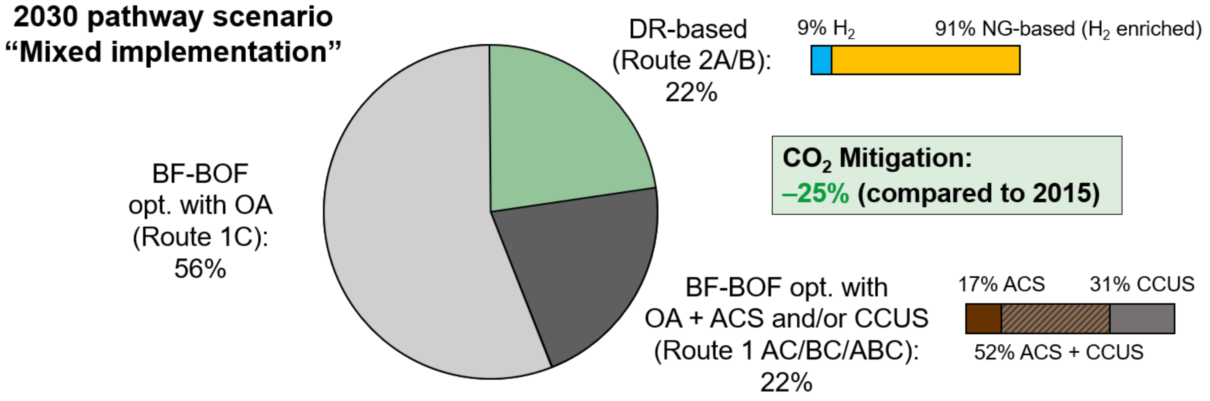
A share of 22% of primary production capacities would face a technology switch towards the direct reduction-based routes 2A (20%) and 2B (2%).

The results of the scenario “Mixed implementation” are further summarised and discussed in the following section.

6.2.2 Pathway scenario

The pathway scenario “Mixed implementation” presents an ambitious scenario with the most plausible share of decarbonisation technologies in 2030. It is based on the implementation of the decarbonisation technologies identified as available in full industrial scale by 2030 (see Table 11). The distribution of these technologies is estimated based on general national and regional framework conditions and on individual investment cycles, conditions and preference, as explained above. It was assumed that the total annual steel production capacity remains constant. The resulting technological distribution by 2030 according to this pathway scenario is visualised in Figure 43.

Figure 43: Pathway scenario “Mixed implementation"



Source: Compiled by the authors.

In this pathway scenario, the production capacities operating the BF-BOF route with incremental process optimisations (Route 1C) account for 56%. A further share of 22% of primary steel production capacities also still based on the BF-BOF route but is significantly optimised by utilisation of alternative carbon sources (Route 1A) and/or CCUS (Route 1B) and incremental process optimisations (Route 1C).

Altogether, 22% of primary production capacities would face a technology switch towards the direct reduction-based routes 2A and 2B (NG-DR / H2-DR). Routes 2A and 2B are combined and visualised as one light green area since in industrial practice, a direct reduction with hydrogen enriched natural gas is assumed as the most plausible implementation in 2030 for most of the plants concerned. Overall, hydrogen enrichment is assumed as 9% referring to crude steel production (corresponding to 25% of volumetric gas usage).

Additionally, it was assumed that the total annual steel production capacity remains constant (compared to 2015). Based on these assumptions, the EU-27 target of 25% cuts in CO_2 emissions could be met. The emission would correspond to 131 Mt CO_2 /a for primary steel and the total emission to 175 Mt CO_2 /a.

However, it must be stressed that this scenario should be rated as quite ambitious with regard to the transformation of primary steel production: The transformation process needed to reach this scenario requires 44% of primary steel production capacities within the EU-27 to undergo a significant technology switch towards direct reduction, alternative carbon sources utilisation or CCUS measures.

A comparison with the investment cycles emphasises the high ambition of this share of 44% of primary steel production to be significantly adapted: Only a primary production capacity share of 54% is subject to upcoming investments (see section 6.2.1): Correspondingly, 81% of this share would have to be significantly adjusted.

Taking into account the significant lead times between the investment decision and implementation, most of the industrial implementation of such technologies by 2030 is expected to happen between 2025 and 2030. In this time frame, only a total primary production capacity share of 29-36% is expected to be subject to investment decisions.

Since the pathway scenario “Mixed implementation” assumes that 44% of primary production capacity will be significantly adjusted (i.e. to Routes 1 AB/AC/ABC or 2 A/B), not only does the relining of each of the blast furnaces between 2025 and 2030 need to be significantly adjusted, but further production shares need to be adjusted either before 2025 or investment cycles need to be shortened.

Policy options to incentivise earlier investment decisions are discussed in WP3 and are presented in the deliverable reports D3.2 and D3.3. Considering the extremely high degree of ambition of the “Mixed implementation scenario” a second scenario assuming a slower implementation of decarbonisation technologies was developed.

6.3 Pathway 2030 scenario “Delayed implementation”

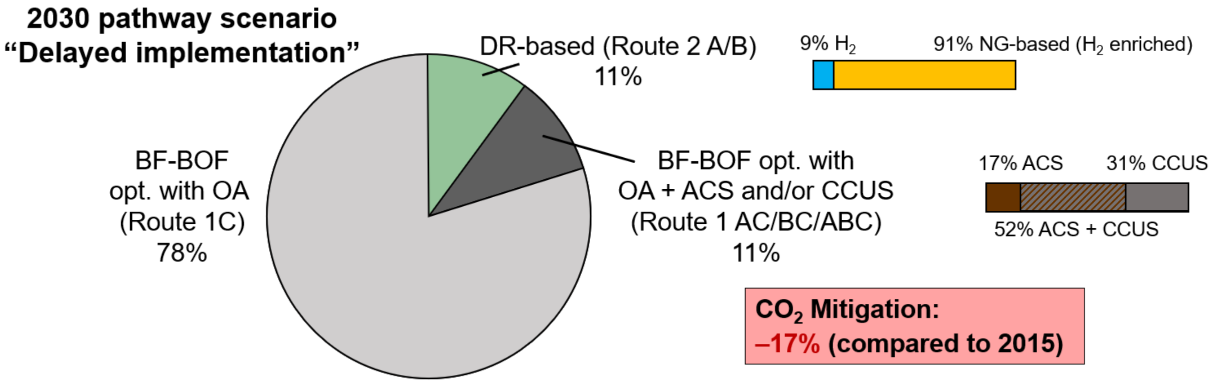
The pathway scenario “Delayed implementation” is based on the pathway scenario “Mixed implementation” described above. It also takes into account the national and regional framework conditions for estimating a plausible distribution of decarbonisation technologies by 2030, but also considers strong limitations regarding significant technology switches.

This pathway scenario is based on the assumption that the share of primary production capacities significantly adapted according to the scenario “Mixed implementation” (i.e. shifted towards direct reduction (Route 2 A/B), alternative carbon source and/or CCUS utilisation (Route 1 AC/BC/ABC)) only reaches 50% by 2030. This may be rated as an assumption with a more realistic consistency to the investments cycles discussed in the last section of this chapter.

It is intended to show the consequences of CO_2 mitigation targets if half of the required significant adjustments are delayed until after 2030, as could be caused by hesitant investment decisions (due to e.g. unclear future framework conditions) or limitations due to investment cycles (see section

6.2.1). As in the first scenario, a constant primary steel production capacity compared to 2015 was assumed. The 2030 pathway scenario “Delayed implementation” results are visualised in Figure 44.

Figure 44: Pathway scenario "Delayed implementation"



Source: Compiled by the authors.

In this 2030 scenario “Delayed implementation” 78% of production capacities will still be operated via the conventional BF-BOF Route and will be subject to incremental BF-BOF optimisation measures (Route 1C) only.

Altogether 22% of primary steel production capacities are significantly adapted either using alternative carbon source or CCUS utilisation (Route 1 AC/BC/ABC) or shifting to direct reduction (Route 2 A/B).

- 11% of total primary steel production would be operated via the BF-BOF route with alternative carbon source utilisation (Route 1AC) and/or CCUS measures (Route 1BC). This share comprises to 52% of combined alternative carbon source and CCUS utilisation (Route 1ABC), 17% of this share comprise to alternative carbon source utilisation (Route 1AC) and 31% to CCUS measures (Route 1BC).
- 11% would be covered by hydrogen enriched direct reduction technologies. Overall, the hydrogen enrichment is assumed as 9% referring to crude steel production (corresponding to 25% referring to volumetric gas usage).

Overall, such a technology distribution along the primary steel production capacities within the EU-27 would lead to cuts of 17% in CO_2 emissions caused by the iron and steel industry. The set target of 25% cuts would be missed by eight percentage points in this scenario.

The CO_2 emissions caused by primary steel production would decrease to 145 Mt annually for a constant crude steel production of 92 Mt per year. This correlates to an average CO_2 intensity for primary steel production of 1580 kg CO_2 per ton of crude steel. The total emission for primary and secondary steel production would correspond to 189 Mt CO_2 /a, thus, missing the target by 14 Mt CO_2 /a.

Several solutions can be discussed to close this gap to the set EU-27 emission targets of 14 Mt CO_2 /a which would still be based on the “Delayed implementation” scenario. Main examples are:

a) Significantly decreasing the CO_2 emissions in secondary steel production by extensive use of renewable power. This can be rated a preferable option since no adaption of steel production sites needing costly investments and involving technical risks is necessary.

b) Increasing the hydrogen enrichment within direct reduction plants (see also next chapter). This can also be rated a preferable option since the hitherto assumed degree of hydrogen enrichment (9% referring to crude steel production or 25% referring to volumetric gas usage) is rather low compared to know enrichment targets already called out by DR plant suppliers.

c) Decreasing energy demand and emissions by increased use of scrap. To some degree an increased use of scrap could be realised in the BF-BOF route, but this is limited by technical reasons. Another alternative would be to replace 11 Mt (12%) of annual steel production from primary steel production with the secondary steel production route. Both approaches are however limited by the availability of scrap with sufficient quality.

d) Another option is that primary steel production sites are shut down. This is a quite concrete risk for several sites if an investment need is coming up and the analysis leads to the conclusion that no sustainable solution for the corresponding site can be found due to the combination of economic and ecologic pressure and uncertainties within the next decades. (Green Steel for Europe, 2021a; Green Steel for Europe 2021b) The EU target would be met in this scenario if the primary steel production throughout the EU-27 is decreased by 9.2% (8.5 Mt annual production). However, due to the most probable consequence of carbon leakage this option can be rated as a worst-case scenario for the European steel industry, for the European economy and for the global climate.

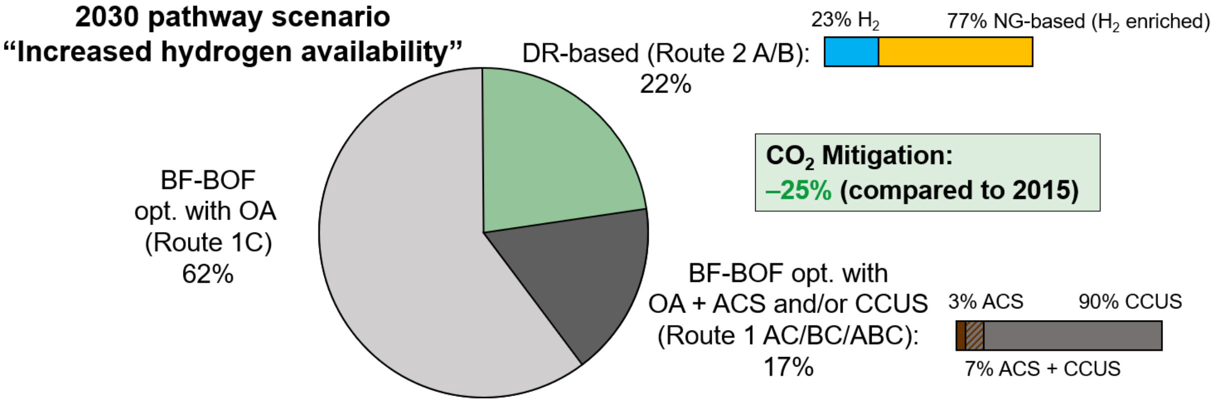
6.4 Pathway 2030 scenario "Increased Hydrogen Availability"

As a variation to the first 2030 scenario considering "Mixed Implementation" of technologies (see 6.2), the scenario "Increased Hydrogen Availability" was developed. This is based on the principal national framework condition analysis as for the previous scenarios but assumes increased hydrogen availability compared to the EU targets of 80 GW renewable hydrogen production by 2030 (European Commission, 2020a). The amounts of (renewably produced) hydrogen available to the iron and steel industry are not clearly defined yet. About 10% of industrial primary energy consumption was due to the iron and steel industry in OECD countries in 2012. (U.S. Energy Information Administration, 2016) A similar rate for renewable hydrogen would lead to 8 GW renewable hydrogen production to the EU-27 iron and steel industry by 2030. This value corresponds to a demand of approximately 0.5 million tons of renewable hydrogen annually available to the iron and steel industry in the EU-27. For this pathway scenario "Increased Hydrogen Availability" an additional availability of 0.2 million tons renewable hydrogen (+25%) was assumed to be utilised by direct reduction processes.

Additionally, the availability of alternative carbon sources to the EU-27 iron and steel industry is not clear. Its assessment is described in detail in chapter 2.6, but as other sectors are also facing a significant transformation due to the decarbonisation challenge, its availability to economical feasible conditions might become limited. Against this background, the pathway scenario "Increased Hydrogen Availability" shows an alternative pathway to reaching EU-27 targets and is based on more hydrogen utilisation and less alternative carbon source utilisation.

To take into account a higher hydrogen utilisation in BF-BOF optimisation measures, the CO_2 mitigation of Route 1C (BF-BOF with other incremental actions) was adjusted from 8% to 10%. As in the other pathway scenarios, the primary steel production capacity was assumed to stay at 92 Mt annually, similar to 2015. The 2030 pathway scenario “Delayed implementation” results are visualised in Figure 45.

Figure 45: Pathway 2030 scenario "Increased hydrogen availability"



Source: Compiled by the authors.

In this pathway scenario, 22% of primary steel production capacities are shifted towards the direct reduction route (Route 2 A/B). Overall, the hydrogen enrichment is assumed as 23% referring to crude steel production (corresponding to 55% referring to volumetric gas usage).

An additional 17% of primary steel production capacities are shifted towards significant utilisation of alternative carbon sources, CCUS measures or their combinations (Route 1 AC/BC/ABC). Only 3% of this share is based on alternative carbon source utilisation (Route 1 AC) in this case, 90% use CCUS implementations (Route 1 BC) and additional 7% use both, alternative carbon sources and CCUS measures (Route 1 ABC).

Altogether 62% of primary steel production capacities are subject to incremental BF-BOF optimisation measures (Route 1C) only. The scenario “Increased hydrogen availability” would meet the EU targets in terms of a 25% cut in CO_2 emissions by 2030 based on 2015 levels.

From a strategic point of view this scenario “Increased hydrogen availability” can be rated as an attractive option since it avoids unrealistic assumptions: The demand for alternative carbon sources is lowered and the share of BF-BOF plants which need significant short-term investments in CCUS and/or ACS technologies is also decreased. Recent trends in research activities of steel producing companies as well as the stakeholder consultations (GreenSteel, 2021b) confirmed an increasing bias towards the direct reduction route. The CCUS and ACS technologies still play an important role but may be considered as intermediate technologies if combined with the BF-BOF route (considering the long-term focus of steel industry investment cycles) and Routes 1A/B/C hardly enable the same degree of CO_2 mitigation as does, for example, hydrogen-based direct reduction (refer to chapter 4 and Table 11).

In summary, the technology distribution along the primary steel production capacities in the EU-27 assumed within the 2030 scenario “Increased hydrogen availability” seems to reflect well the investment conditions in the steel industry. However, increased demands for hydrogen (at sustainable costs!) and hydrogen related infrastructure need to be considered.

7 Decarbonisation Pathways 2050

The 2030 decarbonisation pathways presented above are further complemented by 2050 Decarbonisation Pathways to also respect the long-term perspective of EU decarbonisation measures. The 2050 pathway scenarios build on the 2030 “Mixed implementation” pathway scenarios and show further plausible distributions of decarbonisation technologies in the long-term time frame until 2050.

The decarbonisation technologies and the corresponding assumptions used for the decarbonisation pathway scenarios for 2050 are summarised in Table 12 on page 69. Basically, these technologies can be categorised into two groups: Technologies that were already assumed for implementation by 2030 (with further improvements in CO_2 mitigation) and other breakthrough technologies that might become available by 2050. The first group consists of Route 1 and Route 2 and the second group of Route 3 (IBRSR + CCUS) and Route 4 (other technologies). Due to the currently low maturity, it cannot be estimated if the technologies related to Route 3 and Route 4 will become technically and economically viable options for industrial implementation; the 2050 decarbonisation pathways developed in “Green Steel for Europe” differ especially in that regard. A first 2050 pathways scenario considers no additional availability of other breakthrough technologies and is based on Route 1 and 2 options only. This scenario “Without other technologies” is described in the following section 7.2. An alternative scenario “Other technologies successful” is presented in section 7.3. A third scenario “Increased Scrap Availability” assumes further progress towards a circular economy and an increased replacement of primary steel production by secondary steel production and is presented in section 7.4.

7.1 EU targets for 2050

Within its “2050 long-term strategy” the European Commission set the goal of climate neutrality by 2050 (European Commission, 2020e). The term “climate neutrality” refers to net-zero emissions of greenhouse gases (EC, Kirby, 2008). This is to be achieved by decreasing greenhouse gas emissions as much as possible, while using carbon offsets to neutralise the remaining emissions (Kirby, 2008). In that context, the initial target of 80-95% cuts in greenhouse gas emissions by 2050 set by the European Commission in 2009 was taken as a reference for greenhouse gas emission reductions (European commission, 2018). EUROFER’s “Low Carbon Roadmap” published in 2019, describes the ambitions of the EU-27 iron and steel industry to meet cuts of 80-95% (EUROFER, 2019).

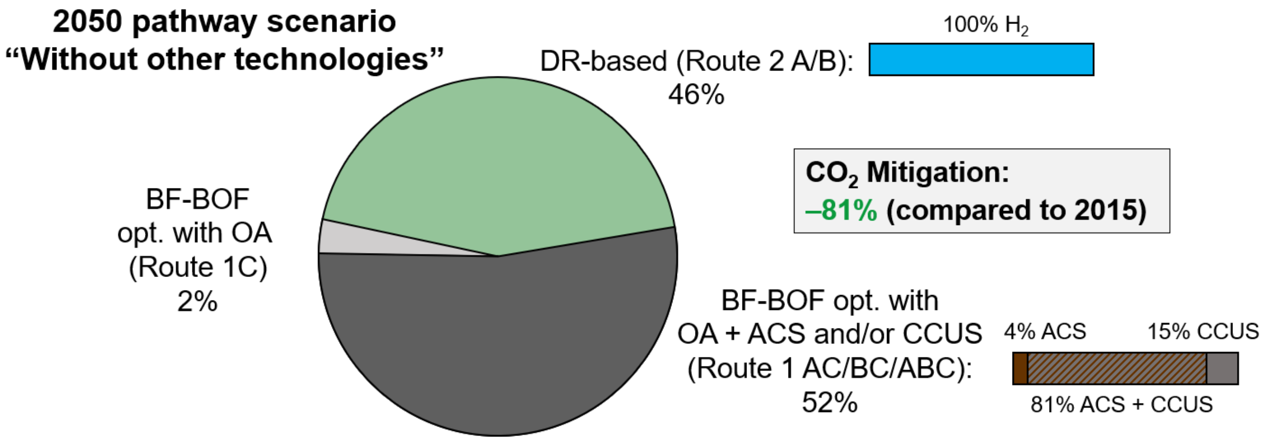
Based on the technology assessment and roadmapping performed within “Green Steel for Europe” (Deliverable 1.2), the CO_2 mitigation potential of some breakthrough decarbonisation technologies are estimated to be up to 95% (see Table 12). However, in the long-term, further combinations of technologies (e.g. hydrogen direct reduction with CCUS and/or alternative carbon sources) may also enable complete carbon neutral steel production or even negative emissions.

7.2 Pathway 2050 scenario “Without other technologies”

The pathway 2050 scenario “without other technologies” is based on an industrial implementation of the technology mix assumed for 2030 (see section 6.2) but after complete roll-out of technologies in the EU-27 steel industry. It assumes a constant annual steel production of 155 Mt in the EU-27 (compared to 2015) and a constant distribution of production between primary (59%) and secondary (41%) steel production, thus, no significant increase in secondary steel production was assumed for this scenario.

Based on the assessment of decarbonisation technologies with the Green Steel for Europe project (Deliverable 1.2) further development of decarbonisation technologies from 2030 to 2050 can be expected. Thus, increased CO_2 mitigation values were considered for 2050. These are summarised in Table 12 in section 5.2.2. Additionally, there are no further limitations regarding investment cycles, as each part of the EU-27 steel production capacity is expected to face the end of an investment cycle before 2050 (see section 5.1). The resulting technological distribution by 2050 according to the pathway scenario “without other technologies” is visualised in Figure 46.

Figure 46: Pathway 2050 scenario "Without other technologies"



Source: Compiled by the authors.

In this scenario, primary steel production is almost completely shifted either towards direct reduction (Route 2) or towards significant modifications of the BF-BOF route (Routes 1 AC, 1 BC, 1 ABC).

For the scenario development, it was assumed that by 2050 the direct production based primary steel production will be entirely based on hydrogen with a CO_2 mitigation of 95% compared to 2015 levels. This leads to a primary steel production capacity share of 46% transformed to direct reduction by 2050.

A share of 52% is optimised by the significant use of alternative carbon sources and/or CCUS measures together with incremental process optimisation (Route 1 AC/BC/ABC). Altogether, 81% of this share, so 42% of overall primary steel production capacities, are calculated to be utilising both alternative carbon sources and CCUS (Route 1 ABC), which are connected to 75% CO_2 mitigation (see Table 12); 15% of this share, so 8% of overall primary steel production capacities, are expected to use CCUS measures without alternative carbon source implementation (Route 1

BC) with 66% CO_2 mitigation for its implemented capacities (see Table 12). The remaining 4% of this share, so 2% of primary steel production capacities, are estimated for alternative carbon source utilisation without subsequent CCUS measures (Route 1 AC). This route is assumed to have 36% CO_2 mitigation by 2050 (see Table 12). A small share of 2% overall primary steel production capacities is subject to incremental process optimisation measures only (Route 1C). This route is assumed to be correlated to 15% CO_2 mitigation by 2050 (see Table 12).

Overall, such a technology distribution together with the assumed route-specific CO_2 mitigation values leads to an overall CO_2 mitigation of 81% in EU-27 primary steel production by 2050. Thus, it is in line with the potential CO_2 mitigation as stated in, e.g. “Low Carbon Roadmap” published by EUROFER (2019).

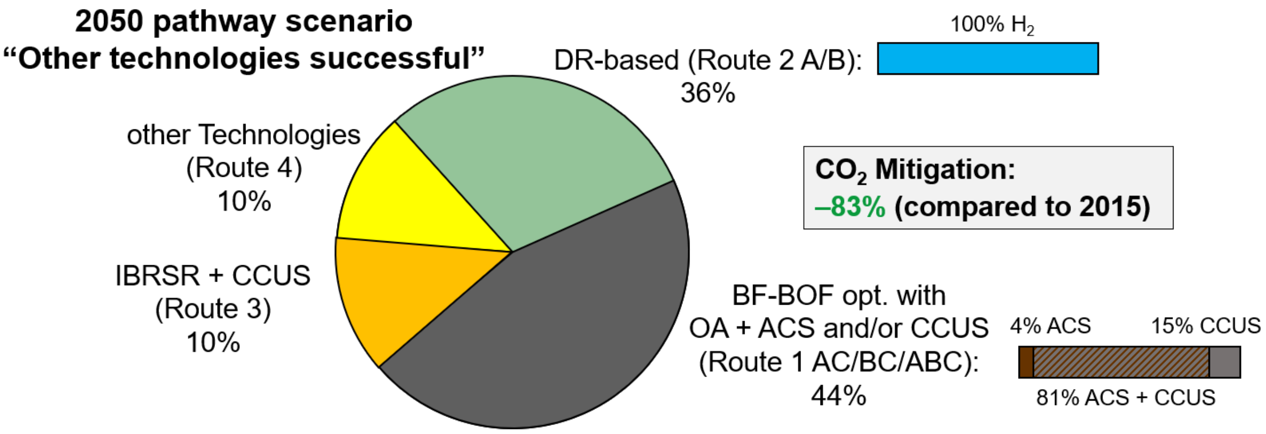
To summarise, according to this 2050 “Without other technologies” scenario almost the entire primary steel production is subject to a transformation process by 2050, resulting in substantial CO_2 mitigation. Secondary steel production can be assumed to have even lower CO_2 emissions in 2050 assuming the use of carbon neutral power supply and implementation of decarbonisation technologies such as, e.g. hydrogen-based burner. This scenario can be rated as conservative since further significant CO_2 mitigation is generally possible by further combinations of technologies such as CCUS and use of alternative carbon sources with hydrogen-based direct reduction or secondary steel production. Thus, reaching the 2050 target of climate-neutral steel production becomes possible.

7.3 Pathway 2050 scenario “Other technologies successful”

The previously presented pathway scenario “Without other technologies” was based on a continued implementation of decarbonisation technologies already expected to be available by 2030 and did not take into account the development and implementation of other decarbonisation technologies. Against this background, this pathway scenario “Other technologies successful” was developed. It is also based on a technology implementation according to the pathway scenario “Mixed implementation” by 2030, followed by further deployment of BF-BOF optimisation measures (Route 1 AC/BC/ABC) and DR-based production (Route 2). In addition, for this scenario the implementation of smelting reduction technology as, e.g. IBRSR coupled with CCUS (Route 3) and potential other technologies as e.g. iron ore electrolysis (Route 4) is assumed. Again, a constant annual steel production of 155 Mt with a constant distribution of 59% primary and 41% secondary steel production was assumed. The results of the pathway scenario “Other technologies successful” are visualised in Figure 47.

This scenario represents a possible technology distribution along EU-27 primary steel production by 2050 which is based on multiple pillars: First, in this scenario, 36% of primary production capacities are shifted towards direct reduction by 2050. Since extensive hydrogen availability is expected by 2050, this DR-based steel production is based on 100% hydrogen utilisation connected with a CO_2 mitigation value of 95% compared to 2015 levels.

Figure 47: Pathway 2050 scenario "Other technologies successful"



Source: Compiled by the authors.

Of EU-27 primary steel production capacities, 44% are assumed to use increased alternative carbon source and/or CCUS. The distribution along this share was assumed to be in line with the pathway scenario "Without other technologies" previously presented: 81% of this share is calculated to be using both alternative carbon sources and CCUS measures along with incremental process optimisation (Route 1 ABC); 15% of this share reflects CCUS measures without specific alternative carbon source utilisation (Route 1 BC), whereas 4% of this share are estimated to use alternative carbon sources without CCUS implementation (Route 1 AC).

In this pathway scenario these two technology routes are complemented with other technologies that are expected to be successfully developed and economically viable by 2050. A share of 10% primary steel production capacities was assumed to be replaced by IBRSR + CCUS technology (Route 3). This route is correlated to 80% CO_2 mitigation as identified in this project's technology assessment (Deliverable 1.2) and summarised in Table 12. An additional share of 10% primary steel production capacity is assumed to be shifted towards other decarbonisation technologies to be developed and deployed by 2050. As one example of such a technology, iron ore electrolysis (see section 4.1.7) was considered. These technologies are calculated on a basis of 95% CO_2 mitigation potential (see Table 12).

Overall, the 2050 scenario "Other technologies successful" results in 81% CO_2 mitigation compared to 2015 levels. This agrees with the potential CO_2 mitigation as presented in the "Low Carbon Roadmap" by EUROFER (2019). As there is a high degree of uncertainty regarding the national and regional framework conditions in 2050, this scenario can be rated as reflecting a situation in which the framework conditions significantly differ throughout the EU-27 and different new breakthrough decarbonisation technologies are successfully implemented in industrial production by 2050.

7.4 Pathway 2050 scenario "Increased Scrap Availability"

The 2050 scenarios described before were based on the assumption that scrap availability is limited, especially in higher quality classes (see section 2.8). As scrap availability is subject to different framework conditions, its availability in 2050 can only be estimated with high uncertainty.

The scrap availability in 2050 will depend not only on scrap production and on scrap trade balances but also on progress in circular economy efforts like scrap sorting and processing. There are studies that expect an increase in scrap availability. Xylia et al. estimate a share of more than 50% secondary steel production by 2050 (Xylia et al., 2017).

Beyond the theoretical scrap availability, the costs of the required scrap qualities must also be competitive to enable this scenario. However, the stakeholder consultations carried out within this project (Deliverable 1.6) revealed that the circular economy as well as decarbonisation are becoming increasingly important for many customers of the steel industry. Thus, premium prices will probably be acceptable to some degree, in particular regarding scrap.

As secondary steel production via the Scrap-EAF route is related to a high CO_2 mitigation potential, this production route is highly relevant to the decarbonisation pathway scenarios formulated. Additionally, the Scrap-EAF route offers a high degree of electrification and thus high potential for sector coupling between the energy and industry sectors.

For the “Increased Scrap Availability” pathway scenario, a constant annual steel production in the EU-27 of 155 Mt compared to 2015 was again assumed. But in this scenario, a 50% production share of secondary steel production via the Scrap-EAF route was assumed. This translates to 77.5 Mt in annual steel production by primary and secondary steel production routes each. This corresponds to a shift of 14.5 Mtof annual steel production towards secondary steel production. This approach seems conservative with regard to the general availability of scrap (disregarding quality demands). Considering the numerous efforts towards a circular economy, the corresponding need to decrease the downgrading along the steel lifecycle may be rated at least as fairly achievable by 2050.

Secondary steel production by the Scrap-EAF route in 2050 was assumed to be utilising CO_2-free electricity leading to CO_2 mitigation of 95% compared to 2015 primary steel production.

Like the previously presented 2050 scenarios which differ regarding the estimated success of other breakthrough decarbonisation technologies, the pathway “Increased Scrap Availability” continues this approach. In the following section a scenario considering increased scrap availability without the implementation of technologies other than those t available by 2030 is presented. In the subsequent section the increased scrap availability in combination with the industrial implementation of other technologies (like smelting and electrolysis) is considered.

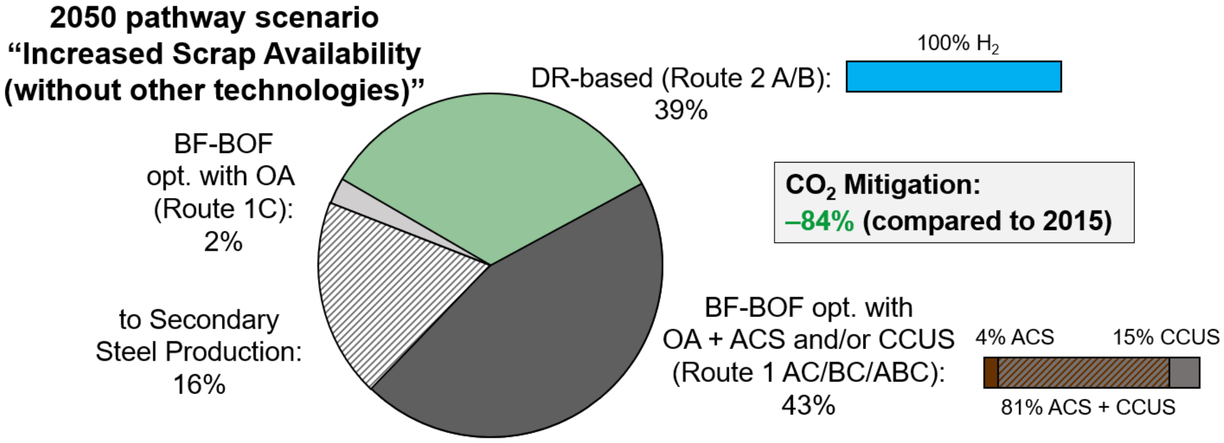
7.4.1 Increased scrap availability without other technologies

The results in scenario “Increased Scrap Availability” in combination with the assumptions met for the “Without other technologies” pathway (see section 7.2) are visualised in Figure 48.

The underlying condition of 50% annual steel production by primary and secondary route leads to 16% of primary steel production capacities being transferred towards secondary steel production. Due to the decrease of primary steel production in 2050 assumed within this scenario, the following percentages refer to the 2015 levels.

It is estimated that 39% of 2015 primary steel production capacities will be replaced by the direct reduction route. In this context it is assumed that there will be sufficient supply of green hydrogen, so that the entire DR-based production is based on 100% hydrogen utilisation.

Figure 48: Pathway 2050 scenario "Increased Scrap Availability (without other technologies)"



Source: Compiled by the authors.

It is estimated that 43% of 2015 primary steel production capacities will continue to be r based on optimised BF-BOF processes by alternative carbon source (Route 1A) and/or CCUS utilisation (Route 1B) together with incremental process optimisation measures (Route 1C). A total 81% of this share, so 35% of overall primary steel production capacities based on 2015 levels, combine both alternative carbon source and CCUS utilisation (Route 1ABC); 15% of this share, so 6% of overall primary production based on 2015 levels, rely on CCUS implementation without alternative carbon source utilisation (Route 1 BC). The remaining 4% of this share reflects alternative carbon source utilisation without CCUS measures (Route 1AC). An additional 2% of primary steel production capacities are assumed to implement incremental process optimisations (Route 1C) only.

Overall, this scenario leads to a CO_2 mitigation of 84% compared to 2015 levels. This value lies in the range of CO_2 mitigation envisaged for the EU-27 iron and steel industry by e.g. EUROFER's "Low Carbon Roadmap" (2019).

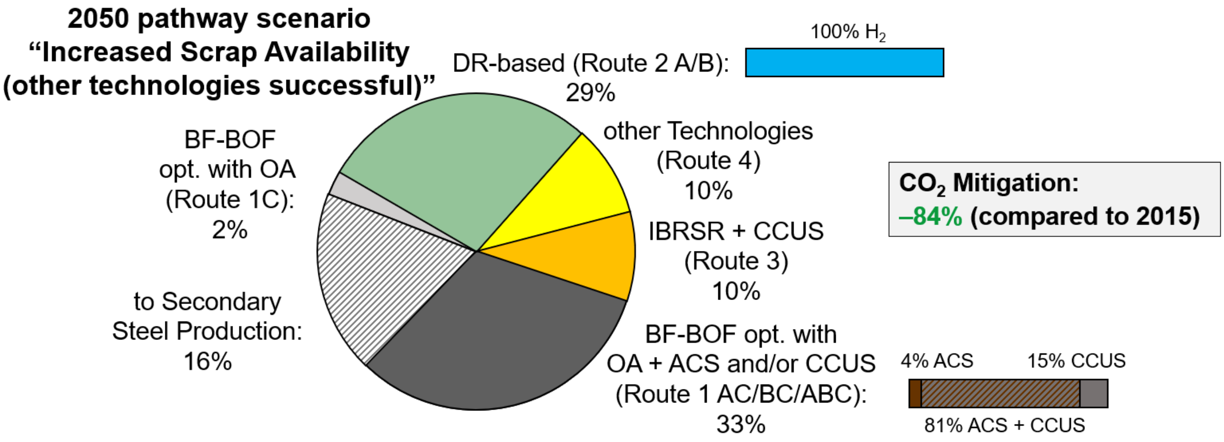
As a conservative alternative, the 80% CO_2 mitigation target could also be reached under this pathway's boundary conditions with another share of technologies, i.e. if 8% BF-BOF would remain with implementation of incremental process optimisation measures only (Route 1), 16% (unchanged) of 2015 primary steel production capacities would shift to secondary steel production, 39% (unchanged) to H_2-DR (Route 2 B) and 37% would use alternative carbon source and/or CCUS (Routes 1 AC/BC/ABC).

As a more ambitious alternative, CO_2 mitigation of 95% and more could be reached if plants no longer operate the BF-BOF route with incremental optimisations only, and if CCUS and the use of alternative carbon sources were also implemented also to Route 2 B and to secondary steel production.

7.4.2 Increased scrap availability with other technologies successful

In this section, the results of the "Increased Scrap Availability" 2050 scenario including Technology Routes 3 (IBRSR + CCUS) and 4 (other Technologies) are presented. The results are visualised in Figure 49.

Figure 49: Pathway 2050 scenario "Increased Scrap Availability (other technologies successful)"



Source: Compiled by the authors.

In this scenario, again a production share of 50% annual steel production by primary and secondary route is assumed leading to 16% of primary steel production capacities being transferred towards secondary steel production. Due to the decrease of primary steel production in 2050 assumed within this scenario, the following percentages refer to the 2015 levels.

The 2050 secondary steel production was assumed with a value of 95% CO_2 mitigation compared to 2015 primary steel production emission levels. This respects the decreasing CO_2 intensity for electricity production, among other optimisation measures.

It is assumed that 29% of 2015 primary steel production capacities are replaced by DR-based technology, which in 2050 is expected to be entirely based on hydrogen utilisation.

It is assumed that 10% of 2015 primary steel production capacities are replaced by IBRSR + CCUS (Route 3) and other technologies such as, e.g. Iron Ore Electrolysis (Route 4) each.

It is calculated that 33% of 2015 primary steel production capacities (39% based on 2050) are based on optimised BF-BOF processes by alternative carbon source (Route 1A) and/or CCUS utilisation (Route 1B) together with incremental process optimisation measures (Route 1C). The distribution within this share is similar to the previously presented pathway scenario "Increased Scrap Availability (without other technologies)". It is assumed that 2% of primary steel production have incremental process optimisation (Route 1C) only.

This scenario pathway leads to 84% CO_2 mitigation compared to 2015 primary steel production levels. In recent studies such as, e.g. EUROFER's "Low Carbon Roadmap" (2019), a range of 80-95% CO_2 mitigation for EU-27 steel production is envisaged. Thus, the calculated CO_2 mitigation value reflects this.

Like the previous scenario, more conservative and ambitious alternatives can be discussed:

If just the lower mitigation target of 80% must be reached a higher share of BF-BOF could remain with incremental process optimisation measures only. CO_2 mitigation of 95% and more could be reached if plants no longer operate the BF-BOF route with incremental optimisations only and if CCUS and the use of alternative carbon sources were implemented also to Route 2 B and to secondary steel production.

8 Concluding remarks

Decarbonisation of the steel industry will be complicated and lengthy to a degree that makes it comparable to an industrial revolution. It requires substantial changes to the most important supply and production chains. Several decarbonisation technology options need time to fully mature. Those achieving extensive CO_2 mitigation still need to be demonstrated in the industrial environment and to scale up to full industrial scale.

However, the dominating framework conditions are those needed for the industrial implementation of decarbonisation technologies: These include production costs, as well as the availability of resources and infrastructure. These conditions are currently far from being met for decarbonisation investments. When and to what extent they may change is not yet predictable. Consequently, the industrial decarbonisation pathways presented for 2030 and 2050 in this report must not be regarded as reliable forecasts, but rather as scenarios which can be expected for certain framework conditions.

Nevertheless, the approach chosen within the Green Steel for Europe project – to combine information from published roadmaps with stakeholder consultations – makes the scenarios as realistic and reliable as possible in light of the numerous uncertainties regarding the future changes of technical, economic and legislative framework conditions. To ensure swift European CO_2 mitigation as well as to maintain Europe’s cutting edge with respect to industrial decarbonisation, the 2030 scenarios should be the main focus.

The basic 2030 scenario “Mixed Implementation” defines a plausible share of the decarbonisation technology routes throughout the European steel industry in 2030 which enables a CO_2 mitigation of 25% compared to 2015. This scenario assumes that 44% of primary production capacity has to be significantly adjusted, 22% will still be based on the BF-BOF route, but 22% already assumes a swift transition to the direct reduction routes. However, as there are significant lead times between investment decisions and industrial implementation, this scenario must be rated as very ambitious. It would need a very fast and very effective change of framework conditions.

Thus, 2 scenarios were developed which use more realistic assumptions regarding the speed of major investments and industrial deployment of decarbonisation technologies. However, these scenarios require a much higher supply of renewable power and/or of hydrogen produced without CO_2 emission. Increased use of scrap would also decrease energy demand and emissions, but due to the shortage of high-quality scrap, this is rated as a rather long-term option.

A worst-case scenario, and one which should be mentioned, would see a shutdown of major European BF-BOF capacities. This would in fact enable the European CO_2 mitigation targets to be achieved but would have the significant economic, social, and environmental drawbacks of carbon leakage.

The current framework conditions are hindering industrial decarbonisation. Appropriate policy actions are urgently needed to create framework conditions which would foster industrial decarbonisation. There is considerable pressure to develop these policy actions due to the long investment cycles and the significant lead times, particularly if the 2030 targets are to be achieved. Actions to safeguard positive decarbonisation investment conditions in the short term and to safeguard the new investments in the long term have to be taken now.

To make the transformation process along the time scale transparent, a decarbonisation investment pathway is presented which differentiates three phases:

(1) First industrial demos,
(2) first roll-out according to local conditions and
(3) massive roll-out.

These phases are linked to different needs and priorities with respect to framework conditions and with respect to related policy actions. The many different policy options are discussed in deliverable D3.2 “Impact assessment report” of the Green Steel for Europe project. The different phases must be assessed in this context.

9 Bibliography

[1] J. F. King, “EU (27) Europe-demand-forecasts-20-Dec-20.xlsx,” [Online]. Available: Steelonthenet.com. [Accessed 21 January 2021].

[2] Polish Steel Association.

[3] J. F. King, “EU (27) steelpricedata and forecasta 2020-11-30.xlsx,” [Online]. Available: Steelonthenet.com. [Accessed 2021 January 21].

[4] European Union, “Study on the EU's list of Critical Raw Materials, Non-Critical Raw Materials Factsheets,” 2020.

[5] worldsteel ASSOCIATION, “Steel industry role in future development path,” in *Steel Industry Forum*, Phnom Penh, Cambodia, 2018.

[6] OECD DSTI Steel Committee, “Latest developments in steelmaking capacities,” *DSTISC,* 2 August 2019.

[7] S. Pauliuk, R. L. Milford, D. B. Müller and J. M. Allwood, “The Steel Scrap Age,” *Environ. Sci. Technol.,* vol. 47, p. 3448–3454, February 2013.

[8] A. Gauffin, “Improved mapping of steel recycling from an industrial perspective”.

[9] M. Xylia, S. Silveira, J. Duerinck and F. Meinke-Hubeny, “Worldwide Resource Efficient Steel Production,” in *Industrial Efficiency 2016: Going beyond energy efficiency to deliver savings, competitiveness and a circular economy*, 2016.

[10] “The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition,” Agora Energiewende, EMBER, 2021.

[11] T. Wyns, G. Khandekar and I. Robson, “Industrial value chain: A bridge towards a carbon neutral Europe,” Institute for European studies, 2018.

[12] C. Wouters, M. Buseman, J. von Tilburg, T. Berg, J. Cihlar, A. V. Lejarreta, J. Jens, A. Wang, D. Peters and K. van der Leun, “Market state and trends in renewable and low-carbon gases in Europe A Gas for Climate report,” Guidehouse, 2020.

[13] D. Peters, v. d. L. Kees, W. Terlouw, J. van Tiburg, T. Berg, M. Schimmel, I. van der Hoorn, M. Buseman, M. Staats, M. Schenkel and G. Ur Rehman Mir, “Gas decarbonisation pathways 2020-2050,” 2020.

[14] C. Kurrer, “The potential of hydrogen for decarbonising steel production,” European Parliamentary Research Service, 2020.

[15] A. Wang, K. van der Leun, D. Peters and M. Busemann, “European Hydrogen Backbone: How a dedicated hydrogen infrastructure can be created,” Guidehouse, 2020.

[16] G. Pawelec, M. Muron, J. Bracht, B. Bonnet-Cantalloube, A. Floristean and N. Brahy, “Hydrogen Europe Clean Hydrogen Monitor 2020,” Hydrogen Europe.

[17] G. Kakoulaki, I. Kougias, N. Taylor, F. Dolci, J. Moya and A. Jäger-Waldau, “Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables,” *Energy Conversion and Management 2282,* 2020.

[18] M. Avarado, “Methanol Industry Overview,” IHS Markit, 2017.

[19] CarbonNext, “Deliverable 2.1: Report on fully integrated and intensified value chain concepts for process selection,” 2017.

[20] S. Holloway, C. Rochelle, K. Bateman, J. Pearce, H. Baily and R. Metcalfe, “The underground disposal of carbon dioxide : final report,” British Geological Survey, Nottingham, 1996.

[21] N. P. Christensen and S. Holloway, “Geological Storage of CO2 from Combustion of Fossil Fuel - Summary Report,” 2003.

[22] P. Scholtz, G. Falus, G. Georgiev, B. Saftic, B. Goricnik, V. Hladik, M. Larsen, N. P. Christensen, M. Bentham, N. Smith, A. Wojcicki, C. S. Sava, J. Kotulova, L. Kucharic and M. Car, “Integration of CO2 emission and geological storage data from Eastern Europe – CASTOR WP 1.2,” 2006.

[23] T. Vangkilde-Pedersen, K. Kirk and N. Smith, “EU GeoCapacity–Assessing European Capacity for Geological Storage of Carbon Dioxide,” 2009.

[24] K. L. Anthonsen, T. Vangkilde-Pedersen and L. H. Nielsen, “Estimates of CO2 storage capacity in Europe,” 2009.

[25] Navigant, “Gas for Climate. The optimal role for gas in a net-zero emissions energy system,” 2019.

[26] EUROSTAT Data Explorer, “Imports of natural gas by partner country,” 2018.

[27] EUROSTAT Data Browser, “Supply, transformation and consumption of gas,” 2018.

[28] Federal Institute for Geosciences and Natural Resources (BGR), “Energy Study 2013. Reserves, Resources and Availability of Energy Resources,” Hannover, 2013.

[29] Eurostat Data Browser, “Gas prices for non-household consumers - bi-annual data (from 2007 onwards),” 2020.

[30] Green Steel for Europe, “Technology Assessment and Roadmapping (Deliverable 1.2),” 2021.

[31] Green Steel for Europe, “Collection of possible decarbonisation barriers (Deliverable 1.5),” 2021.

[32] Green Steel for Europe, “Synopsis report of consultation activities (WP1) (Deliverable 1.6),” 2021.

[33] M. Xylia, S. Semida, J. Duerinck and F. Meinke-Hubeny, “Weighing regional scrap availability in global pathways for steel production processes,” *Energy Efficiency,* 2017.

[34] P. Söderholm and T. Ejdemo, “Steel Scrap Markets in Europe and the USA,” *Minerals & Energy,* 2008.

[35] J. King, “Europe-demand-forecasts-20-Dec-20.xlsx,” [Online]. Available: http://www.steelonthenet.com.

[36] World Steel Recycling in Figures 2015 - 2019, “Steel Scrap - a Raw Material for Steelmaking”.

[37] Material Economics, “ Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry,” University of Cambridge Institute for Sustainability Leadership (CISL), Cambridge, 2019.

[38] M. Wörtler, “Steel's Contribution's To A Low-Carbon Europ 2050 - Technical And Economic Analysis of the Sector's CO2 Abatement Potential,” The Boston Consulting Group, Steel Institute VDEh, Düsseldorf, 2013.

[39] J. T. Ghenda, “A Steel Roadmap for a Low Carbon Europe 2050, IEA Global Industry Dialogue and Expert Review Workshop,” EUROFER, Paris, 2013.

[40] J. B. Fivel, “Achieving a decarbonised European steel industry in a circular economy,” KTH Royal Institute of Technology, Stockholm, 2019.

[41] GreenSteel, “Report_GreeSteelProject£_WP1_IronOre_EUROFER-Contribution.xlsx,” greensteel, 2020.

[42] Material Economics, “The Circular Economy a Powerful Force for Climate Mitigation,” Transformative innovation for prosperous and low-carbon industry, 2018.

[43] United Nations, *Paris Agreement,* Paris, 2015.

[44] European Parliament, *Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814,* Strasbourg, 2018.

[45] European Parliament, *Directive (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement,* Strasbourg, 2018.

[46] European Parliament, *Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework,* Strasbourg, 2018.

[47] European Parliament, *7 Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency,* Strasbourg, 2018.

[48] European Parliament, *Directive (EU) 2018/844 of the European Parliament and of the Council 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency,* Strasbourg, 2018.

[49] European Parliament, *Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast),* Brussel, 2019.

[50] European Parliament, *Regulation (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast),* Brussel, 2019.

[51] European Parliament, *Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC,* Brussel, 2019.

[52] European Parliament, *Regulation (EU) 2019/942 of the European Parliament and of the Council of 5 June 2019 establishing a European Union Agency for the Cooperation of Energy Regulators (recast),* Brussel, 2019.

[53] European Parliament, *Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action,* Brussel, 2018.

[54] European Commission, *Report from the Commission to the European Parliament and the Council – Report on the functioning of the European carbon market,* Brussels, 2020.

[55] European Commission, *Commission Delegated Regulation (EU) 2019/ 331 of 19.12.2018 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council,* Brussels, 2019.

[56] European Commission, *Commission Delegated Regulation (EU) 2019/856 of 26.2.2019 supplementing Directive 2003/87/EC of the European Parliament and of the Council with regard to the operation of the Innovation Fund,* Brussels, 2019.

[57] European Commission, *Commission Implementing Regulation (EU) 2021/447 of 12 March 2021 determining revised benchmark values for free allocation of emission allowances for the period from 2021 to 2025 pursuant to Article 10a(2) of Directive 2003/87/EC,* Brussels, 2021.

[58] European Commission, *Commission Implementing Regulation (EU) 2021/447 of 12 March 2021 determining revised benchmark values for free allocation of emission allowances for the period from 2021 to 2025 pursuant to Article 10a(2) of Directive 2003/87/EC,* Brussel, 2021.

[59] F. Watson, "www.spglobal.com," 03 12 2020. [Online]. Available: https://www.spglobal.com/platts/en/market-insights/latest-news/coal/120320-analysts-see-eu-carbon-prices-at-eur56-eur89mt-by-2030. [Accessed 25 05 2021].

[60] M. Ferdinand and L. Petersen, "https://sdgresources.relx.com/," 01 02 2021. [Online]. Available: https://sdgresources.relx.com/sites/default/files/icis_2021-02-12_european-carbon-market-to-shift-gears.pdf. [Accessed 25 02 2021].

[61] EUROFER, "www.eurofer.eu," [Online]. Available: https://www.eurofer.eu/assets/Uploads/EUROFER-Position-Paper_-Border-Adjustment-and-Carbon-Leakage-Measures.pdf. [Accessed 25 05 2021].

[62] Y. Jadot, “Towards a WTO-compatible EU carbon border adjustment mechanism,” Committee on the Environment, Public Health and Food Safety, Brussels, 2020.

[63] European Parliament, *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources,* Strasbourg, 2018.

[64] European Commission, *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions — The European Green Deal (COM(2019) 640 final,* Brussels, 2019.

[65] General Secretariat of the Council, *European Council meeting (12 December 2019) – Conclusions EUCO 29/19,* Brussels, 2019.

[66] European Commision: DG Climate Action, *Stepping up Europe’s 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people,* Brussels, 2020.

[67] European Commission, *Amended proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law),* Brussels, 2018.

[68] EUROFER, “Map of EU steel production sites,” 13 November 2019. [Online]. Available: https://www.eurofer.eu/assets/Uploads/Map-20191113_Eurofer_SteelIndustry_Rev3-has-stainless.pdf. [Accessed 25 May 2021].

[69] EUROFER, *Why a Carbon Border Measure needs to complement temporarily Free Allocation and Indirect Costs Compensation in the transition towards climate neutrality,* 2021.

[70] A. Ito, B. Langefeld and N. Götz, “The future of steelmaking – How the European steel industry can achieve carbon neutrality,” Roland Berger GmbH, Munich, 2020.

[71] C. Hoffmann, M. Van Hoey and B. Zeumer, “Decarbonization challenge for steel,” McKinsey & Company, 2020.

[72] T. Kempken, T. Hauck, M. De Santis, P. Q. Rodriguez, M. Miranda, D. Gonzalez, F. Simonelli, H. Vu, W. Szulc, D. Croon, J.-T. Ghenda and C. Wang, “Green Steel for Europe-Collection of possible decarbonisation barriers (Deliverable 1.5),” 2021.

[73] T. Hanlon, “https://newseu.cgtn.com/,” 22 08 2020. [Online]. Available: https://newseu.cgtn.com/news/2020-10-22/EU-launches-anti-dumping-inquiry-into-steel-imports-from-China-UMdd3OwgqQ/index.html. [Accessed 25 05 2021].

[74] B. Steil and B. Della Rocca, “https://www.foreignaffairs.com/,” 07 05 2021. [Online]. Available: https://www.foreignaffairs.com/articles/united-states/2021-05-07/trump-disastrous-steel-tariffs. [Accessed 25 05 2021].

[75] S. Wang and S.-L. Wong, “www.reuters.com,” 14 07 2016. [Online]. Available: https://www.reuters.com/article/us-china-eu-steel-idUSKCN0ZU1U7. [Accessed 25 05 2021].

[76] T. Miles and M. Angel, “www.reuters.com,” 05 07 2017. [Online]. Available: https://www.reuters.com/article/us-g20-germany-steel-idINKBN19Q1EU. [Accessed 25 05 2021].

[77] Wirtschaftsvereinigung Stahl, “www.stahl-online.de,” 19 05 2021. [Online]. Available: https://www.stahl-online.de/stahl-online-news/usa-fuer-mehr-engagement-beim-klimaschutz/. [Accessed 25 05 2021].

[78] F. Thompson, “www.gtreview.com,” 28 04 2021. [Online]. Available: https://www.gtreview.com/news/europe/warnings-eus-proposed-carbon-levy-system-could-unfairly-damage-developing-market-exports/. [Accessed 25 05 2021].

[79] EUROMETAL, “https://eurometal.net/,” 11 02 2021. [Online]. Available: https://eurometal.net/thyssenkrupp-to-reline-blast-furnace-this-year/. [Accessed 25 05 2021].

[80] Thyssenkrupp-Steel, “https://www.thyssenkrupp-steel.com/,” 21 07 2014. [Online]. Available: https://www.thyssenkrupp-steel.com/de/newsroom/pressemitteilungen/modernisierung-des-hochofens-2-in-duisburg-schwelgern-auf-gutem-weg.html. [Accessed 25 05 2021].

[81] Salzgitter Flachstahl GmbH, “https://www.salzgitter-flachstahl.de,” 02 12 2015. [Online]. Available: https://www.salzgitter-flachstahl.de/en/news/details/salzgitter-flachstahl-successfully-completes-investment-project-5613.html. [Accessed 25 05 2021].

[82] ArcelorMittal, “https://bremen.arcelormittal.com/,” 2017. [Online]. Available: https://bremen.arcelormittal.com/icc/arcelor-bremen-de/broker.jsp?uMen=d3530b13-48a7-3951-99f8-b4947d7b2f25&uCon=671301b5-d53d-1061-9508-03037d7b2f25&uTem=aaaaaaaa-aaaa-aaaa-aaaa-000000000011. [Accessed 25 05 2021].

[83] ArcelorMittal, “https://corporate.arcelormittal.com/,” 26 06 2018. [Online]. Available: https://corporate.arcelormittal.com/media/news-articles/2018-jun-26-arcelormittal-zenica-completes-eur-30-million. [Accessed 25 05 2021].

[84] A. Villa, “https://eurometal.net/,” 05 03 2021. [Online]. Available: https://eurometal.net/arcelormittal-restarts-upgraded-blast-furnace-b-at-ghent-belgium/. [Accessed 25 05 2021].

[85] C. Bone, “EU GREEN STEELMAKING: Salzgitter begins work on gas and hydrogen DRI plant,” 18 May 2021. [Online]. Available: https://www.metalbulletin.com/Article/3989750/EU-GREEN-STEELMAKING-Salzgitter-begins-work-on-gas-and-hydrogen-DRI-plant.html. [Accessed 21´5 May 2021].

[86] Midrex, “ArcelorMittal commissions Midrex to design demonstration plant for hydrogen steel production in Hamburg,” 16 September 2019. [Online]. Available: https://www.midrex.com/press-release/arcelormittal-commissions-midrex-to-design-demonstration-plant-for-hydrogen-steel-production-in-hamburg/. [Accessed 21 May 2021].

[87] C. Wang and e. al., “Biomass as Blast Furnace injectant - considering availability, pretreatment and deployment in the Swedish steel industry,” *Journal of Energy Conversion and Management,* 2015.

[88] H. Suopajärvia, K. Umeki, E. I. Mousa, A. Hedayeti, H. Romar, A. Kamppainen, C. Wang, A. Phounglamcheik, S. Tuomikoski, N. Norberg, A. Ö. M. Andefors, U. Lassi and T. Fabritius, "Use of biomass in integrated steelmaking - Status quo, future needs and comparison to other low-CO2 steel production technologies," *Applied Energy,* 2018.

[89] J. Orre, L. S. Ökvist, A. Bodén and B. Bjorkman, "Understanding of Blast Furnace Performance with biomass introduction," *Minerals,* 2021.

[90] E. A. Mousa, H. M. Ahmed and C. Wang, "Novel approach towards biomass lignin utilisation in ironmaking blast furnace," *ISIJ International,* 2017.

[91] E. Mousa, M. Lundgren, L. S. Ökvist, L.-E. From, A. Robles, S. Hällsten, B. Sundelin, H. Friberg, El-Tawil and Asmaa, "Reduced Carbon Consumption and CO2 Emission at the Blast Furnace by Use of Briquettes Containing Torrefied Sawdust," *Journal of Sustainable Metallurgy,* 2019.

[92] M. Dees, B. Eibersen, J. Fitzgerald, M. Vis, P. Anttila, N. Forsell, J. Ramirez-Almeyda, D. Garcia, A. Monti, B. Glavonjic, I. Staritsky, H. Verkerk, R. Prinz, S. Leduc, P. Datta, M. Lindner, S. Zudin and M. Höhl, "Atlas with regional cost supply biomass potentials for EU 28, Western Balken Countries, Moldavia, Turkey and Ukraine (Project Report S2BIOM)," 2017.

[93] A. Camia, N. Robert, R. Jonsson, R. Pilli, S. Garcia-Condado, R. López-Lozano, M. van der Velde, T. Ronzon, P. Gurria, R. M'Barek, S. Tamosiunas, G. Fiore, R. Araujo, H. N., L. Marelli and J. Giuntoli, "Biomass production, supply, uses and flows in the European Union (JRC Science for policy report)," European Commission, Brussels, 2018.

[94] H. Mandova, S. Leduc, C. Wang, E. Wetterlund, P. Patrizio, W. Gale and F. Kraxner, "Possibilities for CO2 emission reduction using biomass in European integrated steel plants," *Biomass and Bioenergy 115,* pp. 231-243, 2018.

[95] G. Wang, J. Zhang, J.-Y. Lee, X. Mao, L. Ye, W. Xu, X. Ning, N. Zhang, H. Teng and C. Wang, "Hydrothermal carbonization of maize straw for hydrochar production and its injection for blast furnace," *Applied Energy 265,* 2020.

[96] H. Suopajärvi and T. Fabritius, "Towards a more sustainable ironmaking - an analysis of energy wood availability in Finland and the economics of charcoal production," *Sustainability,* 2013.

[97] M. Skanberg and S. Shields, "Why we expect a capex surge in Europe," 05 August 2018. [Online]. Available: https://www.schroders.com/en/us/private-investor/insights/equities/why-we-expect-a-capex-surge-in-europe/. [Accessed 25 May 2021].

[98] E. Rogers, Diffusion of Innovation, New York: Free Press, 1962.

[99] European Commission, "Stepping up Europe's 2030 climate ambition: Investing in a climate-neutral future for the benefit of our people," European Commission, Brussels, 2020.

[100] European Commission, "2030 climate & energy framework," [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2030_en. [Accessed 26 May 2021].

[101] P. Dahlmann, H. B. Lüngen, M. Sprecher and U. Stellmacher, “Update of the Steel Roadmap for Low Carbon Europe 2050 - Part I: Technical Assessment of Steelmaking Routes - Final Report,” VDEh Steel Institute, Düsseldorf, 2019.

[102] F. Joas, T. Lenck, S. Samadi and W. Witecka, “Klimaneutrale Industrie - Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement,” Agora Energiewende, Berlin, 2019.

[103] UK Steel, “https://www.makeuk.org/,” 19 07 2019. [Online]. Available: https://www.makeuk.org/insights/publications/uk-steel-key-statistics-guide-2019. [Accessed 25 05 2021].

[104] www.eurofer.eu, “European Steel in Figures,” Eurofer, Brussels, 2019.

[105] European Parliament, *Commission Delegated Regulation (EU) 2019/856 of 26 February 2019 supplementing Directive 2003/87/EC of the European Parliament and of the Council concerning the determination of sectors and subsectors deemed at risk of carbon leakage,* Brussels, 2019.

[106] J. Morfeldt, W. Nijs and S. Silveira, “The Future of Global Steel Production,” KTH Royal Institute of Technology, Stockholm, 2013.

[107] EUROFER, “Low Carbon Roadmap: Pathways to a CO2-neutral European Steel Industry,” EUROFER, Brussels, 2019.

[108] European Commission, “A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy,” European Commission, Brussels, 2018.

[109] A. Kirby, Kick the Habit: A UN Guide to Climate Neutrality, Malta: UNEP, 2008.

[110] European Commission, “Submission by Croatia and the European Commission on behalf of the European Union and its Member States,” European Commission, Zagreb, 2020.

[111] European Commission, “EC-Europa,” 2021. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. [Accessed 28 05 2021].

[112] General Secretariat of the Council, “Proposal for a Regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law),” Council of the European Union, Brussels, 2021.

[113] European Commission, “A hydrogen strategy for a climate-neutral Europe,” European Commission, Brussels, 2020.

[114] U.S. Energy Information Administration, “International Energy Outlook 2016,” 2016.

[115] European Commission (DG Energy), “Quarterly Report on European Electricity Markets (Volume 13, Issue 4, fourth Quarter of 2020),” 2021. [Online]. Available: https://ec.europa.eu/energy/sites/default/files/quarterly_report_on_european_electricity_markets_q4_2020.pdf. [Accessed 1 June 2021].

[116] Fuel Cells and Hydrogen 2 Joint Undertaking, “Hydrogen Roadmap Europe,” Publications Office of the European Union, Luxembourg, 2019.

[117] International Energy Agency, “Electricity Market Report, Dezember 2020,” IEA Publications, Paris, 2020.

[118] Fraunhofer-ISI and Ecofys, “Electricity Costs of Energy Intensive Industries,” Ecofys Germany Gmbh, Berlin, 2015.

[119] Westdeutsche Allgemeine Zeitung, “www.waz.de,” 17 07 2020. [Online]. Available: https://www.waz.de/staedte/duisburg/hkm-in-duisburg-einblick-in-die-reparaturen-im-hochofen-id229536210.html. [Accessed 25 05 2021].

[120] EUROFER, “A Green Deal on Steel: Priorities for transitioning the EU to carbon neutrality and circularity,” EUROFER, Brussels, 2020.

[121] EUROSTAT, “Energy imports dependency,” Luxembourg, 2018.

[122] ENTSO-E, “Electricity in Europe 2017: Synthetic overview of electric system consumption, generation and exchanges in 34 European countries,” ENTSO-E, Brussels, 2017.

[123] EUROSTAT Data Browser, “Electricity prices for non-household consumers - bi-annual data (from 2007 onwards),” 22 04 2021. [Online]. Available: ec.europa.eu/eurostat/databrowser/view/nrg_pc_205/default/table?lang=en. [Accessed 22 04 2021].

[124] European Commission, “Bericht der Kommission an das Europäische Parlament, den Rat, den Europäischen Wirtschafts- und Sozialausschuss und den Ausschuss der Regionen Energiepreise und Energiekosten in Europa,” Brussels, 2020.

[125] K. Rademaekers , M. Smith, A. Demurtas, P. C. Torres Vega, N. Janzow, L. Zibell, O. Hoogland, K. Pollier, M. Crénes, G. Radigois, F. Gailland-Blancard, Y. El Idrissi, I. Sakhaoui, J. Pirie, S. Micallef and M. Altman, “Study on energy prices and costs,” Rotterdam, 2020.

[126] EUROSTAT Statistics Explained, “Electricity prices for non-household consumers, first half 2020 (EUR per kWh),” 23 11 2020. [Online]. Available: ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Electricity_prices_for_non-household_consumers,_first_half_2020_(EUR_per_kWh)_v4.png&oldid=506465#filelinks. [Accessed 22 04 2021].

[127] European Commission, “A European Green Deal,” [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. [Accessed 2 June 2021].

[128] Council of the European Union, “Proposal for a Regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law),” Brussels, 2021.

[129] D. Entzian, “World Steel Recycling in Figures,” EFR Branch General Assembly, Brussels, 2021.