Technology Assessment and Roadmapping (Deliverable 1.2)

Monika Draxler, Axel Sormann (K1-MET)

Tobias Kempken, Thorsten Hauck (BFI)

Jean-Christophe Pierret, Jean Borlee (CRM)

Antonello Di Donato, Michele De Santis (CSM)

Chuan Wang (Swerim)

March 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

GREEN STEEL FOR EUROPE

List of symbols, indices, acronyms and abbreviations

AEL	Alkaline water electrolysis
AIE	Alkaline iron electrolysis
Ar	Argon
As	Arsenic
B	Boron
BF	Blast furnace
Bi	Bismuth
BOF	Basic oxygen furnace
C	Carbon
CAPEX	Capital expenditure
CCfD	Carbon contracts for difference
CCS	Carbon capture and storage
CCU	Carbon capture and usage
CCUS	Carbon capture and usage or storage
CDA	Carbon direct avoidance
CE	Circular economy
CO	Carbon monoxide
CO_2	Carbon dioxide
CS	Crude steel
Cu	Copper
DR	Direct reduction
DRI	Direct reduced iron
EAF	Electric arc furnace
EU	European Union
H_2	Hydrogen
H_2-DR	Hydrogen-based direct reduction
H_2O	Water
HBI	Hot briquetted iron
HCl	Hot compacted iron
HTEL	High temperature electrolysis
HPSR	Hydrogen plasma smelting reduction
IBRSR	Iron bath reactor smelting reduction

Mo	Molybdenum
MOE	Molten oxide electrolysis
NG-DR	Natural gas direct reduction
N_2	Nitrogen
O_2	Oxygen
OPEX	Operational expenditure
PEM	Polymer electrolyte membrane
PI	Process integration
R&D	Research and development
Sb	Antimony
SCU	Smart carbon usage
Sn	Tin
t	Ton
TGR-BF	Top gas recycling – blast furnace
TRL	Technology readiness level

Executive summary

To meet the 2050 European climate and energy targets, the iron and steel industry's CO_2 footprint needs to reduce by 80-95%, compared to 1990 levels, by 2050. This can only be done if adequate and innovative solutions are established to shift current processes towards carbon-lean production. The Green Steel for Europe project aims, *inter alia*, to provide transparency about the technologies needed and their impact, and the barriers to be overcome and the remedies needed to initiate the crucial next steps.

Deliverable 1.2 provides the technological foundation for the evaluation of CO_2 mitigation strategies with specific low-carbon technologies, and for implementing complete technology routes in the European steel industry. It summarises iron and steelmaking technologies, supporting technologies and technology routes, describing their technological approaches, their current maturity (in terms of readiness level) and their expected development, and the influencing framework conditions. This deliverable contains the preliminary results of the Green Steel for Europe project. The concluding results, including the development of scenarios, can be found in subsequent deliverables.

The CO_2 mitigation pathways, which are currently being addressed in the European steel industry, are carbon direct avoidance (CDA), process integration (PI) and carbon capture and usage (CCU). The parallel circular economy strategy targets a 'zero waste' concept and complements the above-mentioned pathways as an overarching approach. The CDA pathway primarily focuses on the development of new steelmaking processes using fossil-free reductants and (renewable or clean) energy sources to produce steel from virgin iron ore, thereby avoiding the generation of carbon oxides and its emissions. The PI pathway concerns possible modifications or adaptations to existing steel plants in order to reduce greenhouse emissions, and can be complemented by CCU and/or carbon capture and storage (CCS). CCU consists of the capture of CO_2 or CO from steel production process gases and the production of further valuable carbon-based products from captured fossil carbon, thus mitigating emissions caused by fossil resources in their conventional production chains.

The following technologies were identified as the most relevant within these pathways:

- hydrogen-based direct reduction (H_2-DR)
- hydrogen plasma smelting reduction (HPSR)
- alkaline iron electrolysis (AIE)
- molten oxide electrolysis (MOE)
- carbon oxide conversion (CCU)
- iron bath reactor smelting reduction (IBRSR)
- gas injection into the blast furnace
- substitution of fossil energy carriers by biomass
- high-quality steelmaking with increased scrap usage.

The selection of iron and steelmaking technologies is based on desktop research of various global publications, a comprehensive stakeholder survey and the outcomes from the previous RFCS Project LowCarbonFuture - Exploitation of projects for Low-Carbon Future Steel Industry (Grant Agreement No. 800643).

The majority of the identified technologies have a moderate maturity level, with technology readiness levels between 5 and 7. Certain technologies, such as hydrogen plasma smelting reduction or molten oxide electrolysis, have high CO_2 mitigation potential but are currently at low maturity. Correspondingly, a high number of research and development (R&D) projects are needed, in particular regarding the processes and their upscaling, as well as the related plant technologies, auxiliary processes, material processing and a large number of measurement and control aspects. Table 1 provides an overview of the technologies and their main data.

Table 1: Overview of low-carbon iron and steelmaking technologies (% of average BF-BOF plant; CS - crude steel; ind. deployed - industrially deployed; CAPEX - capital expenditure; OPEX - operational expenditure; impl. – implementation; neg. - negative)

Technology	TRL development			Economic assessment	Reference projects[1]
	2020	2030	2050		
Hydrogen-based direct reduction (100% H_2)	TRL 6-8	TRL 7-9	TRL 9 (ind. deployed)	20-80% cost increase; production costs: ~€532-640/t CS	HYBRIT, SALCOS, tkH_2Steel, Hydrogen Hamburg
Hydrogen plasma smelting reduction	TRL 5	TRL 6	TRL 9 (ind. deployed)	No information on CAPEX or OPEX	SuSteel
Alkaline iron electrolysis	TRL 5-6	TRL 6-8	TRL 9	CAPEX + OPEX: ~€645-828/t CS	ULCOS (SP5-13-14), IERO, VALORCO, SIDERWIN
Molten oxide electrolysis	TRL 2	TRL 3-4	TRL 9	CAPEX: ~€1 K/t CS annual capacity OPEX: increase of 50-80% compared to conventional route	ULCOS, IERO, VALORCO
Carbon oxide conversion	TRL 8 (conversion) TRL 4-5 (impl.)	TRL 9	Ind. deployed	CAPEX increase of ~€13/t CS OPEX increase of €408-629/t CS	Carbon2Chem, Carbon4PUR, STEELANOL
Iron bath reactor smelting reduction	TRL 6	TRL 8	Ind. deployed	CAPEX: €500 M (for a 1.15 Mt/year plant excl. O_2 plant) Neg. OPEX (-25 to -€30/t CS), due to efficiency gains	HIsarna
Gas injection into the blast furnace	TRL 5-8 (preparation / gas reforming) TRL 9 (H_2 rich)	TRL 8-9	Ind. deployed (in 2040)	CAPEX: €80-110 / €110-150/t CS (without / with CCUS) OPEX: €0-10 / €40-50/t CS (without / with CCUS).	ULCOS
Substitution of fossil energy carriers by biomass	TRL 2-7	TRL 8	TRL9 and ind. depl. in 2035	CAPEX relatively low and OPEX depends mainly on the raw materials	SHOCOM, GREENEAF2, ACASOS
High-quality steelmaking with increased scrap usage	TRL 4-8	TRL 7-9	Ind. deployed	OPEX: significant depending on the scrap price	FLEXCHARGE, ADAPTEAF, SSIA, LCS

Source: author's own composition.

Several technologies can be combined in order to raise the overall CO_2 mitigation potential above their individual limits. CO_2 capture and H_2 generation are the main auxiliary processes connected to several of the technologies. As H_2 can be extracted from fossil fuels and biomass, water, or a

[1] This list of reference projects is not exhaustive.

mix of both, there are multiple production processes available such as reforming of gas, gasification (biomass, waste etc.) or water electrolysis.

The analyses showed that for most technologies, a huge amount of additional clean energy is needed and that the material cycles in the plants will be fundamentally influenced. Moreover, many technologies imply a significant increase in terms of CAPEX (due to the need to replace main parts of the upstream process chain) and OPEX (mostly due to expensive renewable energy supply). The exchange of fossil energy sources by biomass usually needs less changes within the process chain; however, its use is strongly limited by the (local) availability of biomass resources.

The technologies described in this report focus on the predominant trends within the EU, supported by a literature review relating to non-EU countries. In Japan, the COURSE50 programme is aiming to mitigate CO_2 emissions in steel production by using several approaches, including hydrogen gas injection into the blast furnace (BF) and carbon capture and storage. The POSCO programme in South Korea focuses on the carbon-lean FINEX process, pre-reduction, heat recovery of sinter, carbon capture and storage as well as hydrogen-based reduction of iron ore. In the US, steelmaking by molten oxide electrolysis, hydrogen flash smelting and CO_2 capture and separation are being investigated. Australia is working on two programmes regarding the utilisation of biomass and heat recovery from molten slags through dry granulation in blast furnaces.

The iron and steelmaking technologies within each pathway (CDA, PI, CCU) can be considered as individual modular components (mitigation options) within the complete steel production chain. Technology routes integrate these components into a full system (process chain), which includes upstream operations (transformation of raw materials into intermediate steel products) and downstream applications (production of final shaped and coated products). The compilation of technologies to technology routes (including the integration into existing/new production chains) needs substantial additional effort, both with respect to R&D activities and to accompanying investments needed. Combining mitigation technologies in technology routes is by essence not limited to a specific mitigation pathway (CDA, PI, CCU) but may include elements from all of them. The CO_2 emission of downstream processes is much lower than from ore-based upstream processes. Therefore, the focus lies on upstream applications and scope 1 (direct emissions) and scope 2 (indirect emissions from the production of required energy) emissions.

Four promising technology routes were identified within the project work as highly relevant (but non-exclusive) examples. The first one is based on conventional BF-BOF plants (blast furnace, basic oxygen furnace), into which a number of add-on CO_2 mitigation technologies are incorporated (PI, CCU). This route can be considered a short-term solution. The second is based on the utilisation of hydrogen-based direct reduction, in which all ironmaking and steelmaking units are replaced by new production methods. The third technology route comprises technologies based on smelting reduction. This includes, on the one hand, the iron bath reactor smelting reduction option, in which the ironmaking part is replaced and, on the other hand, hydrogen plasma smelting reduction, which enables the direct transformation of iron ore into liquid steel. The last technology route refers to the electricity-based steelmaking by iron ore electrolysis, which represents new production methods.

The illustration below (Figure 1) provides a comparative view of the technology routes (green) and the integrated primary steel production route (grey). The process chain is visualised from top to bottom of the figure. The objective is to demonstrate to which extent alterations occur. The route based on conventional BF-BOF and the enhanced iron bath reactor smelting reduction technology route show a horizontal change (i.e. with remaining BOF) as opposed to a widespread vertical alteration within the hydrogen-based direct reduction-electric arc furnace (H_2-DR-EAF) route and the electrolysis-based technology route. The green indications within the flow diagrams show the modifications, whereas the grey-coloured annotations symbolise unchanged procedures.

Although the main existing process units are not replaced with new technologies for the proposed CO_2 mitigation route based on conventional BF-BOF, considerable changes must be carried out in conventional plants. To reach significant mitigation through this technology route, considerable investments are required for the add-on technologies (e.g. carbon capture, usage and storage, biomass preparation, gas preparation and blast furnace gas injection systems).

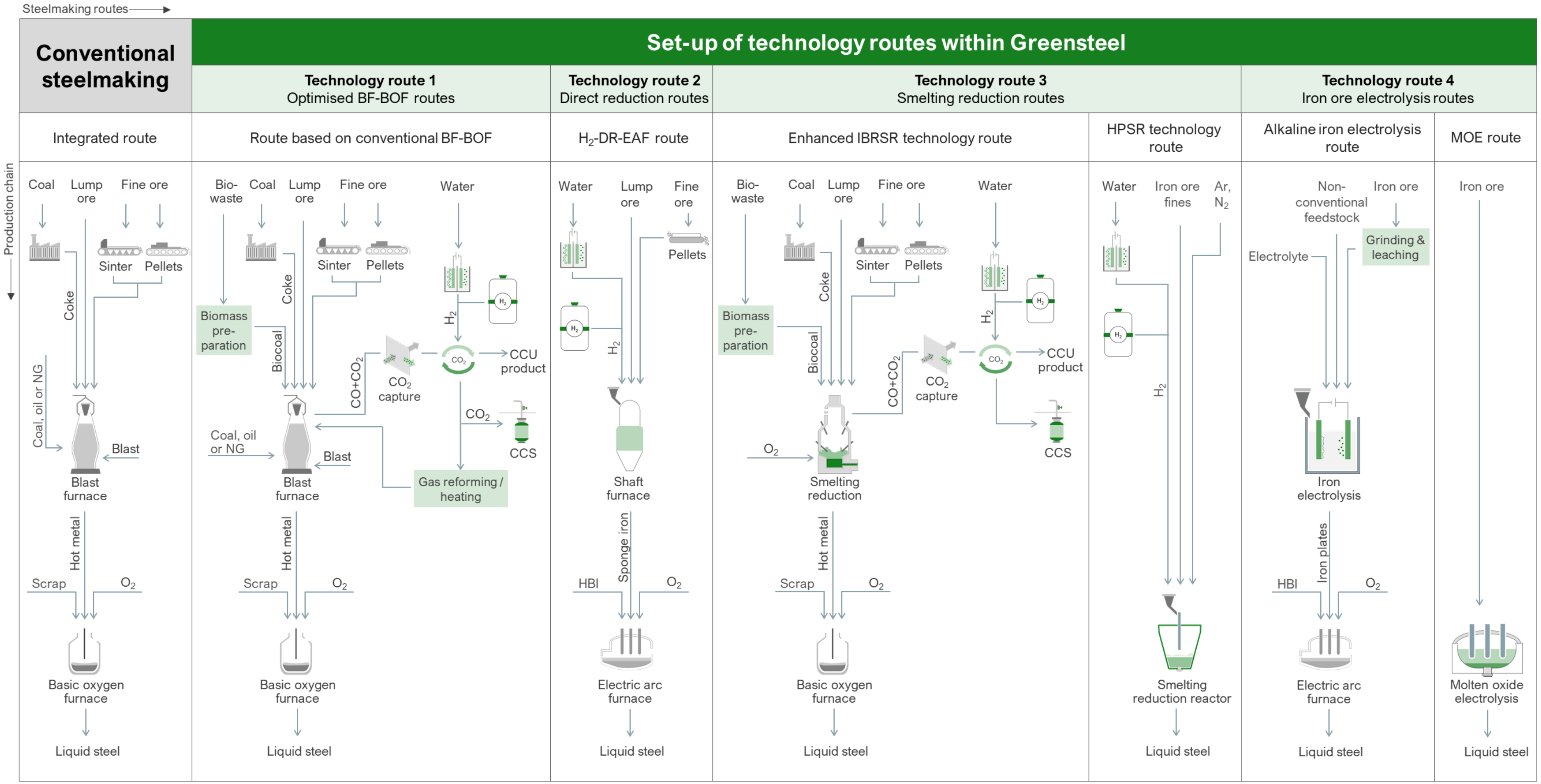
For the H_2-DR-EAF route, the technology route based on hydrogen plasma smelting reduction and the technology routes based on iron ore electrolysis, the full ironmaking and steelmaking capacities of existing BF-BOF plants have to be replaced. The effort is almost comparable to greenfield conditions. The data provided in the figure regarding this route refer to the breakthrough technology with (almost) complete usage of hydrogen as reducing gas for direct reduction.

The smelting reduction technology route replaces the full ironmaking process in conventional plants; further significant investments are required for add-on technologies (e.g. carbon capture, usage and storage and biomass preparation) to achieve extensive CO_2 mitigation.

Starting from individual iron and steelmaking technologies, the roadmaps for the proposed breakthrough technology routes have been created (Figure 2). They indicate the progress and the research needs for each technology involved along the timeline. The needs for integrating the technologies into a complete breakthrough process chain are also visualised. Each line describes one technology. Starting in 2020 (current technology readiness level), the technology readiness level development is shown from left (short-term) to right (long-term) both graphically (grey shaded area) and numerically.

Consistent with all other deliverables within the project, ‘short-term’ refers to the period up to about 2030, while ‘long-term’ refers to a time after 2040. As soon as TRL 9 – and thus the maturity for first industrial deployment – is reached, the mitigation potential is presented in a circular diagram. Research needs were grouped and listed in the associated time period.

Figure 1: Overview of the set-up of technology routes in comparison to the integrated steelmaking route



Source: author's own composition.

An important intermediate step towards the deployment of the H_2-DR-EAF technology route is the direct reduction with natural gas which has been an industrially established technology for a long time. Also, with natural gas the direct reduction technology (NG-DR-EAF) provides a significant CO_2 mitigation potential compared to the conventional BF-BOF-route, and thus, a promising short-term option. The share of hydrogen as a partial substitute for natural gas can be increased stepwise towards the possible later target of complete hydrogen-based reduction. This allows a gradual enrichment with hydrogen on industrial scale and enables a flexible increase of hydrogen concentration depending on availability, price, and technical requirements. Regarding the time scale for industrial deployment, this results in the option of direct reduction plants being built as of now (depending on the individual investment cycles of the respective plants) and their shift towards increased hydrogen usage as soon as possible depending on its availability. Natural gas-based direct reduction can be complemented by CCU and/or carbon capture and storage; the realisation relies on the specific situation of the individual steel production site.

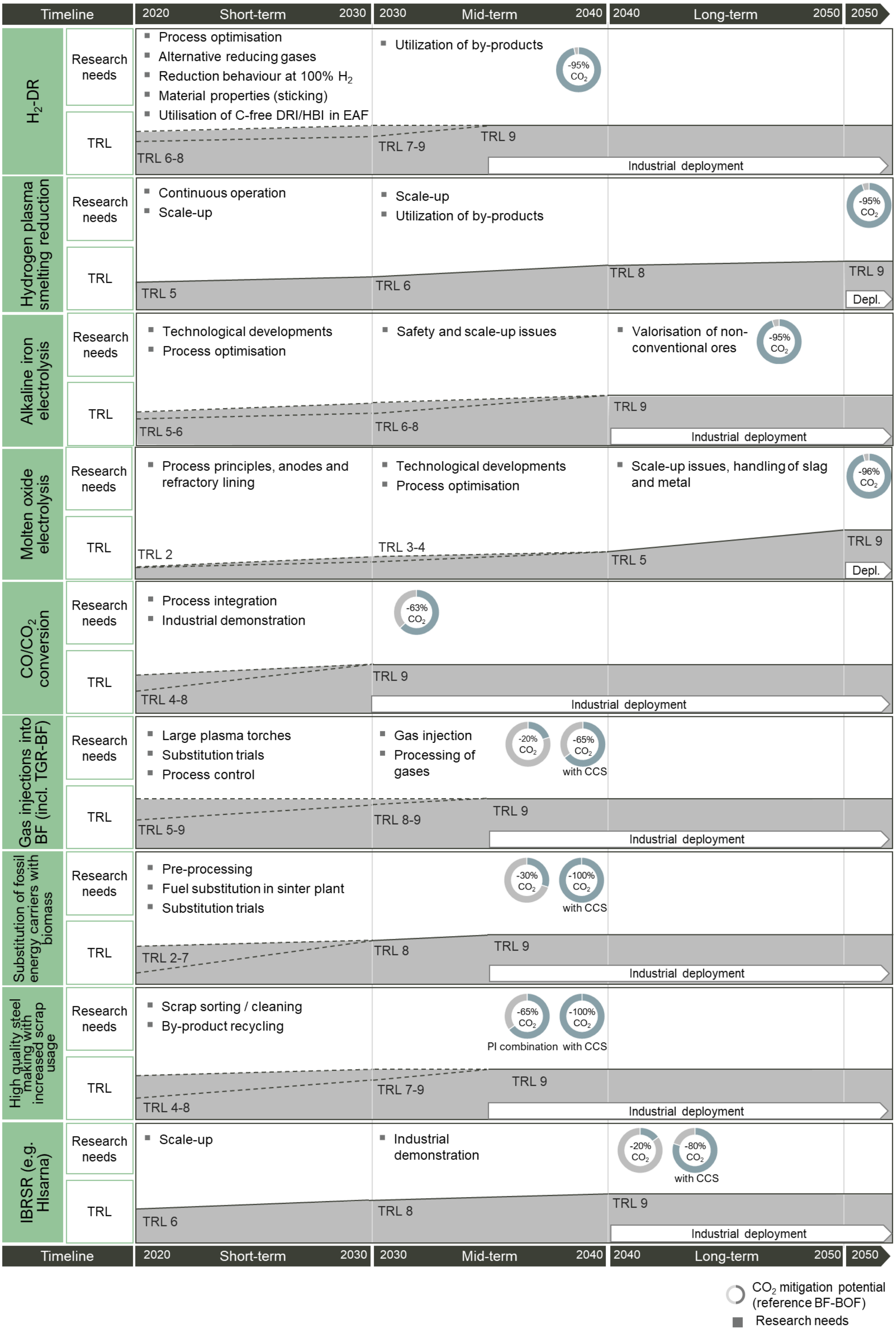
Another promising short-term option is to replace part of the fossil coal used in different plants (e.g. coking plant, sinter plant and blast furnace) with biomass. This can further be combined with recycling the remaining CO and hydrogen in the blast furnace top gas back into the process, effectively decreasing CO_2 emissions. CO and hydrogen can be recovered with a CO_2 separation step. Regarding CO_2 separation technologies, several options have already been proposed. Many gaseous streams in steel plants are concentrated in CO_2, so there is good potential for specific/integrated capture processes.

Besides possible replacement of energy carriers with biomass, the replacement of primary raw materials with increased scrap utilisation according to the Circular Economy strategy is yet another measure for CO_2 mitigation. In direct comparison, secondary steel production via the scrap-EAF route results in about 80% less CO_2 emissions than with the primary BF-BOF-route. Nonetheless, the potential for scrap utilisation is strongly restricted under the requirements for steel product quality. More specifically, the metallurgical requirements for high-quality steel, which is often produced via the primary BF-BOF-route, demand the processing of virgin material and will limit the scrap utilisation significantly for the foreseeable future. A clear R&D demand for improved scrap processing in order to ensure better scrap quality was identified. Indeed, this would alleviate the limitations of scrap utilisation to some extent.

To realise the crucial next step of demonstration and completion in operational environment (TRL 7–8) and to enable the European climate and energy targets to be met, the R&D actions need to be taken immediately. Since the needed R&D actions are widespread and the effort by far exceeds usual R&D needs, collaborative research could be useful for effective progress.

It can be stated that the four proposed technology routes have a CO_2 mitigation potential up to 100%, but not all technologies can be industrially deployed in the short term (by 2030). Some technologies are available, which enable short-term deployment with limited R&D need and investment effort. The technologies need certain framework conditions, the most important one being the availability of sufficient clean energy at costs that are competitive with worldwide levels.

Figure 2: Roadmap of selected CO_2 mitigation technologies



Source: author's own composition.

1 Introduction

In line with the Paris Agreement, the European Union (EU) set out to achieve ambitious climate and energy goals, aiming to reduce greenhouse gas emissions gradually by at least 80% by 2050. One further step towards becoming a fair and prosperous society with a modern, sustainable and competitive economy was taken in 2019 with the Green Deal, a roadmap defining measures to achieve a climate-neutral EU by 2050[2].

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[3] (Mandova et al., 2019). To meet the agreed targets, it is essential to establish adequate and innovative solutions for transitioning current processes towards carbon-lean production. At the same time, considering that this transition takes place in a dynamic environment with worldwide overcapacities, from an EU and industry perspective, preserving competitiveness is an important factor.

When it comes to steel, two different production routes can be distinguished: the primary route, where steel is produced from iron ore, and the secondary route, where steel is produced from scrap melting (Figure 3). The primary route comprises the integrated route, i.e. blast furnace (BF) and basic oxygen furnace (BOF); smelting reduction (smelting reduction plant and BOF) and direct reduction (DR), requiring a direct reduction plant and an electric arc furnace (EAF). In turn, the secondary route produces crude steel by recycling steel scrap in the electric arc furnace.

The integrated route dominates the European steel production and accounted for 58.6% of crude steel (CS) production in the EU28 in 2019, while the scrap-based electric arc furnace route accounted for 41.4%. Although there are regional differences, the share in terms of worldwide crude steel production is comparable to EU values, with 71.5% for the BF-BOF route, 28.0% for the electric arc furnace route and 0.5% for other processes (e.g. open hearth furnace). (World Steel Association, 2003, 2006, 2018, 2019)

The BF-BOF route is highly linked to the element carbon, resulting in high CO_2 equivalent emission intensity despite very high energy efficiency. This is due to the energy intensive reduction process which is needed to produce hot metal out of iron ore. Thus, the CO_2 generated per ton (t) of crude steel produced is approximately 1.9 t, which compared to scrap recycling, generates 2.5 times more emissions per ton of crude steel produced (Mandova et al., 2019; Dahlmann et al., 2019).

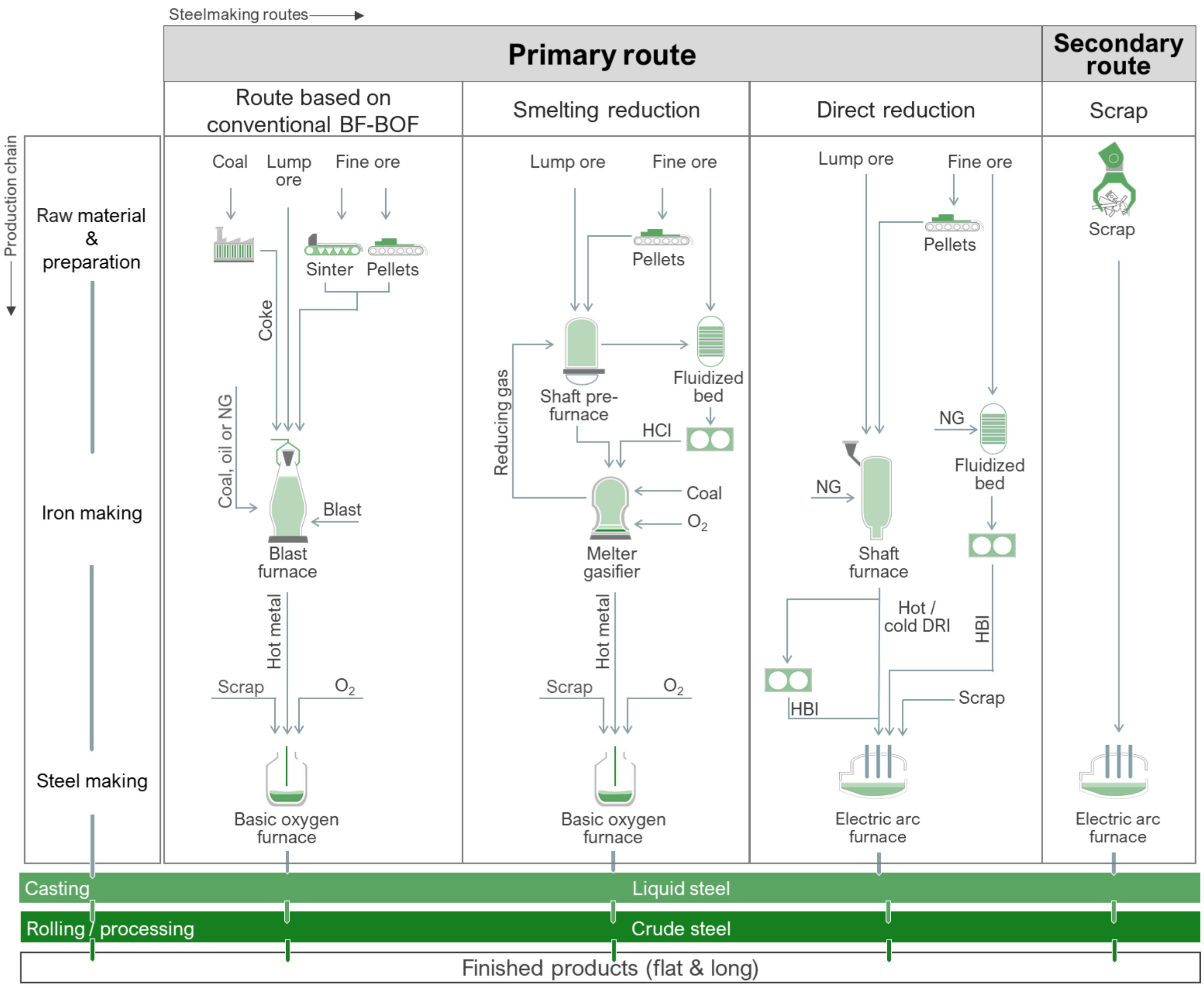
Figure 3 provides an overview of currently established steelmaking routes. Replacing the BF-BOF route with the scrap-based EAF route would theoretically have the potential to reduce CO_2 emissions to approximately 20% per ton of crude steel, depending on the indirect emissions due to CO_2 intensity for electricity production (voestalpine, 2018). However, since steel is an extremely versatile material, the metallurgical requirements for specific steel products are different. and this does not include the specific requirements of raw materials. Many steel producers currently operating on the BF-BOF route will not be able to replace their production with the scrap-based EAF route due to quality demands; similarly, they may not be able to abandon virgin iron ore despite its energy insensitivity.

[2] For further details, please see ec.europa.eu.
[3] For further details, please see ec.europa.eu.

An important and already industrially established alternative for those producers is direct reduction, which can use natural gas as an energy source and reducing agent. This approach is estimated to decrease CO_2 emissions by 35% compared to the BF-BOF route (Schenk, 2016; Bürgler, 2017).

Currently established smelting reduction routes cannot significantly reduce emissions compared to the BF-BOF route without further measures if these remain based on coal. However, this technology still provides major potential for mitigation of CO_2 emissions by further developments.

Figure 3: Overview of actual steel production routes



Source: author's own composition based on (EUROFER, 2013).

In order to realise a major decrease in CO_2 emissions, current steelmaking must shift to breakthrough technologies. Since the development of virgin technologies to full industrial maturity is expected to take decades in the steel industry due to the numerous scale-up steps needed and due to very long investment cycles, this decarbonisation transition must be forced now to stay in line with the CO_2 mitigation ambitions described above.

The aim of project Green Steel for Europe is to ensure the transparency of technologies, including their pathway to industrial maturity, their impact, their needs, barriers, and remedies to support the crucial next steps. This report will provide the technological basis for this goal. The information collected provides an evaluation of the different technologies capable to reduce the iron and steel industry's CO_2 footprint by 80-95% by 2050, compared to 1990 levels. Information and data were derived from a stakeholder questionnaire, publicly available literature and the recent project LowCarbonFuture. LowCarbonFuture is a project funded by the European Commission through the

Research Fund for Coal and Steel (RFCS), whose purpose is collecting, summarising, evaluating and promoting research projects and knowledge dealing with CO_2 mitigation in iron and steel production (LowCarbonFuture, 2020).

Following this introduction, Chapter 2 describes the iron and steel production technologies identified in Task 1.1 of project Green Steel for Europe and further addresses their level of maturity and remaining research and development (R&D) needs. Building on this, technology routes are developed in Chapter 3 by combining the different technologies to complete steel production chains. The results are presented as roadmaps (Chapter 4), which prognose the technology development on the way to industrial deployment by analysing the developments and boundary conditions, timing and value chains needed to produce low-carbon steel in Europe. These roadmaps will provide the basis for the development of future industrial scenarios for the decarbonisation of steel production, which will be performed within the subsequent tasks of project Green Steel for Europe.

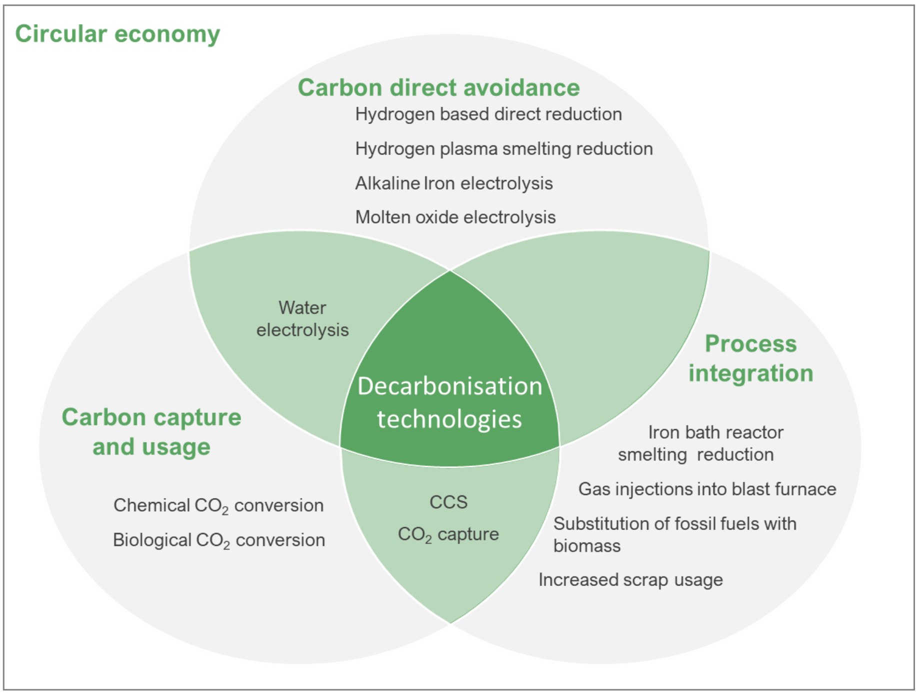
2 Technology assessment

The literature provides different organising principles for CO_2 mitigation technologies. Within the scope of this project, it was decided to make a pathways-based classification aligned with EUROFER principles. The current pathways being pursued regarding CO_2 mitigation within the European steel industry are circular economy, carbon direct avoidance (CDA), process integration (PI) and carbon capture and usage (CCU, Figure 4).

Circular economy is an approach replacing the 'end-of-life' concept with a 'zero-waste' concept by reducing or alternatively reusing wastes (by-products), as well as recycling and recovering energy and valuable materials from these streams in production/distribution and consumption processes. Consequently, circular economy also affects the other pathways described (CDA, PI and CCU).

The CDA pathway mainly focuses on the development of new iron and steel production processes, using fossil-free reductants and/or (renewable) energy sources to produce steel from virgin iron ore. PI and CCU are both part of the smart carbon usage (SCU) pathway and refer to existing routes. PI focuses on possible modifications or adaptations of existing steel production routes to reduce the greenhouse gas emissions, while CCU relies on the capture of CO_2 or CO from steel industry process gases and the production of further valuable carbon-based products from the fossil carbon captured. Both PI and the CCU pathway can be supplemented by carbon capture and storage (CCS) in case not all captured CO_2 can be utilised or converted into a product. However, since the further handling of CO_2 after the capture is not within the specific scope of project Green Steel for Europe, CCS and CCUS are not further discussed in detail.

Figure 4: Decarbonisation technologies according to the pathways classification and their supporting technologies within the European steel industry



Source: author's own composition.

The technologies described within each category can be considered as single modular components within the complete steel production chain. By combining components (iron and/or steel production technologies) with a possible raw material preparation, down-stream processes or/and supporting technologies (Section 2.4 Auxiliary processes), technology routes are compiled representing the entire steel production chain.

The following technologies will be described in detail:

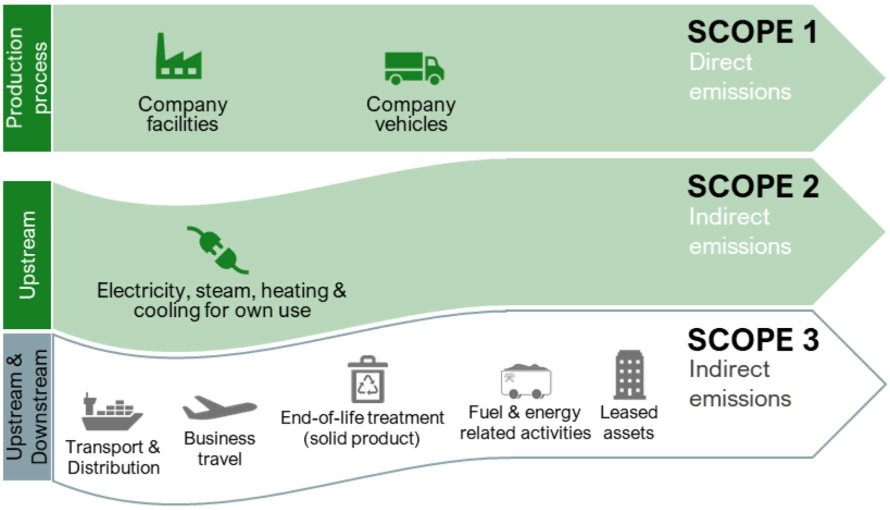
- hydrogen-based direct reduction;
- hydrogen plasma smelting reduction;
- alkaline iron electrolysis;
- molten oxide electrolysis;
- carbon oxide conversion;
- iron bath reactor smelting reduction;
- gas injection into the blast furnace;
- substitution of fossil energy carriers by biomass; and
- high-quality steelmaking with increased scrap usage.

Many parameters are involved in assessing low-carbon steelmaking technologies. Therefore, it is not possible to come to a universal prioritisation. Although it would be technically feasible to rank technologies by maturity or CO_2 mitigation potential, a technology's general suitability cannot be determined from these parameters alone. The suitability of each plant has to be considered individually, since each plant entails different framework conditions. Different European regions and their associated framework conditions are briefly and exemplarily discussed in Chapter 4 Technology routes. A detailed breakdown to EU geographic areas as well as future assumptions (scenarios) regarding the likely future share of production are provided in D1.7 Decarbonisation pathways 2030 and 2050. The four selected technology routes described in Chapter 3 Setup of technology routes in this deliverable reflect the top-priority technologies.

The technologies mentioned in this chapter are a selection of basic technologies singled out as a result of desk research and stakeholder consultations. It must be mentioned that the technologies are not listed in order of importance. As the desk research was conducted based on a wide variety of literature information, including finished and ongoing projects, the data presented stem from different sources, each with its specific definitions. Therefore, not all values could be evaluated on a uniform level. In particular, the assessment of maturity by an overall TRL can be defined quite differently, since most technologies rely on a large number of different, single elements which can have very different TRL. Thus, defining the overall TRL focussing on the least mature element will give much lower results than using an overall TRL averaging all relevant technology elements. The varying definitions in the literature sources are used and described as far as available.

Figure 5 shows the classification of emissions into three scopes according to GHG Protocol standards, and provides a few examples of contributors to the individual categories. The emissions (scope 1 and scope 2) considered within this deliverable are indicated by green arrows in the figure.

Figure 5: Overview of greenhouse gas emissions classified into three scopes based on the GHG Protocol



Source: author's own composition based on (Barrow, 2013).

The deliverable focusses mainly on scope 1 (direct emissions) but also on scope 2 (indirect emissions from the production of the required energy; including the assumption that the electricity used originates from renewable energies) emissions. Scope 3 emissions constitute a small share of the total emissions and are difficult to define in a consistent way. Therefore, these aren't focused upon within this deliverable.

2.1 Carbon direct avoidance

The energy intensive reduction of iron ore into iron (hot metal) accounts for approximately 80% of total primary steelmaking CO_2 emissions (Åhman, 2012). These emissions could be avoided if scrap or iron-bearing residues were to replace virgin iron ore. As stated in the introduction, this is, depending on the requirements of the target steel product, limited due to impurities within (secondary) iron sources or the quantities available. The search for new reducing agents is therefore an important step towards decarbonising the steel industry and the CDA pathway. Consequently, as a reducing agent, carbon is replaced by green hydrogen (discussed in Sections 2.1.1 and 2.1.2) and electricity (Sections 2.1.3 and 2.1.4), thus avoiding the generation of CO_2.

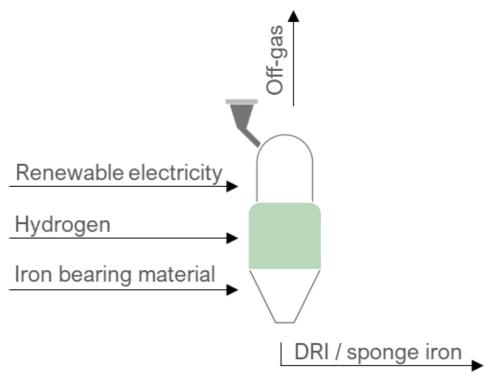
2.1.1 Hydrogen-based direct reduction

Technical description. The H_2-DR route is derived from direct reduction, a well-established process, which is usually operated with natural gas or coal. As this research focuses on breakthrough technologies, the assessment of H_2-DR in this deliverable corresponds to direct reduction with (almost) 100% hydrogen. Natural gas-based direct reduction (NG-DR) could be utilised as an entry point for H_2-DR. This approach could be readily introduced and is estimated to decrease CO_2 emissions by 35% compared to the BF-BOF route (Schenk, 2016; Bürgler, 2017). The operating gas mixture could be gradually enriched with hydrogen, but its share is limited by hydrogen availability, emissions, costs, and process requirements. This enables a very high degree of flexibility, which can pose a strong strategical advantage. Overall, switching from the integrated steelmaking route (BF-BOF) to H_2-DR requires significant changes in the production process. Coking plants, sinter plants, blast furnaces and basic oxygen furnaces would have to be replaced. The plant-wide gas and energy management system would therefore have to be adapted in order to compensate for the missing metallurgical gases required in those processes providing the main share of the internal gas and energy in current integrated BF-BOF plants. The rest of the downstream production remains unchanged and the liquid steel is processed in secondary metallurgy, then cast and rolled in similar steps as in current integrated steelmaking.

Required feedstock, energy sources and other materials. The H_2-DR technology as assessed in this deliverable uses hydrogen as a reducing agent. Due to the fact that hydrogen is an energy carrier and typically occurs in bound form, a dedicated production has to be established (Weigl, 2014). Several methods are available to produce hydrogen. At the current state, most of it is generated by manufacturing processes based on fossil fuels, such as the catalytic steam cracking of methane, the partial oxidation of heavy oil or the gasification of coal (Shell Deutschland Oil GmbH, 2017). For the purpose of decarbonisation, it is essential to produce hydrogen in a low-carbon and renewable way. Electrolysis using renewable energy sources like wind energy, water power, solar energy, biomass or other low carbon sources (i.e. nuclear, but due to sustainability reasons this way should not be preferred) poses a viable option for CO_2-lean hydrogen production and is described later in Section 2.4.2. Regarding solid raw materials, the H_2-DR technology basically relies on iron ore pellets. Since pelletising plants are currently not available in most integrated plants within the EU, these would have to be built or externally supplied. This poses some challenges, since if existing sinter plants are shut down, the internal residue handling has to be fundamentally adapted. External pellet supply would decrease the flexibility with respect to raw material supply and may lead to carbon leakage (if pellets are acquired from outside the EU).

There are different technological approaches to the direct reduction process: the most common approach is direct reduction in a shaft furnace (Figure 6). For this purpose, pellets are used as iron bearing input material. Alternatively, the reduction can also take place in a fluidised bed, where iron ore fines (iron ore powders) are used, thus eliminating the pelletising step.

Figure 6: Schematic and simplified view of a shaft furnace for H_2-DR



Source: author's own composition.

The utilisation of hydrogen accelerates the reduction process (in comparison to the usage of coke as a reducing agent). Due to the endothermic reaction, heat must be added in the process. The additional heat can be provided by burning excess hydrogen or using electricity. The off-gas of this process is mainly water vapor, which could be used for hydrogen production to improve the energy efficiency of water electrolysis (Åhman, 2012). The product of this process is a carbon-free direct reduced iron (DRI) or sponge iron with an iron content of approximately 95% and no carbon content[4]. In a following step, the sponge iron is further processed into liquid steel in the electric arc furnace.

Reference projects. In Europe, steel manufacturer SSAB's project HYBRIT is working on this technology in Sweden, like steel companies ArcelorMittal Hamburg (H2H), Salzgitter (SALCOS) and ThyssenKrupp (tkH_2Steel) in Germany[5]. An example of direct reduction in a fluidised bed is the technology HYFOR of Austrian plant manufacturer Primetals[6].

Economic assessments. Capital expenses (CAPEX) for H_2-DR include the investments for a shaft furnace and are expected to amount to approximately €230/t CS (Wörtler, 2013). When evaluating operating costs (OPEX), electricity costs, resource costs (e.g. ore, lime and scrap) and other variable costs (e.g. maintenance and labour) must be considered (Vogl, 2018).

According to SSAB, the production costs (including CAPEX, energy, raw material and others) of hydrogen-based steel production are expected to increase by 20-30% (basis: greenfield, with current framework conditions; production costs per ton of steel for a production volume of 4 million t/year) in comparison to the current coal-based primary steel production (2018), whereas Austrian steel company voestalpine forecasts an 80% increase (including energy, raw materials, others) in operational costs (Axelson, 2018; Chan, 2019; HYBRIT, 2016-2017).

Overall production costs for 2050 (incl. spec. capital costs/t CS by H_2-DRI (DRI plant, electric arc furnace), operating costs (use of green hydrogen, electricity use in steel plants), other costs (scrap, alloys, etc.)) are expected to be between €532/t CS and €640/t CS, depending on the price of electricity and CO_2 and the amount of scrap applied in the following electric arc furnace process (Chan, 2019; Agora Energiewende and Wuppertal Institut, 2019). The economic viability of hydrogen-based steelmaking largely depends on the price of electricity and the framework conditions for CO_2 pricing. Carbon dioxide mitigation costs are estimated as medium level costs (€60 to 99/t CO_2: €60/t CO_2 in Germany in 2030, resorting to 100% natural gas direct reduction; €99/t CO_2 in Germany, using hydrogen-based direct reduction) (Agora Energiewende and Wuppertal Institut, 2019).

Energy needs. In general, the switch to hydrogen is associated with increased electrical energy demand. The estimated electrical energy requirement is between 3.3 and 3.5 MWh/t CS (including hydrogen production) or 4.1 MWh/t CS (including hydrogen production, chemical energy and pelletising), whereby the largest share is required for hydrogen production. In comparison to the BF-BOF route, chemical energy (primary energy input) decreases, while the electrical energy requirement increases significantly (HYBRIT, 2016-2017; Müller, 2019).

CO_2 reduction potential. H_2-DR utilising 100% hydrogen in combination with renewable energy has high CO_2 mitigation potential and CO_2 mitigation of up to 97% can be reached compared to the BF-BOF route[7] (Agora Energiewende and Wuppertal Institut, 2019; Müller, 2019). If the electricity used in the process is generated from renewable energy, CDA technologies are close to

---

[4] For further details, please see www.hybritdevelopment.com; salcos.salzgitter-ag.com.

[5] For further details, please see www.hybritdevelopment.com; salcos.salzgitter-ag.com; hamburg.arcelormittal.com; www.thyssenkrupp-steel.com/de/unternehmen/nachhaltigkeit/klimastrategie.

[6] For further details, please see www.primetals.com/de/press-media/metals-magazine/issue-02-2020/the-winding-road-toward-zero-carbon-iron.

[7] For further details, please see www.hybritdevelopment.com.

CO_2-neutral. Nevertheless, a certain percentage of CO_2 emissions must be considered for instance due to the use of carbon as electrode material in the following electric arc furnace process.

Technology readiness level (TRL) and research needs. H_2-DR is currently under development and the construction of pilot and demo plants has been initiated. Specifications regarding the current technology readiness level in the literature range from TRL 6 to TRL 8. The current TRL is correlated to the share of hydrogen in the direct reduction process, with lower TRLs for (almost) 100% hydrogen operation. Within the framework of the HYBRIT project, pilot operation is planned for 2020[8] (Agora Energiewende and Wuppertal Institut, 2019). Table 2 provides an overview of the estimated TRL development of H_2-DR.

Table 2: Estimated TRL development of H_2-DR (100% H_2)

Technology readiness level and industrial deployment		
in 2020	**estimated for 2030**	**estimated for 2050**
TRL 6-8	TRL 7-9	industrially deployed

Regarding research needs within H_2-DR, the technology and the auxiliary processes need to be upscaled and optimised. The influences on physical and chemical properties of DRI are not sufficiently investigated and it is a known fact that carbon-free direct reduced iron is highly prone to exothermic re-oxidation. It follows that industrial handling needs to be considered carefully. Due to the lack of carbon, the current electric arc furnace melting process must be slightly adapted to ensure a stable operation, since a small amount of carbon is currently required in the electric arc furnace to produce a foamy slag and avoid energy losses from the electric arc. Thus, the needed R&D activities include, among others, researching carbon-free material melting and transport behaviour as well as slag foaming in the following electric arc process. Additionally, investigations on operational flexibility at fluctuating supply of electricity from renewable sources need to be conducted. (HYBRIT, 2016-2017).

Furthermore, the by-products of these processes will be a topic to focus on. It is not clear yet if the use of oxygen as a by-product of water electrolysis can be economically and technically feasible (e.g. oxyfuel-applications). Another by-product worth mentioning is electric arc furnace slag. Today, blast furnace slag is used by cement producers, resulting in significant CO_2 mitigation, while basic oxygen furnace, electric arc furnace and other slags cannot be used in cement factories yet. Therefore, one important R&D focus will be to create new fields of application as well as make the slags from these CDA processes applicable, for example, as clinker substitutes.

R&D in the field of CDA can be summarised as follows:

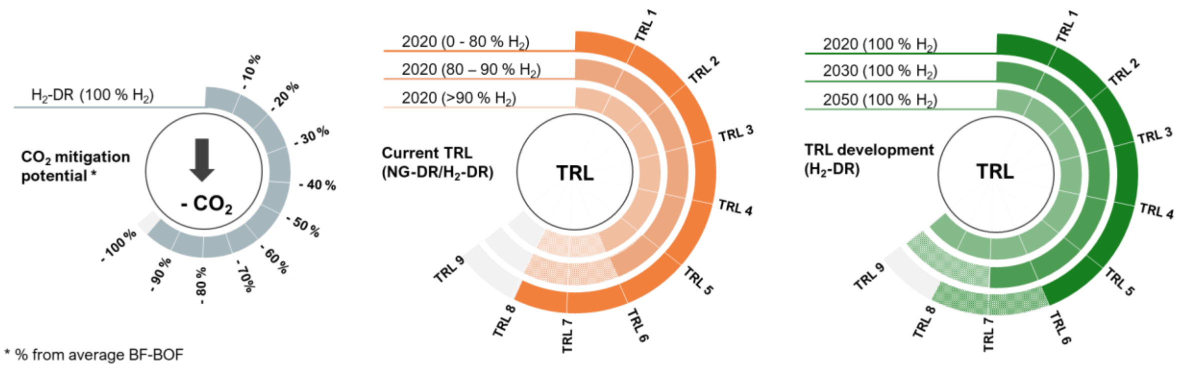
- adjustment of natural gas-based direct reduction towards increased hydrogen usage;
- use of alternative hydrogen-rich reducing gases;
- define feasibility to link hydrogen production with the metallurgical process (e.g. demand, fluctuations in operation and hydrogen storage);
- economically feasible solutions for the use of oxygen as a by-product of electrolysis;
- effects of carbon-free metallurgic processing and ways for carbonising direct reduced iron;
- develop fossil-free agglomeration of iron ore; use of alternative iron oxides;

[8] For further details, please see www.hybritdevelopment.com.

- risk assessment regarding hydrogen handling;
- carbon-free direct reduced iron melting and transport behaviour; and
- industrial validation/demonstration.

Graphical overview. Figure 7 below provides an overview of the CO_2 mitigation potential as well as TRL development of hydrogen direct reduction.

Figure 7: Graphical overview of CO_2 mitigation potential and TRL development (H_2-DR)



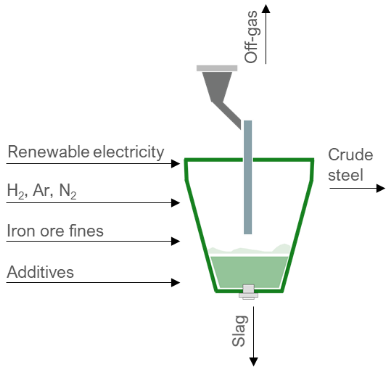
Source: author's own composition.

2.1.2 Hydrogen plasma smelting reduction

Technical description. Hydrogen plasma smelting reduction (HPSR) is a direct transformation from iron oxides into liquid steel by means of ionised H_2 (H^+, hydrogen plasma). Pre-treatment of the ore used is not required and coking plants, sinter plants, blast furnace and basic oxygen furnace would be substituted, contrary to the conventional BF-BOF route.

Required feedstock, energy sources and other materials. The plasma generated by passing an electric current through a gas acts as reducing agent and generates the required energy to melt metallic iron. Argon (Ar) or nitrogen (N_2) are added to the process to conduct the current in the plasma arc. Ar is the preferred choice due to its high ionisation energy and conductivity. The mixture is injected through a hollow graphite electrode into the arc zone of the reactor. The reactor (Figure 8) is electrically insulated, and water cooled from the outside. The exhaust gas is discharged through the lid and then cleaned in a downstream process stage. The non-consumed hydrogen can be reused and the oxidation product (H_2O) is separated from the off-gas. (Bäck, 1998; Schenk, 2018).

Figure 8: Schematic and simplified view of hydrogen plasma smelting reduction



Source: author's own composition based on (Badr, 2007).

Reference projects. In Europe, Austrian steel manufacturer voestalpine Stahl focused on HPSR in the framework of the SuSteel project as well as within the frame of Austrian government-funded competence centre program K1-MET (Austrian Research Promotion Agency, 2017).

Economic assessments. There is currently no precise information on CAPEX or OPEX. Generally speaking, OPEX data are linked to electricity costs, resource costs (e.g. ore, additives and alloys) and other variable costs (maintenance, labour, graphite electrodes).

Energy needs. The expected energy requirement is about 4.2 MWh/t CS (total electrical energy demand including hydrogen production). Similar to H_2-DR, this technology is associated with increased electrical energy requirements compared to the current integrated route.

CO_2 reduction potential. The CO_2 mitigation potential of hydrogen plasma smelting reduction in combination with renewable energy is expected to have a saving potential up to 95% compared to the BF-BOF route (LowCarbonFuture, 2020).

TRL and research needs. The basic feasibility of producing steel directly from iron oxides by hydrogen plasma has already been evaluated in lab-scale. To continue the development towards technological implementation, a pilot plant has been built within project SuSteel. Hydrogen plasma smelting reduction is currently under development with a technology readiness level of approximately 5. Table 3 provides an overview of the estimated TRL development of HPSR.

Table 3: Estimated TRL development of hydrogen plasma smelting reduction

Technology readiness level and industrial deployment		
in 2020	**estimated for 2030**	**estimated for 2050**
TRL 5	TRL 6	TRL 9

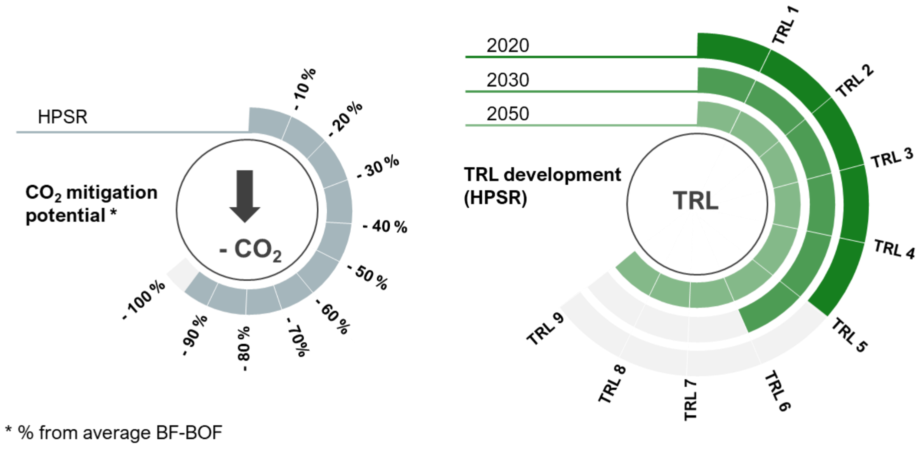
Regarding research needs, the technology and the auxiliary processes must be upscaled and optimised.

R&D main needs are:

- process optimisation for continuous mode operation (instead of batch operation);
- defining feasibility to link hydrogen production with the metallurgical process (e.g. demand, fluctuations in operation and hydrogen storage); and
- process upscaling.

Graphical overview. The figure below (Figure 9) provides an overview of the CO_2 mitigation potential as well as TRL development of hydrogen plasma smelting reduction.

Figure 9: Graphical overview of CO_2 mitigation potential and TRL development (HPSR)



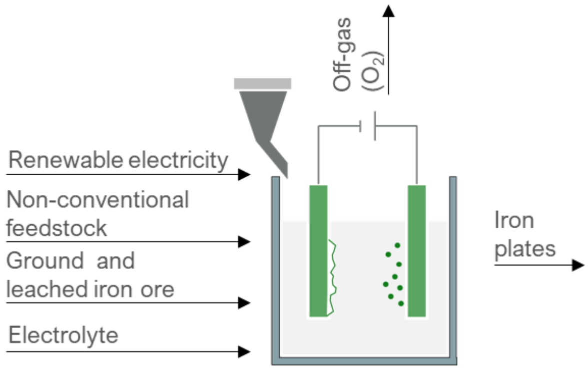
Source: author's own composition.

2.1.3 Alkaline iron electrolysis

Technical description. Low temperature alkaline iron ore electrolysis, or electrowinning, is the direct deposition of iron from its ores on an electrode. Most mitigation technologies proposed for electric arc furnace and all technologies recommended for further process steps (reheating furnaces, hot rolling, downstream) can be combined with alkaline iron electrolysis. It can be easily compared to H_2-DR: both routes produce direct reduced iron-like material, which must be melted in an electric arc furnace and then follow a conventional steelmaking route. In electrowinning, current is passed from an inert anode through a liquid alkaline solution containing small iron particles that deposit and reduce onto the cathode (Figure 10).

Required feedstock, energy sources and other materials. This technology requires preliminary grinding iron ores and leaching out part of their gangue before electrical reduction. Non-conventional feedstock (i.e. by-products from non-ferrous metallurgy residues) can also be used in this process. Suitable electrolytes and process conditions (110°C) are also required.

Figure 10: Schematic and simplified view of alkaline iron electrolysis



Source: author's own composition.[9]

Because of the nature of the alkaline process and its low temperature operation (110 °C), it can be easily adapted to the intermittent nature of renewable electricity: the process can be easily stopped and restarted to take full advantage of low-cost electricity periods, while avoiding production during expensive high-demand periods. The electrolysis step produces almost pure iron plates which must be further melted in an electric arc furnace to provide crude steel for the following refining processes. Natural gas for burners and/or pulverised coal for slag foaming still must be used for the electric arc furnace step, except if replaced with non-fossil alternatives. Additionally, scrap, direct reduced iron or any other iron source could be added into the electric arc furnace. As the steel is produced mainly from ores, the process can provide high-quality steel with low residuals or tramp elements. During the electrolysis step, the released gas is almost pure oxygen, which can be recovered, compressed, and used in the electric arc furnace and downstream processes. An electrolyte make-up is necessary (small amounts of electrolyte are lost when extracting iron plates). Gangue leaching before electrolysis produces some sludge as a by-product and electric arc furnaces produce the usual by-products, i.e. slag, dust and off-gases.

Reference projects. This technology has been and is still studied in different projects, such as ULCOS (SP5-13-14, ULCOWIN), ASCoPE, IERO, VALORCO and SIDERWIN[10] (French National Research Agency, 2007-2013; Lavelaine de Maubeuge, 2016). The latter project, SIDERWIN, is supported by H2020 SPIRE and is planned to be completed in 2022.

Economic assessments. Considering that the process can be run on conventional pellet-feed-type ore, OPEX data is fully linked to the cost of electricity (see specific energy needs below). Any forecast on the price of electricity can easily be used to calculate OPEX. Low-cost electricity (intermittent power used only in low-demand periods) will profitably be valorised in this route. Similar to the H_2-DR-EAF route, CAPEX is linked to the full replacement of the upstream part of the BF-BOF route (coke plant, sinter plant, blast furnace, basic oxygen furnace); this can be roughly estimated at €800/t CS annual capacity.

The production costs for 2050 (including specific capital cost/t CS, operating costs, electricity use, other costs (raw ore, scrap, alloys, lime, coal, compensation for loss of metallurgical gas use) are

[9] For further details, please see www.siderwin-spire.eu.
[10] H2020 Project ID: 768788: Development of new methodologieS for InDustrial CO2-freE steel pRoduction by electrowinning

expected to be between €645 and €828/t CS (Agora Energiewende and Wuppertal Institut, 2019). Obviously, electricity costs would largely increase when fossil fuel expenditure will be reduced.

Energy needs. Based on the last 15 years of R&D on the subject[11] (French National Research Agency, 2007-2013; Lavelaine de Maubeuge, 2016), the energy requirement of the process is estimated as follows, for a total energy need of 3600 kWh/t CS:

1. ore preparation (grinding, gangue leaching): 400 kWh/t CS
2. electrolysis and production of oxygen: 2750 kWh/t CS
3. plate melting (electric arc furnace) and steel casting (similar to the H_2-DR-EAF route): 450 kWh/t CS

In terms of energy, electricity is required only for ore electrolysis and further melting of plates produced in the EAF.

CO_2 reduction potential. If electricity is generated by renewable means, CO_2 emissions could be very low, with a mitigation potential of up to 95% of direct CO_2 emissions compared to BF-BOF (including upstream processes and rolling).

TRL and research needs. The electrowinning process is currently under development with a technology readiness level of approximately 5-6. The development and construction of a pilot plant is currently in progress and the construction of a demonstration plant is expected for 2030. The current SIDERWIN project is bringing TRL level from 4 (at start) to 6 (in 2022). It is then estimated that TRL 7 can be fully reached in 2030 and final TRL 9 demonstrated in 2040.

Table 4: Estimated TRL development of alkaline iron electrolysis

Technology readiness level and industrial deployment		
in 2020	**estimated for 2030**	**estimated for 2050**
TRL 5-6	TRL 6-8	TRL 9

In terms of specific further R&D needs, beyond process scale-up (maximum cell size, arrangement of multiple cells) and demonstration at industrial scale, the following elements can be mentioned:

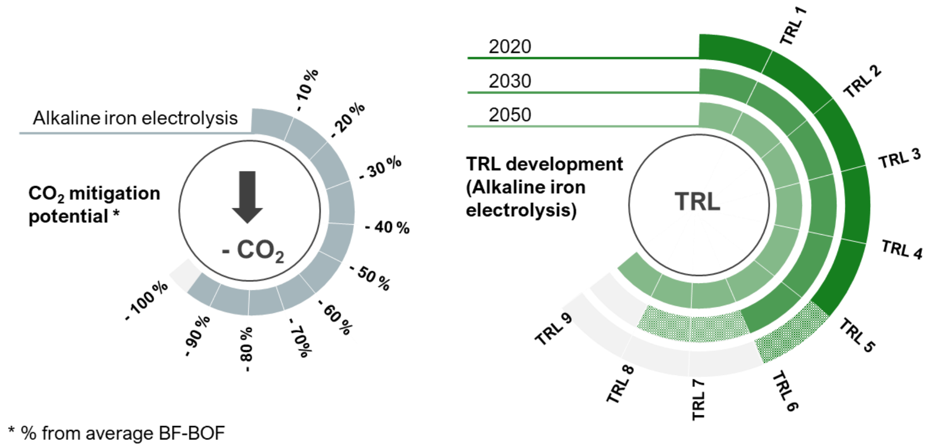
- utilisation of secondary raw materials as iron source (mine tailings, by-products, etc.);
- cost reduction (cell building materials);
- recovery of oxygen, purification, and compression;
- automated, large-scale harvesting of metal plates;
- continuous supply of input material according to its consumption;
- smart integration of electrolysis plants to the power grid;
- handling, post-processing and storage of iron plates;
- charging of metal plates in the electric arc furnace or other melting processes (induction furnace, etc.);
- slagging mechanism in the electric arc furnace;
- applicability of biogenic carbon sources in the electric arc furnace;
- optimisation of melting conditions at the electric arc furnace or other melting processes (induction furnace, etc.); and

[11] H2020 Project ID: 768788: Development of new methodologieS for InDustrial CO2-freE steel pRoduction by electrowinning

- valorisation of electric arc furnace slag (new fields of application and/or modification regarding its applicability as clinker substitute) and electric arc furnace dust (alternative to start-of-the-art treatment routes).

Graphical overview. Figure 11 below provides an overview of the CO_2 mitigation potential as well as the TRL development of alkaline iron electrolysis.

Figure 11: Graphical overview of CO_2 mitigation potential and TRL development (alkaline iron electrolysis)



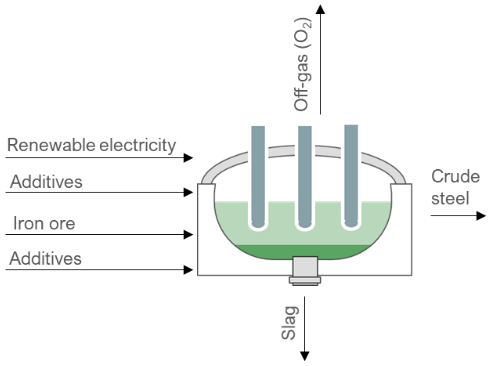
Source: author's own composition.

2.1.4 Molten oxide electrolysis

Technical description. Molten oxide electrolysis (MOE) is an electrometallurgical technique enabling the direct production of liquid state metal from oxide feedstock. Compared with traditional extractive metallurgy methods, molten oxide electrolysis seems to offer at once substantial simplification of the process and significant reduction in energy consumption. It is a fully electrified route, from unprepared iron ore to liquid steel, and a single-step process with a unit operation where iron ore is decomposed, and iron metal is melted like in aluminium electrolytic cells.

Required feedstock, energy sources and other materials. Molten oxide electrolysis does not require any leaching operation and the ore is directly melted in the electrolysis slag. Basically, the process only needs virgin ores and additives for slag conditioning as feed materials and is able to provide liquid crude steel (in fact almost pure liquid iron) to feed the steelmaking chain without any further steps (Figure 12). Until now, molten oxide electrolysis has been demonstrated using anode materials that are consumable (graphite for use with ferro-alloys and titanium) or unaffordable for steelmaking applications (iridium for use with iron). To enable metal production without process carbon, molten oxide electrolysis either requires anode material capable of resisting depletion while sustaining oxygen evolution or has to use a different anode principle such as a consumable iron oxide anode.

Figure 12: Schematic and simplified view of molten oxide electrolysis



Source: author's own composition.[12]

Electrolysis slag and some dust are generated along with the iron, but the released gas is almost pure oxygen, which can be recovered, compressed, and used for downstream processes.

Reference projects. This technology is currently being developed in the EU, mainly by ArcelorMittal (ULCOS, IERO and VALORCO projects) and in the USA by the MIT and the Boston Metal company (Agora Energiewende and Wuppertal Institut, 2019; Lavelaine de Maubeuge, 2011; Wang, 2011).

Economic assessments. The process can be run on raw iron ore and therefore OPEX data are fully linked to the cost of electricity (see specific energy requirement below). CAPEX is linked to the full replacement of the upstream part of the BF-BOF route (coke plant, sinter plant, blast furnace, basic oxygen furnace); this can be roughly estimated at €1 K/t CS annual capacity according to an analogy with aluminium plants.

Energy needs. Based on experimental laboratory results and on extrapolation by engineering scale-up, the overall energy need is estimated at 4.1 MWh/t CS.

CO_2 reduction potential. CO_2 mitigation potential is calculated at 96% of the direct CO_2 emissions of the BF-BOF route (including up streams and rolling).

TRL and research needs. Principally, electrolysis is not a new technology when it comes to the production of metals. However, in this form of application, it is still considered a comparatively young technology. The current technology readiness level of molten oxide electrolysis is low (estimated at 2). The VALORCO project has developed a plan to address proof of concept, which corresponds to TRL 3. Through intensive R&D efforts on technology development (anode, refractory lining, etc.) and scale-up issues, TRL it is expected to be brought to level 9 by 2050, allowing the industrial deployment in the following years.

Table 5: Estimated TRL development of molten oxide electrolysis

Technology readiness level and industrial deployment		
in 2020	**estimated for 2030**	**estimated for 2050**
TRL 2	TRL 3-4	TRL 9

The technological challenges for iron production are numerous. Process temperature is very high, making cell containment difficult, especially considering the corrosive nature of molten slag.

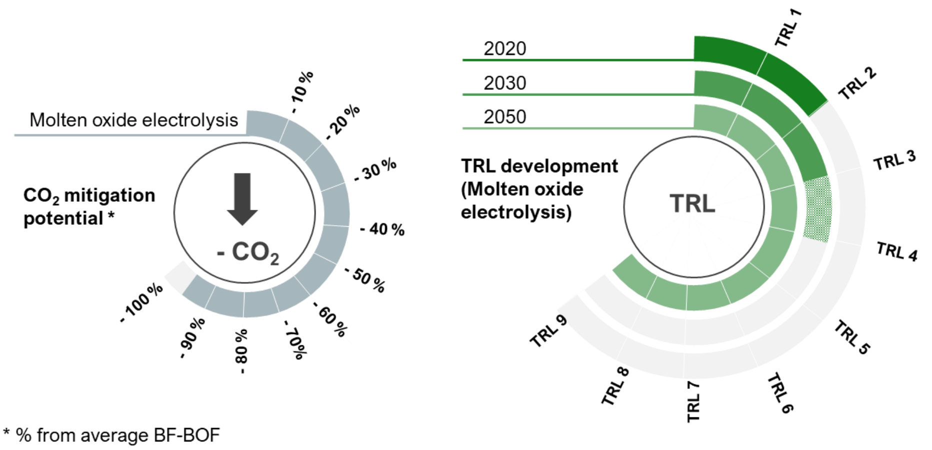
[12] For further details, please see www.siderwin-spire.eu.

R&D main needs are:

- investigation of operational flexibility at fluctuating supply of electricity from renewable sources (e.g. demand needed, fluctuations in operation and storage of electricity);
- improvement of efficiency;
- inert anode development and improvement; long-term anode stability; and
- process upscaling.

Graphical overview. Figure 13 below provides an overview of the CO_2 mitigation potential as well as TRL development of molten oxide electrolysis.

Figure 13: Graphical overview of CO_2 mitigation potential and TRL development (molten oxide electrolysis)



Source: author's own composition.

2.2 Carbon capture and usage

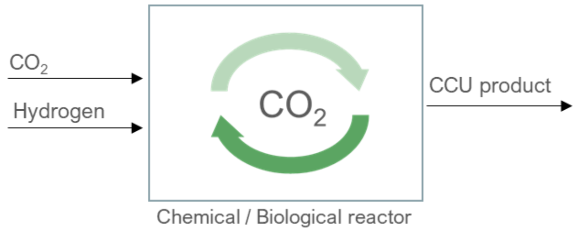
In general, CCU is defined as the overall process of capturing carbon oxides and converting them into more valuable products. As such, it combines the processes of carbon capture and other auxiliary processes (e.g. water electrolysis) with a step of chemical or biological conversion. The conversion step is characteristic for CCU technologies. Required auxiliary CO_2 capture or water electrolysis processes will be presented at a later stage (see 2.4).

2.2.1 Carbon oxide conversion

Technical description. 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, 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.

Required feedstock, energy sources and other materials. CO_2 capture from the industrial process gases is the first step of many CCU processes. CO and CO_2 conversion processes can be categorised based on the type of conversion (e.g. chemical or biological) as well as on the desired product (e.g. fuel, chemical, polymers or their precursors and synthesis gases). Typically, additional auxiliary units, e.g. the provision of other process gases such as hydrogen, are required. At this stage, the conversion of carbon oxides into other products is being defined and assessed. Technologies for capturing CO_2 as well as for producing hydrogen are described in Section 2.4.

Figure 14: Schematic and simplified visualisation of CCU



Source: author's own composition.

Reference projects. Current chemical conversion pilot and demonstration projects exist, namely Carbon2Chem® by ThyssenKrupp, BASF, Covestro, Linde and others or Carbon4PUR by ArcelorMittal, Covestro, Recticel, Dechema and others (Dahlmann, 2019; Agora Energiewende and Wuppertal Institut, 2019). Within Carbon2Chem®, the partners are investigating the conversion of coke oven gas, blast furnace gas and basic oxygen furnace gas into methanol or higher alcohols (Agora Energiewende and Wuppertal Institut, 2019). In Carbon4PUR the conversion of these gases into precursors for polyurethane production is being explored (Agora Energiewende and Wuppertal Institut, 2019). The biological conversion of carbon oxides is being researched, among others, by the STEELANOL project by ArcelorMittal and LanzaTech (Dahlmann, 2019; Agora Energiewende and Wuppertal Institut, 2019). The project is investigating the conversion of carbon monoxide into ethanol by bacteria (Agora Energiewende and Wuppertal Institut, 2019; Ghenda, 2017).

Economic assessments. The increase in CAPEX by carbon oxide conversion is estimated to €129/t of annual production capacity of crude steel or €13/t CS. The effect on OPEX is related to three different sources. The increased electricity demand results in additional OPEX of €30-35/t CS. Hydrogen provision causes OPEX to increase between €310/t CS and €526/t CS. Other materials require additional OPEX of €68/t CS. This results in total OPEX increase of €408-629/t CS. Overall, the production costs of CS are expected to increase between 63% and 119%. (Agora Energiewende and Wuppertal Institut, 2019)

Combining the economical assessment with the CO_2 mitigation potential, specific CO_2 abatement costs of €231-439/t CO_2 are estimated for carbon oxide conversion processes in 2030. Costs are expected to decrease to €178-379/t CO_2 in 2050. (Agora Energiewende and Wuppertal Institut, 2019)

Energy needs. The main energy demand for carbon oxide conversion processes is related to the production of hydrogen. If there is no external or internal source of hydrogen available, hydrogen has to be produced, for example, via water electrolysis, resulting in a significant electrical energy demand of 4-5 kWh_{el}/m^3 H_2 (see Section 2.4.2). The specific electric energy demand at full technological maturity is estimated at 3.6 MWh_{el}/t CS (Agora Energiewende and Wuppertal Institut, 2019). Additional thermal energy demands for the conversion processes may arise, depending on the specific technology.

CO_2 reduction potential. The overall CCU mitigation potential by carbon oxide conversion is estimated to up to 63% (Agora Energiewende and Wuppertal Institut, 2019). In terms of biological conversion processes, a 30-50% CO_2 mitigation potential in terms of electricity production is stated in (Ghenda, 2017). As the conversion processes rely on the direct utilisation of process gases from integrated steel mills or on the post-process separation of carbon oxides from them, CCU concepts can generally be combined with other CO_2 mitigation technologies that still leave carbon oxide-bearing process gas streams available.

TRL and research needs. Both types of chemical and biological carbon oxide conversion processes currently have a TRL of 8 (Dahlmann, 2019). The overall system for their implementation within integrated steel plants is currently in the demonstration phase, resulting in TRLs of 4-5 (Agora Energiewende and Wuppertal Institut, 2019). The first industrial deployment and the achievement of TRL 9 are estimated for the years 2025-2030 (Agora Energiewende and Wuppertal Institut, 2019). In the long-term scale, a full industrial deployment of this technology is expected by 2050. The expected TRL development of carbon oxide conversion processes is summarised in Table 6.

Table 6: Estimated TRL development of carbon oxide conversion

Technology readiness level and industrial deployment		
in 2020	**estimated for 2030**	**estimated for 2050**
TRL 8 (conversion process) **TRL 4-5 (integration into steel production)**	TRL 9	industrially deployed

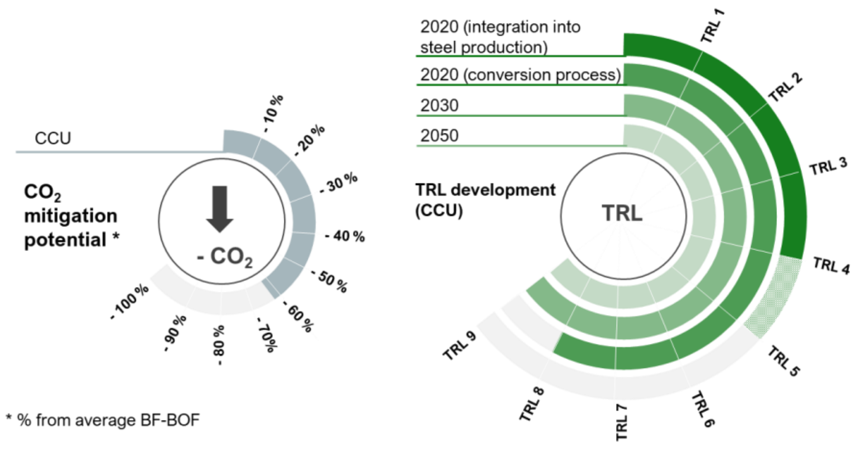
Current R&D needs are: research on process integration as well as industrial demonstration. Currently, both the application in integrated steel works for the production of valuable products or precursors as well as the possible integration into local industry clusters for further precursor processing are topics of interest. The application into integrated steel works is the subject of industrial demonstration.

R&D main needs are:

- process integration into existing plants; and
- industrial demonstration.

Graphical overview. Figure 15 below provides an overview of the CO_2 mitigation potential as well as TRL development of carbon capture and usage.

Figure 15: Graphical overview of CO_2 mitigation potential and TRL development (CCU)



Source: author's own composition.

2.3 Process integration

The PI pathway refers to existing steel plants and their possible adaptations to emit less greenhouse gases. There are numerous alternatives, including circular economy options.

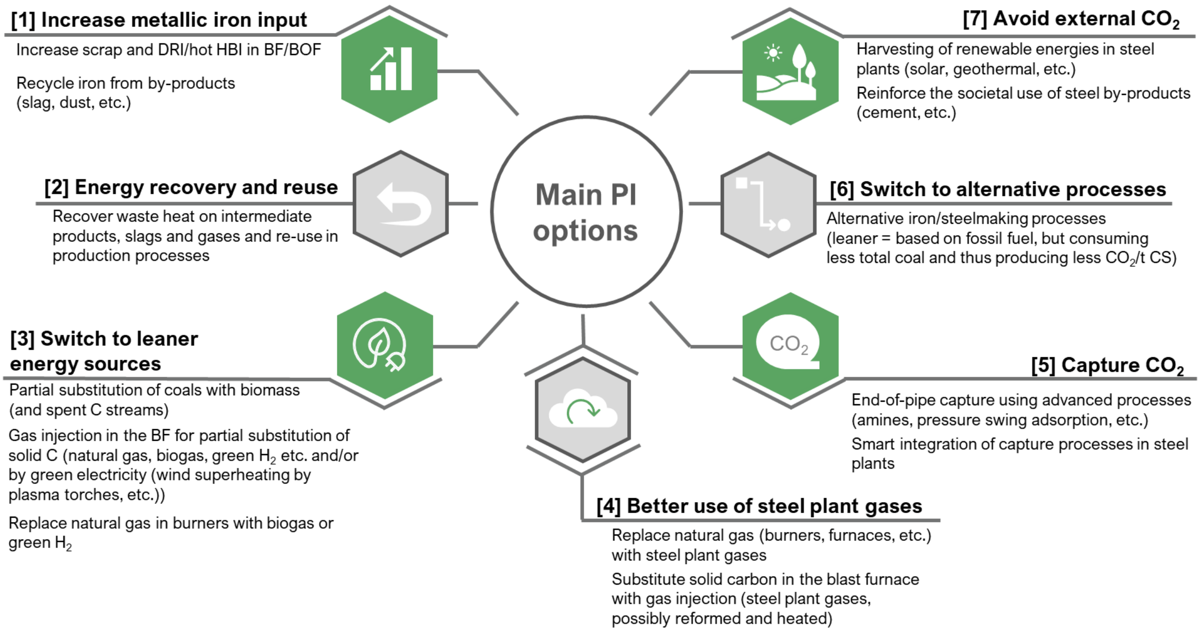
Significant local specificities exist in each steel plant, which are basically linked to:

- raw materials available;
- access to transportation networks;
- product mix (grades of steel, type of products);
- level of plant integration (internal/external production of coke, sinter, pellet, lime, oxygen, power, etc.);
- local availability of raw materials/residues/energy sources at low cost;
- direct environment of the plant (sea shore, proximity to a city, etc.); and
- many other factors.

All the mitigation options described here cannot be applied to each and every steel plant with the same effects.

The main PI options are presented in the figure below (Figure 16). Moreover, these options can often be combined in one plant to reach higher mitigation potentials. They can even reach negative CO_2 emission levels, when combining actions on fossil fuels (involving biomass) and capture (CCUS).

Figure 16: Overview of main PI options



Source: author's own composition based on (Borlee, 2020).

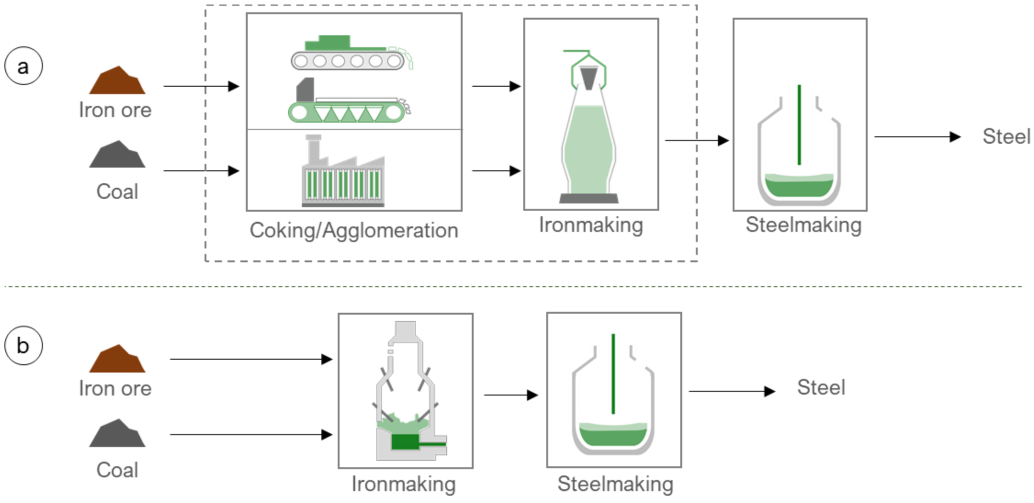
Among these options, a selection was made according to mitigation potential, applicability in existing plants and R&D requirements. Against this background, the following were selected:

- option 6 (alternative iron/steelmaking processes), more particularly iron bath reactor smelting reduction (IBRSR) processes;
- option 3 (switch to leaner energy sources), focusing on gas injection into the blast furnace and on substitution of fossil fuels by biomass;
- option 4 (better use of steel plant gases) for what also connects to gas injections into the blast furnace; and
- option 1 (increase metallic iron input), through increased scrap usage.

2.3.1 Iron bath reactor smelting reduction

Technical description. One of the options to mitigate the CO_2 emissions of BF-BOF plants is to switch to a leaner alternative iron/steel production process. This means a process that is still based on fossil fuels but consumes less total coal, and thus produces less CO_2 than conventional blast furnaces, while fitting into existing facilities (brownfield construction projects). Among the PI options, this is the one that obviously implies more significant changes to existing plants. Compared to the blast furnace route, IBRSR eliminates the cokemaking and ore agglomeration steps (Figure 17). This results in considerable streamlining of the ironmaking facilities for integrated steelmaking works.

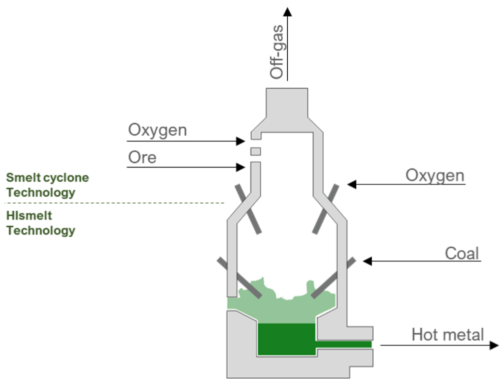
Figure 17: Comparison of the integrated steelmaking route (a) and the HIsarna® technology (b)



Source: author's own composition based on (Tata Steel, 2019).

Required feedstock, energy sources and other materials. IBRSR (e.g. HIsarna®) is an ironmaking process that can produce liquid hot metal directly from raw materials, namely iron ore fines and coal. HIsarna® (Figure 18) consists of a reactor in which iron ore is injected at the top. 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 is the base material to produce high-quality steel. Due to the full O_2 operation, the gases leaving the HIsarna® reactor are concentrated on CO_2. The technology removes several pre-processing steps and requires less stringent conditions on the quality of the raw materials used. This results in efficiency gains.

Figure 18: HIsarna® technology



Source: author's own composition based on (Tata Steel, 2019).

Reference projects. HIsarna® was first studied in ULCOS, then in several successive research programmes by a consortium of EU partners led by Tata Steel (Tata Steel, 2019; Meijer, 2015). An 8 t/h pilot plant is operated by Tata Steel at its European site of IJmuiden. A study for the installation of CO_2 capture (purification and compression) facilities at the pilot plant was recently completed (project timescale expected: 2021-2025).

Economic assessments. CAPEX strongly depends on the scale. For a 1.15 Mt/year plant, Tata Steel estimates an investment at €500 M, excluding the oxygen plant (€435/t-capacity). For a

1.5 Mt/year plant (future IJmuiden design), the costs per ton-capacity should be lower, around 400 €/t.

OPEX is expected to be negative (-€25/t CS to -€30/t CS) due to various efficiency gains, the use of low-grade raw materials (non-coking coals, notably) and lower personnel cost.

Energy needs. For the HIsarna® reactor, based on pilot plant campaigns results, the (green) electrical energy consumption of a full-sized production reactor is estimated at 0.5 MWh per ton of crude iron.

CO_2 reduction potential. This technology reduces CO_2 emissions by 20% and reduces the emissions of fine particles, sulphur dioxide and nitrogen oxide by 60-80%. HIsarna® also allows the recovery of zinc from coated steel scrap.

Since the HIsarna® installation produces highly concentrated CO_2 as off-gas, it is suited for carbon capture and either storage (CCS) or use (CCU), without the need for a costly gas separation stage. The combination of HIsarna® with storage could lead to total CO_2 savings of 80% from the steel production process. The HIsarna® mitigation potential, when calculated on a full production perimeter, from raw materials to hot rolled coil is -10% to -15% without CCUS and increases to -80% to -85% with carbon capture.

TRL and research needs. Most of the technologies in Figure 16 have currently reached high technology readiness levels (TRLs) of 6 to 8 and can be progressively activated in the short to mid-term, since the necessary R&D&I has been successfully completed. In general, they still require industrial testing and demonstration before deployment.

The current TRL of HIsarna® is 6 (large pilot plant operated for years in an industrial environment) and scale-up to 7 is under way. Several production campaigns have already been performed on the pilot plant inside Tata Steel's Ijmuiden plant. TRL 8 is expected in 2030 and TRL 9 and industrial deployment are expected in 2035.

Tata Steel is planning for industrial implementation of HIsarna® and CO_2 capture at IJmuiden in 2033. After the first demonstration, the industrial deployment of this technology is foreseen in the mid-term (from 2040 on).

Table 7: Estimated TRL development of iron bath reactor smelting reduction

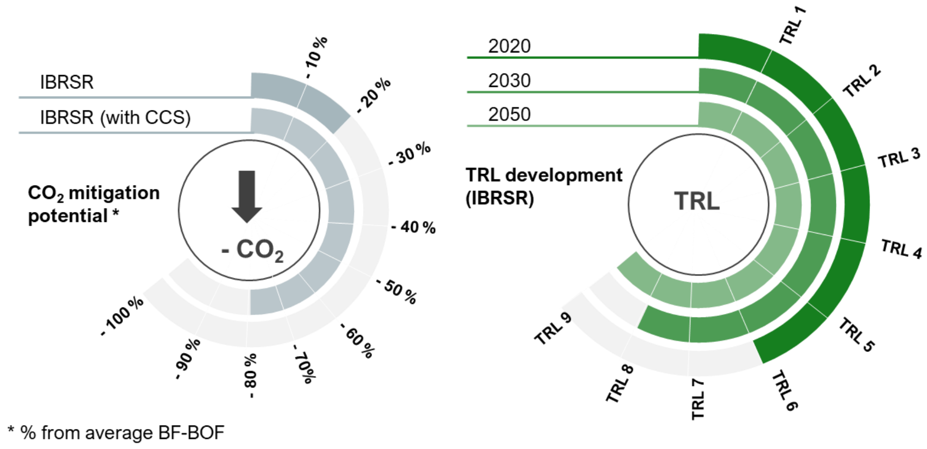
Technology readiness level and industrial deployment		
in 2020	**estimated for 2030**	**estimated for 2050**
TRL 6	TRL 8	Industrially deployed

The main R&D needs are:

- demonstration of alternative processes; and
- combination of technologies.

Graphical overview. Figure 19 below provides an overview of the CO_2 mitigation potential as well as TRL development of the iron bath reactor smelting reduction technology.

Figure 19: Graphical overview of CO_2 mitigation potential and TRL development (IBRSR)



Source: author's own composition.

2.3.2 Gas injection into blast furnace

Technical description. In BF-BOF plants, the blast furnace process is by far the process step where most of the fossil carbon is consumed. Both, the coke charged with the burden at blast furnace top and/or the coal injected in blast furnace tuyeres (pulverised coal injection) can partly be substituted by injecting reducing gas, preferably hot, directly into the reduction bed.

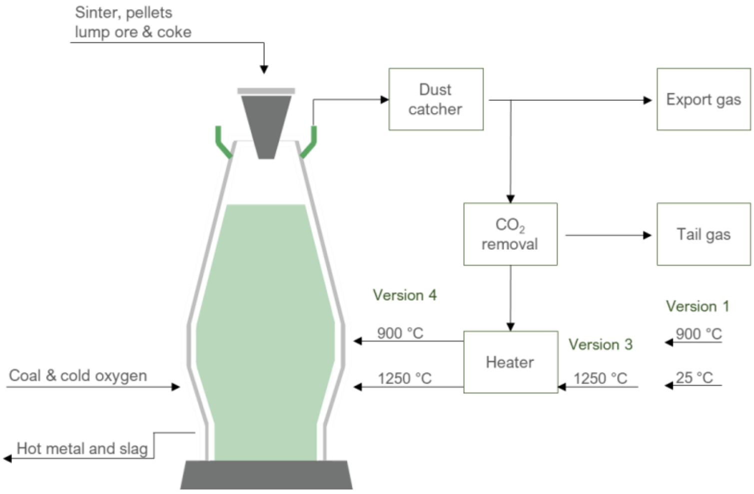
To efficiently mitigate CO_2 emission, the injected reducing gas can originate from various sources:

- green hydrogen, produced from low-CO_2 electricity;
- natural gas and all non-conventional fossil gases (shale gas, tight gas, coal-bed methane, etc.) or – even better from a CO_2 perspective – biogas, methanation gas or syngas produced from biomass; these methane-containing gases require purification, heating and/or reforming to be really beneficial to blast furnace operation;
- gas resulting from carbon recycling inside the steel plant: either steel plant gases (that are partly combusted to produce electricity) or gases resulting from CCUS processes applied inside steel plants; these gases also generally require filtration, compression, purification (removal of CO_2 and H_2O), heating and/or reforming to be suitable for blast furnace operation.

Required feedstock, energy sources and other materials. A specific process was developed for direct carbon recycling in blast furnace: the top gas recycling blast furnace (TGR-BF), where the top gas is recycled inside the blast furnace itself after CO_2 removal and re-heating (Figure 20). To avoid nitrogen build-up, the blast furnace needs to operate on oxygen instead of a hot blast. Whatever the origin of the reducing gas, the heating step before injection is a real technical challenge in terms of materials (metals and refractor lining); one of the possible options is to combine heating with reforming in a plasma system powered with green electricity. This combination is currently studied in the IGAR project.[13]

[13] ArcelorMittal funded by French agency ADEME: IGAR: Validation pré-industrielle de l'injection de gaz réducteur dans un haut-fourneau sidérurgique.

Figure 20: Schematic view of TGR-BF



Source: author's own composition.[14]

Reference projects. In Europe, this technology was studied and tested on pilot scale (1.5 t/h) in the frame of the ULCOS project.[15]

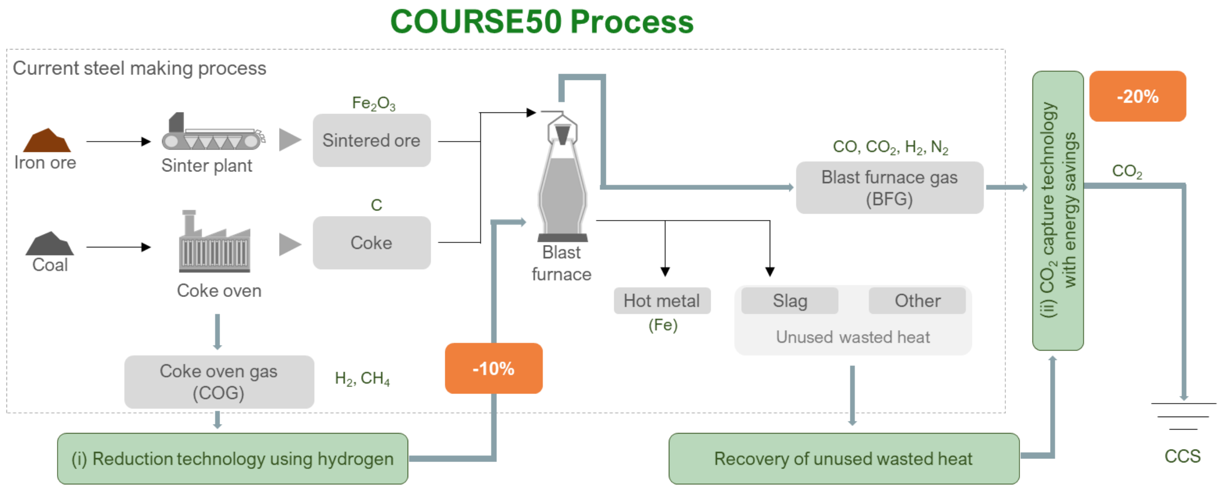
Regarding world-wide approaches, the Japanese COURSE50 program (Figure 21) is aiming to reduce CO_2 emissions in steel production by combining various options, including hydrogen gas injection into the blast furnace. COURSE50 stands for 'CO_2 Ultimate Reduction System for Cool Earth 50' (Birat, 2020) and consists of two adjustments to the conventional blast furnace process (Nippon Steel Corporation, 2019; New Energy and Industrial Technology Development Organization, 2019):

- amplification of hydrogen content in coke oven gas and its utilisation as replacement for coke as a reducing agent; and
- CO_2 separation from blast furnace gas using unused exhaust heat and storage or usage of the captured CO_2.

[14] Based on: ULCOS Subprojects SP 1 to SP 15.

[15] ULCOS Subprojects SP 1 to SP 15; RFSR-CT-2004-00005 ULCOS new Blast Furnace Process (ULCOS), 01/07/2004 to 30/06/2009; RFSR-CT-2009-00002 ULCOS Top gas recycling blast furnace (ULCOS TGRBF), 01/03/2009 to 31/12/2012.

Figure 21: 'COURSE50' process scheme



Source: author's own composition (Nippon Steel Corporation, 2019).

The reduction technology developed using hydrogen requires the injection of a hydrogen-rich gas mixture through the tuyeres. This mixture would be provided by coke oven gas resulting from the production of coke. The injection is meant to split the cohesive zone into two regions: in the bottom part, the direct reduction of iron ore by carbon takes place and in the upper part iron ore is reduced by hydrogen via indirect reduction. Both reactions are endothermic, therefore the required thermal energy must be provided by combustion at the tuyere noses as well as from the exothermic CO indirect reduction of descending burden. In a conventional blast furnace, approximately 60% of the ferrous burden is reduced by CO indirect reduction, approximately 10% by hydrogen indirect reduction and 30% by carbon direct reduction.

Within the COURSE50 concept, the injection of hydrogen-rich gas mixtures is complemented by CO_2 separation of blast furnace gas for further CO_2 mitigation. The thermal energy demand of this step is intended to be covered by currently unused waste heat. The results of this development lead to ESCAP® (energy saving CO_2 absorption process) and have been demonstrated in two cases outside the steel industry. The processed blast furnace gas with increased shares of CO and hydrogen is intended to be re-injected into the blast furnace, similar to the TGR-BF concept described before.

Economic assessments. CAPEX and OPEX data are largely dependent on the origin of the injected gas, on the extent of gas injection (in Nm^3/t CS) and on the gas pre-treatment steps required/considered (from cleaning to heating). As concerns the TGR-BF process, the following numbers can be given: CAPEX: €80-110 /t CS annual capacity without CCUS and €110-150/t CS with CCUS (i.e. including all the necessary purification and compression steps required for CCUS); and OPEX: in the range between €0-10/t CS without CCUS and €40-50/t CS with CCUS. It must be noted that OPEX values largely depend on reference prices taken for coke, electricity and O_2. Furthermore, impacts on the internal gas nets have to be considered. These can be quite different, depending on the approach used and the local conditions.

Energy needs. When modifying a blast furnace for gas injection, the additional energy need is largely dependent on the equipment lay-out. In simple reducing gas injection (as coke oven gas), simple compression and cleaning of the gas should be sufficient and not requiring a significant amount of energy. In the case of hydrogen injection, the main energy consumer would be the hydrogen production step (e.g. water electrolysis). And in the more complex case of flue gases injection, some steps are needed: catching, cleaning, separation – if needed – from CO_2, compression, heating and potential reforming. In the case of project IGAR, the estimated external energy demand was 2 MWh per ton of hot metal, largely compensated by the gain in carbon consumption. Furthermore, it has to be considered that recycling BF gas disables its current utilisation for the production of heat and power. This results in additional energy needs in the corresponding parts of the plants and may particularly inhibit the integrated plant to remain self-sufficient in terms of external power supply.

CO_2 reduction potential. Because it combines gas injection in the blast furnace with oxygen operation, carbon recycling, gas heating and CO_2 capture, 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 (Ghenda, 2017). Without CCUS (thus releasing the captured CO_2 into the atmosphere), the savings are limited to 35% at blast furnace level and 15-20% on a full production perimeter. The COURSE50 reduction technology is expected to raise the share of hydrogen indirect reduction to 20%, reducing the share of carbon direct reduction to 20%. Thus, 10% of CO_2 emissions are expected to be mitigated by this measure (Nippon steel Corporation, 2019; Higuchi, 2020). In case of permanent storage of the separated CO_2 (CCS), CO_2 emissions could be lowered by further 20%, resulting in a 30% total decrease thanks to the COURSE50 concept (New Energy and Industrial Technology Development Organization, 2019).

TRL and research needs. The current technology readiness level (Table 8) of these technologies is between 5 and 8 and their time horizon is industrial deployment on the mid-term (2040). The injection of H_2-rich gas mixtures has already been demonstrated on industrial scale and can be rated as TRL 9, although several R&D challenges remain (e.g. adaption of BF and raceway processes at high injection rates). Several experiments have already been performed at lab and pilot scale as well as digital modelling. Estimating that gas injection alone can save at a maximum 100 kg coke/t CS, the corresponding mitigation potential of blast furnace gas injection is 15-20%. The TGR-BF process is currently at TRL 7 (engineering of an industrial demo plant).

Table 8: Estimated TRL development of gas injection into the blast furnace

Technology readiness level and industrial deployment		
in 2020	**estimated for 2030**	**estimated for 2050**
TRL 5-8 (preparation / gas **reforming)** **TRL 9** **(H_2-rich gas mixtures)**	TRL 8-9	Industrial deployment

The main R&D needs for the industrial implementation of gas injection options are: pre-processing of the various gases, especially steel plant gases and biogas (filtering, compression, purification, reforming); industrial demonstration of large plasma torches in heating/reforming applications; and gas injection systems in the blast furnace (modified tuyeres, injections in shaft).

The main external limiting factor is the availability of biogas, green hydrogen and green electricity when needed. The injection of metallurgical gases into the BF is a measure which enables significant short-time CO_2 mitigation in many plants due to the high TRL.

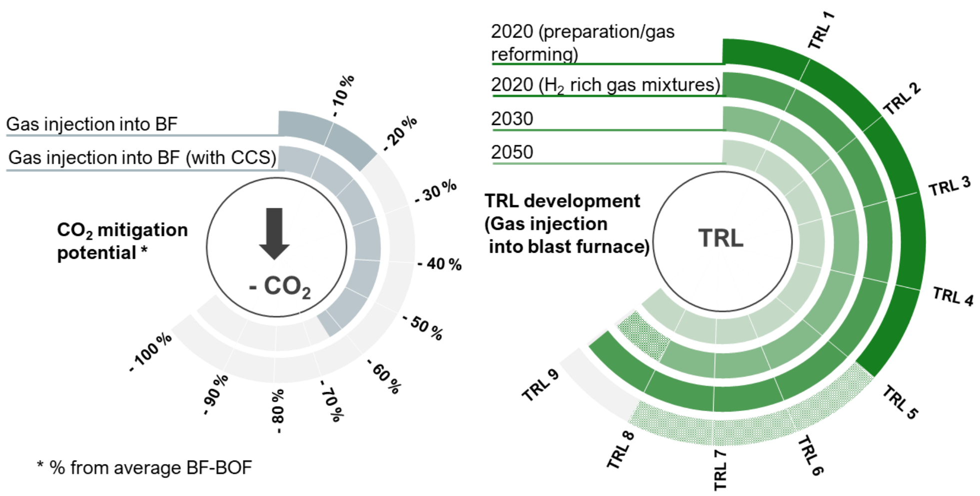
R&D main needs are:

- gas injection systems in the blast furnace;
- processing of steel plant gases (cleaning, separation, reforming, compression, etc.);

- industrial demo of large plasma torches;
- pre-processing of biogas;
- adaptation of advanced capture processes to capture conditions; and
- in-process integration of capture.

Graphical overview. Figure 22 below provides an overview of the CO_2 mitigation potential as well as TRL development of gas injection into blast furnace.

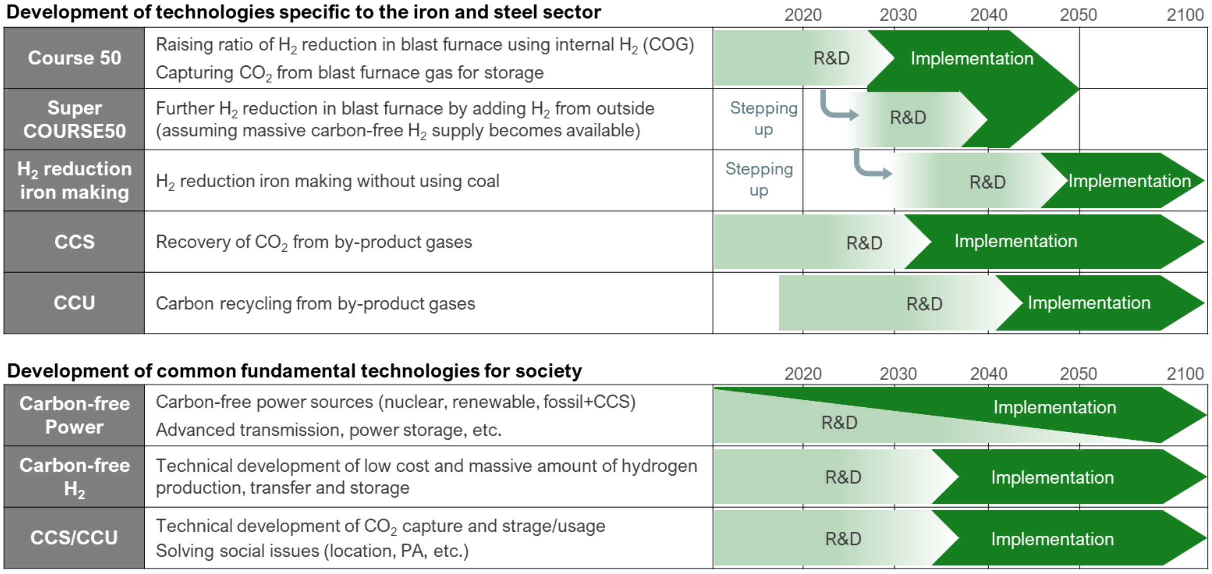
Figure 22: Graphical overview of CO_2 mitigation potential and TRL development (gas injection into blast furnace)



Source: author's own composition.

The current state of technological development of the Japanese COURSE50 program is characterised by the development of so-called 'super-innovation technologies'. In 2018, the Japan Iron and Steel Federation announced the Challenge to Zero Carbon Steel with the target of developing zero-carbon emission steel production by 2100. The roadmap for Japanese technology development and implementation regarding future iron and steel production is illustrated in Figure 23 (Nippon Steel Corporation, 2019).

Figure 23: Roadmap for the Japan Iron and Steel Federation long-term vision for climate change mitigation



Source: author's own composition based on (Japan Iron and Steel Federation, 2019).

2.3.3 Substitution of fossil energy carriers with biomass

Technical description. Fossil coal can also be substituted by biomass and carbon-containing waste. Regarding biomass, secondary biomass, i.e. residues from biomass processing, will presumably be most relevant for industrial processing in order to minimise costs and prevent competition with food production. For simplification, within this report the overall term 'biomass' is used to summarise the different materials.

Required feedstock, energy sources and other materials. Because of high moisture and volatile contents, most biomass materials have to undergo some level of preliminary thermal treatment such as torrefaction or carbonisation beforehand. In BF-BOF plants, some pre-processed biomass can be blended to the coal charge of coke ovens, replace anthracite in the sinter plant mix or be used in the blast furnace as a substitute of injected coal (pulverised coal injection) or coke. In some steel plants without iron ore sintering processes, biomass products (torrefied material or charcoal) can be used to make cold-bonded briquettes together with in-plant fines, then top charged into the blast furnace. Due to the high reactivity of biomass products, low thermal reserve zone temperature could be obtained, improving the overall efficiency of the blast furnace and leading to low coke consumption.

In electric arc furnace plants, carbonised biomass can substitute coal injected in the melting furnace and/or charged in scrap baskets. Biomass options should not be limited to charcoal produced from harvested wood: alternative biomass sources are varied and range from agriculture to the paper and food-processing industry, and should also include secondary wood (spent wood from the construction/demolition sector). The use of these alternative biomass sources is attractive because of the availability and low market value of these materials. Moreover, the use of spent carbon streams, much like plastic fractions, paper and biogenic materials in societal waste streams, is an option that also allows to increase the circularity of carbon use and spare natural resources. However, these carbon-rich organic residues usually need to be upgraded before use in order to obtain the required metallurgical properties (grindability, low ash and volatile content, low alkali content, etc.). Furthermore, local availability is a major limiting factor to avoid further emissions and costs. This sets clear limits for the complete mitigation potential of this technology.

Reference projects. A large number of projects dealing with biomass were performed during the last years and some are still running, especially in Nordic countries, where forestry resources are abundant. Following are several selected examples:

- RFSR-CT-2005-00001 Short term CO_2 mitigation for steelmaking (SHOCOM), 01/07/2005 to 30/06/2008, Report EUR 24989;
- RFSP-CT-2014-0003 Biochar for a sustainable EAF steel production (GREENEAF2), 01/07/2014 to 30/06/2016);
- RFSR-CT-2007-00003 Alternate carbon sources for sintering of iron ore (ACASOS), 01/07/2007 to 31/12/2010, Report EUR 25151;
- RFSR-CT-2010-00001 Innovative carbon products for substituting coke on BF operation (‘INNOCARB’), 01/07/2010 to 31/12/2013, Report EUR 27121;
- H2020 project ID 745810 – Torero;
- NYPS 20200224, EU Interreg Nord project of RENEPRO - Renewable Energy Sources in Steel Plant Processes: Biomass-based Reductants, Fuels and Chemicals. Metal industries and wood-based biomass industries are important for the Nordic countries. Metal production is for the most part based on the use of fossil-based energy sources, thus leading to significant CO_2 emissions. The main objective of this research project is to demonstrate the technological, economic and environmental feasibility of the novel bioeconomy-steel industry production platform (integrated steel, bio-based reductant and chemical production) with extensive laboratory investigations, system analysis and carbon footprint assessments. Biomass reductants are wood-based biochar;
- OSMET project, financed by the Swedish Innovation Agency, Vinnova. The project aims at investigating the possibilities of using hydrochar produced by the hydrothermal carbonisation process by using various types of organic sludge in various metallurgical applications. Since they contain valuable components (coal and lime), they help to mitigate climate impact while at the same time sustainably reducing waste to landfill; and
- Bio-agglomerate project, financed by the Swedish Energy Agency. The objective of this project was to improve blast furnace energy efficiency by controlling thermal reserve zone temperature via top charging bio-briquettes, i.e. developed biomass containing burden material.

Economic assessments. CAPEX values are relatively low and only the pre-processing and upgrade of biomass and alternatives has to be integrated in steel plants. OPEX values and external limiting factors for these options depend mainly on raw materials (price and availability).

Energy needs. The energy consumption to turn biomass into usable form (biocoal in most of the cases) is highly dependent of initial biomass quality (size, moisture, fumes treatment in case of paints etc.). A wide range of 3 to 20 MWh per t of biocoal could be foreseen.

CO_2 reduction potential. It is estimated that the mitigation potential of these options is 25-30% (in full steel plant emissions). Moreover, they can be combined with other mitigation routes, such as gas injection in the blast furnace or CCUS.

TRL and research needs. Current TRL is 2 to 7, TRL 8 is expected in 2030, TRL 9 and industrial deployment in 2035 (Table 9).

Table 9: Estimated TRL development of substitution of fossil energy carriers with biomass

Technology readiness level and industrial deployment		
in 2020	**estimated for 2030**	**estimated for 2050**
TRL 2-7	TRL 8	industrially deployed

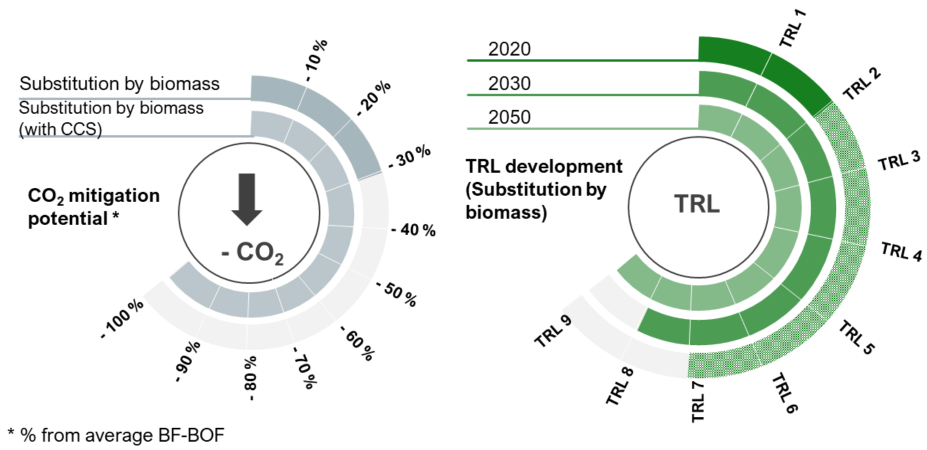
The main R&D needs to demonstrate these options focus on pre-processing (e.g. drying) and upgrading (e.g. pyrolysis and hydrothermal carbonisation): test, scale-up and optimisation of processes, with special focus on smart integration in steel plants (energy, logistics, off-gas treatment, etc). It will also be necessary to perform validation tests (substitution trials) to demonstrate the high potential of biomass and spent carbon.

Among R&D challenges, one can cite:

- production of biogas (based on new types of biogenic materials as well as scale-up issues in regard to the quantities required by the iron and steel industry);
- pre-processing of biomass and biogas for application in the iron and steel industry; and
- substitution trials (coke, sinter, blast furnace, electric arc furnace).

Graphical overview. Figure 24 below provides an overview of the CO_2 mitigation potential as well as TRL development of the substitution of fossil energy carriers with biomass.

Figure 24: Graphical overview of CO_2 mitigation potential and TRL development (substitution by biomass)



Source: author's own composition.

2.3.4 High-quality steelmaking with increased scrap usage

Technical description. Producing steel from iron ore consumes almost 3 times more energy and generates 2.5 times more emissions per ton of crude steel than the production from recycled scrap. Therefore, enhancing metallic iron recycling, both externally (directly produced in the manufacturing plants) and internally (produced and used inside the workshop) is an important topic in the steel industry. Scrap is mainly fed to electric arc furnaces. It can also be used in basic oxygen furnaces. However, its potential is limited by the energy demand for melting. Furthermore, it strongly depends on individual quality requirements.

Required feedstock, energy sources and other materials. Scrap contains several residual and alloying elements (Cu, Sn, Sb, As and Bi, but also Cr, Mo, B), which prevent the production of many steel grades. Thus, the potential of this approach strongly depends on the individual steel grade produced and its quality requirements and is consequently specific to different steel producers.

Depending on its premature usage, the concentrations of those impurities vary strongly. This may be overcome to some extent, but more actions are necessary to increase the use of scrap, not only in terms of technological development (International Energy Agency, 2017). To achieve increased scrap usage, significant changes in scrap handling (collection, preparation, and use) are required together with the implementation of technological innovations.

The main guidelines for increasing scrap usage are (Energy Transition Commission, 2018):

- indirect increase (avoiding the progressive lowering of steel quality from scrap by implementing systems for on-line analysis, characterisation, and sorting);
- increasing scrap yield; and
- direct increase (avoiding the minor loss of steel scrap, which is not recycled).

Reference projects. The projects CONOPTSCRAP (CONOPT SCRAP, 2009), FLEXCHARGE (FLEXCHARGE, 2013), and ADAPTEAF (Elsabagh, 2019) provide examples for increasing scrap yield. The general aim of these projects is to allow the best and most economic use of scrap in steelmaking operations.

The European project SSIA was focused on the development and assessment of solutions to strengthen and maintain refractory properties and prevent excessive wear rate in the scrap impact area of BOF converters (SSIA, 2013). The project demonstrated the reliability of repairing techniques and defined operating practices that can apply to industrial operations.

Regarding the indirect increase of scrap usage, several projects have tackled the issue of progressive lowering of steel quality from recycled scrap. The goal is to increase the ability to identify, select and separate scrap in the bulk composition – by implementing solutions based on modern systems for on-line analysis and scrap sorting. Several techniques have been investigated in European projects, including: laser-induced breakdown spectroscopy, prompt gamma neutron activation analysis (PGNAA), pulsed fast thermal neutron activation (PFTNA), and muons tomography. Different levels of reliability and industrialisation are reported in the projects LCS (LCS, 2012), IPRO (IPRO, 2016), SCRAP PROBE (SCRAP PROBE, 2013) and MU-STEEL (MU-STEEL, 2014). In the project SUPERCHARGEEAF, statistical methods are applied to calculate the likely accuracy of the estimated material properties of individual materials. The project aims at the development of a supervision system for early detection of charge materials in EAF with incorrect properties, thereby supplying information for charge optimisation in view of the target.[16] The projects regarding the development of new process pre-treatment include REDILP[17], PROTECT (PROTECT, 2015) and FIMECC (Aromaa, 2016).

Economic assessments. Regarding increased scrap yield, the costs for implementing analysis and sorting technologies can be considered marginal. An estimation is reported in the final report

[16] SUPERCHARGEEAF Supervision of charge material properties in EAF steelmaking utilising advanced statistical methods.

[17] REDILP: Recycling of EAF dust by an integrated leach-grinding process (REDILP).

of the ADAPTEAF project (Elsabagh, 2019) concerning the costs for installation, maintenance, and current use of the various technological systems. Globally, the CAPEX to be invested for the different measures is about €115 K, and the OPEX for maintenance and additional probes amounts to approximately €40 K/year. These OPEX/CAPEX amounts have to be compared to the cost savings in electrical energy, estimated at €95 K/year, and to the cost savings generated by increased productivity, estimated at €200 K/year. Thus, the amortisation time for the total costs of all measures performed within the project is well below one year. This result cannot be directly extrapolated to the whole European steel industry due to very different quality requirements of different producers. Furthermore, it must be considered that increased scrap demand in Europe may significantly raise the price of high-quality scrap, which is already much higher than the price of virgin materials as iron ore or pellets.

Energy needs. The production of steel from metallic iron (scrap) requires about 75% less energy than the production from iron ore. The energy input is mainly required for melting, whereas the energy-intensive reduction of virgin iron ore oxides becomes obsolete.

CO_2 reduction potential. The use of scrap in an EAF accounts currently for about 0.4 t/CO_2 per ton of CS, also considering the indirect emission for electricity generation, with potential further reduction when electrical energy is produced from renewable resources – this compares to CO_2 emissions of about 1.9 t/CO_2 per t/CS via the conventional integrated route. The flexibility of scrap utilisation is limited by product quality requirements. The metallurgical quality requirements of high-quality steel products usually force a significant use of virgin iron ore (despite its energy demand) and limit the use of scrap as raw material. This is expected to be also the case for the foreseeable future, even if several producers will probably be able to increase their scrap usage after some technological progress.

Furthermore, almost all of EU's scrap is recycled (either in Europe itself or after export to other countries). Decreasing the scrap exports to achieve a circular economy and to mitigate CO_2 emissions in Europe will therefore increase emissions in other parts of the world. Since steel production in many other countries is more CO_2 intensive as in Europe, a decrease of scrap exports may even result overall in an increase of worldwide CO_2 emissions.

TRL and research needs. The following table (Table 10) provides an overview of individual approaches with regard to the increased use of scrap as well as their TRL development and necessary research needs.

Table 10: Overview of TRL development regarding high-quality steelmaking with increased scrap usage

Technology readiness level and industrial deployment					
Technology	**TRL 2020**	**TRL 2030**	**R&D needs**	**Focus**	**Estimated 2050**
Implementation of digitalisation, industry 4.0, blueprint solutions	8	9	Adaptation to scrap market and management	Demo projects	Routine use
Development of new processes for scrap pre-treatments	5–6	7–8	Complete validation of the low environmental impact	Research projects	Large diffusion
Development of technologies facilitating the use of scrap in conventional processes	8	9	No significant needs	Not attractive	Niche application
Measurement systems and equipment for continuous on-line and off-line scrap analysis and sorting	4–7	8–9	Improved performance. Reliability, easy use	Research projects	Large diffusion
Process optimised and more flexible to increase scrap yield	6–8	9	Adaptation of the current processes to more variable feedstocks and more flexible operations. Key performance indicator-based approach	Research project	Large diffusion
Circular economy approach	6–7	9	Cross sectorial Integration of materials and technological solutions	Cross-sectorial projects	Industrially deployed
Scrap quality upgrading	6–7	9	Development, improvement of scrap cleaning, upgrading, etc. technologies	Research project	Large diffusion

Source: (FLEXCHARGE, 2013; SSIA, 2013; LCS, 2012; IPRO, 2016; SCRAP PROBE, 2013; MU-STEEL, 2014, SUPERCHARGEEAF, 2017, REDILP, 2007; Murri, 2019; SCHROTT24, 2018).

2.4 Auxiliary processes

The main auxiliary processes/supporting technologies connected to the described iron and steelmaking technologies are CO_2 capture and hydrogen generation.

2.4.1 CO_2 capture

Technical description. Generally, the separation of CO_2 contents from gas streams can be technically implemented in three different ways: before its utilisation ('pre-combustion'), after its usual utilisation ('post-combustion') and after its utilisation with pure oxygen ('oxy-combustion').

Required feedstock, energy sources and other materials. The pre-combustion capture mainly applies to CO_2 capture from synthesis gases. In post-combustion capture, the gas streams to be treated consist of relatively low CO_2 concentration, as in most cases air is used for oxidation, resulting in higher shares of nitrogen in the exhaust gases. In oxy-combustion capture, oxidation with pure oxygen is utilised, so that exhaust gases mainly consist of H_2O and CO_2. The separation of CO_2 can then be achieved by water condensation. For applications in the iron and steel industry, 'post combustion' CO_2 capture is currently the most relevant. Decarbonisation technologies utilising CO_2 capture are CCU technologies as well as e.g. TGR-BF or COURSE50 (see Section 2.2 and 2.3.2).

The most suitable process principle for post-combustion capture lies in the chemical absorption process. The CO_2 capture potential by application of amine scrubbing in an industrial blast furnace is estimated at 50-75% of overall CO_2 emissions (Leeson, 2017; Bardow, 2018).

An alternative to chemical absorption is the application of adsorption processes such as vacuum pressure swing adsorption. Adsorption technologies are currently processing significantly smaller gas flows than provided by integrated steel works.

Reference projects. Current research projects of carbon capture in the context of iron and steel production are given in e.g. FReSMe and STEPWISE. Among other targets, in FReSMe, CO_2 capture from process gases of an integrated steel mill is going to be demonstrated. In STEPWISE, the utilisation of sorption-enhanced water gas shift adsorption for CO_2 capture is investigated in a pilot plant of 580 kg CO_2 per hour.

Economic assessments. Based on a generic steel plant located in Finland, a required CAPEX of approximately €90/t CO_2 to be captured annually was calculated. The correlating OPEX accounts for approximately €40/t CO_2 separated (Skagestad, 2014). Current production costs of iron and steel production range around €391/t CS with emissions of 1876 kg CO_2/t CS, resulting in CO_2 specific crude steel production costs of €208/t CO_2. Assuming a depreciation period of 15 years, the CAPEX and OPEX of CO_2 capture results in a production cost increase of 22%. A study conducted by Agora Energiewende calculated a production cost increase of 63-119% incurred by implementing an overall CCU process (Dahlmann, 2019; Agora Energiewende and Wuppertal Institut, 2019).

Energy needs. The energy demand correlated with post-combustion capture by chemical absorption is 2.5-2.9 GJ/t CO_2 (Moser, 2018). It is required mainly in the form of thermal energy, allowing for e.g. the integration of excess heat from other processes. The production of crude steel via the BF-BOF route requires 11 GJ of thermal energy per ton of crude steel (Fruehan, 2000), resulting in 5.9 GJ/t emitted CO_2 in current production processes. Subsequently, CO_2 capture by chemical absorption requires an additional 42-49% of the thermal energy required for crude steel production by the current BF-BOF route. For adsorption technologies, energy consumption values of 0.5-0.7 GJ/t CO_2 are reported (Agora Energiewende and Wuppertal Institut, 2019; Shen, 2012). This amount is required mainly as electrical energy. Thus, it is not directly comparable to the mainly thermal energy demand of amine scrubbing.

TRL and research needs. The current state of CO_2 capture in steel production plants in terms of technology readiness lies in the range of TRL 5-6.[18] The achievement of TRL 9 is expected in mid-range around 2030-2040, followed by first industrial deployment. In the long-term, full industrial

[18] For further details, please see https://cordis.europa.eu/project/id/884418; www.fresme.eu.

deployment is expected by 2050. The expected technology readiness level development is summarised in Table 11.

Table 11: Estimated TRL development of CO_2 capture

Technology readiness level and industrial deployment		
in 2020	**estimated for 2030**	**estimated for 2050**
TRL 5-6	TRL 8-9	industrially deployed

Current R&D needs are:

- Setup of demonstration plants within the steel industry; and
- Development of more efficient absorbents.

2.4.2 Water electrolysis

Technical description. A wide variety of decarbonisation technologies relies on the utilisation of hydrogen, thus depending on its production. H_2-DR needs large amounts of hydrogen (see Section 2.1.1). In CCU processes, hydrogen is used to create stoichiometric synthesis gas for carbon conversion (see 2.2). In terms of PI measures, the increased hydrogen injection into the blast furnace is another application for hydrogen utilisation (see Section 2.3.2). Hydrogen plasma smelting reduction also relies on hydrogen utilisation (see Section 2.1.2).

Hydrogen can be generated by different processes differing in range of emission, energy source, operating conditions, material and cost. Currently, about 75% of hydrogen is produced from natural gas (International Energy Agency, 2019), whereby with respect to decarbonisation, it is recommended to target CO_2 lean production methods.

Water electrolysis is a process to produce hydrogen (and oxygen) from water by electric current. For industrial large-scale application, there are three specific technologies available: polymer electrolyte membrane (PEM) electrolysis, alkaline water electrolysis (AEL) and high temperature electrolysis (HTEL). These technologies differ in terms of electrolyte material, operating temperature and pressure as well as in the degree of maturity and capacity regarding dynamic operation.

Required feedstock, energy sources and other materials. Alkaline water electrolysis operation is mainly stationary at low operation temperatures (40-90 °C) and pressures (1-30 bar). Polymer electrolyte membrane electrolysis is also operated at low temperatures (20-100 °C), but at elevated pressure levels (30-50 bar). High temperature electrolysis requires temperature levels of 700-1,000 °C , exploiting lower energy demand for the separation process of water at higher temperatures. Operation at higher temperature levels allows the integration of e.g. industrial excess heat. An operation pressure level of 10-30 bar is targeted with raising technological maturity of high temperature electrolysis (Smolinka, 2018; Friedrich, 2013).

Reference projects. Water electrolysis as a process for industrial-scale hydrogen production is topic of numerous recent research projects. Close cooperation with the iron and steel industry occurs, among others in H2Future (voestalpine, K1-MET), GrInHy 2.0 (Salzgitter AG, Tenova, Paul Wurth) or WindH2 (Salzgitter AG).[19]

Economic assessments. For alkaline water electrolysis, the production capacity of 1 m^3 H_2 per hour translates to CAPEX needs of €3-5.5 K. Accordingly, the current CAPEX demand of polymer electrolyte membrane electrolysers is €6.7-7.5 K/(m^3 H_2) per hour, while high temperature electrolysis accounts for €5-13.6 K/(m^3 H_2/h). As the hydrogen production process via electrolysis is highly energy intensive and thus strongly correlated to energy prices, OPEX can at this stage only be regarded as increased operational cost for maintenance only. Under these assumptions, current values range from €11-15 per year and kW_{el} for polymer electrolyte membrane electrolysers to approximately €32 per year and kW_{el} for high temperature electrolysis. Current maintenance-related OPEX demand for alkaline water electrolysis accounts for €13-25/kW_{el} annually (Smolinka, 2018).

Energy needs. Hydrogen production via water electrolysis has significant energy demand, mainly in the form of electrical energy. Current electrical energy demand for polymer electrolyte membrane electrolysers and alkaline water electrolysis range from 4.4-4.9 kWh_{el}/m^3 H_2. As high temperature electrolysis also utilises thermal energy, the corresponding electrical energy demand is reduced to 3.8-3.9 kWh_{el}/m^3 H_2 (Smolinka, 2018).

TRL and research needs. Regarding the current technology readiness level of water electrolysis, there are technology-specific differences. Currently, polymer electrolyte membrane electrolysers and alkaline water electrolysis range between TRL 7-8, while high temperature electrolysis is currently ranging between TRL 5-6. Technological maturity on an industrial scale is expected for polymer electrolyte membrane electrolysis and alkaline water electrolysis by 2030. High temperature electrolysis is estimated to take until 2040 to reach TRL 9. Overall, all three solutions are expected to reach industrial deployment in the long-term by 2050. The technology readiness level development of water electrolysis technologies is summarised in Table 12 (LowCarbonFuture, 2020).

Table 12: Estimated TRL development of water electrolysis

Technology readiness level and industrial deployment		
in 2020	**estimated for 2030**	**estimated for 2050**
TRL 7-8 **(PEM electrolysis and AEL)** **TRL 5-6 (HTEL)**	TRL 9 (PEM electrolysis and AEL) TRL 7-8 (HTEL)	industrially deployed

Current research needs of high temperature electrolysis are further technological improvements, such as internal process optimisation. Then this solution will move on to the phase in which polymer electrolyte membrane electrolysis and alkaline water electrolysis already are: facing the challenges of process upscaling to industrial demands and integration into industrial processes (LowCarbonFuture, 2020). The development of electrolysis matters both in terms of its investment and operating cost, as well as its energy efficiency and flexibility. Analysing the development of

[19] For further details, please see www.h2future-project.eu; www.green-industrial-hydrogen.com; www.windh2.de.

electrolysis with the aim of understanding the various driving markets and applications is needed to understand the risks and opportunities of this technology development.

2.5 Summary of the assessed technologies

The technologies identified within this chapter can be classified into the two pathways carbon direct avoidance and smart carbon usage. While carbon direct avoidance deals with new processes utilising new reducing agents (hydrogen or electricity), smart carbon usage focuses on the optimisation of the existing and carbon-based steel manufacturing route.

Hydrogen-based processes, which are part of the carbon direct avoidance pathway, involve technologies that use hydrogen as a reducing agent. Thereby, iron ore is reduced either in the liquid state (hydrogen plasma smelting reduction) or in the solid state (hydrogen-based direct reduction). The electricity-based processes also belong to the carbon direct avoidance pathway and are processes in which electricity is used directly to produce steel by electrolysis of iron ore. Such processes can be performed either at high or low temperature.

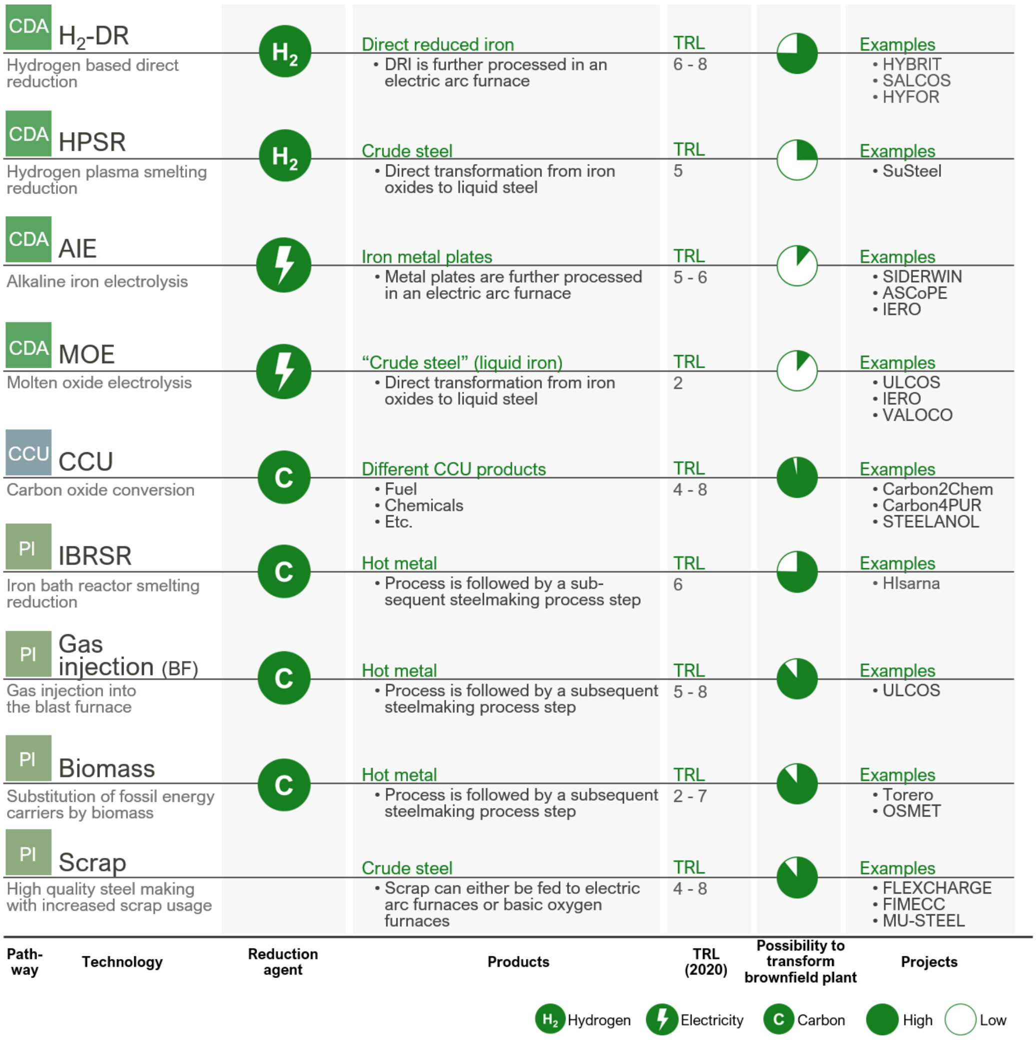
Technologies in the field of process integration, which is a part of the smart carbon usage pathway, are devoted to process modifications of existing steel plants either to reduce CO_2 production or to capture CO_2 in line with production processes. This includes alternative iron or steelmaking processes. Process integration can be divided into several subgroups. In the context of this deliverable, the focus is on iron bath reactor smelting reduction, gas injection into the blast furnace, substitution of fossil energy carriers by biomass as well as increased usage of high-quality scrap.

Carbon capture and utilisation, another pathway within smart carbon usage, involves the capture of CO_2 or CO from process gases in the steel industry and the production of other valuable products. Carbon captured in process gases is utilised through various inorganic, biological and chemical processes to generate products such as carbonates for the construction sector, fuels, or basic chemicals (ethanol, methanol, urea, etc.) or polymers and polymer precursors. Most information provided for CCU is also valid for the alternative of storing the captured CO_2 (CCS) instead of processing it into new products (also referred to in a general way as CCUS). Since the further handling of CO_2 after capture is not in the special focus of project Green Steel for Europe CCS and CCUS are not further discussed in detail.

Figure 25 provides a graphical summary of the technologies. Starting from the left, it displays the technology label including its associated pathway. This is followed by the reduction source (green dot) and the output of the process. The following two columns provide information regarding the current technology readiness level and an estimation concerning the possibility to transform a brownfield plant into a plant utilising the respective technology. A full circle (green) indicates high likelihood, while an empty circle (white) means low likelihood. The last column lists examples of projects within the respective mitigation technology.

In addition to the technologies listed, depending on country-specific regulations, carbon capture and storage technology can further increase the mitigation potential of decarbonisation technologies (especially when considering process integration).

Figure 25: Overview of mitigation technologies in the iron and steel industry



Source: author's own composition including information from (Ito, 2020).

The characterised technologies themselves are just a part of the complete steel production process chain. Therefore they have to be combined with the possible, but not mandatory, pre-treatment of raw materials (e.g. grinding, pelletising or leaching) and subsequent downstream processes (steelmaking, rolling and casting). Moreover, many of the technologies can be combined with one another in order to increase the degree of CO_2 mitigation. In addition to core technologies, auxiliary processes (hydrogen production, CO_2 capture technology) are needed. The following chapter defines promising combinations of processes and technologies as technology routes.

3 Setup of technology routes

Technology routes integrate several components (mitigation technologies) into a full system, in a complete steel production route (complete process chain) including both upstream operations (transformation of raw materials into intermediate steel products) and downstream units (production of final shaped and coated products). The CO_2 emission of downstream operations is limited. Therefore, the following discussion will be focused on the upstream side. The selected technology routes correspond to primary steel production, since energy and CO_2 emission-intensive primary steel production provides the highest CO_2 mitigation potential, in particular with regard to scope 1 emissions (which are main focus of this project).

Combinations of mitigation options in technology routes are by essence not limited to a specific mitigation pathway (SCU-PI, SCU-CCU or CDA) but may include elements from all of them. This section has thus been structured according to the classification of upstream operations. Currently, it is predominantly the conventional route based on blast furnace, basic oxygen furnace and hot rolling (BF-BOF) that needs to be modified with new breakthrough production processes.

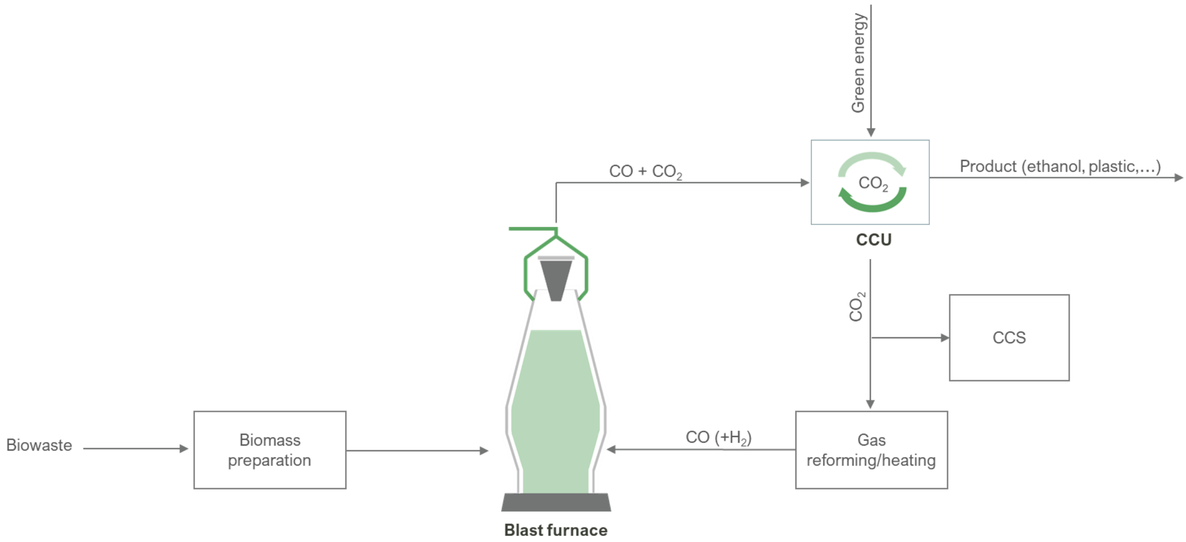
Four breakthrough technology routes are presented below. The first one is based on conventional BF-BOF plants, into which a number of CO_2 mitigation technologies are incorporated as add-ons or retrofits. This route was selected because it enables short-time transformation of many plants. The second one is based on the H_2-DR option, in which all ironmaking and steelmaking units have to be replaced with new production steps. This route also has the advantage of short-time CO_2 mitigation via NG-based DR, which can be utilised as an entry point into this route and be further improved by increased hydrogen contents in a flexible manner. The third one is based on smelting reduction and comprises an intermediate route, based on iron bath reactor smelting reduction and hydrogen plasma smelting reduction. Finally, the fourth technology route includes technology routes that are derived from technologies based on the electrolysis of ore.

3.1 Technology routes based on optimised BF-BOF

The heart of the technology routes in many existing assets is the blast furnace, where – by far – most of the carbon is consumed in conventional plants to enable the energy-intensive reduction of ores into hot metal. This conventional BF-BOF route can be optimised, mostly on the short-term, via several combinable options. Figure 26 below illustrates a combination of the basic options plugged on a blast furnace: partial replacement of fossil carbon (as presented in Section 2.3.3) with gas injection in the blast furnace (Section 2.3.2) and conversion of carbon oxides contained in the blast furnace top gas (CCUS to avoid combustion, Section 2.2.1).

As regards initial plant configuration and local specificities, this combination of technologies is flexible. Different biomass preparation processes can be proposed to prepare suitable bio-coal for injection in the blast furnace, to accommodate the various types of raw materials (woody biomass, green or secondary biomass, agricultural residues, sewage sludge or even mixed waste streams containing plastics and biogenic materials). Various options/combinations can be used for CCU and/or CCS operations. Gas injection (usually hydrogen-rich gases to minimise or to avoid CO_2 formation) can also be performed at different levels in the blast furnace (tuyeres, shaft) with different preparation steps required (cleaning, reforming, heating), depending on the origin of the injected gas: recycled steel plant gas, biogas, green hydrogen, etc. The TGR-BF process presented in Section 2.3.2 is one of the specific combinations of that kind.

Figure 26: Schematic and simplified view of a combination of mitigation technologies based on conventional BF-BOF



Source: author's own composition.

This initial core of combination options around the blast furnace can then be combined with additional mitigation technologies applied upstream and downstream the blast furnace, among them:

- substitution of a fraction of fossil coal with biomass or carbon-bearing residues at the coke plant;
- waste gas recirculation and use of low-CO_2 fuels at the sinter plant;
- increased scrap usage, mainly at the basic oxygen furnace plant (as presented in Section 2.3.4), but possibly also at the blast furnace; and
- operation of new heating applications on hydrogen or internally generated gases, provided these gases replace natural gas imported in the steel plant. This means e.g. new types of burners, especially for reheating furnaces in hot rolling plants.

3.1.1 Extent of modifications to be implemented in existing plants

Although the main existing process units are not replaced with new technologies for this proposed CO_2 mitigation route, very significant changes have to be carried out in conventional plants:

- the blast furnace requires gas injections which, if pushed to a significant level, require significant revamping of tuyeres, gas mains, gas distribution and possibly even blast furnace shell and structure. Furthermore, new safety, measurement and control measures are needed to handle new technologies and process states;
- the blast furnace stoves have to be completely or partly revamped and oxygen consumption in the blast furnace is significantly increased since additional heat is needed with an increasing replacement of carbon with hydrogen within the reduction process.

- around the blast furnace, many new plants have to be built with auxiliaries: the biomass preparation plant, CCUS units and gas heating/reforming plants, which are all significant in size, complexity and requirements (energy, storage, maintenance, etc.);
- coke, sinter and basic oxygen furnace plants can remain relatively unchanged, except if the additional mitigation options mentioned above for these plants are implemented; and
- energy and gas networks will require significant adaptations, including burners in heating applications since the blast furnace top gas will be significantly affected.

The estimated mitigation potential of this combined breakthrough route in comparison to an average BF-BOF plant can reach up to 100%. Indications for individual contributions are stated in the following table (Table 13).

Table 13: Estimated mitigation potential of specific technology routes based on optimised BF-BOF

	Mitigation potential (% of average BF-BOF plant)
Use of biomass and spent-carbon streams at the blast furnace	20-25%
Gas injection in the blast furnace **(including the energy required for preparing the gas)**	15-20%
Use **of some biomass and spent-carbon streams at the coke plant**	5%
Actions at the sinter plant	5%
Operation of heating applications using low-carbon fuel gas	5%
CCS on steel plant **gases**	40%
∑	90-100%

Source: author's own composition based on (LowCarbonFuture, 2020).

3.1.2 Framework conditions

To reach significant mitigation through this technology route, significant investments are required for add-on technologies (e.g. CCUS, biomass preparation, gas preparation and blast furnace gas injection systems).

Before biomass can be used within the steelmaking process, it generally needs to be prepared in terms of physical form and chemical content. Physical processing involves de-structuring like cutting, shredding, or crushing and, for some applications, pelletising or briquetting with a dedicated binder. Due to their generally high moisture and volatile content, a thermal pre-treatment (drying, then torrefaction or charring) is required for most biomass materials. Therefore, smart integration of these processes in conventional steel plants needs to be considered. Furthermore, there is still a lack of market infrastructure for biomass and biochar. The local availability of alternative carbon sources as well as pre-treatment processes have a significant impact on the chances and limits of their utilisation for an economic production, while the required know-how and the lack of availability of renewable energy can make the implementation of these options challenging.

When it comes to the integration of carbon capture processes, the costs of current end-of-pipe capture technologies are high (approximately €46/t CO_2, see 2.4.1), and the full mitigation potential of these technologies only comes into effect if the captured CO_2 can afterwards be stored or utilised. Energy-efficient separation and purification technologies may be required for the utilisation of CO_2 from industrial waste gas streams. Further aspects to be taken into consideration are the targeted CCU products and cost-competitive access to CO_2 for the valorisation of the different applications. In addition, many products synthesised from CO_2 require hydrogen, making low-CO_2 hydrogen production, the availability and volatility of renewable energy as well as the design and operation of CO_2 and hydrogen transport systems key factors regarding the relevant framework conditions.

In addition to the technical and financial aspects mentioned above, ensuring social acceptance of carbon capture and storage technologies can also be challenging.

The presented options can on the one hand be integrated from a technical point of view in many large steel works, and thus enable significant decarbonisation of the European steel industry on short-term. Chances of deployment are strongly linked to the needed framework conditions, in particular to the availability and price of biomass, the marketability and price of CCUS products, the acceptance and cost of carbon capture and storage, and the availability and price of limited quantities of green electricity and hydrogen.

3.2 Technology routes based on direct reduction

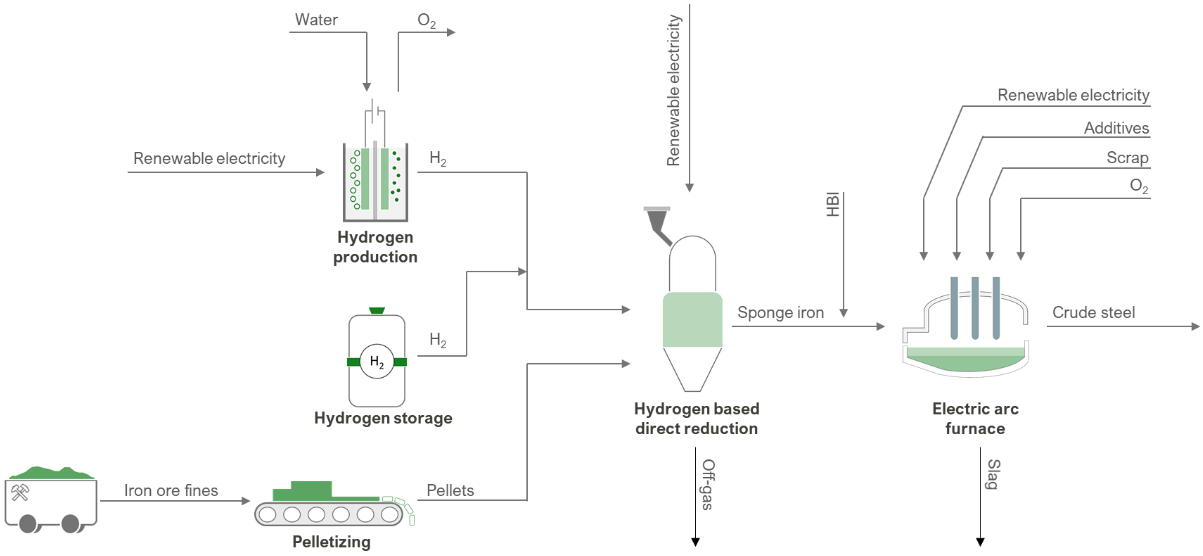
Several of the main options for mitigation of CO_2 emissions impose the full replacement of entire upstream iron and steelmaking facilities. This is especially true for CDA options such as electrolysis processes and H_2-based direct reduction, as described below. The basis of the H_2-DR-EAF route (Figure 27) is the H_2-DR option presented in detail in section 2.1.1.

Since current direct reduction plants (generally using natural gas) are already operated with rather high internal hydrogen contents, the main parts of the process technology can be rated to be already fully mature. This can be an important intermediate step towards short-term CO_2 mitigation which might furthermore strongly speed up the deployment of the H_2-DR-EAF technology route. Direct reduction with natural gas (NG-DR-EAF) provides a significant CO_2 mitigation potential compared to the conventional BF-BOF-route, and thus, a very promising short-term option.

The share of hydrogen as a partial substitute for natural gas can be increased stepwise towards the target of 100% hydrogen-based reduction. This allows gradual hydrogen enrichment on industrial scale and enables flexible increase of hydrogen concentration depending on availability, price, and technical requirements. As regards the time scale of industrial deployment, much depends on direct reduction plants being built as of now (corresponding to the individual investment cycles of the respective plants) and their shift towards increased hydrogen usage as soon as possible, also considering availability and technical requirements. Natural gas-based direct reduction can be complemented by CCU and/or carbon capture and storage. The realisation relies on the specific situation of each individual steel production site.

However, the carbon content in current DRI product has an important effect on the physical and chemical properties and on the energy demand in the EAF process. Concerning (almost) 100% hydrogen usage, several open issues still remain (as described in more detail in section 2.1.1). Consequently, the technology readiness level is rated as 6-8. Thus, further R&D activities are needed and the operation of a direct reduction plant without any carbon still needs to be validated on a larger scale.

Figure 27: Schematic and simplified view of the H_2-DR-EAF technology route



Source: author's own composition.

Direct reduced iron could be fed as ferrous burden to an electric arc furnace, in addition to scrap, complying as far as possible with the quality requirements of the steel grades produced. Beside this, green hydrogen used for direct reduction could be produced directly at the steel plant by renewable energy water electrolysis to ensure its availability. Bio-coal could be added respectively for carburising steel and as foaming agent in the EAF to further reduce the carbon footprint of such plant. However, the initial ore requires pelletising before use, thus resulting in the demand for (new) pellet plants to be built as well as heating gas, potentially consisting of additional hydrogen or biogas to limit CO_2 impact. Although such pellets can currently be bought on the market, on-site production may be preferred to increase flexibility and avoid carbon leakage. In any case, corresponding CO_2 emissions need to be considered in the carbon balancing.

The CO_2 mitigation potential of this route is almost 100%, without any need of CCUS. Studies by several European steelmakers have already started, proving the high industrial interest and priority of this route. CAPEX and OPEX have been discussed in previous chapters and have to be added directly, as they refer to distinct parts of the process.

3.2.1 Extent of modifications to be implemented in existing plants

Such plants would replace the full ironmaking and steelmaking capacities of existing BF-BOF plants and thus often have to be built in 'greenfield-like' conditions. Although the switch can be done stepwise in existing plants operating more than one blast furnace, all main facilities and equipment (cokemaking, sintering, blast furnace and converter plants) have to be replaced with new production units. Since the metallurgical gases of these process steps (blast furnace-top gas, coke oven gas, converter gas) are used for heating the integrated works, the internal gas networks energy management as well as the connected furnaces also have to be substantially modified. This applies also to internal power supply, which is nowadays often utilising the metallurgical gases.

Further auxiliary facilities such as raw materials storage, energy networks with boilers and oxygen production plants, internal transportation means, maintenance areas, etc., can probably be partly retrofitted from the existing plants, but still require significant revamping. Thus, the deployment of this route strongly depends on the investment cycles in the corresponding plants. Finally, as already mentioned iron ore pelletisation and the production of bio-coal, if used at the electric arc furnace, should be accounted for, both in terms of CO_2 emissions and investment needs (or OPEX, if these materials are not produced on-site).

3.2.2 Framework conditions

Natural gas direct reduction plants can be built as of now in many sites and can be further developed to increase the use of hydrogen up to (almost) 100%. However, to initiate such investments the price and the availability of natural gas are key framework conditions. It has to be ensured that the energy costs of NG-DR-EAF plants are competitive as of now or that the higher costs are compensated (e.g., by means of carbon contracts for difference - CCfD).

This transition process towards hydrogen-based metallurgy will require a new energy system without (or with minimal) carbon input. The new works will be much more dependent on external power supply. A higher degree of electrification will require strengthening high-voltage grids between renewable energy production and industrial consumers. The deployment of such networks will need considerable (external) investment and time (e.g. planning, permitting and public acceptance). When producing steel using renewable energy sources (wind, water and solar energy), the issue of their fluctuating availability needs to be addressed. Otherwise, new demand-side management approaches may be developed to bring substantial changes to process control and plant management systems.

Moreover, new hydrogen supply infrastructure will be needed. As an alternative, on-site production of hydrogen could offer the advantage of providing network services (grid balancing) to increase the flexibility of the electricity grid. Hydrogen production could also create synergies with various sectors such as transport, petrochemicals, and ammonia production. However, the deployment of the H_2-DR-EAF route will require major external and internal infrastructure investments. In addition, hydrogen storage infrastructure must be provided.

However, the deployment of the H_2-DR-EAF technology route will involve major external and internal infrastructure investments. In addition, hydrogen storage infrastructure must be provided.

3.3 Technology routes based on smelting reduction

These technology routes are based on two smelting reduction technologies: enhanced iron bath reactor smelting reduction and hydrogen plasma smelting reduction. In addition to the aforementioned routes, further options that were not considered in detail in this deliverable are the FINEX technology (which allows a changeover to the use of hydrogen) and the Tecnored technology.

3.3.1 Enhanced IBRSR technology route

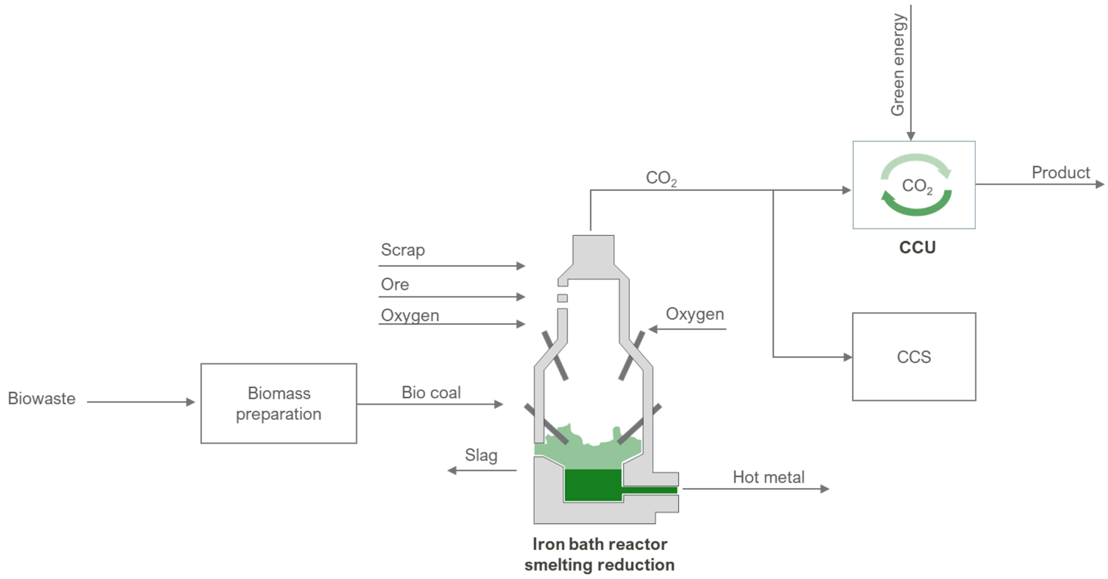
The IBRSR technology described in section 2.3.1 could also be combined with other technologies in order to increase its environmental benefits. The main improvements which could be added to the ‘basic’ tool are the following:

- replace injected fossil coal with bio-coal;

- replace part of the iron ore with scrap; and
- combine with carbon capture, utilisation and storage technologies.

The last topic (CCUS) is of particular interest for IBRSR, as the off-gases are mainly pure CO_2. This allows very efficient recovery and requires limited preparation before use or storage.

Figure 28: Schematic and simplified view of the enhanced IBRSR technology route



Source: author's own composition.

With these various add-ons, the reduction of CO_2 emissions would be almost 100% compared to the current status for a blast furnace plant. The IBRSR, e.g. HIsarna® process (Figure 28), replaces the full ironmaking side of conventional plants: it replaces the blast furnace and eliminates the need for cokemaking and sintering (or pelletising) the iron ore. The steelmaking and hot rolling sections can remain unchanged or, if desired, can accommodate the additional changes presented in the blast furnace route above.

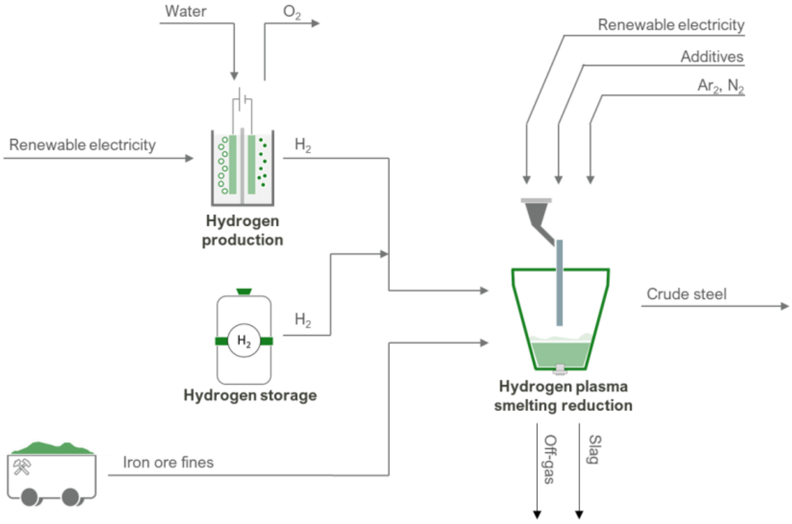
The IBRSR unit requires auxiliaries equipment for iron ore and coal grinding and drying, additional oxygen capacity and dedicated off-gas treatment (steam recovery, scrubbing, de-SOx, bag-houses), especially if the off-gas (concentrated in CO_2) is directly valorised or stored.

Similar to the technology routes based on conventional BF-BOF, significant investments are first required for add-on technologies (e.g. CCUS and biomass preparation).

3.3.2 Technology route based on hydrogen plasma smelting reduction

The technology route based on hydrogen plasma smelting reduction is derived from the technology discussed in Section 2.1.2, supplemented by necessary upstream and downstream processes (Figure 29). As an advantage, this route allows to produce steel within one process step and avoid the need for ore pre-processing.

Figure 29: Schematic and simplified view of the technology route based on HPSR



Source: author's own composition.

HPSR replaces the entire iron and steelmaking chain (BF-BOF) by directly converting iron ore into steel. Consequently, facilities like coking plants, sinter plants, blast furnaces and basic oxygen converter need to be replaced by new production equipment. Since this route is a new development, gas networks, energy management and internal power supply as well as connected furnaces have to be adapted.

Similar to hydrogen direct reduction, this route requires a new energy system with no or minimal carbon input. Additionally, the availability of renewable energy and the relevant infrastructure (such as hydrogen pipelines) are a prerequisite for successfully deploying this technology route.

3.4 Technology routes based on iron ore electrolysis

The described technology routes is based either on low temperature alkaline iron ore electrolysis (Section 3.4.1) or high temperature iron ore electrolysis (Section 3.4.2).

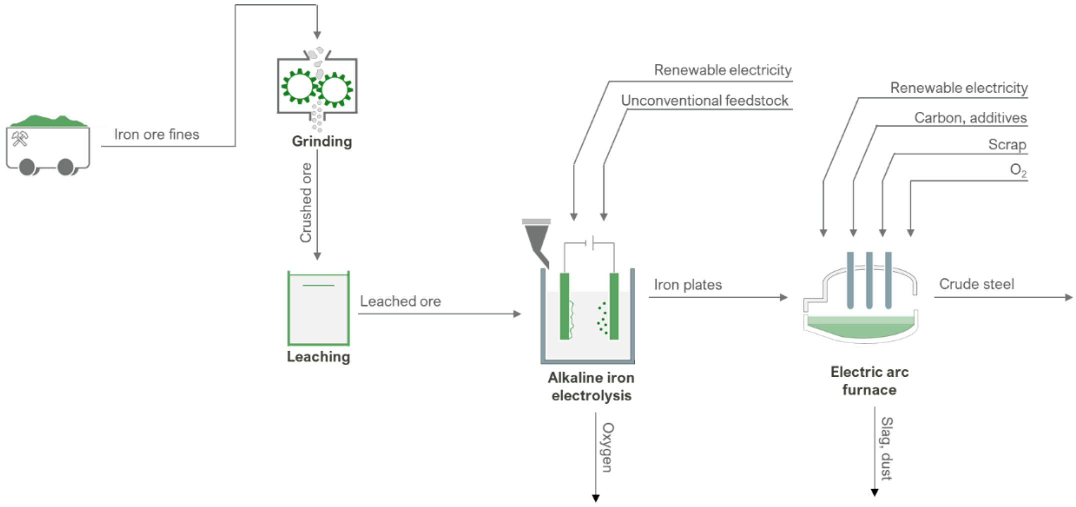
3.4.1 Technology route based on alkaline iron electrolysis

In the H_2-DR-EAF technological route (section 3.2), renewable electricity is used to electrolyse water and produce hydrogen, which is later used for ore reduction. Electrolysis processes avoid the hydrogen production step and use electricity to directly reduce iron ore. The details of the alkaline electrolysis technology have been presented in section 2.1.3. As described previously, the technology readiness level is rated at 5-7. Thus, further R&D activities are needed to scale the technology up and prove its industrial viability.

Similar to hydrogen reduction, the carbon content in iron plates is close to zero. This has an important effect on the energy demand in the EAF process. The ensuing iron could feed ferrous burden to an electric arc furnace, possibly completed with scrap as far as possible according to the quality requirement of the steel grades concerned. Bio-coal could be added for carburising steel and as foaming agent to further reduce the carbon footprint of such a plant.

Auxiliary systems mainly include ore and raw materials preparation before electrolysis (unconventional feedstock is a beneficial option) and the purification and compression of the oxygen produced by electrolysis for use in the steel plant (notably in the EAF, Figure 30).

Figure 30: Schematic and simplified view of the alkaline iron electrolysis technology route



Source: author's own composition.

The CO_2 mitigation potential of this route is almost 100%, without any need of CCUS. CAPEX and OPEX have been discussed in previous chapters as all of them are directly related to this technology.

As CDA plants would replace the full ironmaking and steelmaking facilities of existing BF-BOF plants they may be built in 'greenfield-like' conditions. Again, the transformation can be done stepwise in existing plants operating several blast furnaces, all main facilities and equipment being replaced with new production units. Gas networks, energy management and internal power supply have to be substantially changed as well as the connected furnaces. Anyway, several auxiliary facilities such as raw materials storage, energy networks with boilers, internal transportation means, maintenance areas, etc., can be partly retrofitted from the existing plants, but would require significant revamping. The oxygen production plant is to be replaced by cleaning, compression and storage solutions for the oxygen produced by electrolysis cells.

Finally, as already mentioned, iron ore crushing and leaching and the production of bio-coal, if used at the electric arc furnace, should be accounted for, both in terms of CO_2 emissions and investment needs (or OPEX, if these materials are not produced on-site).

This transition process towards electricity-based metallurgy will require a new energy system with no (or minimal) carbon input. All the considerations related to dependence to external power supply, strengthening of high-voltage grids, variability of renewable energy sources and adaptation of process control and plant management presented in the H_2-DR-EAF technology route are also valid for the two electrolysis routes.

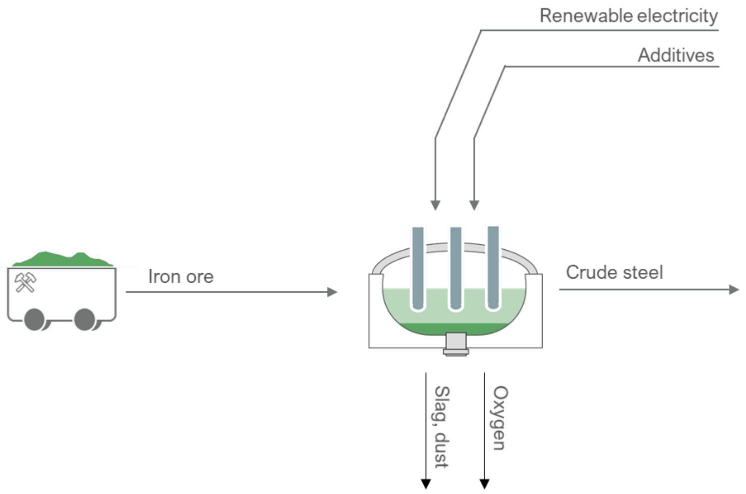
Thus, the application of the iron alkaline electrolysis technology route will involve significant infrastructure investments for ore preparation (grinding and leaching) and electrolysis. The maturity does not allow for industrial deployment on the short-term, though it may allow for mid-term implementation.

3.4.2 Technology route based on molten oxide electrolysis

The second electrolysis technology route is based on molten oxide electrolysis (Figure 31), as described in section 2.1.4. In this specific case, upstream and downstream processes are very limited as the technology is able to directly handle iron ore without important preparation steps and directly uses (green) electricity without going through another media, e.g. hydrogen. The resulting metal is liquid steel (the small amount of carbon required can be supplied inside the electrolysis cell).

As the current TRL of the technology is still quite low (TRL 2), extensive R&D work is necessary to make it ready for industrial implementation. In particular, liquid iron and slag handling must be carefully considered. Consequently, maturity does not allow an industrial deployment on short- or mid-term but offers a long-term perspective.

Figure 31: Schematic and simplified view of the molten oxide electrolysis technology route



Source: author's own composition.

4 Technology routes roadmapping

The target of technology route roadmaps is to combine all information assessed within this deliverable with the results of a stakeholder consultation (as reported in deliverables D1.3 and D1.5), organise them along different time scales until 2050, and finally provide transparent visualisation. The complete process chain is considered, and different breakthrough technologies are combined into the four technology routes as defined in Chapter 3, each of them representing a possible complete future iron and steel production chain. Visualisation schemes were developed to provide a prognostic view of technology progress toward industrial deployment, CO_2 mitigation potential, important framework conditions, investment needs as well as main value chains needed. Due to this huge amount of information, the roadmaps are not exclusive but try to summarise the most important information in a transparent manner.

In keeping with all other deliverables within the Green Steel for Europe project, ‘short-term’ refers to the period until about 2030, while ‘long-term’ refers to a time after 2040 and the final target in 2050. These roadmaps will provide the background for the planned industrial deployment scenarios for 2030 in Task 1.4 and for 2050 in Task 1.5 as well as for the related impact analyses in Work Package 3 within Green Steel for Europe.

As stated before, data relevant to the roadmap – i.e. when each technology route will reach a certain technology readiness level – were collected and compiled from literature as well as from stakeholder consultations. It is therefore important to note that the statements involve a certain degree of uncertainty as they relate to assumptions and unknown future boundary conditions.

Most technology routes with the ability to mitigate CO_2 emissions in the iron and steel industry require upscaling (e.g. hydrogen plasma smelting reduction and alkaline iron electrolysis) as well as the development and financing of an adequate environment (infrastructure). Therefore, it is essential to map the requirements in relation to the respective technology route. Resulting from this, necessary constraints (or vice versa, remaining barriers) can be revealed and prioritised. In a following step, strategies regarding how to deal with the identified constraints/barriers must be developed. This is part of the project work package 3, where policy options and approaches are recommended and assessed (e.g. deliverable 3.1- inception impact assessment report).

Figure 32 below describes the current technology landscape in Europe (EU28, 2020) regarding steel production sites utilising blast furnaces and basic oxygen furnaces (primary steel production). Similarly, Figure 33 shows electric arc furnaces in Europe (secondary steel production) to provide an overview of the current situation of European steel production. In Figure 32 each symbol corresponds to one steelmaking site, whereas in Figure 33, the plants that can be grouped together due to their geographical proximity are indicated by a single symbol. A complete list of European steelmaking plants, including their production capacities, is provided in the appendix (Annex I).

Figure 32: Technological landscape of Europe's iron and steelmaking production sites utilising blast furnaces and/or basic oxygen furnaces (EU28, 2020)

Source: author's own composition.[20]

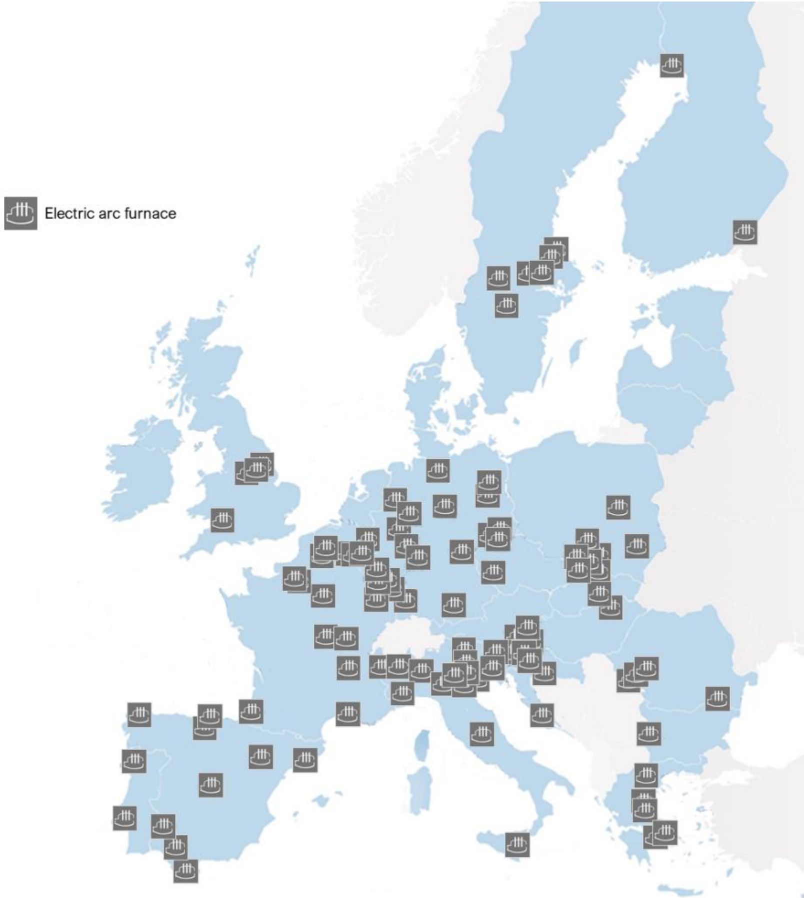
There are currently 24 integrated steel production sites (blast furnace and oxygen blast furnace) in Europe with a finished steel capacity of 104,290,000 tons/year. These integrated plants are the main focus of the analyses since they provide the largest CO_2 mitigation potential.

However, generally speaking, electric arc furnaces must not be neglected since they will have increasing importance as part of future integrated plants, given that innovative EAF technology will be needed to reach highly anticipated long-term CO_2 targets. Figure 33 shows that there are currently 126 sites with one or more electric arc furnaces with a capacity of 89,515,000 tons/year.

As outlined in Chapter 2, the implementation potential of technology routes is linked to local/regional framework conditions and will be discussed in detail within deliverable 1.7 - Decarbonisation pathways 2030 and 2050. Nevertheless, in order to get an impression of regional differences and possibilities, significant examples of individual countries are described for each technology route in the following chapters.

[20] For further details, please see www.eurofer.eu.

Figure 33: Technological landscape of Europe's iron and steelmaking production sites utilising electric arc furnaces (simplified, EU28, 2020)



Source: author's own composition.[21]

4.1 Technology routes based on optimised BF-BOF

Current blast furnaces are efficient and highly optimised, and the potential for further decrease of carbon consumption (and thus CO_2 emissions) in these furnaces is reaching its limits. A promising short-term option is to replace part of fossil coal with biomass. This can further be combined with recycling the remaining CO and hydrogen in the blast furnace top gas back into the BF process, effectively reducing emissions as described in Section 3.1. CO and hydrogen can be recovered from BF top gas for recycling after the CO_2 separation step. Furthermore, other metallurgical gases (e.g. coke oven gas) can be injected into the BF to maximise an effective use of carbon for metallurgical processes. The metallurgical use of these gases can decrease their use for power production, which is a highly CO_2-intensive approach.

Regarding CO_2 separation technologies, several options have already been proposed, such as recycling fumes in blast furnace hot stoves or some new, in-process, capture technologies, which are of primary interest when the CO_2 stream can be of limited purity. Many gaseous streams in steel plants have a rather high concentration of CO_2, so there is a good potential for specific/integrated capture processes.

[21] For further details, please see www.eurofer.eu.

In Belgium, the ArcelorMittal plant in Gent is planning to implement this route and currently the focus is among others on projects Torero (biomass use) and STEELANOL (CCU).[22] Furthermore, the plants in Fos and Dunkerque, France, may implement the optimised BF-BOF route. Especially Dunkerque has an IGAR pilot plant (reformed gas injection) and started the project 3D (CCUS) (ArcelorMittal, 2020). Within this project, an industrial demonstrator is planned by 2023 and industrial installation is estimated by 2030.[23] Additionally, CCUS project VASCO was carried out at the Fos plant while a follow-up project (Vasco3) is being prepared.[24] An additional project that can be mentioned is CarbHFlex. The project is based on STEELANOL and the commissioning of the gas and water treatment plants is planned for 2026.[25]

In the Netherlands, the plant in Ijmuiden may implement some of the technologies of this route, in particular the use of biomass, CCUS technologies and increased use of scrap (Keys et al., 2019).

Currently in Austria there are two integrated steel mills and, in relation to the optimised BF-BOF technology route there are projects planned to convert CO_2 from process gases and use it in combination with hydrogen in the energy and chemical sectors (voestalpine, 2018-2019).

In Germany, the project Carbon2Chem is also focusing on CCU. As all individual components of the Carbon2Chem pilot plant have already reached TRL 9, there is no need to build a demonstration plant. Industrial use for plant retrofitting in the blast furnace route will be possible in 2025 at the earliest (Agora Energiewende and Wuppertal Institut, 2020).

In Italy, there is one steel production site with the BF-BOF route (Taranto), while the remaining steel production sites follow the EAF route. There are currently no large plants available in terms of CCU/CCS. However, projects in other sectors are being launched and the results may be transferred to the steel sector.

The possibility of underground storage of CO_2 (CCS) as a possible extension of this technology route is restricted in some EU member states. For example, CCS is prohibited in Austria, except for research projects up to a storage volume of 100,000 t/CO_2 (Hammerschmid et al., 2020). In Finland, CO_2 storage is allowed only for demonstration purposes until 2024 (IOGP, 2020).

Starting from individual technologies, Figure 34 below shows a roadmap for the proposed breakthrough technology routes based on conventional BF-BOF route optimisation, including main information for the various mitigation technologies used. It indicates the progress as well as research and investment needs for each technology (shown as green rows) over time as well as the needs to integrate the technologies into the process chain. The complete breakthrough process chain in connection with the needed framework conditions is also presented as separate summary against a grey backdrop. The colours used for the framework conditions provide information about their urgency: a red line marks a critical condition; green lines represent a non-critical condition.

Starting in 2020 (current technology readiness level), the technology readiness level development is shown from left (short-term) to right (long-term) both graphically (grey shaded area) and numerically. As soon as TRL 9 – i.e. the maturity for first industrial deployment – is reached, its mitigation potential is presented in a circular diagram. Research needs were grouped and listed in

[22] For further details, please see www.torero.eu; www.steelanol.eu/en

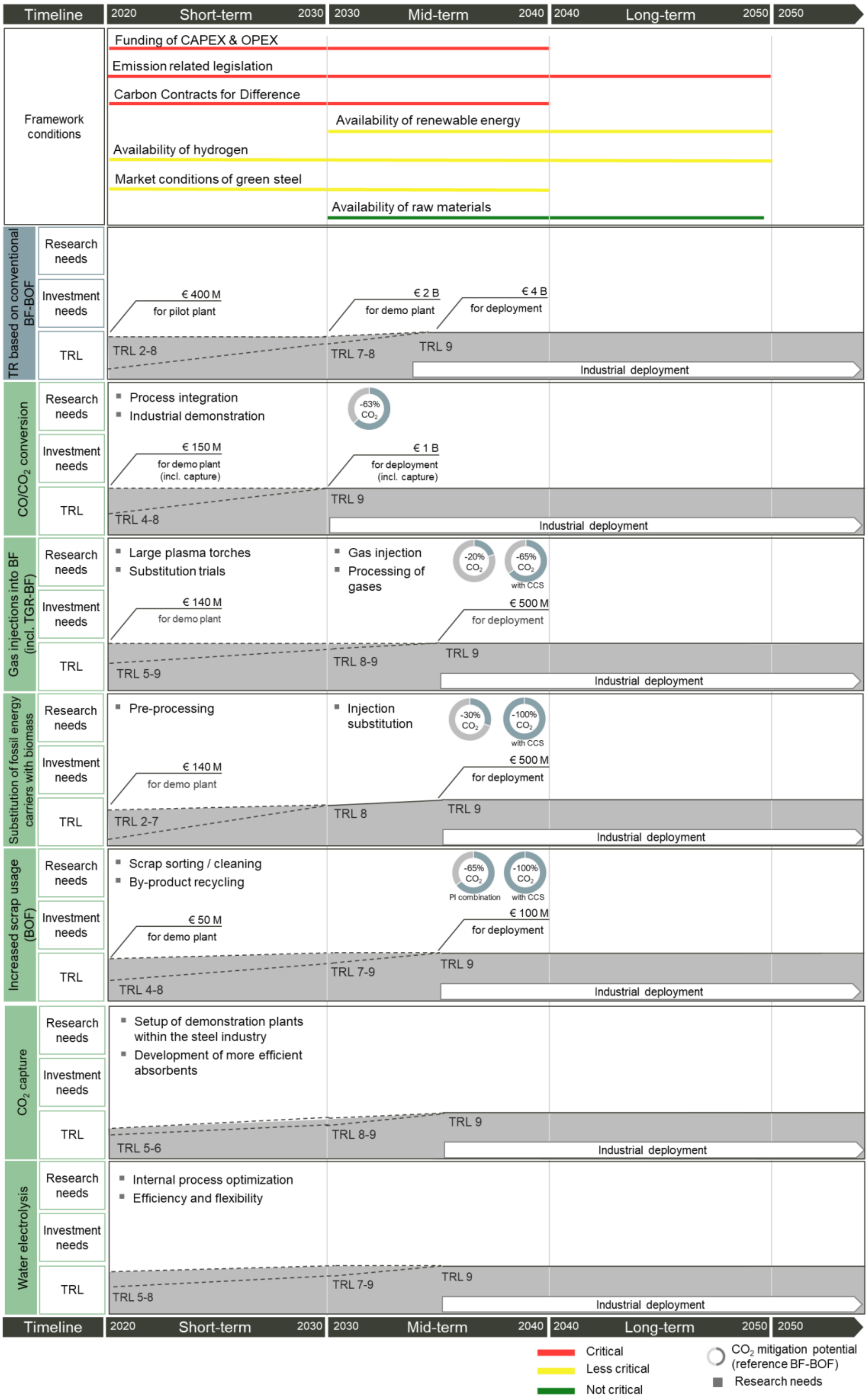
[23] For further details, please see 3d-ccus.com.

[24] For further details, please see france-sandiego.org/2019/05/21/new-rd-avenues-in-fos-to-recover industrial-emissions; www.marseille-port.fr/en/projets/vasco-2-0.

[25] For further details, please see www.steelguru.com/steel/arcelormittal-france-starts-projects-for-green-steel; www.businews.fr/ArcelorMittal-a-Fos-se-projette-sur-les-aciers-verts_a3433.html.

the relevant time period. Necessary investment needs are also displayed in connection with the time periods. Since the focus lies on the actual steel production technology, the economic assessment of the auxiliary technologies is neglected at this point.

Figure 34: Roadmap of breakthrough technology routes based on optimised BF-BOF



Source: author's own composition.

4.2 Technology routes based on direct reduction

An important intermediate step towards the deployment of the H_2-DR-EAF technology route is direct reduction with natural gas as a bridge technology. The reason is that the share of hydrogen as a partial substitute for natural gas can be potentially increased stepwise towards complete hydrogen-based reduction. This allows for gradual enrichment with hydrogen on industrial scale and enables a flexible increase of hydrogen concentration depending on availability, price, and technical demands.

Regarding the time scale of industrial deployment, this enables building direct reduction plants as of now (corresponding to the individual investment cycles of the respective plants) and subsequently shifting their operation towards increased hydrogen usage in a flexible manner.

The Tata Steel Europe plant in Ijmuiden may replace part of its BF-BOF production with H_2-DR-EAF by 2050 (Tata Steel, 2020). In Germany, this technology route is being pursued in several projects: ArcelorMittal plans to start operating a demonstration plant in 2023 in Hamburg. Salzgitter Flachstahl GmbH also plans to implement this technology route (Agora Energiewende and Wuppertal Institut, 2020).[26] A modular approach will be used to gradually convert the integrated steel plant in Salzgitter to a hydrogen-based direct reduction site.[27] H_2-based direct reduction as a technology is also strongly promoted in Austria. Since large-scale deployment of H_2-based direct reduction is not expected until after 2030/35, bridge technologies are being developed (voestalpine, 2018). Sweden is planning to establish this technology route as part of the HYBRIT project. As part of the initiative, demonstration plant trials (2025-2035) and the construction of a hydrogen storage research facility for energy storage are planned.[28]

In general, the implementation of this route is particularly suitable in places where large quantities of renewable energies will be available. Thus, the framework conditions for this route do not seem promising in Poland on the short- or mid-term: the energy mix for 2019 was approximately 76% coal-based and approximately 10.5% from renewable sources. The ministry of energy believes that even a 21% share of renewable energies in 10 years will be a challenge for Poland.[29] The ministry for climate and the environment is working on a national hydrogen strategy, which is to be published in the first quarter of 2021.[30] Therefore, it should be expected that the supply of green hydrogen in Poland will increase over time, allowing for a wider introduction of hydrogen technologies in the steel industry.

In Spain, the final energy demand in the industrial sector accounted for around 24% of the overall energy demand in 2015. Renewable energy sources (primarily biomass) covered 7% of this demand. There is potential for biomass, as well as other thermal renewable energy sources (particularly, biogas and solar thermal energy) to contribute to the decarbonisation of the industrial sector (Ministry of Ecological Transition, 2016).

Another important factor in the successful implementation of the hydrogen direct reduction technology routes is the production, distribution, and storage of CO_2-neutral hydrogen. As a bridge technology, the use of natural gas for direct reduction will be quite important to enable quick

---

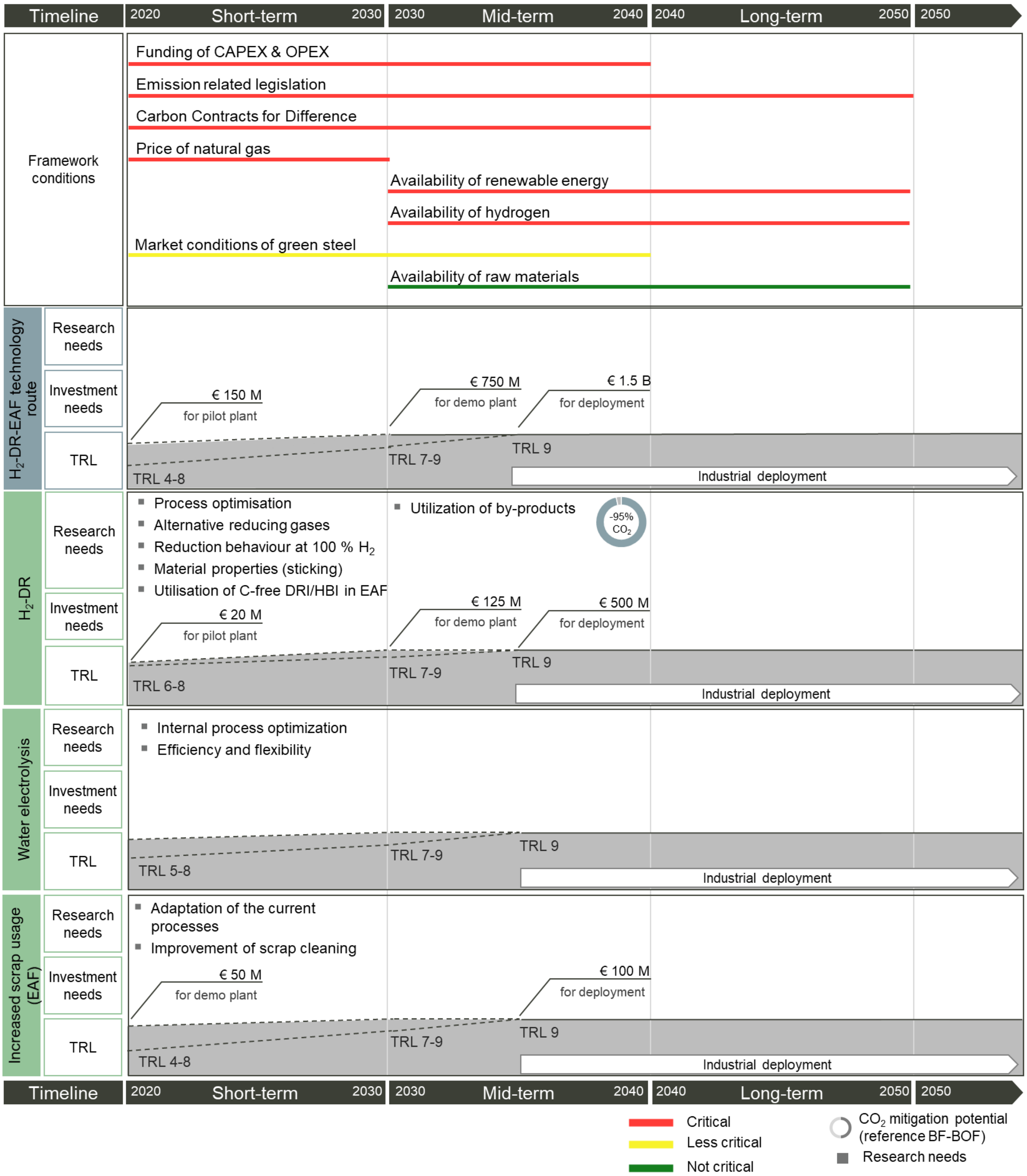
[26] For further details, please see hamburg.arcelormittal.com.
[27] For further details, please see salcos.salzgitter-ag.com.
[28] For further details, please see www.hybritdevelopment.com.
[29] For further details, please see wysokienapiecie.pl.
[30] For further details, please see www.gov.pl/web/climate/letter-of-intent-to-establish-a-partnership-for-building-a-hydrogen-economy-signed.

industrial implementation. There are country-specific differences in the availability of the necessary infrastructure (e.g. pipelines) and regulations regarding the possible injection of hydrogen into the natural gas grid. In Austria a maximum of 4% (mol-basis) can be injected into natural gas grids (guideline ÖVGW 31 in combination with ÖVGW 33).[31]

Figure 35 describes the H_2-DR-EAF breakthrough technology route roadmap (consistent with the detailed information in Section 3.2) as summary for the complete route (grey backdrop) as well as research needs, investment needs, mitigation potential and TRL development for the single technologies it includes: H_2-DR, water electrolysis for hydrogen production and, possibly, increased scrap usage.

[31] For further details, please see www.hylaw.eu .

Figure 35: Roadmap of the technology routes based on direct reduction



Source: author's own composition.

4.3 Technology routes based on smelting reduction

The breakthrough steelmaking routes based on smelting reduction technology include IBRSR (iron bath reactor smelting reduction) and HPSR (hydrogen plasma smelting reduction). Since IBRSR is much more advanced in terms of technical maturity, most information presented focus on this approach.

The IBRSR core reactor first has to be validated at a larger scale in terms of a new pilot plant. In parallel with this core development, auxiliary ones – namely, replacement of coal with biomass and validation of CCUS technologies – could be performed and validated on existing steel plants running on the BF-BOF route. These technologies are expected to be easily transferred to the IBRSR route when the core reactor will be fully efficient.

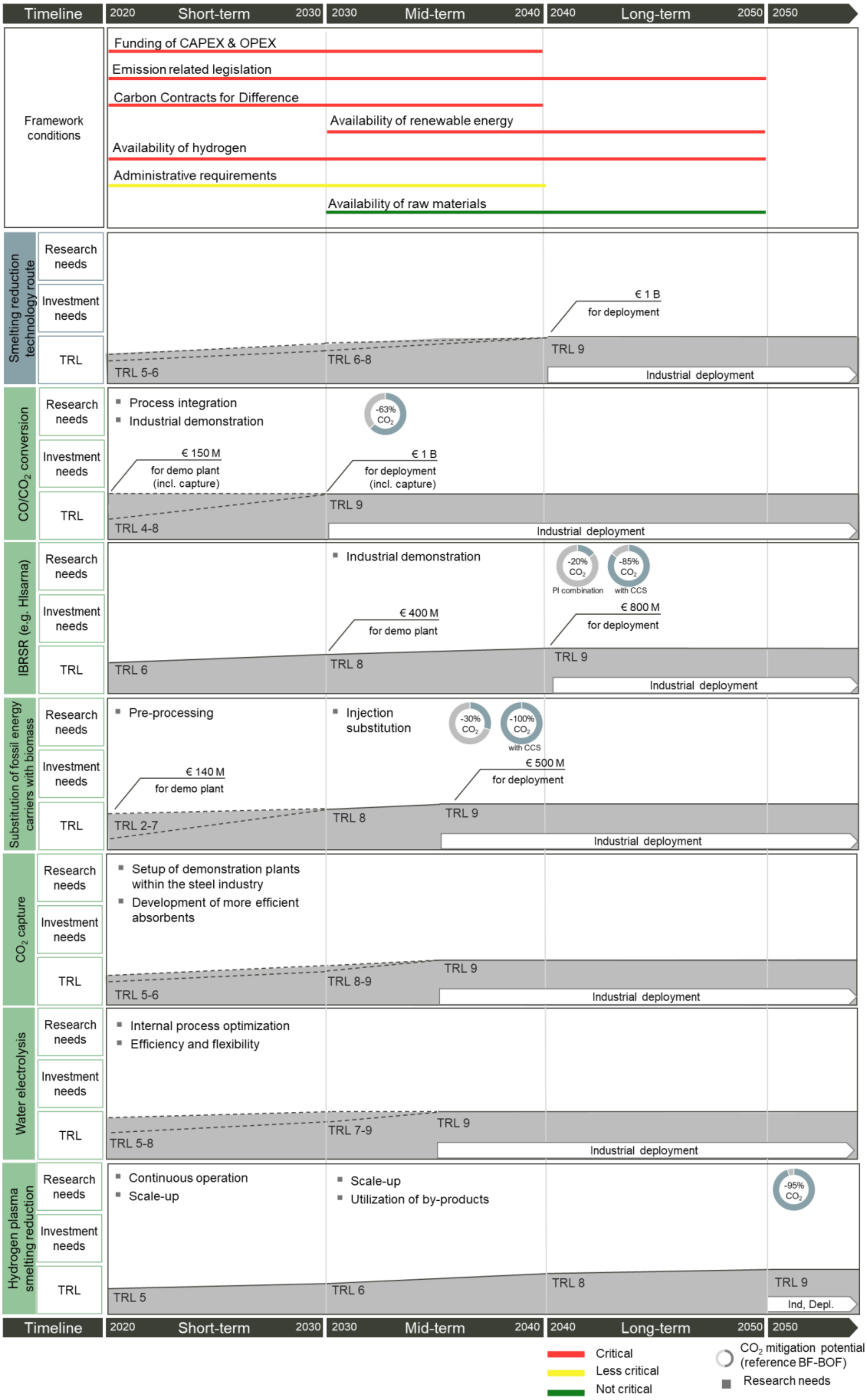
The IBRSR technology route is being developed at Tata Steel Europe's Ijmuiden plant (HIsarna®). All the related investment, energy, feedstock, and infrastructures are therefore to be addressed first in the Netherlands. The industrial deployment of the technology route is foreseen after 2040 (Tata Steel, 2020).

In Austria, research is being conducted on hydrogen plasma smelting reduction and an experimental plant has been built within project SuSteel (Austrian Research Promotion Agency, 2017). The technology is assumed not to appear on the market on a commercial level before 2050.

In Italy, steelmakers using EAF are interested in the development of smelting reduction technologies utilising iron-bearing waste (i.e. scale, slag, EAF dust, etc.) in order to increase steel quality (Guglielmini et al., 2005).

Figure 32 below provides a roadmap of the complete route (grey backdrop) and the different mitigation technologies used within these routes (green row) as summary for the complete route (grey row) and the research and investment needs, mitigation potential and TRL development for the single technologies they include: IBRSR and HPSR, CO_2 capture and CO/CO_2 conversion, use of biomass, HPSR and, finally, water electrolysis.

Figure 36: Roadmap of the technology routes based on smelting reduction



Source: author's own composition.

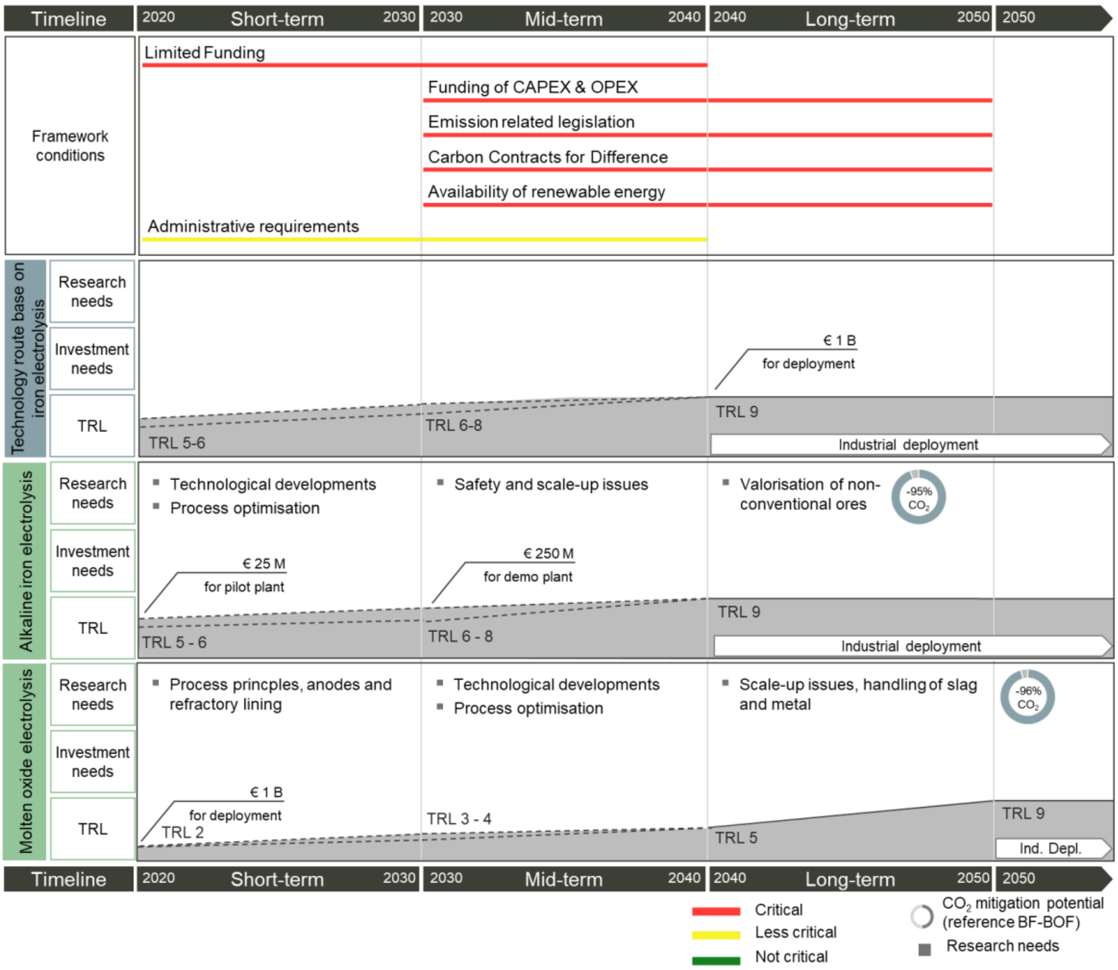
4.4 Technology routes based on iron ore electrolysis

The iron ore electrolysis breakthrough steelmaking routes include alkaline iron electrolysis and molten oxide electrolysis. Since alkaline iron electrolysis is much more advanced in terms of technical maturity, most information presented focus on this approach.

Besides the need of renewable electricity in large quantity, the main development need of alkaline iron electrolysis is upscaling. At any rate, such auxiliary steps as recovery, purification and compression of oxygen and continuous supply of input material have to be investigated before implementing the technology. Iron plate management and charging into an EAF also have to be considered. Moreover, production costs need to be reduced. As a first step, these plates could be only a minor part of the metallic burden (the rest being scrap) to limit the impact of the melting process. In a second step, with the progressive increase of this new burden, the EAF process will have to be adapted to carburise steel and optimise charging, melting, and foaming. Finally, new valorisation routes for arc furnace slag need to be found.

As molten oxide electrolysis is currently at low technological maturity, the detailed estimation of its future development is difficult. In particular, the development of adequate inert, long-term stability anode is highly challenging. Afterwards, process scale-up will have to be tackled as well as the development of possible up- and downstream processes for input materials, liquid steel, and by-products. Figure 37 below provides a roadmap for the two mitigation technologies based on iron electrolysis considered within this technology route.

Figure 37: Roadmap for the technology routes based on iron electrolysis



Source: author's own composition.

This alkaline iron electrolysis technology route could be developed in France based on the SIDERWIN project outcomes; indeed, the development and construction of a pilot plant (2017-2022) is currently being planned (Agora Energiewende and Wuppertal Institut, 2020).

Outside Europe, Boston Electrometallurgical Corporation (USA) is working on the further development of molten oxide iron ore electrolysis and plans to build a demonstration plant by 2022. From today's perspective, with optimum technology development the earliest possible large-scale use of this technology is not expected before 2050. However, demonstration plants are estimated to be established within Europe by 2050 (Agora Energiewende and Wuppertal Institut, 2020).

5 Concluding remarks

This report supports CO_2 mitigation of the European steel industry by proposing four breakthrough technology routes, each with CO_2 mitigation potential up to 100%. As a main result of the project, single decarbonisation technologies have been comprehensively assessed and the selected technologies were summarised along the complete iron and steelmaking process chains, all the way to hot rolling.

Divided into three technical pathways (CDA, PI and CCU), the eleven most relevant technologies were selected and analysed in detail and the most important information were summarised: relevant maturity progress, framework conditions needed, corresponding research needs and expected timeline for initial industrial deployment as first-of-a-kind.

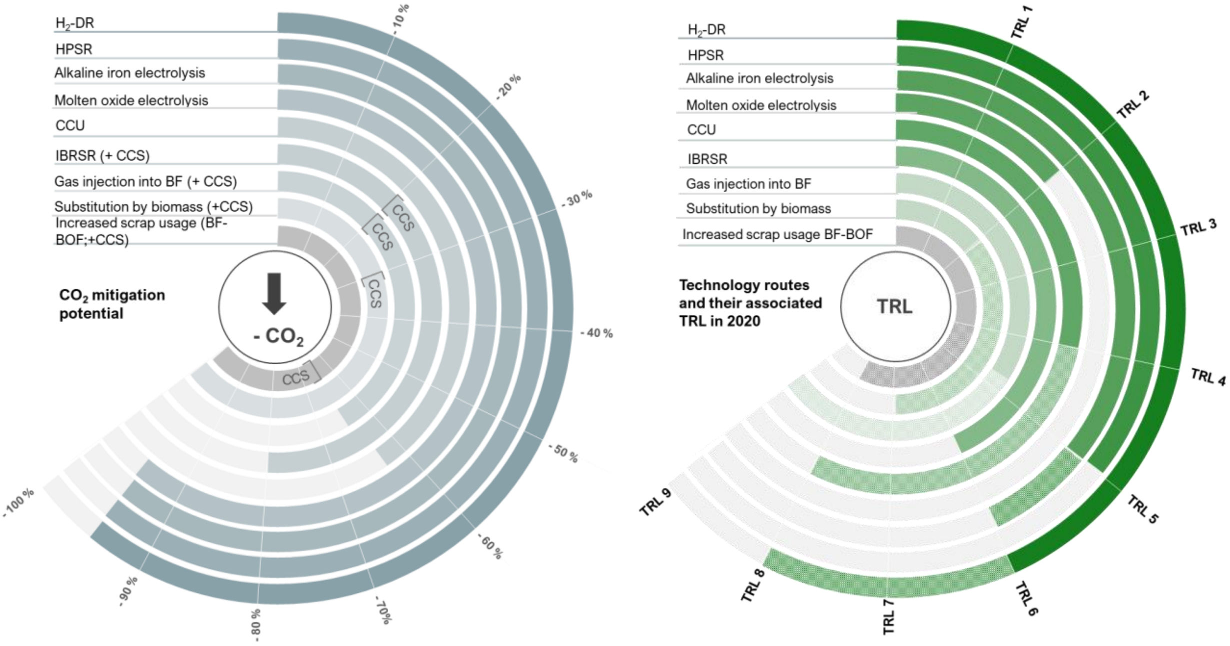
It should be noted that the analyses focus on scope 1 and scope 2 emissions and include the assumption that the use of electricity originates from renewable sources. Scope 3 emissions were neglected since they correspond only to a small share compared to scope 1 and 2. For most technologies a huge need of renewable energy is needed and the material cycles in the plants are fundamentally affected. For many technologies a significant increase in OPEX (mainly due to more expensive renewable energy supply) and CAPEX (due to the need to replace main parts of the upstream process chain) are also expected. As the main exception (with limited need to replace parts of the process chain) the exchange of fossil energy sources with biomass may be mentioned, which is however strongly limited by the (local) availability of biomass resources.

Most identified technologies have moderate maturity level (TRL at 5–7). Some technologies have high CO_2 mitigation potential but are currently at low maturity (such as hydrogen plasma smelting reduction at TRL 5 or molten oxide electrolysis at TRL 2). Correspondingly, a high number of R&D needs exist. These R&D needs are directed towards developing plant technology processes (on a larger scale) but also towards proper technology integration into existing process chains. Furthermore, the necessary auxiliary processes, material processing and a large number of measurement and control aspects need further research. Figure 38 provides an overview of the CO_2 mitigation potential as well as current TRLs of the technologies described in this deliverable.

The following four breakthrough technologies were developed as possible routes:

- technology based on an optimised conventional blast furnace - basic oxygen furnace (BF-BOF) route, applying a combination of PI technologies with CCUS for fast and high CO_2 mitigation;
- hydrogen-based direct reduction and electric arc furnace technology routes (H_2-DR-EAF) which require significant modifications of existing plants but achieve high CO_2 mitigation without need for carbon capture and usage/storage (CCUS);
- smelting reduction technology routes based on iron bath reactor smelting reduction (IBSR), enabling high bio-coal and scrap usage and effective combination with CCUS technologies, or hydrogen plasma smelting reduction; and
- iron ore electrolysis technology routes, including alkaline iron electrolysis and molten oxide electrolysis (AIE, MOE).

Figure 38: CO_2 mitigation potential and TRL of the selected technologies



Source: author's own composition.

The findings were summarised into technology-specific roadmap visualisations, which show the main aspects along the 2020-2030-2050 timeline in a transparent manner. From this information it can be concluded that:

- some technologies are available for short-term deployment with limited R&D need and investment effort, which provide significant but not (almost) complete CO_2 mitigation;
- many technologies for (almost) complete CO_2 mitigation could be industrially deployed in the mid- to long-term (after 2030); and
- the industrial deployment of technologies needs specific framework conditions, the most important one being, from a technical perspective, the availability of sufficient clean energy at competitive costs.

To realise the crucially-important next steps, more specifically demonstration and completion in an operational environment (TRL 7-8) and to further develop the less mature technologies consistently with European climate and energy targets, the R&D actions need to be taken immediately. The combination of technologies to technology routes (i.e. integration into existing/new production chains) needs substantial additional effort, both with respect to R&D activities and accompanying investments. Since the necessary R&D actions are widespread and the effort by far exceeds the usual R&D needs, collaborative research (for instance large, EU-wide projects) is needed to achieve effective progress.

Bibliography

Agora Energiewende and Wuppertal Institut, (2019), “Klimaneutrale Industrie: Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement”.

Åhman, M., Nikoleris, A. and Nilsson L., (2012), “Decarbonising industry in Sweden an assessment of possibilities and policy”.

ArcelorMittal, (2020), “Climate Action in Europe: Our carbon emission reduction roadmap: 30% by 2030 and carbon neutral by 2050”.

Aromaa, J., (2016), “New hydrometallurgical approaches for stainless steel dust treatment,” Mineral *Processing and Extractive Metallurgy*.

Austrian Research Promotion Agency (FFG), (2017), “Stahlherstellung ohne CO_2,” *Produktion der Zukunft*, p.27.

Axelson, M., Robson, I., Khandekar, G. and Wyns T., (2018), “Breaking Through: Industrial Low-CO2 Technologies on the Horizon”.

Bäck, E. and Hiebler, H., (1998), “Schmelzreduktion von Eisenoxid mit Wasserstoff in einem Plasmaofen”, *BHM*, pp. 153–158.

Badr, K., Bäck, E. and Krieger, W., (2007), “Plasma Reduction of Iron Oxide by Methane Gas and its Process Up-Scaling”.

Bardow, A. and Green, D., (2018), “Low-Carbon Process Industries Through Energy Efficiency and Carbon Dioxide Utilisation, A study in support of a DG Research & Innovation Projects for Policy (P4P) report”.

Barrow, M., Buckley, B., Caldicott, T., Cumberlege, T., Hsu, J., Kaufmann, S., Ramm, K., Rich, D., Temple-Smith, W., Cummis, C., Draucker, L., Khan, S., Ranganathan, J. and M. Sotos, (2013), “Technical Guidance for Calculating Scope 3 Emissions”.

Birat, J.P., (2020), “Society, Materials, and the Environment: The Case of Steel,” *Metals*.

Borlee, J. and Pierret, J.C., (2020), “LowCarbonFuture Results – Pathway Process Integration”, *Final Webinar of the LowCarbonFuture project*.

Bürgler, T., (2017), “H2Future: Green hydrogen for steelmaking”.

Chan, Y., Petithuguenin, L., Fleiter, T., Herbst, A., Arens, M. and Stevenson, P., (2019) “Industrial Innovation: Pathways to deep decarbonisation of Industry Part 1: Technology Analysis”.

CONOPT SCRAP, (2009), “Final Report: Control and optimisation of scrap charging strategies and melting operations to increase steel recycling ratio”.

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

Elsabagh, S., Gogolin, S., Haverkamp, V., Hellermann, O., Kleimt, B., Kordel, T., Pierre, R., Rekersdrees, T. and Schlinge, L., (2019), “Adaptive EAF online control based on innovative sensors and comprehensive models for improved yield and energy efficiency (ADPTEAF),” *Adaptive EAF online control based on innovative sensors and comprehensive models for improved yield and energy efficiency (AdaptEAF)*, Vol. 29547, Publications Office of the European Union.

Energy Transition Commission, (2018), “Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century”.

EUROFER, (2013), “A steel roadmap for a low carbon Europe 2050”.

FLEXCHARGE, (2013), “Final Report: Cost and energy effective management of EAF with flexible charge material mix”.

French National Research Agency, (2007-2013), “Project Acier sans CO_2 par electrolyse”.

Friedrich, K.A. and Schiller, G., (2013), “Wasserstoffherstellung mittels Hochtemperaturelektrolyse”.

Fruehan, R.J., Fortini, O., Paxton, H.W. and Brindle, R., (2000), “Theoretical Minimum Energies To Produce Steel for Selected Conditions”.

Ghenda, J. T., (2017), “Ferrous and non-ferrous metals”, *EUROFER conference Finance for Innovation: Towards the ETS innovation fund*.

Guglielmini, A., Chiapelli, L., Bertossi, P. and De Marchi, G. (2005), “Redsmelt NST plant at Piombino: First results and future outlook,” *Stahl und Eisen*, Vol. 125(5), pp. 29-38.

Hammerschmid, M., Müller, S., Fuchs, J. and Hofbauer, H., (2020), “Evaluation of biomass-based production of below zero emission reducing gas for the iron and steel industry,” *Biomass Conversion and Biorefinery*.

Higuchi, K., Matsuzaki, S., Saito, K. and Nomura, S., (2020), “Improvement in Reduction Behavior of Sintered Ores in a Blast Furnace through Injection of Reformed Coke Oven Gas,” *ISIJ International*, Advance Publication by J-STAGE.

HYBRIT brochure, (2017), “Summary of findings from HYBRIT Pre-Feasibility Study 2016-2017”.

International Energy Agency, (2017), “IEA Energy Technology Perspectives 2017”.

International Energy Agency, (2019), “The Future of Hydrogen”.

IOGP, (2019), “The potential for CCS and CCU in Europe: Report to the thirty second meeting of the European gas regulatory forum”.

IPRO, (2016), “Final Report: Inline elemental characterisation of scrap charging for improved EAF charging control and internal scrap recycling”.

Ito, A., Laangfeld, B. and Götz, N., (2020), “The future of steelmaking - How the European steel industry can achieve carbon neutrality”.

Japan Iron and Steel Federation, (2019), “JISF long-term vision for climate change mitigation - A challenge towards zero-carbon steel”.

Keys, A., van Hout, M. and Daniëls, B., (2019), “Decarbonisation options for the Dutch Steel industry”.

Lavelaine de Maubeuge, H., Stoesel, F. and Birat, P., (2011), “ASM International: ULCOLYSIS: Liquid Steel from Iron Ore Electrolysis in Molten Slag”, *Liquid metal processing and Casting*, pp. 183-184.

Lavelaine de Maubeuge, H., van der Laan, S., Hita, A., Olsen, K., Serna, M., Haarberg, G.M. and Frade, J., (2016), “Grant Agreement RFSR-CT-2010-00002 (IERO): Iron production by electrochemical reduction of its oxide for high CO_2 mitigation,” *Iron production by* *electrochemical reduction of its oxide for high CO_2 mitigation (IERO)*, Vol. 28065, Publications Office of the European Union.

LCS, (2012), “Final Report: Laser-induced breakdown spectroscopy for advanced characterisation and sorting of steel scrap”.

Leeson, D., Mac Dowell, N., Shah, N., Petit, C. and Fennell, P.S., (2017), “A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources,” *International Journal of Greenhouse Gas Control*, Vol. 61, pp. 71-84.

LowCarbonFuture RFCS Project, (2020), “Final Report”.

Mandova, H., Patrizio, P., Leduc, S., Kjärstad, J., Wang, C., Wetterlund, E., Kraxner, F. and Gale, W., (2019), “Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage,” *Journal of Cleaner Production,* Vol. 218, pp. 118-129.

Meijer, K., Borlee, J., Skorianz, M., Feilmayr, C., Treadgold, C., Zeilstra, C., Keilman, G., Teerhuis, C. and Ouwehand, M., (2015), “HIsarna — Highly Energy-Efficient Ironmaking,” *Hisarna experimental campaigns B and C (HISARNA B and C)*, Vol. 27515, Publications Office of the European Union.

Ministry of Ecological Transition, (2016), “La Energía en España”.

Moser, P., Wiechers, G., Schmidt, S., Stahl, K., Vorberg, G. and Stoffregen, T., (2018), “OASE® blue - Optimierte CO_2-Abtrenntechnik als Ergebnis des 10-jährigen Entwicklungsprogramms von BASF, Linde und RWE Power im Innovationszentrum Kohle in Niederaussen,” *VGB PowerTech*, Vol. 1/2.

Müller, N., Herz, G., Redenius, A., Hille, V., Reichelt, E. and Jahn, M., (2019), “Assessment of the transition from coal-based steelmaking to hydrogen-based steelmaking”, Metec Estad, Düsseldorf.

Murri, M., (2019), “Essa Deliverable 2.1 Digital Transformation in European Steel Industry: State of Art and Future Scenario”.

MU-STEEL, (2014), “Final Report: Muons scanner to detect radioactive sources hidden in scrap metal containers”.

New Energy and Industrial Technology Development Organization (NEDO), (2019), “NEDO’s Environmental Technology Activities in 2019”.

Nippon Steel Corporation, (2019), “Nippon Steel’s Environmental Initiatives”.

PROTECT, (2015), “Final Report: Processes and technologies for environmentally friendly recovery and treatment of scrap”.

REDILP, (2007), “Recycling of EAF dust by an integrated leach-grinding process (REDILP)”.

Schenk, J. and Züngen, H.B., (2016), “Evaluation of the capabilities of direct and smelting reduction process to enhance energy efficiency and to reduce CO_2 emission of the steel production in Europe,” *7th European Coke and Ironmaking Congress* - ECIC, pp. 13-23.

Schenk, J. and Naseri Seftejani, M., (2018), “Fundamentals of hydrogen plasma smelting reduction (HPSR) of iron oxides, a new generation of steelmaking processes”.

SCHROTT24, (2018), “Scrap dealing in the digital age: a transparent and efficient platform for price and supply chain management”.

SCRAP PROBE, (2013), “Final Report: On-line bulk composition analysis of steel scrap using PGNAA”.

Shell Deutschland Oil GmbH, (2017), “Shell Hydrogen Study: Energy of the Future? Sustainable Mobility through Fuel Cells and H2”.

Shen, C., Liu, Z., Li, P. and Yu, J., (2012), “Two-Stage VPSA Process for CO_2 Capture from Flue Gas Using Activated Carbon Beads,” *Industrial and Engineering Chemistry Research*, pp. 5011-5021.

Skagestad, R., Onarheim, K. and Mathisen, A., (2014), “Carbon Capture and Storage (CCS) in industry sectors – focus on Nordic countries,” *Energy Procedia*, Vol. 63, pp. 6611-6622.

Smolinka, T., Wiebe, N., Sterchele, P., Palzer, A., Lehner, F., Jansen, M., Kiemel, S., Miehe, R., Wahren, S. and Zimmermann, F., (2018), “Studie IndWEDe: Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr,” *Strom und Wärme*.

SSIA, (2013), “Final Report: Strengthened scrap impact area in BOF converters”.

SUPERCHARGEEAF, (2017), “Supervision of charge material properties in EAF steelmaking utilising advanced statistical methods”.

Tata Steel, (2019), “Tata Steel's new HIsarna technology exceeds expectations in sustainable steel production”, *MPT International,* Vol. 1/2019.

Tata Steel, (2020), “Tata Steel in Europe Sustainability Report”.

voestalpine AG, (2019), “Geschäftsbericht voestalpine 18/19”.

voestalpine, K1-MET, (2018), “Energy in Future Steelmaking” EU Seminar *European Steel: The Wind of Change*”.

Wang, D., Gmitter, A.J. and Sadoway, D.R., (2011), “Production of Oxygen Gas and Liquid Metal by Electrochemical Decomposition of Molten Iron Oxide,” *Journal of The Electrochemical Society*, Vol. 158(6), pp. E51-E54.

Weigl, M., (2014), “Ganzheitliche Bewertung zukünftig verfügbarer primärer Stahlherstellungsverfahren”.

World Steel Association, (2003), Steel statistical yearbook.

World Steel Association, (2006), Steel statistical yearbook.

World Steel Association, (2018), World steel in figures 2018.

World Steel Association, (2019), World steel in figures 2019.

Wörtler, M., Schuler, F., Voigt, N., Schmidt, T., Dahlmann, P., Löngen, H.B. and Ghenda, J.T., (2013), “Steel’s Contribution to a Low-Carbon Europe 2050”.

Annex I

Table 14: European steelmaking sites equipped with blast furnaces and basic oxygen furnaces (2020)

Blast furnace and basic oxygen furnace (EU28, 2020)				
Location		**Hot metal capacity in '000 tonnes/year**	**Finished steel capacity in '000 tonnes/year**	**No. of furnaces**
Austria	Donawitz (Leoben)	1370	1570	2
	Linz	4340	6000	3
Belgium	Ghent	4430	5000	2
Czech Republic	Ostrava	3200	-	3 -blast furnace only
	Trinec	2100	2400	2
Finland	Raahe	2400	2600	2
France	Dunkerque	6800	6750	3
	Fos-Sur-Mer	5160	5100	2
Germany	Bremen	3960	3800	2
	Dillingen	4790	2760	2
	Duisburg	11600	11560	4
	Eisenhüttenstadt	2340	2400	2
	Salzgitter	4800	5200	3
	Völklingen	-	3240	Basic oxygen furnace only
Hungary	Dunauijvaros	1310	1650	2
Italy	Taranto	9590	11500	4
Netherlands	Ijmuiden (Velsen-Noord)	6310	7500	2
Poland	Dabrowa Gornicza	4500	5000	2
	Krakow	1310	2600	1
Romania	Galati	3250	3200	2
Slovakia	Kosice	2850	4500	2
Spain	Aviles	-	4200	Basic oxygen furnace only
	Gijon	4480	1200	2
Sweden	Lulea	2200	2200	1
	Öxelösund	1800	1700	2
United Kingdom	Port Talbot	4770	4900	2
	Scunthorpe	3590	3200	3

Source: author's own composition.[32]

[32] Based on: *www.eurofer.eu*

Table 15: European steelmaking sites equipped with electric arc furnaces (2020)

Electric arc furnace (EU28, 2020)			
Location		**Capacity in '000 tonnes/year**	**No. of furnaces**
Austria	Graz	365	1
	Kapfenberg	180	1
	Mitterdorf	300	1
Belgium	Charleroi	850	1
	Charleroi (Marchienne-au-Pont)	350	1
	Chatelet (Chatelineau)	1000	1
	Genk	1200	2
Bulgaria	Pernik	1000	2
Croatia	Sisak	350	1
	Split	185	1
Czech Republic	Ostrava	120	1
	Plzen	150	2
Finland	Imatra	360	1
	Tornio	1300	2
France	Bayonne (Boucau)	1200	1
	Bonnieres-Sur-Seine	550	1
	Chateauneuf, R. de Giers	100	1
	Fos-Sur-Mer	480	1
	Gargenville	700	1
	Hagondange	460	1
	Imphy	90	1
	Le Creusot	150	1
	Montereau	720	1
	Neuves Maisons	800	1
	St. Saulve	730	1
	Trith St Leger	800	1
	Ugine	250	2
Germany	Bous/Saar	350	1
	Brandenburg	1800	2
	Freital	90	1
	Georgsmarienhütte	1100	1
	Gröditz	100	1
	Hamburg	1100	1
	Hennigsdorf	1000	2
	Herbertshofen	1180	2
	Kehl	2500	2
	Lingen	620	1

	Peine	1000	1
	Riesa	900	1
	Siegen	600	1
	Siegen	150	1
	Unterwellenborn	1100	1
	Völklingen	300	1
	Wetzlar	400	1
	Witten	480	1
Greece	Almyros-Magnisia	1200	1
	Aspropyrgos	400	1
	Eleusis	800	1
	Thessaloniki	600	1
	Velestino	450	1
Hungary	Ozd	400	1
Italy	Aosta	260	1
	Bolzano	200	2
	Borgo Valsugana, TN	600	1
	Breno, BS	100	1
	Brescia, BS	1200	2
	Brescia, BS	650	1
	Camin, Padova	600	1
	Caronno, VA	780	1
	Catania, Sicilia	500	1
	Cividate al Piano, BG	250	1
	Cremona	3850	2
	Dalmine, BG	700	1
	Lesegno, CN	600	1
	Lonato, BS	1100	1
	Lonato, BS	600	1
	Lovere, BG	150	1
	Odolo, BS	900	1
	Osoppo. UD	2200	1
	Ospitaletto, BS	150	1
	San Zeno Naviglio, BS	800	1
	Sarezzo, BS	540	1
	Terni	1450	2
	Udine	500	1
	Udine	770	1
	Vallese D. Oppeano, VR	450	1
	Verona, VR	1250	2
	Vicenza	170	1
	Vicenza, VL	1200	1
Luxemburg	Esch-Sur-Alzette	2250	2

Poland	Chorzow	145	1
	Czestochowa	800	1
	Gliwice	250	1
	Katowice	65	1
	Ostrowiec	900	1
	Stalowa Wola	240	1
	Warszawa	750	1
	Zawiercie	1340	2
Portugal	Maia (Porto)	600	1
	Seixal	1100	1
Romania	Calarasi	470	1
	Hunedoara	550	1
	Otelu Rosu	830	1
	Resita	450	1
Slovakia	Podbrezova	350	1
Slovenia	Celje-Store	150	1
	Jesenice	500	1
	Ravne	140	1
Spain	Amurrio, Avala	150	1
	Amurrio, Avala	360	1
	Azpeitia	800	1
	Basauri, Vizcaya	740	1
	Bilbao	1100	1
	Castellbisbal, Barcelona	2400	2
	Galindo, Vizcaya	400	1
	Getafe, Madrid	600	1
	Jerez de Los Cabelleros II	1300	1
	Loiu, Vizcaya	130	1
	Los Barrios, Cadiz	1200	3
	Naron, La Coruna	700	1
	Olaberria	2450	1
	Reinosa, Cantabria	240	1
	Santander, Cantabria	750	1
	Sestao, Bilbao	2000	2
	Sevilla	1300	2
	Zaragoza	500	1
Sweden	Avesta	500	1
	Björneborg	95	1
	Hagfors	120	1
	Hofors	500	1
	Sandviken	200	1
	Smedjebacken	480	1
	Aldwarke, Rotherham	1220	2

United Kingdom	Sheffield	150	1
	Shepcote lane (SMACC), Sheffield	500	1
	Tremorfa, Cardiff	1200	1

Source: author's own composition.[33]

[33] Based on: *www.eurofer.eu*