INVESTMENT NEEDS

Michele De Santis, Antonello Di Donato (CSM)

Tobias Kempken, Thorsten Hauck (BFI)

Monika Draxler, Axel Sormann (K1-MET)

Paula Queipo (IDONIAL)

Wojciech Szulc (IMZ)

Danny Croon, Jean-Theo Ghenda (EUROFER)

Chuan Wang (SWERIM)

Jean-Christophe Pierret, Jean Borlee (CRM)

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

List of symbols, indices, acronyms and abbreviations

ACER	Agency for the cooperation of energy regulators
AEL	Alkaline electrolysis
AIE	Alkaline iron electrolysis
BF	Blast furnace
BOF	Basic oxygen furnace
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCU	Carbon capture and usage
CCUS	Carbon capture and usage or storage
CDA	Carbon direct avoidance
CE	Circular economy
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
CS	Crude steel
CS-PPP	Clean steel public private partnership
DR	Direct reduction
DRI	Direct reduced iron
EAF	Electric arc furnace
EU	European Union
FP	Framework Programmes
GHG	Greenhouse gas
GREENSTEEL	Green Steel for Europe
H_2	Hydrogen
H_2-DR	Hydrogen-based direct reduction
HBI	Hot briquetted iron
HTEL	High temperature electrolysis
HPSR	Hydrogen plasma smelting reduction
IBRSR	Iron bath reactor smelting reduction
IMF	International Monetary Fund
INDC	Intended nationally determined contributions
LULUCF	Land use, land-use change and forestry
MOE	Molten oxide electrolysis
MSW	Municipal solid waste
N_2	Nitrogen
NG-DR	Natural gas-based direct reduction
O_2	Oxygen

OPEX	Operational expenditure
PEM	Polymer electrolyte membrane
PCI	Pulverised coal injection
PI	Process integration
R&D	Research and development
R&D&I	Research, development and innovation
RDF	Refuse-derived fuel
RFCS	Research Fund for Coal and Steel
t	Tonne
TGR-BF	Top gas recycling – blast furnace
TRL	Technology readiness level

Executive summary

The production of steel must undergo a deep decarbonisation process if it is to meet the CO_2-reduction objectives envisaged by the European Green Deal, which aims to bring about a transition to a competitive low-carbon economy by 2050. The Green Steel for Europe (GREENSTEEL) project, for its part, aims to promote a green revolution in the steel industry.

This report focuses on the investment needs for the expected steel-industry decarbonisation (aimed at reducing steel industry CO_2 emissions by at least 80%) and suggests an investment roadmap. To this end, the report includes a thorough investigation of the following elements:

a) the current **technology** developments in the field of CO_2 reduction in the steel industry, with a focus on their related **investment needs**;
b) an **investment roadmap**, describing the investment needs for the technologies up to industrial deployment; and
c) the current **regulation** and **market context**, which shapes to the real economic framework in which the EU steel industry must evolve (sustainable transition).

a) Technologies, technology routes and related investment needs

The selection of technologies was derived from deliverable D1.2 of the GREENSTEEL project. The following were identified as the most relevant technologies:

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

Several technologies can be combined to raise the overall CO_2-mitigation potential above their individual limits. The main auxiliary processes connected to many of the above-mentioned technologies are CO_2 capture and H_2 generation.

These technologies can be considered as individual modular components within the complete steel production chain. Technology routes integrate these components into a full process chain, including upstream operations (transformation of raw materials into intermediate steel products) and downstream applications (production of final shaped and coated products). The amalgamation of technologies into technology routes (including the integration into existing/new production chains) needs substantial additional investment. Four groups of technology routes were identified within the project as being highly relevant (but non-exclusive) examples:[1] routes based on the optimised

[1] The groups were the same as those in the D1.2 report of the GREENSTEEL project "Technology assessment and roadmapping".

conventional blast furnace-blast oxygen furnace-route (BF-BOF-route), on direct reduction (DR), on smelting reduction and on iron ore electrolysis.

Technology routes based on optimised BF-BOF

The first technology route consists of adjustments to the conventional BF-BOF ironmaking process, many of which are possible in the short term. These adjustments include the injection of hydrogen-rich gases and the increased use of alternative energy carriers, such as biomass and scrap. Furthermore, the addition of carbon capture and usage or storage (CCUS) units to conventional processes is also considered, since CCUS is quite a flexible option that can be combined with almost all other techniques, e.g. electric arc furnace (EAF), natural gas direct reduction (NG-DR) plants or downstream processes.

The investment needs can be apportioned as follows:

- *up to 2030*: industrial investment for first implementations in existing BF-BOF plants and technological investment for other less mature options, including CCUS; and
- *up to 2040*: industrial investment for full implementation and minor technological investment for other less mature options.

Technology routes based on direct reduction (e.g. H_2-DR-EAF route)

This route proved to be among those allowing major CO_2 mitigation potential. However, its success in the European steel industry depends on the availability and cost of ‘clean’ energy (hydrogen and electricity). Therefore, starting with NG-DR is a plausible and more realistic first step for industrial deployment, which would still enable high CO_2 mitigation. For both variants (NG/H_2-DR), challenges and investments should be considered, which are linked to the restructuring of the existing industrial systems (i.e. the adaption of material, gas and heat supply chains).

The investment needs can be apportioned as follows:

- *up to 2030*: industrial investment in DR plants using natural gas and technological investments to increase hydrogen content and upgrade the technology readiness level (TRL) up to industrial level; and
- *up to 2040*: industrial investment in the implementation of H_2-DR-EAF and the progressive replacement of blast furnaces (and related plants).

Technology routes based on smelting reduction (e.g. enhanced IBRSR route)

The technology route based on iron bath reactor smelting reduction (IBRSR) technology replaces the BF and eliminates the need for the cokemaking and sintering (or pelletising) of the iron ore. The steelmaking and hot-rolling sections can remain unchanged or, if desired, they can accommodate the additional changes presented in the BF route above.

The investment needs can be apportioned as follows:

- *up to 2030*: technological investment in scaling up to TRL 8; and
- *up to 2040*: industrial investment in the progressive replacement of BFs and related plants and, subsequently, for industrial deployment in the European industry.

Technology routes based on iron ore electrolysis

These routes comprise two technologies, alkaline iron electrolysis (AIE) and molten oxide electrolysis (MOE), which both reduce iron ores through direct use of electricity but which currently have different technical maturity levels: moderate (TRL 5-6) for AIE and low (TRL 2) for MOE. Both technologies depend on the availability of large amounts of CO_2-free electricity at affordable prices.

For the alkaline electrolysis (AEL), the investment needs can be apportioned as follows:

- _up to 2030_: technological investment in scaling up to TRL 8; and
- _up to 2040_: industrial investment in the implementation of AEL plants, for progressive replacement of BFs and related plants, and subsequently for deployment in European industry.

For MOE, the investment needs can be divided as follows:

- _up to 2030_: technological investment in both fundamental and low-scale developments (e.g. laboratory, pilot plant); and
- _up to 2040_: industrial investment in further upscaling in view of achieving TRL 9 in 2050.

Note that some of the above-mentioned technologies can be in direct competition with each other, meaning that only one can be implemented. For example, H_2-DR, AIE/MOE and mixed solutions (HPSR) are in competition, whereas several others may be combined with high synergy (e.g. CCU and biomass with several other technologies).

b) Investment roadmapping

As to the investment needs, publicly available data have been combined with information derived from interviews with steel producers and technology providers. In order to design an investment roadmap, the investment needs for the main technological solutions (the so-called technology routes in the D1.2 report "Technology assessment and roadmapping") have also been considered in the context of the periods in which they will be needed by 2050.

An investment roadmap has been developed based on the analysis of the selected decarbonisation technologies and their investment needs. The arising within this timeframe are set out as follows:

1. **the cost for development up to TRL 8**: these are the investment needs to upgrade the technology from the existing TRL to complete systems, including small-scale demonstration in an operational environment;
2. **the cost for the first industrial deployment (TRL 9)**: these are the investment needs for the scale up and full industrial validation of a first-of-a-kind industrial plant;[2]
3. **the cost for production plants**: these are the investment needs for a full-scale industrial production plant (normalised to 1 M t production capacity); and
4. **the cost for the deployment of auxiliary technologies**: these are the investment needs for enabling auxiliary technological solutions, with similar development/investment steps as those described above.

Notably, most of the overall investment needs from 2020 onwards will be concentrated in the period 2030-2050.

A summary of the investment roadmap for single technologies and technology routes is shown below, in Table 1.

[2] At least a one-year operation with about 30% (or more) industrial plant production capacity.

Table 1: Summary of investment roadmapping for single technologies and technology routes

Single decarbonisation technologies							
Technology	TRL development			Investment needs up to TRL 8 (M€)	Investment needs for 1st industrial depl. TRL 9 (M€)	Investment needs for full industrial plant (M€)	CO_2 abatement (max %)
	2020	2030	2050				
H_2-DR (100 % H_2)	6–8	7–9	9 (ind. depl.)	100	150	250*	95
HPSR	5	6	9 (ind. depl.)	100	200	500	95
AIE	5-6	6–8	9	250	500	Not evaluated due to low TRL	95
MOE	2	3-4	9	1000	Not evaluated due to low TRL		95
CCUS	5- 8	9	9 (ind. depl.)	150	300	1000	60
IBRSR	6	8	9 (ind. depl.)	400	850 **		20-80
BF-Gas injection	5–9	8–9	9 (ind. depl.)	150	400**	600**	20-60
Biomass usage	2–7	8	9 (ind. depl.)	5	15		30-100
Increased scrap usage	4–7	7–9	9 (ind. depl.)	50	100		100 (with CCS).
Auxiliary technologies							
Technology	TRL development			Investment needs up to TRL 8 (M€)	Investment needs for 1st industrial depl. TRL 9 (M€)	Investment needs for full industrial plant (M€)	CO_2 abatement (max %)
	2020	2030	2050				
CO_2 capture	5–6	8–9	9 (ind. depl.)	(independent from steel industry, n		200	-
Water electrolysis	5–8	7–9	9 (ind. depl.)	Not evaluated (independent from steel industry)		100	-
Technology routes							
Technology route	TRL development			Investment needs up to TRL 8 (M€)	Investment needs for 1st industrial depl. TRL 9 (M€)	Investment needs for full industrial plant (M€)	CO_2 abatement (max %)
	2020	2030	2050				
Optimised BF-BOF	2-9	7–9	9 (ind. depl.)	2,000***	4,000		95
Direct reduction	4-8	7-9	9 (ind. depl.)	500		650	95
Based on smelting reduction	2-6	6–8	9 (ind. depl.)	400	500**	600**	85
Based on iron electrolysis	2-6	3-6	9	250	400	Not evaluated due to low TRL	95

*Source: authors' own composition based on desk research and stakeholders' interviews (complete references in the bibliography). Note: data refer to a crude steel capacity of 1 Mt/a as a reference[3]. * €500 M including EAF. ** Excluding CO_2 transport and storage. *** From greenfield (brownfield CAPEX costs 40% with respect to BF-BOF). For the abbreviations used, please see the list of symbols, indices, acronyms and abbreviations.*

The table is divided into three parts. The first shows the investment needs for the development of the single technologies, the second includes the needs for auxiliary technologies, and the third shows the needs for the technology routes resulting from a combination of technologies, to account for complete steel production chains. Where information was lacking, general TRL info or a common investment need for plant deployment is given.

It should be noted that the above-mentioned data refer to technology development from greenfield.[4]

The investment costs correspond to one (pilot/demonstration/industrial) plant at a time. However, operating at least two plants for each technology is strongly recommended to ensure reliable results and gather a broad range of experiences. The information on the technical maturity is given as a TRL range, representing different aspects of the respective technology/technology route. Regarding the readiness for first industrial deployment, the upper limit of the TRL range is relevant, since the less mature aspects are usually optional.

Technologies vs CO_2 emission-abatement potential

The investment roadmap needs to be put into **the sustainability perspective** – allowing for a sustainable transition, leading to a competitive and resource-efficient industry and providing enhanced worker safety and new job opportunities. Therefore, the costs of the different options must be considered in relation to their CO_2 emission-abatement potential.

Furthermore, the technologies' expected maturity progress has to be considered, since the CO_2 emission abatement should be achieved as soon as possible, in particular in light of the long investment cycles of the steel industry. Table 1 allows for both aspects of the technologies to be compared.

Technologies related to biomass, increased scrap usage, gas injection in BF and CCUS have lower impact on CO_2 emissions when applied individually, but are the closest to industrial development and have relatively low investment costs. Conversely, the new innovative steelmaking technologies, such as HPSR and AIE iron ore electrolysis, have a big potential, but their industrial deployment requires more time and large investments due to rather low TRLs to date.

The H_2-DR technology offers a compromise, with its moderate TRL and very high CO_2 abatement potential, even in the medium term. The direct-reduction technology also guarantees a significant CO_2 abatement in the short term via the natural gas-based direct reduction (NG-DR). Since this is already an industrially established technology, industrial plants can be installed in Europe in the short term, which would enable a significant short-term decrease of the CO_2 footprint of the European steel industry.

---

[3] In general, real industrial plant sizes differ depending on a specific technology. Taking for example BF-gas injection technology and the route based on smelting reduction, the investment needs for the Hisarna plant with a 1.5 Mt/a CS capacity are reported in Section 2.5.3.

[4] In fact, in Europe the optimised BF-BOF route will most probably be based on existing installations (brownfield) rather that new installations (greenfield). The CAPEX for BF-BOF brownfield (BF-BOF retrofit) is estimated to be a bit less than 40% of the CAPEX for greenfield BF-BOF (Ghenda, 2013).

These industrial DR plants could afterwards be used for further R&D activities, with the aim of maximising the ratio of hydrogen to natural gas and further decreasing industrial emissions. With this approach, major CO_2 abatement of industrial emissions would be possible, without having to wait several years for less mature techniques to be developed. Instead, depending on the local environment (e.g. favourable conditions with respect to economic and legal barriers and energy/resource costs), first industrial sites could build DR plants within a couple of years. However, this approach would have a significant impact on investment needs. As can be derived from Table 1, huge investments on industrial scale (up to €1-2 B) would be necessary in the short term, bypassing the cheaper demonstration-plant step.

As a general remark, even though across Europe there is a wide distribution of projects and related experimental and demo plants based on the new technologies (see comprehensive list in D1.1), how many EU plants will really be involved in the options identified within the GREENSTEEL project will depend on several factors (enablers, legal framework, especially public financial support for R&D&I and upscaling of the current demo). New low-CO_2 production technologies will require a €50-60 B investment, with €80-120 B per year capital and operating costs. The cost of production per tonne of primary steel will increase by 35% up to 100%. The new technologies would result in additional production costs for the EU steel industry of at least €20 B per year compared to the retrofitting of existing plants (i.e. the upgrading of existing plants with the best available techniques). At least 80% of this share is related to operational expenditure (OPEX), mainly due to increased use and higher prices for CO_2-lean energy.
Moreover, local conditions can foster the deployment of some of the presented technologies, as is the case, for example, for Belgium, France and the Netherlands, which can take the opportunity of using carbon capture and storage (CCS) in the North Sea ports, or Sweden, which can rely on the availability of green energy. Turning all opportunities into reliable pathways will also depend on other external aspects (e.g. financial support or policies). A thorough analysis of the most promising pathways, together with a general indication of the expected positive effect on investment needs will be detailed in a dedicated report.

c) Regulatory and market context

Climate protection is a central element of the European regulatory context and is enshrined in the European Green Deal Communication, with sets the goal of making the EU carbon neutral by 2050.

The study also looks into the market context, as it affects the investment environment. Steel is a heavily traded commodity on the global market. Global trends in steel demand, steel supply capacity and steel trade flows shape the dynamics of the steel industry. Global crude steel production reached 1.87 B tonnes in 2019, 8.5% of which was produced in the EU. In the last decade, steel imports to the EU have been increasing while steel exports from the EU have been decreasing, with the EU being a net importer of finished steel products. The outbreak of the Covid-19 pandemic across the EU and all world regions has slashed steel consumption and production forecasts as well as impacting the overall economic outlook.

The production of clean steel will entail (much) higher costs for several reasons, at least for the foreseeable future. Therefore, as already discussed in the deliverables D1.2 (Technology assessment and roadmapping) and D1.3 (Technology and investment need assessment from stakeholder consultation), new markets and business models for clean steel must be established.

This need was confirmed by the first part of the GREENSTEEL stakeholder consultation: steel producers ranked “unknown market conditions for clean steel” among the three main barriers hindering the projected CO_2-emission reduction level in the decarbonisation of steel production. In order to create a proper market context for clean steel and related products, incentives are recommended for the use of clean steel (and related products), and for the promotion of clean steel products in public procurements and the adaption of standards.

There are some decarbonisation technologies, currently available, which enable a short-term deployment with limited R&D and investment needs, but their mitigation potential is also limited. Consequently, as there is no single technology which fulfils all demands, parallel investments in the development and deployment of several technologies are needed. These technologies, which can also be combined, provide alternatives and offer individual advantages, depending on the different framework conditions and time scales.

Although all the presented technologies are expected to reach an industrial deployment by 2050 at the latest, only some of them (namely, H_2-DR, CCUS, gas injection on BF, increased scrap usage) are expected to achieve TRL 9 close to 2030. Most development investments (including demonstration) are therefore needed before 2030, whereas most investments for industrial deployment will occur between 2030 and 2050.

However, the DR technology provides a different opportunity, as industrial plants based on natural gas could be built and then further developed for increasing hydrogen usage. This approach would require large investments in the short term but would enable a significant short-time mitigation and a flexible and highly efficient mitigation in the medium term.

The huge investment needs and the related technical-economical risks call for adequate financial support of the development activities. Parallel to financial support, regulatory initiatives are needed to support clean steel markets, with the objective of propelling the technological development and the industrial deployment towards the CO_2-mitigation targets.

The results of this report will be used for the upcoming work within the project Green Steel for Europe, more specifically in work package 3 (Impact Assessment) which analyses and recommends different policy options.

1. Introduction

The project Green Steel for Europe (GREENSTEEL) addresses the challenge of decarbonising the EU steel industry, which requires considering in an integrated way the following three key aspects:

- the individuation of technologies with appropriate maturity.
- the boundary conditions which support the industrial deployment, in particular with respect to the investments needed; and
- the appropriate business environment ensured by the adoption of adequate economic and regulatory policies.

This report (Deliverable D2.2) focuses on the technologies identified and synthesised to technology routes in the project Task 1.2. The report is composed of three main parts:

- analysis of investment policies and stakeholders' investment strategies (Chapter 2);
- analysis of the regulatory and market context (Chapter 3); and
- investment roadmapping (Chapter 4).

In chapter 2, two different kinds of investment needs are considered:

- investment needs for technical development (in particular, demonstration plants); and
- investment needs for industrial deployment (considering the decarbonisation processes themselves and including the additional costs to integrate new processes in existing brownfield sites/production chains).

In Chapter 3, the regulatory and market context is analysed, given the important role it plays in driving stakeholders' investment strategies.

In Chapter 4, the information gathered is used to elaborate an investment roadmap for the identified technologies.

The report relies on information from the following sources:

- the project LowCarbonFuture[5] and the parallel activity carried out within the GREENSTEEL project in its first work package (WP1), which is dedicated to technological needs;
- the scoping interviews conducted with stakeholders (for which more detail can be found in the Deliverable D1.3 (Preliminary findings from stakeholder consultation);
- the desk research on the mentioned issues (for which more detail can be found in the Deliverable D1.2, "Technology assessment and Roadmapping"); and
- the parallel activities carried out when setting up of the Clean steel partnership (CS-PPP), aimed at "helping remove R&D&I and systemic bottlenecks such as the transition from the pilot phase to industrial-scale deployment, high technology risks, large capital requirements and higher production costs", to "tackle two major challenges: climate change and sustainable growth for the EU".

[5] For further details, please see https://www.lowcarbonfuture.eu.

2. Technologies, technology routes and related investment needs

In this chapter, the investment needs for the most promising technologies (selected in Deliverable D1.2) for decarbonisation of the steel industries are presented.

The complete elimination of fossil energy carriers is a logical, direct and drastic way to achieve deep decarbonisation. A second possibility is to capture the produced CO_2 and store it in clearly confined sites, or to use it as raw material to produce chemical products.

At the same time, a large variety of technologies for reducing the consumption of fossil energy carriers are either under development or already partly tested in the European steel industry.

According to a widespread classification, also adopted in D1.2, these decarbonisation options are called, respectively:

- carbon direct avoidance (CDA);
- carbon capture and storage / carbon capture and usage, (CCS/CCU); and
- process integration (PI).

All the options, especially PI, are ever more conceived according to the new paradigm of the **circular economy (CE)** approach**.** This approach replaces the 'end-of-life' concept with a 'zero-waste' concept by reducing, or alternatively reusing, by-products and residues, as well as recycling and recovering energy and valuable materials from production/distribution streams and consumption processes.

The investment needs are analysed following this classification of technologies (as in D1.2) and presented in the related paragraphs 2.1, 2.2 and 2.3, respectively. In D1.2, the Section 2.4 is dedicated to the two main auxiliary processes of CO_2 capture and H_2 generation, which are required, for example, for CCS/CCU or hydrogen-based steelmaking. These technologies are not specific to the iron and steel industry and are therefore being developed independently. However, their application in steelmaking processes requires specific characteristics, in terms of performance and capacity and, consequently, specific investment needs that cannot be separated from the investment needs for their application in the steel industry. For this reason, the investment needs for these technologies have been included in Section 2.4.

The investment needs of the considered technologies are distributed as follows[6].

1. **costs for development up to TRL 8:** these are the investment needs to upgrade the technology from the current technology readiness level (TRL) to demo level, as reported in D1.2.
2. **costs for development up to first industrial deployment**: these are the investment needs to upgrade the technology from the current TRL to first industrial deployment, as reported in D1.2; and
3. **costs for production plants**: these are the forecast investment needs to implement the technology at industrial scale, after reaching industrial deployment maturity.

In some cases, a further type of investment need should be considered, where necessary:

[6] See also D1.2. Report of the GREENSTEEL project "Technology assessment and roadmapping".

4. **costs for deployment of auxiliary technologies:** these are the investment needs for auxiliary enabling technologies, which have not yet been industrially deployed for application in steelmaking and which are required for the development of other technologies.

Estimates are based on information from literature, from the already allocated or requested funds for the development of the technologies (e.g. European funded projects in RFCS, Horizon2020, FP's, and national funding), and from interviews with producers and technology providers performed in the frame of the GREENSTEEL project[7]. The experience of the partners of the project has also been considered as a reliable source of information.

Because of the large variety of technologies, maturity levels (in terms of TRL) and framework conditions, the investment needs are evaluated and explained case by case according to the following general guidelines:

- the investments concerning upscaling and optimisation have been estimated only for technologies at a TRL higher than five. The evaluation is mainly based on the envisaged costs for pilot and demonstration plants, operated for R&D purposes, and thus not for commercial production. The published estimated costs have been used, when available. In other cases, the evaluation is based on an analogy with plants, projects and objectives that can be considered similar in terms of typology, size and complexity of the equipment,
- estimates of the costs concerning production and auxiliary plants are limited to the main components representing the distinguishing features of the technology while the general ancillary equipment (common to many other processes and plants) is neglected. The investment needs inherit the capital expenditure (CAPEX) of these components. The operational expenditure (OPEX) is just presented when referenced. More detailed assessment will be done in further reports which will focus on the decarbonisation pathways;
- in general, CAPEX (and OPEX when available and referenced) is expressed in specific terms and referred to a specific mass of product (e.g. crude steel, CS) or to its production in a defined timeframe. When applicable, the cost for a plant has been calculated, assuming a production capacity of 1Mt per annum (Mt/a) as reference. Extrapolation to larger capacities can then be utilised, e.g. by linear proportionality. The approximation according to which 1Mt/a production capacity corresponds to a 100 t/h production rate has been adopted. Although a more accurate value is estimated to be around 115 t/h, this difference falls within the precision intervals of the calculation. Overall, the aim of these evaluations is not to establish the most precise estimated cost for future plants, but rather to give an indication of the impact of different decarbonisation technologies on investment and operating costs;
- the investment needs are evaluated for each single technology and for one single application. An extrapolation to a wider application, with many installations diffused in the European industry, as well as the mutual interactions between investments for different technologies, are discussed in Chapter 3.

[7] Aggregates info in the GREENSTEEL D1.3 report, available upon request

- in most cases the estimates resulted in wide ranges of investment needs, due to the complexity of the subjects, the large number of existing projects and applications and the variety of sources. To facilitate the reader and the further use of the information, a summary of each investment need was prepared for every technology, in terms of cost and impact on CAPEX. The values reported in this summary are not mere arithmetic means of the detailed data, but rather a first approximation, given in order of magnitude; and
- the specified costs focus on the technologies, neglecting in most cases the costs of integration into existing (brownfield) plants. These additional costs are significant and highly relevant for investment decisions for industrial deployment of techniques; however they depend on individual plant conditions and are difficult to specify.

Most promising technologies for the decarbonisation of the steel industry

In Europe, about 60% of steel is produced via the primary (or integrated) route, based on blast furnace (BF) and basic oxygen furnace (BOF) units. The BF uses iron ore (in pellet or in sintered form) together with coal and coke (derived in turn from coal) for producing liquid hot metal (carbon-saturated iron), which is further converted into liquid steel. The remaining 40% of steel production is based on recycling steel scraps (secondary route), which are melted to liquid steel in electric arc furnaces (EAF).

Beside these industrial technologies mostly deployed in Europe, a third (also primary) route is utilised, mainly in other parts of the world. It is based on direct reduction (DR) of iron ore (in pellets or briquettes) into solid iron (sponge iron or direct reduced iron, DRI), generally by using natural gas as reductant and fuel. The DRI is then melted in an EAF, thus producing liquid steel. Today DR accounts for about 5% of the global steel production (World Steel Association, 2019 (worldsteel, 2020)). Due to its full industrial maturity, this route offers a strong potential for fast decarbonisation of the European steel production. At the same time, it offers the opportunity for increase CO_2 mitigation by further developing it to hydrogen based direct reduction (H_2-DR) in a flexible way.

The production of steel from iron ore consumes much more energy and fossil energy carriers than the production from recycled scrap. In general, steel production via primary route (BF and BOF) causes 1.9 t CO_2/t CS (tonnes of CO_2 emissions per tonne of produced crude steel, CS) (Wörtler et al., 2014 (Wörtler, et al., 2013)). The secondary route (recycling of scrap in EAF) accounts for about 0.4 t CO_2/t CS. This value includes also the indirect emission for electricity generation. The production via direct reduction with natural gas results in about 1.2 t CO_2/t CS (Wörtler, et al., 2013). However, the primary route enables the production of all kinds of (high quality) steel products, whereas the secondary route is often preferred to produce construction steel (for which a lower metallurgical purity is required) due to the impurities brought in by the scrap (for further details, please see Deliverable D1.2).

Analyses show that for most technologies, huge amounts of CO_2-free energy sources[8] are needed and that the material cycles in the plants will be considerably influenced. Also, significant increases of OPEX (mostly due to expensive renewable energy supply) and of CAPEX (due to the need to replace main parts of the upstream process chain) are expected. Most identified technologies have a moderate maturity level (TRL at 5-7). Some technologies have a high CO_2 mitigation potential

[8] The EU steel industry will require approximately 400 TWh of CO_2-free electricity every year by 2050 (including electricity for the production of yearly 5.5 Mt of hydrogen).

but are currently at low maturity (e.g. hydrogen plasma smelting reduction, HPSR, at TRL 4, molten oxide electrolysis, MOE, at TRL 2). Correspondingly, a high number of R&D needs exist, particularly regarding the processes themselves and their upscaling, the related plant technologies, necessary auxiliary processes, material processing and a large number of measurement and control aspects. More details regarding the technological assessment are given in Deliverable D1.2.

The main conclusions of the analyses are synthesised as follows:

1. many breakthrough decarbonisation technologies are not available for industrial deployment in the short term (until 2030);
2. there are some decarbonisation technologies currently available which enable short-term deployment with limited R&D need and investment effort, but their mitigation potential is also limited; and
3. all decarbonisation technologies need certain framework conditions, with the most important one being sufficient renewable energy at competitive costs.

To realize the crucial next step of demonstration and completion in an operational environment (TRL7-8) and to further develop the less mature breakthrough technologies, the R&D actions need to be taken now. Since there is a great variety of R&D actions needed and the effort by far exceeds the usual R&D needs, collaborative research is essential for effective progress.

One of the main results of the project was identifying relevant decarbonisation technologies to complete steel production chains, with a view of proposing breakthrough technology routes with high potential CO_2 emission reduction (see Deliverable D1.2). The following breakthrough technology routes were identified:

1. **BF-BOF-HR route:** the technology route based on the conventional route of blast furnace-basic oxygen furnace-hot rolling (BF-BOF-HR) with applications of several PIs and/or carbon capture and usage or storage (CCUS) technologies for fast and high CO_2 mitigation;
2. **H_2-DR-EAF route:** the technology route based on direct reduction (with high hydrogen utilization) and electric arc furnace (H_2-DR-EAF). While this route needs significant modifications of existing plants, it achieves high CO_2 mitigation without need for CCUS;
3. **Enhanced IBRSR (iron bath reactor smelting reduction) route:** the technology route based on smelting reduction which enables high bio-coal, fine ore and scrap usage as well as effective combination with CCUS technologies; and
4. **Iron-ore electrolysis route:** the technology route based on iron ore electrolysis which is directly electrifying iron production. It is still at lower technological maturity but could be an option for high CO_2 mitigation in the long term.

Even though these technology routes represent end points of the decarbonisation process, the technology implementation (i.e. integration into existing/new production chains) needs substantial additional effort, both with respect to R&D activities and with respect to accompanying investments.

These conclusions shortly summarise the current results obtained within the GREENSTEEL project and will be further developed by the following prognosis of industrial deployment scenarios for 2030 and 2050 in Task 1.4/1.5, as well as the linked impact analyses in work package 3.

2.1. Carbon direct avoidance

The carbon direct avoidance (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, avoiding the generation and hence emission of carbon oxides. Basically, there are two possible options to replace fossil energy carriers in steelmaking processes based on iron ore: by electricity and/or hydrogen produced from renewable or CO_2-free sources. The third option, using char and syngas produced from biomass, is very limited in Europe (for further details please see Section 3.1 of D1.2).

With respect to this technology, the following paragraphs present the investment needs for:

1. the direct reduction with (almost) 100% hydrogen (Section 2.1.1), which represents the end point of the technology route based on the mature natural gas-based direct reduction (NG-DR);
2. the emerging technologies, which are:
   - HPSR (based on a mixed use of hydrogen and electricity) in Section 2.1.2; and
   - AIE (alkaline iron ore electrolysis) (paragraph 2.1.3) and MOE (Section 2.1.4), in which the metallic iron is produced from iron ore only by means of electrical energy.

The investment needs are assessed in terms of the upgrading of the technology from the current status to a level potentially exploitable for industrial deployment. However, to actualise this industrial deployment, significant adaptions of existing plants and internal/external infrastructure are necessary. For the specific case of the presented CDA technologies, the availability of electrical energy from renewable sources and clean hydrogen, e.g. produced from such electrical energy, are main enabling conditions.

2.1.1. Hydrogen-based direct reduction

The hydrogen-based direct reduction (H_2-DR) is a technology derived from the existing direct reduction process using natural gas or coal. Starting from NG-DR, it is possible to progressively enrich the operating gas mixture with hydrogen, depending on plant framework conditions (i.e. availability of hydrogen). There are different technological approaches: The most common approach is DR in a shaft furnace, where pelletised iron ore is reduced to DRI by means of hydrogen gas. Another option consists in the DR of fine ore in a fluidized bed by means of hydrogen gas. In the conversion process of integrated steel plants towards H_2-DR steelmaking process, the BF and BOF units become obsolete. Downstream of this step, an EAF is utilised to melt the produced DRI by direct use of electricity. The subsequent downstream processes (secondary metallurgy and subsequently casting and rolling) mostly do not require significant changes.

Upstream of the DR step, sinter plants may be replaced by pelletising plants, since DR-plants are usually operated with iron ore pellets. Due to the fact that the majority of European plants buy pellets from external suppliers, the industry position on how many new pelletising plants will be built on-site in Europe is not clear yet. This entails an increased risk of carbon leakage if pellets are bought from non-European (e.g. oversea) suppliers. Furthermore, in this case the advantages of sinter plants are lost, more specifically the strategical advantage with regard to flexible and tailor-made sinter produced on-site from iron ore fines and concentrates from different suppliers as well as the ecological advantage of recycling most internal iron-bearing residues via the sinter. This might induce investments for alternative recycling plants.

The currently most common DR technologies on the market are MIDREX and HYL/ENERGIRON[9]. Both solutions can be applied for H_2-DR as both suppliers claim that quite high hydrogen contents should be technically feasible in a short time. The remaining risks and the needs for further development are difficult to assess, since evidence for DR plants operated with pure hydrogen on large scale is not yet available. However, due to the high maturity of NG-DR plants, the TRL is higher and the remaining risks lower than for most other technologies.

Several demonstration activities for H_2-DR have already started. Two European examples are: the ArcelorMittal demonstration plant in Hamburg which is based on the MIDREX Technology[10], and the HYBRIT consortium which signed an agreement with Tenova for using the HYL technology.

Technical details aside, the end point of a passage from natural gas to hydrogen-based technology will probably require similar investment needs, irrespective of the adopted commercial solution.

Investment costs for development up to TRL 9

Several European steelmakers are currently developing H_2-DR, adopting one of the two predominant technologies with the construction of pilot and demonstration plants with a current European TRL of 6-8, for the usage of (almost) pure hydrogen.

The technology providers claim that their DR plants could operate with 100% hydrogen without major modifications. The analysis performed in D1.2 confirms that optimisation is related more to operational aspects and product qualities than to basic plant engineering. The most important issue that the pilot and demonstration plants need to study is the perfect integration of the three main units: the electrolyser for producing clean hydrogen (water electrolysis), the shaft furnace for DR process and the EAF to melt the DRI. This includes, for example, developing the solutions to compensate the expectedly variable hydrogen-production rate determined e.g. by the use of fluctuating electrical energy from renewable sources and optimising the melting process of a DRI in the EAF without carbon (being produced from hydrogen).

The construction of several pilot and demonstration plants has already been initiated and the first ones with a capacity of up to 1Mt/a (ArcelorMittal, 2019) are planned to be completed in 2020. (Agora-Energiewende, 2019). In that context, achievement of TRL 9 is expected before 2030. The investment costs for these plants depend on the production capacity, auxiliary equipment and technological objectives. As an estimate, investment costs in the range of €100-200 M can be expected for a single installation of H_2-DR process from pilot to demonstration. As an example, the total cost of the pilot phase of the HYBRIT project was €136 M (Bioenergy International, 2018).

In parallel, investments are necessary to study the melting process of carbon free DRI from hydrogen in EAF units. In principle, this step does not require the construction of new plants, as the existing EAFs (at any scale) can already be suitable for this purpose. However, the carbon neutral operation of EAFs too needs further development since electrodes and auxiliary burners currently cause some CO_2 emissions. The corresponding investment needs can be estimated in the order of magnitude of demonstration projects, resulting in €10-20 M for three-year projects.

[9] The technology is HYL, owned by Tenova. Tenova HYL and Danieli & C. have formed a partnership for the design and construction of the HYL technology under the ENERGIRON trademark.

[10] For further details please see https://corporate.arcelormittal.com/media/case-studies/hydrogen-based-steelmaking-to-begin-in-hamburg.

In summary, the investment costs for upgrading the hydrogen-based technology up to TRL 9, hence ready for industrial scale, can be estimated at around €250 M.

Investment costs for production plants

A sum of €230/t CS is required for the direct reduction shaft (Wörtler, et al., 2013). Assuming that 1 t DRI is required for the production of 1 t CS, this results in investment costs of €230 M for the industrial deployment of the H_2-DR technology with an annual production capacity of 1 Mt CS. These costs are complemented by significant additional costs for the EAF (for the conversion of DRI into CS) and the water electrolysis for hydrogen production. These costs are further assessed in the scope of the complete technology route in Section 2.5.2.

Based on existing reference on OPEX, the total production costs are estimated at around €500/t of CS, depending on the amount of scrap used and especially electricity and CO_2 prices. As to electricity, the energy requirement is estimated from 3.3 to 4.1 MWh/t CS, of which the largest share is required for H_2 production. Overall, CO_2 mitigation costs are estimated as medium level costs (€60 to 99/t CO_2; estimates for 2030, Germany: €60/t CO_2 for NG-DR; €99/t CO_2 for H_2-DR) (Agora-Energiewende, 2019).

Investment needs for H2-DR are summarised as follows:

- investment needs for achieving TRL 8–9: up to about €100-150 M (for a single demonstration plant);
- investment needs for industrial deployment: about €250 M for a first industrial plant of capacity 1Mt/a; and
- the unique situation of DR being industrially established via natural gas (NG-DR) enables to build industrial NG-DR plants in the short term and raise the hydrogen content successively towards the midterm H_2-DR target (e.g. (SALCOS, 2020)[11]).

2.1.2. Hydrogen plasma smelting reduction

The hydrogen plasma smelting reduction (HPSR) is a direct transformation from iron ore fines to liquid steel and represents an evolution from the classical smelting reduction process. In a smelting reduction the feedstock is fine iron ore. Carbon acts as reductant and provides energy. It is supplied through fossil energy carriers, typically coal or natural gas. Green alternatives are char and syngas from biomass. The final product is liquid hot metal (carbon-saturated iron).

In the HPSR process, iron ore fines are converted to liquid steel by means of ionized H_2 (H^+, hydrogen plasma). The plasma, generated by passing an electric current through hydrogen gas, acts as a reducing agent and in addition supplies the energy needed to melt the metallic iron.

Investment costs for development up to TRL 9

The HPSR technology is currently under development with medium technological maturity (TRL 5 at best). The upgrading to TRL 6 and TRL 7 requires investment in different areas. On the one hand, fundamental research on the process needs to be carried out at large laboratory scale. On the other hand, the scale-up needs to be investigated in large scale pilot plants.

The subjects under study are diverse and complex, including complete understanding of the fundamental thermodynamic and kinetic mechanisms of the process, selection and design of

[11] For further details, please see SALCOS, salcos.salzgitter-ag.com.

materials, design of the plasma system and vessel geometry to maximise the productivity. A full industrial deployment is not expected until 2050.

These research projects need investments. Some were funded outside of the EU. In 2012, the University of Utah was awarded $8.9 M by the US Department of Energy to perform tests to determine the best vessel configuration (Sabat & Murphy, 2017). It is expected that the investment needs to bring this technology to TRL 9 significantly exceed this funding. The stakeholder consultations conducted within the GREENSTEEL project provide stakeholders' estimations of investment needs in the order of €100 M (excluding H_2 production) to bring this technology to TRL 8. This can be achieved with a demonstration plant in the order of 10 t/h. Estimates for the required investment costs for first industrial deployment of HPSR are available in the literature. The investment costs for new iron ore reduction technologies are estimated to be in the range of €100-200 M within ten years to realize a first industrial plant (Hiebler & Plaul, 2004). Overall, investment needs in the range of €100–200 M are therefore expected to raise the current technological maturity of HPSR from TRL 5 to TRL 9.

Investment costs for production plants

The requirements of an industrial plant of 1 Mt CS annual production capacity are:

- a refractory lined vessel, adequate to charge, process and cast at the required capacity,
- an electric system (transformer, electrodes, control, etc.) able to supply 150 MWh per hour; and
- the supply of 70,000 m^3 H_2 per hour.

Although the utilisation of hydrogen is directly linked to the iron and steelmaking by HPSR technology, the costs for hydrogen production or provision can be assessed separately. Further information regarding the production of hydrogen and the correlated investment costs can be found in Section 2.4.2.

The vessel and the electrical system are expected to have the dimension of currently existing large EAFs with a capacity of 300 t/h. Based on the assumption that the future cost of a HPSR plant will not exceed the cost of a state-of-the-art modern EAF by more than 10% and taking a reference value for EAF of €184/t CS (Wörtler, et al., 2013), the costs for a HPSR plant process unit are estimated below €200/t CS. This results in total investment needs of up to €200 M for a process unit in a plant of 1Mt CS annual production capacity.

Additionally, the HPSR technology requires more complex units, including systems for iron ore pre-heating, new materials at high performance for temperature and hydrogen plasma, systems to control large volumes of gas, probably under pressure, etc. It is estimated that requirements will at least double the cost, leading to a final value in the order of €500 M. This value is in line with the indications received by the stakeholder consultations.

Operational expenditures of an industrial plant

Accurate data for calculating the OPEX of a HPSR plant are not available. Basic comparisons between conventional route (BF-BOF), DR route (DR-EAF) and HPSR can be found (Hiebler & Plaul, 2004), (Behera, Bhoi, Paramguru, Mukherjee, & Mishra, 2019). In these references, the OPEX of HPSR is reported to be 21% lower than the conventional route, despite a 40% increase in electrical energy costs. The main advantage of the HPSR is the use of a single compact reactor, which reduces the CAPEX and personnel costs (Behera, Bhoi, Paramguru, Mukherjee, & Mishra, 2019). Overall, the OPEX for HPSR is difficult to forecast accurately at this stage and will mainly depend on the cost of the electrical energy.

Investment needs for HPSR technology are summarised as follows:

- investment needs for achieving TRL 8: up to about €100 M (excl. H_2 production);
- investment needs for achieving TRL 9: up to about €200 M (excl. H_2 production); and
- investment needs for industrial deployment: about €500 M (excl. H_2 production) for an industrial plant of 1Mt CS/a capacity.

2.1.3. Alkaline iron electrolysis

The alkaline iron electrolysis (AIE) is a process whereby electrical energy is used as reductant and energy source to transform the iron ore in almost pure solid iron. The product can then be melted in an EAF. Hence, the whole process is completely based on electrical energy.

This technology has been and is still studied in different projects (ULCOS, 2011), (ASCOPE, 2011), IERO (Lavelaine de Maubeuge, 2016), (VALORCO, 2014)[12] (SIDERWIN, 2020).[13]

Investment costs for development up to TRL 9

The technology is currently under development with a TRL of approximately 5. The budgets for the projects IERO and SIDERWIN are €2.4 M and €6.8 M, respectively. However, IERO includes both alkaline electrolysis and molten slag electrolysis, as presented hereafter.

The IERO project upgraded the technology from TRL 3 to TRL4.

The aim of the SIDERWIN project is to validate the technology at TRL 6 by 2022 by means of a pilot plant. The further step to TRL 7 and TRL 8 will require the design, construction and operation of a pilot plant of a threefold or fourfold capacity, with a corresponding increase of the investment costs that can be very roughly estimated at around €25 M, in line with the opinion of stakeholders.

Investment costs for production plants

The production plant basically consists of two units: an electrochemical reactor to produce solid iron, and an EAF to melt this solid iron into liquid steel. The electrochemical unit produces oxygen as by-product, which can be valorised in the steelworks.

Sludge containing water and gangue from the original iron ore is also produced from the alkaline electrolysis process. Hence, the plant will need auxiliary equipment to separate and recycle these materials. These units can be realized with conventional technologies. Sludge can be recycled in an EAF or in ancillary processes for the valorisation of by-products, which are increasingly common in the steel industry.

The capital cost of the electrolytic unit is difficult to estimate at this stage, as dimensions, materials and productivity are still under evaluation. Considering the few upstream operations, the low temperature and a unique energy source (electricity) a CAPEX significantly lower than other technological solutions can be expected.

A Roland Berger Focus estimated a CAPEX in the order of the 25% of a reference BF-BOF plant from greenfield (Ito, Langefeld, & Goetz, 2020)), which means around €400/t for producing liquid steel from alkaline electrolysis and EAF, and consequently €400 M for a plant for 1Mt/a.

---

[12] For further details, please see www.ademe.fr/valorco.
[13] For further details, please see www.siderwin-spire.eu.

From the information collected from stakeholders in the frame of the consultation activities for the GREENSTEEL project, the investment costs for an industrial plant are estimated at around €250 M for the electrolytic unit for a plant of 1Mt/a.

Adding the cost of the EAF (€184 M), the total value is comparable with the previous one.

Investment needs are summarised as follows:

- investment needs for achieving TRL 7: up to about €25 M (based on pilot plant);
- investment needs for achieving TRL 8: up to about €250 M (based on demonstration plant) for the electrolytic unit producing solid iron;
- investment needs for industrial deployment: about €500 M for a first industrial plant of 1Mt/a capacity; and
- the current low TRL does not allow for an evaluation of the investment needs for full industrial plants.

2.1.4. Molten oxide electrolysis

Molten oxide electrolysis (MOE) is an alternative to alkaline electrolysis of iron ore. Both technologies use only electricity. The fundamental difference is that MOE directly produces liquid metal from an electrochemical process performed inside liquid oxide (electrometallurgy). Consequently, there is no need for a melting step in an EAF, as is the case for alkaline electrolysis.

The process is simplified and compact. The process, based on great energy intensity and temperature higher than 1600°C, demands greater material performance.

The simplification of the process implies less energy consumption with respect to the conventional processes, when the maximum efficiency will be achieved. This is greatly valuable for CO_2 emission reduction in steelmaking.

Today, the technology has a low TRL (TRL 2)[14]. The above-mentioned project IERO (Lavelaine de Maubeuge, 2016) included the development of the MOE technology.

The energy demand of the optimised process is estimated at 4100 kWh/t CS (D1.2. Section 2.1.4).

Investment costs for development up to TRL 9

According to all the forecasts, this technology will require long time to achieve industrial deployment. Much research is still needed to design a pilot plant, both for fundamental aspects and technological solutions. It cannot be considered a potential option in the short term (2030-2040), optimistically an industrial development can be expected for 2050 and beyond.

Considering the long-term perspective and the necessary improvements, the investment costs can be estimated at not less than €1,000 M for achieving a TRL 8.

At this stage, any prediction on industrial deployment could be rather premature.

2.2. Carbon capture and usage

Besides CDA, which mitigates the formation of CO_2 in the iron and steelmaking process, another option is to only mitigate CO_2 emission instead of its formation. One basic idea is to separate CO_2 at the end of the industrial process and to store it in compressed and/or liquefied form, indefinitely,

[14] For further details please see www.ademe.fr/valorco.

in geologically stable sites. This approach is referenced to as carbon capture and storage (CCS). Instead of storing it, the separated CO_2 can be alternatively used as an input flow for a following conversion process into more valuable products such as urea, methanol, plastics or other chemical precursors. This CO_2 utilisation is referenced to as carbon capture and usage (CCU). In these applications, CO_2 is stored within the products. As CCU applications replace conventional production processes, the correlated CO_2 emissions are ultimately mitigated.

This section summarises the investment needs specifically for the conversion step of CCU technologies as selected in D1.2. The additional processes of CO_2 separation and H_2 provision are assessed separately in Section 2.4.

2.2.1. Carbon oxide conversion

The implementation of CCU processes includes a carbon oxide conversion step. This step can be categorized based on the type of conversion (namely chemical or biological) as well as on the desired product (e.g. fuel, chemical, polymers or its precursors, synthesis gases). Typically, these processes require the provision of other process gases, such as H_2. There are many technical solutions currently under development for the use of CO_2 in chemical or biological conversion processes (see Deliverable D1.2 for more details). At this stage, the conversion processes are assessed in a grouped manner.

Overall, these technical solutions are currently at TRLs ranging between 6 and 8 for application in the iron and steel industry. In cases of application in other industry sectors (e.g. chemical industry), a TRL of 8 is reached (Dahlmann, 2019). The implementation into integrated steel plants is currently in demonstration phase at TRL 4-5[15]. The achievement of TRL 9 and first industrial deployment is estimated for 2025-2030 (Agora-Energiewende, 2019). A full industrial deployment is expected to be available in the long term, before 2050.

Investment costs for development up to TRL 9

As to a further technological development, there are two specific examples available in Europe, reflecting respectively the chemical and biological conversion processes: Carbon2Chem® (ThyssenKrupp, 2020) and Steelanol of ArcelorMittal (STEELANOL, 2015).

Carbon2Chem® aims at developing a chemical conversion process in quasi-industrial scale. This process is supposed to convert shares of exhaust gas (top gas) from coke oven, BF and BOF into ammonia and methanol. Within the industrial pilot phase, an industrial-scale plant is scheduled to be established by 2025. The external funding for the project by the German federal government amounts to over €60 M, with investment needs even higher than this value.

The project Steelanol has the objective to treat about 15% of the available top gases from a BF and biologically convert it into bioethanol. The budget for the corresponding Horizon2020 project is €87 M and the total investment for the project, presented under the commercial name Carbalyst® (CARBALYST, 2015), is €120 M[16].

Based on these two examples, investment needs in the order of €100-150 M are calculated for upgrading the technological maturity of each of the chemical and biological routes.

[15]For further details, please see www.greencarcongress.com/2019/12/20191215-arcelormittal.html.
[16]For further details, please see https://corporate.arcelormittal.com/corporate-library/reporting-hub/carbalyst-capturing-carbon-gas-and-recycling-into-chemicals.

Investment costs for production plants, excluding auxiliary plants

The investment needs of carbon oxide conversion strongly correlate to auxiliary processes, as their main demand is related to the (electrical) energy for production of H_2 via e.g. water electrolysis. Additional thermal energy demands may arise depending on the specific technology.

A study conducted by Agora Energiewende (Agora-Energiewende, 2019) has assessed the investment needs for the overall CCU process. The results include CAPEX, specifically for the installation of additional units, and OPEX for the operation of these units. The study estimates the specific CAPEX for carbon oxide conversion at €129/t CS annual production capacity. The influences on the OPEX are related to electricity demand, H_2 provision and the requirement of other materials. The increased electricity demand results in requirements amounting to €30-35/t CS. The main investment need results from the provision of H_2 with €310-526/t CS. Other material requirements cause additional €68/t CS. Overall, the OPEX requirements sum up to €408-629/t CS.

Overall, the CAPEX demands translate into investment needs of €129 M for 1 Mt annual crude steel production capacity for the carbon oxide conversion step alone.

Investment costs for production plants, including auxiliary plants

As CCU processes typically contain both CO_2 separation and carbon oxide conversion steps, the overall investment needs can be derived from the partial investment needs. As the technological maturity of CCU processes is currently in demonstration phase, investment needs of €100-150 M arise for each chemical or biological CCU process. After the demonstration phase, further investments in the range of several hundred M€ are required for the first industrial deployments. Once full technological maturity is reached for CCU technology as application in the steel industry, the investment needs for industrial deployment of a complete CCU process are estimated from the literature (Agora-Energiewende, 2019); (Skagestad, Onarheim, & Mathisen, 2014) to be around 300 M€ per 1 Mt CS annual production capacity. According to current estimates, at full technological maturity 57% of these investments are required for CO_2 separation (for further details please see Section 2.4.1), whereas 43% are required for carbon oxide conversion. The costs for hydrogen provision are not included in these figures.

Based on the values given in the Steelanol project (STEELANOL, 2015)[17], extrapolating the value of 15% of the top gas treated to 100%, a proportional investment would result in overall investment needs of about €800-1,000 M for an industrially scaled steel production plant.

Investment needs are summarised as follows:

- investment needs for achieving TRL 8: up to about €150 M (for a single demonstration plant);
- investment needs for achieving TRL 9: up to about €300 M (for a first installation plant); and
- investment needs for industrial deployment: about €1,000 M.

2.3. Process integration

The process integration (PI) pathway refers to existing steel plants and their possible adaptations to emit less greenhouse gases. Circular economy (CE) strategies too are included in the PI pathway.

---

[17] For further details, please see http://www.steelanol.eu/en.

PI refers to modifications of existing ironmaking and steelmaking processes, or implementation of innovative processes, based on fossil fuels, which would help to reduce the use of carbon, and thus the CO_2 emission. The definition does not refer to the final CO_2 reduction, which could be also considerable, but rather on the type of action.

The PI technologies are addressed both to the BF-BOF route and the EAF route. Many solutions are quite mature or even already adopted and can be rolled out in the steel industry in the short term. The main ones are the followings:

- production of hot metal from a smelting reduction process integrated with a CO_2 capturing system, for partial or total replacement of BF production;
- gas injections in the BF, comprising in particular hydrogen-rich gases (e.g. coke oven gas, natural gas) but also gases produced from biomass and waste;
- use of biomass derivatives and by-products to replace fossil coal or natural gas in some phases of the process. Biomass and by-products can be treated with pyrolysis or gasification processes to obtain, respectively, char or syngas to be used as alternative fuels, both in the BF and in the EAF;
- energy recovery from hot, gaseous and solid by-products of steel manufacturing processes; and
- scrap selection and production of quality steel from an electric oven, thus reducing the share of BF production.

Following the same logic adopted in D1.2, the investment needs are presented for the technologies combining a high mitigation potential, a wide applicability in existing plants and significant needs in terms of R&D investments.

2.3.1. Iron bath reactor smelting reduction

The smelting reduction is a process where hot metal, with characteristics comparable with that produced by a BF, is produced directly from fine iron ore and coal. The process uses pure oxygen for coal gasification and post-combustion of CO, which is the energy source for the process. For this reason, the top gas is essentially CO_2 and minor amounts of H_2O, easy to separate. Consequently, the process is very suitable for CO_2 capture technologies (both for CCS and CCU), much more than other ironmaking processes. This advantage is accompanied by significant energy savings, as it does not need a costly gas separation stage, and by a net total CO_2 saving of 80% compared to the conventional integrated steel production process.

Moreover, the potential use of alternative green fuels, such as syngas and char from biomass, and the possibility to recycle scraps and other industrial residues, recovering valuable materials (e.g. zinc from scrap) makes the technology attractive for integrating or replacing conventional ironmaking processes.

HIsarna® (Hisarna, 2020) is a European project to develop an IBRSR. It is the only IBRSR under development. The investment needs reported below are based on information supplied by the developer (Tata Steel).

Investment costs for development up to TRL 9

The current TRL of HIsarna® is estimated to be 5. TRL 7 is expected to be reached in 2030, whereas TRL 9 and industrial deployment in 2035-2040. For the development from the current status up to industrial deployment, Tata Steel estimated an initial need of about €20 M for initial consolidation of the project and an investment of about €250-300 M for an industrial-size demo plant of a 0.5-1 Mt/y capacity.

Overall, the investment needs for achieving TRL 8 can be estimated at roughly €400 M.

Investment costs for production plants

The industrial plant requires an installation for continuous production of oxygen and must be integrated with an industrial system for CCS, which requires electrical energy. Based on pilot plant campaigns' results, the electrical energy consumption of a full-sized production reactor with CO_2 capture is estimated at 0.5 MWh/t CS, but most of this electricity can be produced from the hot reactor off-gas.

The CAPEX strongly depends on the scale: for a 1.15 Mt /a plant, Tata Steel estimates the investment at €500 M (€435/t CS) but €600 M for a 1.5Mt/a plant (€400/t CS).

At 1.15 Mt/a, the additional CAPEX for a O_2 plant is of about €140 M (€120/t CS) and for CO_2 capture it is about €65 M (€45/t CS), not including the external transport network and injection well.

Investment needs are summarised as follows:

- investment needs for achieving TRL 8: about €400 M (based on demonstration plant); and
- investment needs for industrial deployment: €850 M for a 1.5 Mt/a scale (based on first industrial plant, including O_2 production and CO_2 capture and compression, but excluding transport and storage services).

2.3.2. Gas injections into the blast furnace

The current BFs are efficient and highly optimised reactors. Lowering the carbon usage (and thus CO_2 emissions) by increasing efficiency in these furnaces is approaching its limits. Currently, BFs are usually fed with coke and injected with pulverised coal and the coke consumption has been optimised at the minimum value. Instead of further aiming for efficiency increases in carbon-based reduction, one decarbonisation approach is the substitution of carbon-based energy carriers by hydrogen-based gas injections.

The most simple and fast applicable option is to inject H_2-rich gases in the BF, which can have various origins and compositions (including coke oven gas, biomass, wastes or pure hydrogen). A further technical possibility is the recycling of CO and H_2 from BF top gas back into the BF process after separation of CO_2 (Budinis, 2018 (Budinis, Krevor, MacDowell, Brandon, & Hawkes, 2018)). This technology was developed and validated as pilot in the frame of the ULCOS project, which allows a mitigation potential of up to 25% and more in combination with CCUS (ULCOS, 2011 (ULCOS, 2011)). Both options will be assessed separately. Irrespective of the utilised gas stream, the most important technical challenge is currently the implementation of the heating step for reducing gas before injection. One possible option is to combine heating with reforming in a plasma system powered with green electricity. This combination is currently studied in the IGAR project (IGAR, 2020).[18]

2.3.2.1. Injection of hydrogen-rich gases into the blast furnace

[18] For further details, please see www.ademe.fr/sites/default/files/assets/documents/igar.pdf.

Investment costs for development up to TRL 9

The estimates for investment costs vary significantly depending on technical implementation details. For example, gas injection at the tuyeres (where currently pulverised coal is injected) was already demonstrated generally with different gases on full industrial level. The remaining R&D needs concentrate on adaption of BF control. In this implementation, the CO_2 mitigation is limited (up to 10%)[19].

The injection into the shaft (the upper part of the BF) can achieve higher CO_2 mitigation, in the range of 17% to 50% (Agrawal, et al., 2019)). This solution requires an investment cost of the order of €10 M specifically for the gas injection. Additionally, the costs for the development of a suitable technology for the pre-processing of the gas, which is currently pursued by means of reforming technologies, are much higher. For instance, the project IGAR (IGAR, 2020) aiming to equip one tuyere with plasma reforming technology has a budget of €20M. According to information collected from the stakeholder consultations in the frame of the GREENSTEEL project [20], the total investment costs for a first implementation of injection of H_2-rich gas in the BF shaft is estimated at €140 M. Consequently, the total investment costs sum up to the order of €150 M.

Investment costs for production plants

The CAPEX of industrial plants for gas injection in BF is largely dependent on the origin of the injected gas, on the extent of gas injection (in Nm^3/t CS) and on the required/considered gas pre-treatment steps (from cleaning to heating). Specific costs are linked to the pre-processing of the various gases, especially steel plant gases and biogas (filtering, compression, purification, reforming), to the large plasma torches in heating/reforming applications and to the gas injection systems in the BF (modified tuyeres, injections in shaft).

2.3.2.2. Top gas recycling in the blast furnace

Investment costs for development up to TRL 9

Top gas recycling in the blast furnace (TGR-BF) has already been validated on pilot scale in an operational environment by trials in an experimental BF and is currently at TRL 7 (Toktarova et al., 2020 (Toktarova, et al., 2020)). During the stakeholder consultations[21], a technology provider estimated the current TRL of top gas recirculation at only 5, expecting to reach TRL 7 in the short term (2025) with an investment of €5 M. This provider foresees a quite fast development, with TRL 8 reached in 2028 and TRL 9 as soon as 2030.

A full detailed engineering study was performed in 2011 in the frame of the ULCOS project (ULCOS, 2011), aimed at the development of TGR-BF up to TRL 9 in the plant of Florange (France). Development costs have thus been quite precisely estimated on a complete perimeter, including CO_2 transport and storage in deep saline aquifer (CO_2 purification, compression, infrastructure for transport, storage and monitoring of the storage site). Depending on costs for energy and CO_2, the full project cost was €500-550 M. Notably, the additional oxygen was supplied by a gas supplier,

[19] For further details, please see www.lowcarbonfuture.eu.
[20] Data were gained from the scoping questionnaires and then further submitted to technology providers in the frame of the GREENSTEEL project (see also D1.3 report) to better integrate and substantiate the investment needs figures. Cost levels up to €150 M were also mentioned by some stakeholder.
[21] For further details, please see https://www.lowcarbonfuture.eu.

thus without directly charging the corresponding investment to the project but including in the operating costs the full cost to be paid for the oxygen consumed.

Investment costs for production plants

For the TGR-BF process, estimates (Toktarova, et al., 2020)) provide a value of €639 M for a 1 Mt /y production capacity. However, the above-mentioned ULCOS study indicates significantly lower costs: in the frame of a BF relining, the additional investment for revamping the existing BF in full TGR-BF configuration were calculated at about 135 €/t CS, excluding some external services (additional oxygen supply and the transport and storage of CO_2).

The influences on the OPEX largely depend on reference prices taken for coke, electricity and O_2, but the operation of a TGR-BF is generally up to €10/t CS more expensive than conventional operation (including the purchase of the extra oxygen). For transport and storage services, various references indicate additional costs between €15-50/t CS when provided by an external company mutualising several CO_2 sources.

Investment needs are summarised as follows:

- investment needs for achieving TRL 9: about €200 M at a 1.3 Mt/y scale, excluding the investment for the extra oxygen supply and the transport and storage infrastructure, and €500-550 M when including transport and storage infrastructure and all project operating costs; and
- investment for further relining of existing BF plants: €325 M for a 2 Mt CS/y BF, including additional oxygen plant but excluding the external infrastructure for CO_2 storage (pipeline and injection well).

2.3.3. Substitution of fossil energy carriers with biomass

Biomass is considered CO_2 neutral[22]. Hence solid charcoal or syngas from biomass entail a net reduction of fossil coal or natural gas. When applied in the integrated route, pre-processed biomass can be blended to the coal charge of coking ovens, substituted to anthracite in the sinter plant mix or used in the BF as a substitute of pulverised coal. In EAF-based plants, carbonized biomass can substitute coals injected in the melting furnace and/or charged in the scrap baskets.

The current TRLs of related technologies and investments vary greatly. Within this project, five steelmakers and one technology provider gave their own estimation about fossil fuel substitution by biomass in the coming years[23]. The main reason for the scattering of information and data is that the use of biomass-derived materials is already well assessed for the EA- based route, where many European projects have been successfully concluded.[24]

---

[22] Schematically, biomass can derive from dedicated cultivation (e.g. eucalyptus plantation in Brazil) or from residues of agriculture, wood industry and so on. In Europe, only residues can be used in steel industry. This biomass, in a first approximation, can be considered neutral.

[23] Data were gained from the scoping questionnaires and then further submitted to technology providers in the frame of the GREENSTEEL project (see also D1.3 report) to better integrate and substantiate the investment needs figures. Cost levels as high as up as €150 M were also mentioned by some stakeholder.

[24] For further technical details, please see also Green Steel for Europe - D1.2 and https://op.europa.eu/en/publication-detail/-/publication/e7dc500c-82de-4c2d-8558-5e24a2d335fb.

Investment costs for development

Besides biomass, other carbon-based waste can also be considered. Refuse-derived fuel (RDF) is a fuel produced from various types of waste, such as municipal solid waste (MSW), industrial waste or commercial waste. All these materials can replace fossil fuels.

Because of the variability of feedstocks and technology, a quantification of investment needs, as well as CAPEX and OPEX, is difficult. The following figures should be considered as indicative.

In the EAF-based route, the current TRL is 6 to 7. TRL 8 is expected in a short time, first industrial deployment (TRL 9) should arise between 2025 and 2033 and full deployment between 2025 and 2035 with additional investment estimated at €5 M.

In the integrated route, TRL is rated from 2 to 7 depending on the answering company. When TRL 7 is not already attained, the investment needs are estimated between €0.1 and 0.5 M. TRL 8 is foreseen to be reached between 2022 and 2028, with related investment in the range of €10-15 M.

Investment costs for production plants

The main investment costs for the industrial deployment concern the construction of infrastructures for biomass collection, storage and distribution in the territory as well as the building of the necessary plants for supplying charcoal and syngas from biomass in the necessary amount and consistency. The large spectrum of scenarios prevents a reliable evaluation of investment costs.

Apart from the CAPEX for the infrastructure, additional CAPEX is relatively low: only the pre-processing (e.g. drying) and upgrade (e.g. pyrolysis, hydrothermal carbonization, etc.) of biomass (and alternatives) have to be integrated in steel plants. Smart integration (energy, logistic aspects, off-gas treatment, etc.) also has to be considered.

The main limit in biomass usage is caused by price and raw material availability. The effort to turn biomass into a usable substance (biochar in most of the cases) is highly dependent on the initial quality of the biomass itself (size, moisture, fumes treatment in case of paints).

Investment needs are summarised as follows:

- investment needs for achieving TRL 8: about €5 M (based on first installation);
- investment needs for achieving TRL 9: up to about €15 M; and
- impact on CAPEX up to 15 €/t CS.

2.3.4. High quality steel making with increased scrap usage

The internal scrap (produced and used inside the workshop) and the prompt scrap (directly produced in the manufacturing plants) are already fully recycled. The recycled fraction of the obsolete scrap (derived from discarded industrial and consumer items) is high, but there is room for improvement. A certain (and limited) increase of scrap usage in the integrated route is possible. It is a market decision and no significant technological investment is necessary.

The increase of scrap usage entails allowing steel production via EAF with a larger and more efficient (higher yield and better selection) use of scrap, thus reducing the necessity of cast iron and DRI, used for quality steel.

As described in D1.2., the guidelines for increasing scrap usage are:

- direct increase: reducing the loss of unrecycled steel scrap;
- Indirect increase: avoiding the progressive lowering of quality of steel from scrap by implementing systems for on-line analysis, characterization and sorting; and

- increasing scrap yield;

The main related development needs are:

1. technologies for selecting and sorting scrap; and
2. technologies for monitoring and controlling more flexible multi-feedstocks processes.

Investment costs for development

Although there are great expectations and hope for new technologies allowing accurate and continuous measurement of scrap properties and automatic selection, and even though many promising results have been achieved, no industrial routine applications are known to date. The current TRLs range from 4 to 7.

Considering the typical budget of the performed and proposed projects on this subject, a rough estimate of the investment needs for achieving TRL 8 lies at around €20-30 M in 10 years.

Investment costs for production plants

The implementation of both the scrap analysis and sorting system and the new process monitoring and control are marginal[25], once these systems will be available for routine application.

A typical cost of around €50 M can be considered.

Investment needs are summarised as follows:

- investment needs for achieving TRL 8: about €50 M (development of technologies and first installation); and
- investment needs for achieving full industrial deployment: about €100 M.

[25] An estimate is available in the final report of the RFCS ADAPTEAF project (RFSP-CT-2014-00004, see final report at https://op.europa.eu/en/publication-detail/-/publication/d472d319-4478-11e9-a8ed-01aa75ed71a1) concerning the costs for installation, maintenance, and current use of the various technological systems. Here, the CAPEX for investments needed for application of the different measures is estimated at around €115K, and the OPEX for maintenance and additional probes at around €40K/year. These OPEX/CAPEX have to be compared to the cost savings in electrical energy, estimated at €95K/year, and to the cost savings due to increased productivity, estimated at €200K/year. Thus, the amortization time for the total costs of all measures performed within the project is well below one year.

2.3.5. Summary of technologies investment needs

Table 2 summarises the expected evolution of the analysed technologies and the investment needs for their development.

Table 2: Investment needs for the development of single technologies

Single decarbonisation technologies							
Technology	TRL development			Investment needs up to TRL 8 (M€)	Investment needs for 1st industrial depl. TRL 9 (M€)	Investment needs for full industrial plant (M€)	CO_2 abatement (max %)
	2020	2030	2050				
H_2-DR (100 % H_2)	6–8	7–9	9 (ind. depl.)	100	150	250*	95
HPSR	5	6	9 (ind. depl.)	100	200	500	95
AIE	5-6	6–8	9	250	500	Not evaluated due to low TRL	95
MOE	2	3-4	9	1,000	Not evaluated due to low TRL		95
CCUS	5- 8	9	9 (ind. depl.)	150	300	1,000	60
IBRSR	6	8	9 (ind. depl.)	400	850 **		20-80
BF-Gas injection	5–9	8–9	9 (ind. depl.)	150	550**	850**	20-60
Biomass usage	2–7	8	9 (ind. depl.)	5	15		30-100
Increased scrap usage	4–7	7–9	9 (ind. depl.)	50	100		100(with CCS).

*Source: authors' own composition based on desk research and stakeholders' interviews (complete references in the bibliography). Note: data refer to a crude steel capacity of 1 Mt/a as a reference[26]. *€500 M including EAF. ** Excluding CO_2 transport and storage. For the abbreviations used, please see the list of symbols, indices, acronyms and abbreviations.*

2.4. Auxiliary processes

The previous sections focused on the technologies specific to the iron and steel industry, some of which require additional auxiliary processes, independent from iron and steel production. In this regard, the separation of CO_2 from gas flows (CO_2 capture) and the provision with hydrogen are the most relevant topics (for further details, please see Deliverable D1.2). Generally, there are two options as to the assessment of investment needs for hydrogen provision: the external purchase of H_2 (mainly increasing the OPEX of iron and steel production) and the internal production of H_2 within the boundaries of the iron and steel plant (mainly additional CAPEX). In the scope of this report, the internal production of H_2 by water electrolysis is assessed.

[26] In general, real industrial planta have different dimensions depending on a specific technology. For example, for BF-gas injection technology and smelting reduction, in the text data on Hisarna plant report1.5 Mt/a (CS).

2.4.1. CO_2 capture

The options for the separation of CO_2 from gas streams can be clustered into three categories according to when the process gases are treated for CO_2 separation:

1. before the process gases are utilised (pre-combustion);
2. after their regular utilization (post-combustion); and
3. after their utilization with pure oxygen (oxy-combustion).

Within the iron and steel industry, the post-combustion and oxy-combustion options are considered most suitable for CO_2 capture, as there are various CO_2-containing gas streams directly available within integrated iron and steel plants. A promising technology for post-combustion capture lies in the chemical absorption process. In this process, CO_2 is directly absorbed by chemical substances, such as amines, which are then regenerated in a desorbing unit under addition of heat (Sadoway, 2019)). Whereas these processes are being developed in other industry sectors since several years, the current TRL of CO_2 capture within the iron and steel industry is in the range of TRL 5-6 (FReSMe, 2017); (CORDIS, 2020)). As this approach is currently considered a research focus, TRL 9 is expected to be reached in mid-term scale between 2030 and 2040, which would allow a full industrial deployment by 2050 (for further details please see Deliverable D1.2).

Investment costs for development up to TRL 9

CO_2 capture (Bui, 2018)) depends on the type of technology and the process location (BF in most of the research project). Post-combustion capture from the BF has been estimated to cost up to €100/t of mitigated CO_2 emission. A top-gas recycling blast furnace using post-combustion capture can capture 65% of emissions at 70€/t of avoided CO_2. Post-combustion capture from the coke oven will also cost an average of €70/t of avoided CO_2 (27% of total emissions). Based on the conventionally taken value of ton CO_2/t CS, a cost of about €120 M can be expected.

Investment costs for industrial deployment

Besides the investment costs to bring CO_2 capture processes to full technological maturity, there are specific investment costs for the deployment of industrially-sized plants into the iron and steel production processes. These costs are assessed exemplarily for the implementation of chemical absorption, as this is currently regarded as the most promising technology.

The concept of chemical absorption results in different influences on the production costs. Basically, there are specific 'overnight' investment needs in terms of CAPEX requirements for the additional absorbing and desorbing units and their installation. Besides that, additional OPEX requirements result from the absorbents itself and their losses during operations as well as in terms of their regeneration by desorption under the addition of heat. These costs are complemented by additional fixed OPEX, e.g. by personnel and maintenance required for the additional plants.

In an extensive Australian study conducted in 2013 (Minh-Ho, Bustamante, & Wiley, 2013), the CAPEX and OPEX requirements for CO_2 separation, including its compression for transport, were estimated. In this study, five different components of CAPEX were analysed: general equipment, compression unit, separation unit, pre-treatment unit and set up costs. These components sum up to a specific CAPEX of €12-20/t CO_2. Approximately 50% of it is attributed to equipment costs, while another 50% correlates to the required set up costs. Just as a reference, OPEX was here analysed in terms of three different components: energy, materials replacement (including absorbents) and fixed OPEX. According to the study, the OPEX demand amounts to €60/t CO_2. Its main share of 65% is correlated to energy expenses (Minh-Ho, Bustamante, & Wiley, 2013)).

A study conducted for the Northern European countries (Skagestad, Onarheim, & Mathisen, 2014)) calculated the corresponding investment needs for a generic steel plant located in Finland. Here, a CAPEX of 90 € /t CO_2 annual capacity is reported. The correlating OPEX accounts for about €40/t separated CO_2. As the production of 1 t CS is correlated to the emission of 1.9 t CO_2, an implementation of a full CO_2 separation in a steel production plant of 1 Mt / a capacity in Europe would result in €171 M.

2.4.2. Water electrolysis

As one approach for decarbonisation of iron and steel production is the substitution of carbon by hydrogen in terms of reduction agents, the provision of clean hydrogen becomes important if not critical for the implementation of such technologies. Currently, the most promising approach for clean hydrogen production is water electrolysis utilizing electricity from preferably renewable sources. In this section, the investment needs for implementing water electrolysis within the boundaries of an iron and steel plant are assessed. This basically results in high investment needs (CAPEX).

For an industrial large-scale application, there are three specific technologies available: polymer electrolyte membrane (PEM) electrolysis, alkaline electrolysis (AEL) and high temperature electrolysis (HTEL). These technologies differ in the utilized electrolyte material, operating temperature and pressure as well as in the degree of maturity and capacity regarding dynamic operation. More details are available in the technological assessment in Deliverable D1.2.

Regarding the current state of technology readiness, there are technology-specific differences. Currently, the industrial applications with flexible operation of PEM electrolysis and AEL range between TRL 7-8, while those of HTEL range between TRL 5-6. Technological maturity in industrial scale is expected for PEM electrolysis and AEL by 2030[27]. Overall, it is expected that all the three technologies will reach a possible industrial deployment in a long-term scale, by 2050.

Investment costs for development up to TRL 9

As the water electrolysis is technologically decoupled from the iron and steel production, its investment costs for development are independent from the steel sector. Therefore, these investment needs are beyond the scope of the GREENSTEEL project.

Investment costs for industrial deployment

Separated from the investment costs for the technological development, the subsequent industrial deployment into iron and steel production plants is connected to specific investment needs. As water electrolysis is subject to further technological improvements, the investment needs are expected to decrease over time. Table 3 gives an overview of current and future CAPEX requirements specific for each of the three water electrolysis technologies (IndWEDe, 2018)).

[27] For further details, please see GREENSTEEL D1.2. "Technology assessment and roadmapping".

Table 3: Specific CAPEX demands for several electrolysis technologies

Year	PEM electrolysis - [€ / (m^3 H_2/h)]	AEL - [€ / (m^3 H_2/h)]	HTEL - [€ / (m^3 H_2/h)]
2018	6,700 – 7,500	3,000 – 5,500	5,000 – 13,600
2030	2,500 – 5,500	1,800 – 4,200	1,200 – 2,200
2050	1,000 – 3,500	1,200 – 3,200	500 – 1,500

Source: (IndWEDe, 2018)*)*

Currently, the AEL is regarded as the most mature technology. Its current specific CAPEX demands are the lowest. The production capacity of 1 m^3 H_2 per hour relates to CAPEX needs of €3,000-5,500. The current CAPEX demand for PEM electrolysis is €6,700-7,500 per m^3 H_2 per hour, while HTEL accounts for €5,000-13,600 € per m^3 H_2 per hour. Due to further technological improvements, the CAPEX demands are expected to decrease over time as well as shift between the electrolysis technologies. From 2030, HTEL is expected to be the cheapest technology to implement in terms of CAPEX. The specific investment needs for HTEL are expected to decrease to 500-1500 per m^3 H_2 per hour in 2050. The correlating values for PEM electrolysis and AEL are in the range of €1,000–3,500 per m^3 H_2 per hour in 2050.

Besides the 'overnight' investment needs for the installation and set-up of water electrolysis plants, there are also correlated OPEX requirements, which arise and have to be met over time. Generally, the hydrogen production process via water electrolysis is very energy intensive and thus strongly correlates with the electricity prices. As electricity prices are highly volatile, differ nationally and/or regionally and their developments over the next decades cannot be predicted with a sufficient degree of certainty, the correlating OPEX is out of the scope of this report.

Nonetheless, the OPEX correlated to the maintenance of water electrolysis plants can be estimated based on the values available in the literature (IndWEDe, 2018). Current values range from €11-15 per year and kW_{el} for PEM electrolysis to around €32 per year and kW_{el} for HTEL. The current maintenance-related OPEX demand for AEL accounts for €13-25/kW_{el} annually. These values are expected to decrease to €4-13 per year and kW_{el} for PEM electrolysis, €18-36 € per year and kW_{el} for AEL and around €8 per year and kW_{el} for HTEL by 2050 (IndWEDe, 2018).

The current overall investment needs for the industrial deployment of water electrolysis can be estimated using basic assumptions. A prudential value of specific investment needs of €5,000/(m^3/h) and a total operating time of the electrolyser of 50,000 hours (Smolinka et al, 2018 (IndWEDe, 2018)) lead to a specific CAPEX of €0.10 per m^3 H_2. If this water electrolysis is operated for the purpose of serving a H_2-DR plant and a hydrogen demand of 900 m^3/t DRI (Bhaskar, Assadi, & Nikpey Somehsaraei, 2020) is assumed, the specific CAPEX results in €90 per ton of DRI.

Further utilising the basic assumption of 1 t DRI leading to 1 t CS in steel production, the current CAPEX demand for water electrolysis is estimated at 90 € per ton of crude steel (for H_2-DR), leading to €90 M investment needs for industrial deployment of 1 Mt annual crude steel production capacity. Due to the expected technological improvements of water electrolysis technologies, the investment needs for water electrolysis might decrease to 18 € per ton of crude steel in 2050 (based on specific investment needs of €1,000/(m^3/h), see Table 3 (IndWEDe, 2018).

2.4.3. Summary of auxiliary processes investment needs

The auxiliary processes investment needs are summarised in Table 4.

Table 4: Auxiliary processes investment needs

Auxiliary technologies							
Technology	TRL development			Investment needs up to TRL 8 (M€)	Investment needs for 1st industrial depl. TRL 9 (M€)	Investment needs for full industrial plant (M€)	CO_2 abatement (max %)
	2020	2030	2050				
CO_2 capture	5–6	8–9	9 (ind. depl.)	(independent from steel industry, existing reference on €120 M)		200	-
Water electrolysis	5–8	7–9	9 (ind. depl.)	Not evaluated (independent from steel industry)		100	-

Source: authors' own composition based on desk research and stakeholders' interviews (complete references in the bibliography). Note: data refer to a crude steel capacity of 1 Mt/a. For the abbreviations used, please see the list of symbols, indices, acronyms and abbreviations.

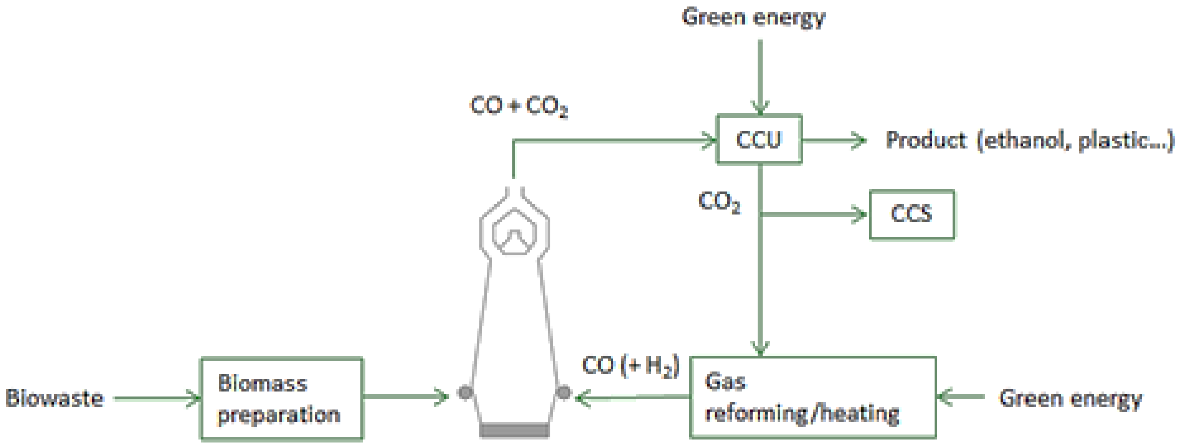
2.5. Set up of technology routes

In this section, the investment needs for the four technology routes identified in the D1.2. report "Technology assessment and roadmapping" are shown. These routes have been considered as important cases from the desk research and the first stage of stakeholder consultation (scoping questionnaire, as reported in Deliverable D1.3). Further input and insight will be gathered during the upcoming in-depth stakeholder consultations and the analysis of relevant scenarios for industrial deployment pathways in Tasks 1.4 and 1.5 ("Decarbonisation pathways 2030 / 2050"). Technology routes integrate new, auxiliary and conventional (optimised) processes to complete crude steel production chains.

2.5.1. Technology routes based on optimised BF-BOF-HR

As for Deliverable D1.2, the case study is a combination of several basic options, plugged on a BF partial replacement of fossil carbon with gas injection in the BF and conversion of carbon oxides contained in the BF top gas (CCUS to avoid combustion). The current TRL of such a combination of technologies (see Figure 1) ranges widely from 2 to 9, due to the different technologies considered. However, the industrial deployment of this route can start in the short term, since the main technologies employed have rather high TRLs.

Figure 1: Schematic and simplified view of a combination of mitigation technologies based on conventional BF-BOF-HR



Source: authors' own composition

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 existing conventional plants which result in dedicated CAPEX:

- the BF requires gas injections which, if pushed to a significant level, require a significant revamping of the tuyeres, gas mains, gas distribution and possibly even BF shell and structure. Furthermore, a bunch of new safety, measurement and control measures are needed to handle the new technologies and process states;
- the BF stoves may have to be completely or partly revamped and the oxygen consumption of the BF is significantly increased since additional heat is needed with increasing replacement of carbon by hydrogen within the reduction process; and
- the coke, sinter and BOF plants can remain relatively unchanged, except if additional mitigation options for these plants are implemented.

Beyond these adaptations of the existing elements, significant investments are required for the add-on technologies (e.g. CCUS, biomass preparation, gas preparation, BF gas injection systems, etc.), therefore many new plants have to be erected around the BF with auxiliaries which are all significant in size, complexity and requirements (energy, storage, maintenance, etc.). The main ones are:

- the biomass preparation plant; and
- the CCUS units and the gas heating/reforming plants.

Concerning the latter, when it comes to the integration of carbon capture processes, the costs of current end-of-pipe capture technologies are high, and the full mitigation potential of these technologies only comes into effect if the captured CO_2 can afterwards be utilized or stored. Energy-efficient separation and purification technologies may be required for the utilization of CO_2 from industrial waste gas streams.

The in-scoping questionnaires in the frame of the GREENSTEEL project deliver information that, considering the important modifications and additions which have to be applied to a state-of-the-art plant, lead to an estimated CAPEX increase of 50%.

Taking these elements into account, the estimated investment needed for pilot scale tests at TRL 6-7 is around €400 M. TRL 8 may be reached by 2025 but would need investments of up to €2 B (in a very first calculation). The first industrial deployment (at least one-year operation with about 30% or higher industrial plant production capacity), namely TRL 9, is foreseen for 2030 with full industrial implementation[28] and investment needs amounting to €4 B and. Notably, the above-mentioned data refer to technology development from greenfield.[29].

For the TGR-BF process, the following numbers can be given (already reported in D1.2, derived from ULCOS (ULCOS, 2011)): CAPEX up to €110/t CS annual capacity without CCUS and up to €150/t CS with CCUS (i.e. including all the necessary purification and compressions steps required for CCUS).

These values are In line with the evaluation derived from the questionnaires submitted to technology providers.

Investment needs can be summarised as follows:

- investment needs for achieving TRL8: about €2 B (first calculation, greenfield);
- investment needs for industrial deployment: up to about €4 B (greenfield); and
- impact on CAPEX up to €150/t CS.

2.5.2. Technology routes based on direct reduction

Since current DR plants (using generally natural gas) are already operated with rather high internal H_2 contents, main parts of the H_2-DR-EAF route can be considered to be well advanced with a corresponding TRL between 4 and 8.

Plants utilising the H_2-DR-EAF route would replace the full ironmaking and steelmaking capacities of existing BF–BOF, thus having to be erected often in greenfield conditions. Although the transition can be done stepwise in existing plants operating more than one BF, all main facilities and equipment (cokemaking, sintering, BF and BOF plants) need to be replaced with new production units.

Further auxiliary facilities (raw materials storage, energy networks with boilers and O_2 production plants, internal transportation means, maintenance areas, etc.) can probably be partly retrofitted from the existing plants. However, these auxiliary facilities would still require significant revamping.

The investment costs of an industrial plant include the DR shaft furnace, the EAF and the electrolyser for producing green hydrogen.

Investment costs for production plants.

The investment costs of an industrial plant comprise the units of the DR shaft (including directly linked auxiliary aggregates) and the EAF. The CAPEX for shaft and EAF is estimated as being

---

[28] Values include plant modifications, e.g. for biomass usage + CCU.

[29] In fact, it is worth noting that in Europe the optimized BF-BOF route will most probably be based on existing installations (brownfield) rather that new installation (greenfield)._The CAPEX for BF-BOF brownfield (BF-BOF retrofit) is estimated to be a bit less than 40% of the CAPEX of greenfield BF-BOF (Ghenda, 2013 (Ghenda, 2013)).

equal to that for the natural gas-based DR, as operated outside the European Union. The capital costs for shaft and EAF are expected to be constant from today to 2030. Reference values are €230/t CS for the shaft and €184/t CS for the EAF. As already mentioned, these cost figures do not include the adaption of existing brownfield integrated plants where BF and BOF should be replaced. These costs are significant since they include the adaption of most internal and external supply chains (raw materials, residues and by-products, gas distribution system and power supply).

Total investment costs for the development of an industrial H_2-DR plant

Considering the shaft, EAF and electrolyser units, the total CAPEX of a H_2-DR plant sums up to €470/t of CS. As mentioned above, a value of €230/t CS is required for the shaft, €184/t CS for the EAF and €90/t DRI for the electrolyser utilising the basic assumption of 1 t DRI leading to 1 t CS in steel production (for further details, please see Section 2.4.2). The electrolyser represents around 18% of total CAPEX. In Vogl et al. (2018) (Vogl, Åhman, & Nilsson, 2018), a CAPEX of €160/t CS is given for the electrolyser, which would represent 28% of the total CAPEX.

Overall, the absolute cost of the electrolyser is not negligible. For a plant with a capacity of 1Mt/a CS (i.e. around 100 t/h) and assuming for simplicity the equivalence 1t CS = 1 t DRI, the cost of the electrolyser would result in €90 M. This estimate is in line with the information obtained by stakeholder consultations.

According to consultations with the stakeholders[30] within the GREENSTEEL project, the investment costs for H_2-DR-EAF steelmaking are estimated to have an increase in the range of 20-30% compared to current coal-based primary steelmaking.

The CAPEX for shaft and EAF can be considered practically equal to that for the natural gas-based DR.

The CAPEX is comprised of the following cost components:

- pelletising plant (if not already existing and produced on-site);
- production of bio-coal (if needed and produced on site);
- an electrolyser (+ storage);
- a shaft furnace; and
- an EAF.

When assuming €230/t CS for the reduction shaft, €184/t CS for the EAF and €90/t CS for hydrogen production - as described in Section 2.1.1 - the CAPEX for the technology route based on DR amounts to €504/t CS.

The information gained from literature and the stakeholders consultation varies strongly depending on the prevailing framework conditions:

- the CAPEX for H_2-DR plant would amount to €574/t CS capacity (= €160/t capacity for the electrolyser + €230/t CS for the shaft + €184/t CS for the EAF) (Vogl, 2018 (Vogl, Åhman, & Nilsson, 2018)). This results in a 30% increase compared to a greenfield-integrated BF-BOF: and
- a CAPEX of approximately €874/t CS capacity was estimated (Fischedick, Marzinkowsk, & Winzer, 2014). The difference with respect to other approaches (Vogl, Åhman, & Nilsson,

[30] For further details, please see GREENSTEEL - D1.3.

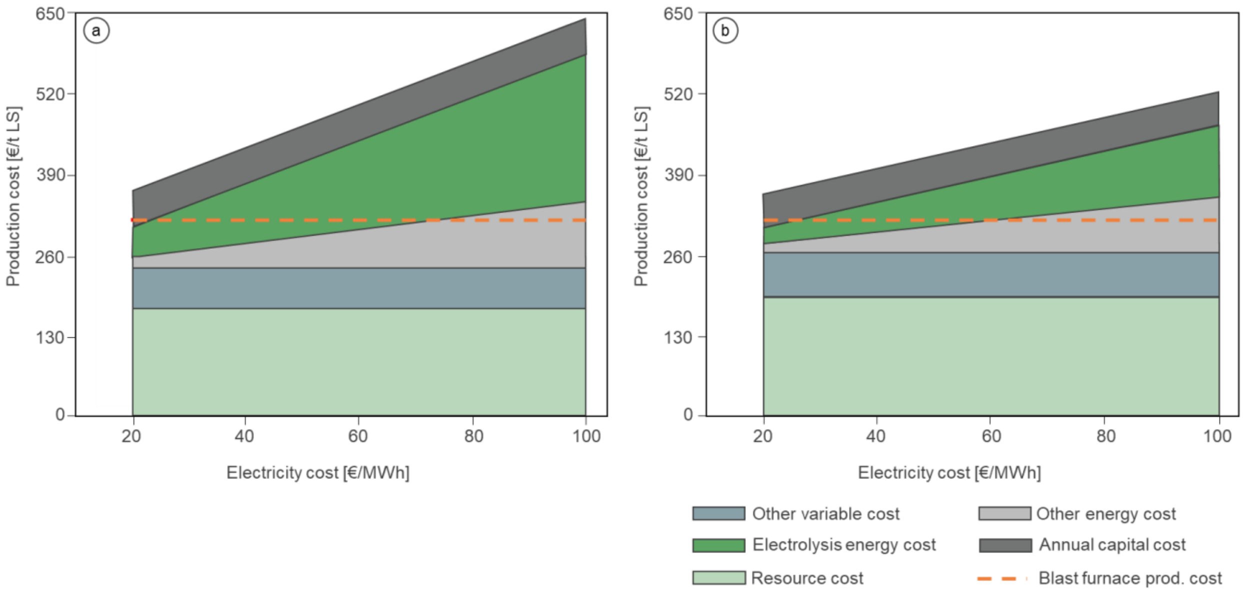
2018) lies within the initial investment for the electrolyser, which has increased capacity and a large-scale storage, due to the fewer operating hours.

For example, when using a 50:50 charge of hot briquetted iron (HBI) and scrap, the overall production costs decrease compared to pure HBI operation. Because of the higher scrap price compared to pellet prices, resource costs slightly increase when feeding more scrap in the EAF. Depending on certain market conditions, this trend can be reversed due to strong modulation of ore and scrap market prices.

Generally, the production costs of this route are expected to be higher than those of the BF-BOF route. Based on the study of the Wuppertal Institute in Germany, the production costs are estimated between €532-630/t CS in 2050 resulting in an increase of 36% to 61% compared to the conventional BF-BOF route (Lechtenbommer, Nilsson, Åhman, & Schneider, 2015)). Similar values can also be found in DEEDS (DEEDS, 2020).

However, it could be a competitive alternative when taking low energy prices into account. Furthermore, the oxygen obtained during hydrogen production could be used to generate additional revenues if a suitable market is found. Figure 2 shows the production costs relative to the electricity costs considering two different scrap quantities (0% and 50%).

Figure 2: H_2-DR route production costs as a function of the electricity costs



Source: Vögl[31]. Note: the production costs are estimated for two scenarios: a) 0 % scrap charge and b) 50 % scrap charge.

Considering the combination of the three basic units (electrolysis, DR and EAF) for producing steel without scrap, the total CAPEX becomes €470/t CS (€230/t for the shaft, €184/t for the EAF, €56/t for the electrolyser). The electrolyser represents around 12% of the total CAPEX.

[31] For further details, please see https://op.europa.eu/en/publication-detail/-/publication/e7dc500c-82de-4c2d-8558-5e24a2d335fb.

The absolute cost of the electrolyser is not negligible. For a plant with a capacity of 1Mt/a CS (i.e. around 100 t/h), assuming for simplicity the equivalence 1t CS = 1 t DRI, the cost of the electrolyser is around €560 M. This estimate is in line with the information from the questionnaires.

According to the information gained in the frame of the GREENSTEEL consultations, investment costs have an increase in the range of 20%-30% compared to current coal-based primary steelmaking (SSAB) to a much larger increase of 80% (Voestalpine).

However, the main reason for the large difference between SSAB and Voestalpine estimates is probably attributable to the above-mentioned upstream processes (SSAB has no sinter plant since several years, unlike Voestalpine).

The information gathered from the stakeholders (in-scoping questionnaires) within the project[32] and from literature confirm the above-mentioned figures. The total production costs are estimated at around 500 €/t CS depending on the amount of scrap used, electricity and CO_2 price.

2.5.3. Technology routes based on smelting reduction

Steelmaking routes based on smelting reduction technology comprise the IBRSR and HPSR technologies. As the IBRSR technology is more advanced in terms of technical maturity, most information is focused on this approach.

The technology route based on the IBRSR technology is technically presented in deliverable D1.2. Based on the basic HIsarna process[33], there are additional options for the implementation of further decarbonisation measures, namely:

- replace injected fossil coal by bio-coal;
- replace part of the iron ore by scrap; and
- integrate CCUS technologies.

In terms of CAPEX, the IBRSR, e.g. HIsarna® process, replaces the full ironmaking side of conventional plants: it replaces the BF and eliminates the need for cokemaking and sintering (or pelletising) of the iron ore. Obviously, one single reactor is much cheaper than the several ones which become useless. Anyway, when implemented in an existing plant, investments are needed to remove the former part of the steelmaking chain and install the new one. Additionally, the IBRSR unit requires auxiliaries such as grinding and drying equipment for iron ore and coal, additional O_2 capacity and dedicated off-gas treatment (steam recovery, scrubbing, desulphurisation, baghouses), especially if the off-gas (concentrated in CO_2) is directly valorised or stored. The steelmaking and hot rolling sections can remain unchanged or, if desired, can accommodate the additional changes presented in the above-mentioned BF route. Similar to the technology routes based on the conventional BF-BOF-HR, significant investments are first required for the add-on technologies (e.g. CCUS, biomass preparation etc.).

Based on the status of the different elements of the technological route, a global current TRL 5 may be estimated. Based on information from the in-scoping questionnaires, bringing the route up to TRL 8 could be expected by 2035 and TRL 9 by 2045 with investment in the order of €1 B.

---

[32] For further details, please see GREENSTEEL - D1.3.

[33] The HIsarna process uses one reactor for two process stages of iron-ore liquefaction in a high-temperature cyclone with following pulverised coal injection (PCI). The reactor is fed directly with iron ore, so pre-processing steps such as sintering, or pelletising become obsolete.

The CAPEX strongly depends on the scale: for a 1.15 Mt /a plant, Tata Steel estimates[34] the investment at €500 M (€435/t CS) but €600 M for a 1.5Mt/a plant (€400/t CS), and a CAPEX for O_2 plants is of about €120/t CS.

CCS too requires notable infrastructures to capture and transport CO_2 from the steelworks to the storing site. Hence, the investment costs for an industrial plan of about €600 M are estimated at 1 Mt/a scale (based on first industrial plant, including O_2 production and CO_2 capture and compression, but excluding transport and storage service).

2.5.4. Technology routes based on iron ore electrolysis

For the AIE option, the production plant consists, basically, of two units: an electrochemical reactor, to produce solid iron, and an EAF, to melt it to liquid steel. The electrochemical unit produces oxygen as by-product, which can be valorised in the steelworks.

Sludge containing water and gangue from the original iron ore is also produced from the AIE process. Hence, the plant will need auxiliary equipment to separate and recycle these materials. These units can be realized with conventional technologies. Sludge can be recycled in EAF or in ancillary processes for the valorisation of by-products, which are increasingly common in the steel industry.

The capital cost of the electrolytic unit is difficult to estimate at this stage, as size, materials, and productivity are still under evaluation. Considering the few upstream operations, the low temperature and a unique energy source (electricity), a CAPEX significantly lower than other technological solutions can be expected.

A Roland Berger Focus estimated a CAPEX at 25% of a reference BF-BOF plant from greenfield (Ito, Langefeld, & Goetz, 2020), which means around 400 €/t for producing liquid steel from AIE and EAF, and consequently €400 M for a plant for 1Mt/a.

From the collected stakeholder information, the investment costs for an industrial plant are estimated at around €250 M for the electrolytic unit for a plant of 1Mt/a. Adding the cost of the EAF (€184 M), the total value is comparable with the previous one.

CAPEX (and also OPEX, depending on the cost of electricity) are difficult to forecast at this stage.

The MOE is a self-consistent process, which produces liquid steel directly from raw materials. At this stage of development, the evaluation of the industrial cost of steel with this technology is premature.

[34] Information gained in the consultation activities in the frame of the project GREENSTEEL.

2.5.5. Summary of technology route investment needs

The technology route investment needs are summarized in Table 5.

Table 5: Technology route investment needs

Technology routes							
Technology route	TRL development			Investment needs up to TRL 8 (M€)	Investment needs for 1st industrial depl. TRL 9 (M€)	Investment needs for full industrial plant (M€)	CO_2 abatement (max %)
	2020	2030	2050				
Optimised BF-BOF	2-9	7–9	9 (ind. depl.)	2,000*	4,000		95
Direct reduction	4-8	7-9	9 (ind. depl.)	500		650	95
Based on smelting reduction	2-6	6–8	9 (ind. depl.)	400	500**	600***	85
Based on iron electrolysis	2-6	3-6	9	250	400	Not evaluated due to low TRL	95

*Source: authors' own composition based on desk research and stakeholders' interviews (complete references in the bibliography). Note: data refer to a crude steel capacity of 1 Mt/a as a reference[35]; * Greenfield (brownfield CAPEX costs 40% with respect to BF-BOF; Ghenda, 2013); **500 including EAF. *** Excluding CO_2 transport and storage. For the abbreviations used, please see the list of symbols, indices, acronyms and abbreviations.*

3. Investment roadmapping

The aim of this chapter is to elaborate an investment roadmap for the technologies identified in work package 1. The main goal of this roadmap is to facilitate the decarbonisation of the European steel industry. For this purpose, the roadmap proposes blending and sequencing solutions to reduce the times for industrial deployment of the technologies, and to maximise the impact on decarbonisation.

A roadmap needs to consider the most important technical alternatives to mitigate CO_2 emissions. To this end, in the Section 3.1, the information in the Tables 1 and 3 for the selected decarbonisation technologies is critically discussed and assessed.
In Section 3.2, the roadmap for investments is presented as a set of investments versus time. The possible synergies between the various investment lines are considered.

3.1. Grouping of technologies

The main following indications can be drawn from Table 2, Table 4 and Table 5.

[35] In general, real industrial plant sizes are different depending on a specific technology. Taking for example BF-gas injection technology and the route based on smelting reduction, the investment needs for Hisarna plant with a 1.5 Mt/a CS capacity are reported in Section 2.5.3.

Technologies related to biomass, increased scrap usage, gas injection in BF and CCUS have lower impact on CO_2 emissions as single application but are the closest to the industrial development and need relatively low investment costs. Conversely, the new, innovative steelmaking technologies, such as HPSR and IOE have a high potential, but their industrial deployment requires long time and large investments, due to currently rather low TRLs.

The H_2-DR technology provides a good compromise, with a moderate TRL and a very high CO_2 abatement potential, already in the medium term. Furthermore, the DR technology enables a significant CO_2 abatement in the short term via the NG-DR. Since this is already an industrially established technology, industrial plants can be installed in Europe in the short term and would enable a significant short-term decrease of the CO_2 footprint of the European steel industry.

These industrial DR plants could afterwards be used for further R&D activities, with the aim of maximising the hydrogen-to-natural-gas ratio to further decrease industrial emissions. With this approach, major CO_2 abatement of industrial emissions would be possible, without having to wait several years for less mature techniques to be developed. Instead, depending on local conditions, first industrial sites could build DR plants within a couple of years. However, this approach would also have a significant impact on the investment needs. Huge investments on industrial scale would be necessary in the short term, instead of lower investments for demonstration plants.

In general, the development of a technology is not neutral when it comes to the development of the others. In some cases, the impact is 'positive': the development of a technology pulls the development of another one. In other cases, the technologies are in competition. As an example, let us consider the two options with the highest decarbonisation potential:

a) hydrogen-based steelmaking; and
b) electricity-based steelmaking.

Both a) and b) are based on completely different processes and plants. Namely, the hydrogen-based steelmaking will be based on a modification of the DR process, whilst the electricity-based steelmaking will be used to produce iron in electrolytical processes (in water or in molten oxides) but, in any case, with technologies completely different from the DR. Consequently, the problems to face, the research needs and the required technical background for the development of the two options are completely different. This means that the success of one option, inevitably will impair the development of the other one, meaning that the two options are in competition. The most appealing line will get more interest and more investments.

In particular, a wide variety of projects and related experimental and demo plants based on the new technologies are emerging across Europe (see comprehensive list in D1.1). How many EU plants will be really involved in the options identified within the GREENSTEEL project will depend on several factors (e.g. enablers, legal framework, especially public financial support for R&D&I and upscaling of the current demo). New low-CO2 production technologies will require €50-60 B investment, with capital and operating costs at €80-120 B per year. The cost of production per tonne of primary steel will increase by 35% up to 100%. The new technologies would result in additional production costs for the EU steel industry for at least €20 B per year compared to the retrofitting of existing plants (i.e. upgrading of the existing plants with the best available techniques). At least 80% of this share is related to OPEX, mainly due to increased use and higher prices for CO_2-lean energy. Just as an example (EUROFER, 2019), the steel production in 2050 arising from new technologies could amount to 50%, with a CO_2 emission reduction going up to 94% in a best-case scenario (depending on the availability of green hydrogen).

Moreover, local conditions can foster the deployment of some of the presented technologies. For example Belgium, France and The Netherlands can benefit from CCS opportunities in North Sea ports, and Sweden (Bioenergy International, 2018) and Finland from green-energy availability (about 80% of electricity production in Sweden comes from nuclear and hydroelectric power, about 12% from wind power, and combined heat and power (CHP) plants account for the remaining 8%, mainly powered by biofuels). The availability of biomass resources too is a relevant factor. In Italy there is a large availability of biomass coming from agricultural wastes (a detailed biomass atlas already exists), but currently no large plants and technologies on CCU/CCS are available, even though large projects are going to start in other sectors and results could be applied to steel sector.

How these opportunities can be turned into reliable pathways, will also depend on other external aspects (e.g. financial support or policies). A thorough analysis of the most promising, together with a general indication of the expected positive effects on the investment needs will be detailed in a dedicated and separate report.

3.2. Investment roadmapping by technology routes

The investment roadmap is based on the technology routes presented in Chapter 2 and detailed in deliverable D1.2 (Technology assessment and roadmapping). As mentioned in Chapter 2, these routes are just selected cases which shall enable a concretisation of the investments needs, considering the complete process chain. In fact, many more additional combinations of decarbonisation technologies could be implemented.

3.2.1. Investment for the technology routes based on optimised BF-BOF

The routes based on the **optimisation** of the conventional **BF-BOF** iron and steelmaking processes include several options, e.g. BF gas injection or increasing biomass and scrap usage. These routes imply investments for a large number of technologies and projects sizes. A further main option for this route - namely to apply **CCUS** - specifically implies investments for supporting many different projects, since a large variety of technology combinations are possible. CCUS is indeed a quite flexible option, which can be combined with almost all other techniques (with the BF but also for example with EAF, DR plants or downstream processes).

This route should be targeted for 2030-2040, as it is relevant for existing plants and for new plants e.g. those based on NG-DR. After 2040, CCU should be more oriented to the EAF-based route and still existing BFs. The investment needs can be distributed as follows:

- *up to 2030*: industrial investment of first implementations in existing BF-BOF plants and technological investment for other less mature options including e.g. CCUS.
- *up to 2040*: industrial investment for full implementation and remaining technological investment for other less mature options.

3.2.2. Investment for the technology routes based on direct reduction

The route **H_2-DR-EAF** was shown to be among the most promising ones for its CO_2 mitigation potential. On the other hand, its success in the European steel industry depends on the availability and cost of CO_2-free energy (hydrogen and electricity from renewable sources). Therefore, starting with NG-DR is a plausible and more realistic first step for industrial deployment, which would enable major CO_2 mitigation. For both variants (NG/H_2-DR), challenges and investments have to be considered, which are linked to the restructuration of the existing industrial systems (i.e. in particular the adaption of material, gas and heat supply chains).

The investment needs can be distributed as follows:

- *up to 2030*: industrial investment for DR plants using natural gas and technological investments for increasing hydrogen content and for upgrading the TRL up to industrial level; and
- *up to 2040*: industrial investment for H_2-DR-EAF implementation and for progressive replacement of BFs (and related plants).

3.2.3. Investment for the technology routes based on smelting reduction

The route based on **smelting reduction** implies investments for the technology improvements and auxiliaries, such as grinding/drying equipment for iron ore and coal, additional O_2 capacity and dedicated off-gas treatment (steam recovery, scrubbing, desulphurisation, baghouses), especially for off-gas valorisation or storage. TRL 8 could be reached by 2030 and the industrial deployment on a mid-term scale (2040).

The investment needs can be distributed as follows:

- *up to 2030*: technological investment for upscaling IBRSR up to TRL 8; and
- *up to 2040*: industrial investment for the implementation of IBRSR plants, for progressive replacement of BFs and related plants, and then for industrial deployment in the European industry.

3.2.4. Investment for the technology routes based on electrolysis

The routes based on **iron ore electrolysis** include two technologies, AEL and MOE, which have different technical maturity.

AEL is currently under development with a TRL 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. TRL 9 is expected to be demonstrated in 2040.

The investment needs can be distributed as follows:

- *up to 2030*: technological investment for upscaling up to TRL 8; and
- *up to 2040*: industrial investment for the implementation of AEL plants, for progressive replacement of BFs and related plants, and then for industrial deployment in the European industry.

MOE currently has a rather low TRL of 2. Despite intensive R&D efforts on the technological developments (anode, refractory lining, etc.) and on scale-up issues, it is expected to be brought up to TRL 9 by 2050, allowing then industrial deployment in the subsequent years.

The investment needs can be distributed as follows:

- *up to 2030*: technological investment for fundamental and low-scale development (laboratory, pilot plant); and
- *up to 2040*: industrial investment for further upscaling in view of achieving TRL 9 in 2050.

4. Analysis of regulatory and market context

Within this chapter, the regulatory and market context is analysed, as it is a driver for the investment strategies of stakeholders. Current and expected regulatory trends and targets (e.g. emissions, CO_2 targets) are considered with respect to what producers need to adapt to such regulatory aims (EUROFER, 2020)).

4.1. Regulatory context

The institutions of the European Union have made **climate protection a central element of the European Union policy**. There are two main dimensions to this approach. First, the precautionary principle, as embedded in article 191 of the Treaty on the Functioning of the European Union, which is interpreted (European Commission, 2000 (COM, 2019)) as mandating that decision-makers faced with an unacceptable risk, scientific uncertainty and public concerns have a duty to find answers. The scientific consensus on the risks emanating from manmade climate change provides the basis for said prioritization. Second, across all EU institutions there is the perception that a carbon-lean economy would in all aspects be superior to the current economy, which completely ignores, in its main paradigms, the aspects of carbon use, greenhouse gas emissions and the consequences of both. Provided this superiority is being granted, the question of why this change of paradigm has not occurred is ascribed to the severe failures in the market system generated by the currently dominating economic model. These market failures, amongst them welfare-distribution problems at a global level (Schutti, 2013 (Schutti, 2013)), would affect the current economic model. Hence, political action is deemed necessary to overcome these.

Against the background of these two fundamental drivers, it does not come as a surprise that the EU institutions designed the respective implementation structures, procedures and rules as the solution to a **management task**. This consists in the definition of quantitative targets, which guide the establishment and design of implementing instruments, rules and actions. This approach differs significantly to the approaches of other big greenhouse gas emitters. The Unites States of America rely on a technology-based and market-guided approach. China applies central planning-oriented command and control policies. It is interesting to note that the international negotiations are currently very much focused on objective setting. This allows the speculation that one reason for the lack of progress of the international efforts may be the difficulty of many regions and countries to align their strategies with a management approach.

The most recent and significant milestone of the **international negotiations** was the Paris agreement in 2015, which calls for zero net anthropogenic greenhouse gas emissions to be reached during the second half of the 21st century. In the adopted version of the Paris agreement, the parties will also "pursue efforts to" limit the temperature increase to 1.5 °C. Prior to the conference, 146 national climate panels publicly presented a draft of national climate contributions (called "intended nationally determined contributions ", INDCs). The European Union suggested INDC is a commitment to a 40% reduction in emissions by 2030 compared to 1990. All parties to the agreement are to present long-term low greenhouse gas emission development strategies by 2020 that deliver on its objectives.

The INDC of the European Union is derived from the EU's official internal **targets for 2030** on reducing greenhouse gas emissions by at least 40%, increasing the share of renewable energy to at least 27%, and achieving an energy efficiency improvement of at least 27%. Legislation, provisionally agreed in July 2018, revises two targets upwards to at least 32.5% for energy efficiency and at least 32% for renewables. These targets spawned a wide range of regulation.

Governance regulation is typical of the management approach of the European Union, as it is an instrument to ensure coherent long-term energy and climate policy planning. The legislative framework for a 40% GHG emission reduction target has been established by the revised emission trading system directive, the effort sharing regulation and the land use land use change and forestry (LULUCF) regulation. To support the renewable and energy efficiency targets, in May 2020 the EU institutions achieved an agreement on the adoption of the package 'Clean energy for all Europeans', which consists of a directive on energy performance in buildings, a directive on renewable energy, a directive on energy efficiency, an electricity regulation, an electricity directive, a regulation on risk preparedness and the Agency for the cooperation of energy (ACER) regulation. The above-mentioned three targets inspire and guide legislative and political initiatives for the mobility sector (three mobility packages consisting of 16 initiatives[36]), on circular economy, the common agriculture policy, the cohesion policy, waste policy, the European Union's multiannual financial framework and climate mainstreaming in financing as well as special initiatives for the aviation and maritime sectors. All of these pieces of legislation interact either directly with the steel industry or indirectly with its markets and steel product end users, with the objective to propel these sectors and markets towards the 2030 targets.

On the 11th of December 2019, the Commission published a proposal on how to intensify the European Union's climate policies, which is called the Green Deal communication (European Commission, 2019 (European Commission, 12 December 2019)) and is designed to support increased ambitions for 2030. It puts forward a proposal for the target of climate neutrality in 2050, together with a bundle of measures to advance towards this new **2050 target**. Only one day later the European Council approved the target and tasked the Commission to immediately commence with the deliberation and publication of the proposed measures.

The conclusions of the European Council (2019 (European Commission, 12 December 2019)) on the communication on a European Green Deal and the content of this communication devote **considerations specifically for carbon-intensive sectors and energy-intensive industries**, **notably steel**. Because they are deemed indispensable for the supply of key value chains, an enabling framework is to be put in place, which will allow their modernization and thereby their transformation to carbon neutrality via integrated evolution.

In line with the management approach described in this chapter, the core of the implementation activities of the Green Deal is a proposal on a European 'climate law', legally enshrining a **2050 climate neutrality target** and a plan to **increase the EU 2030 climate target** to at least 50% and towards 55%. As with past targets, also these will give birth to a very large number of legal and political initiatives, all expected to see the light of the day between 2020 to 2022.

---

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

The **initiatives directly relevant to the manufacturing industry**, as announced in the Green Deal communication, are: a review of the emissions trading system directive; a review of the effort-sharing regulation; a review of the LULUCF regulation; a review of the energy efficiency directive; a review of the renewable energy directive; CO_2 emissions performance standards for cars and vans; a proposal for a revision of the energy taxation directive; a proposal for a carbon border adjustment mechanism for selected sectors; a new EU strategy on adaptation to climate change; a strategy for smart sector integration; a 'renovation wave' initiative for the building sector; an evaluation and review of the trans-European network – energy regulation; a strategy on offshore wind; an EU industrial strategy; a circular economy action plan; initiatives to stimulate lead markets for climate neutral and circular products in energy intensive industrial sectors; a proposal to support zero carbon steel-making processes by 2030; legislation on batteries; legislative waste reforms; a strategy for sustainable and smart mobility; a revised proposal for a directive on combined transport; a review of the alternative fuels infrastructure directive and the trans-European network – transport regulation; a proposal for more stringent air pollutant emissions standards for combustion-engine vehicles; a chemicals strategy for sustainability; a zero pollution action plan for water air and soil; a revision of measures to address pollution from large industrial installations; a proposal for a just transition mechanism, including a Just Transition Fund and a sustainable Europe investment plan; a renewed sustainable finance strategy; a review of the non-financial reporting directive; a review of the relevant State aid guidelines, including the environment and energy State aid guidelines; and the proposal for an 8th environmental action programme. Again, all of these will interact either directly with the steel industry or indirectly with its markets and steel product end users, this time with the objective to propel these sectors and markets towards the 2050 target.

4.2. Market context

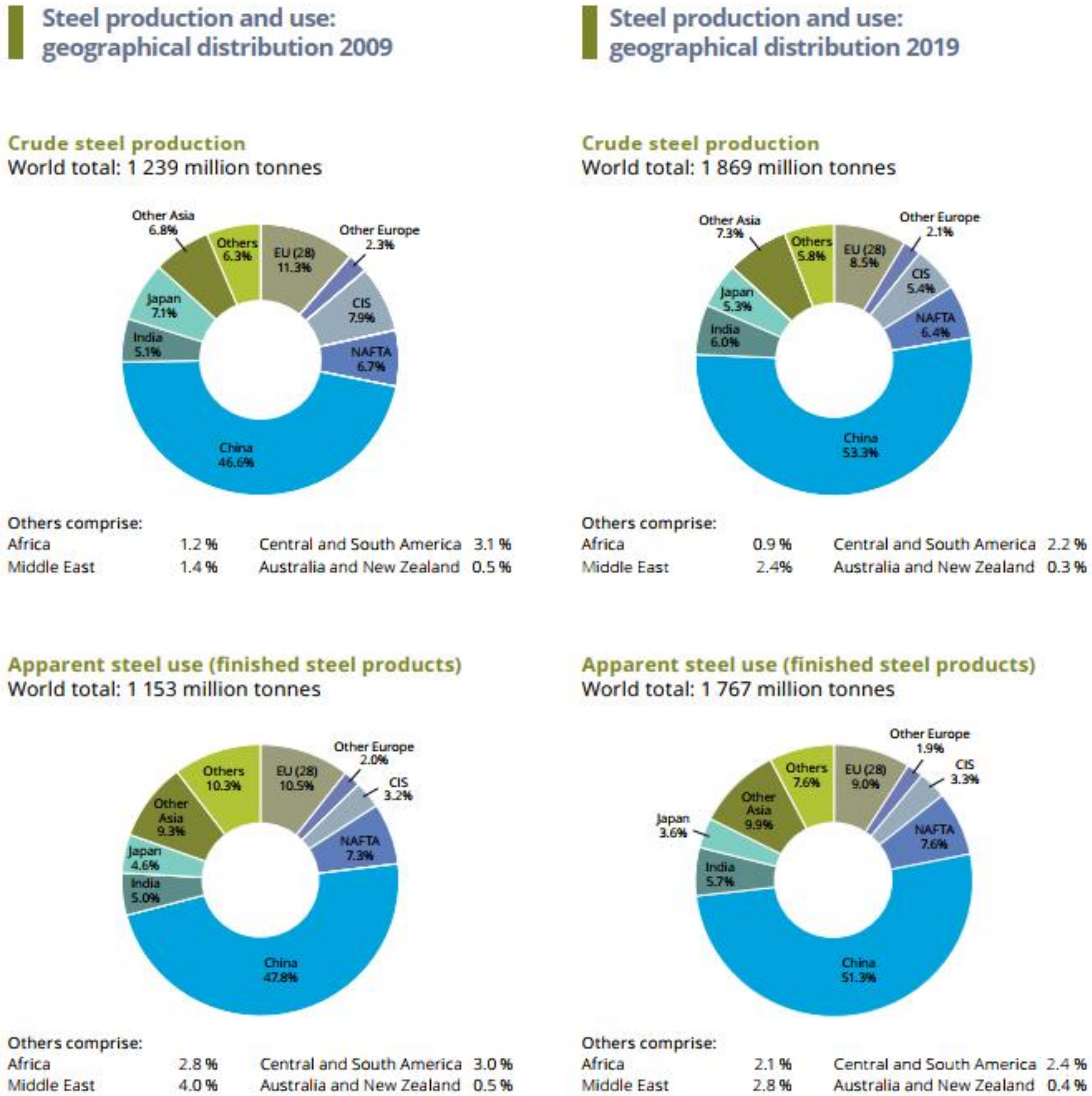
Steel is a widely heavily traded commodity on the global market. Hence, global trends in steel demand, steel supply capacity, steel trade flows shape the steel industry dynamics. The global crude steel production reached 1.87 B tonnes, 8.5% of which was made in the EU. Global steel consumption patterns have changed dramatically over the past decade, with China becoming a dominant player with 53.3% of global production (World Steel Association, 2020 (worldsteel, 2020); see Figure 5).

In the EU, about 58.6% of crude steel production comes from the integrated route (steel production from virgin iron ore through the BF-BOF route). The remaining 41.4% is produced only via the recycling of steel scrap EAFs (EUROFER, 2020); see Figure 6).

Major steel-using sectors in the EU are: construction (35% of total finished steel demand); automotive (19%); mechanical engineering (15%); and metal ware (15%) (see Figure 7).

In the last decade, steel imports to the EU have been increasing while steel exports to the EU have been decreasing. The EU is a net importer of finished steel products: in 2019 the EU imported 25.3 M tonnes of finished steel products and exported 20.5 M tonnes (EUROFER, 2020)), as shown in Figure 6 and Figure 7.

Figure 3: Steel production and use



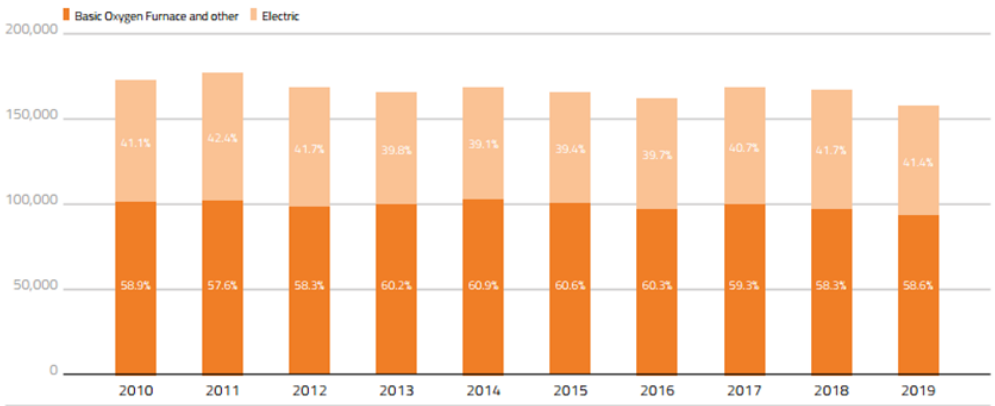
Source: *World Steel Association* (worldsteel, 2020).

Figure 4: EU crude steel output by production route

EU CRUDE STEEL OUTPUT BY PRODUCTION ROUTE TABLE, CHART • 2010 – 2019

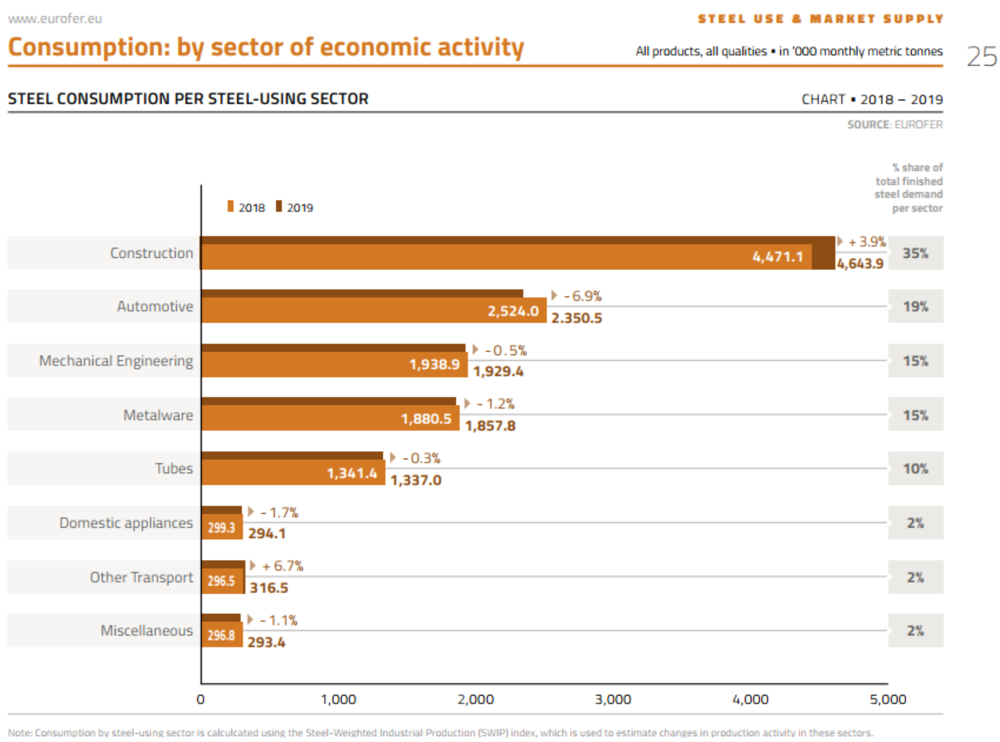
SOURCE: EUROFER

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	% shares 2019
Basic Oxygen Furnace and other	101,790	102,3710	98,316	100,106	103,024	100,577	97,642	99,925	97,588	92,382	58.6%
Electric	70,995	75,204	70,266	66,069	66,074	65,519	64,351	68,497	69,781	65,171	41.4%
Total Crude Steel	**172,785**	**177,576**	**168,583**	**166,175**	**169,098**	**166,096**	**161,993**	**168,422**	**167,370**	**157,553**	**100%**



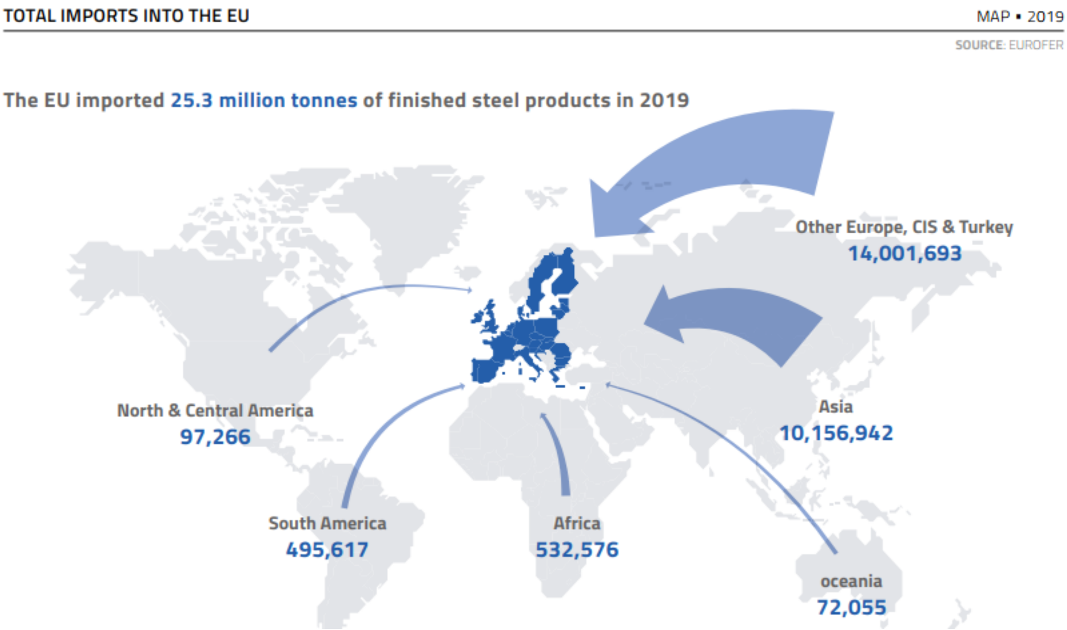
Source: EUROFER (2020) (EUROFER, 2020). *Note: the unit is million tonne.*

Figure 5: Steel consumption by sector of economic activity



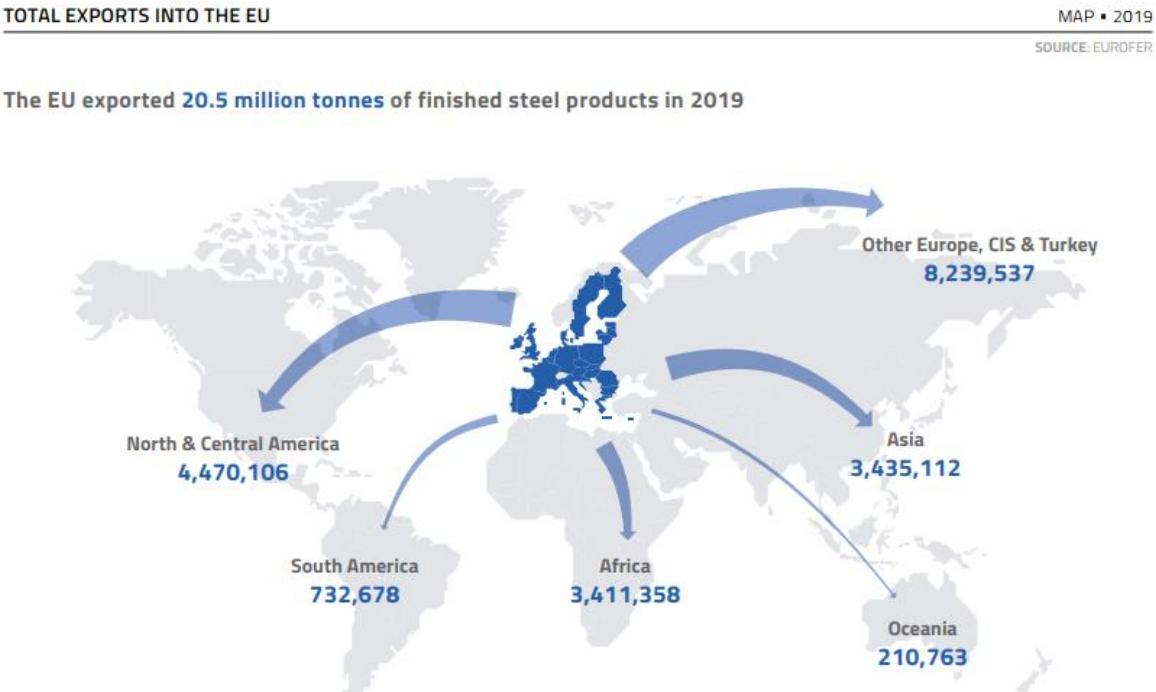
Source: EUROFER (EUROFER, 2020). *Note: the unit is million tonne.*

Figure 6: Total imports into the EU



*Source: EUROFER **(EUROFER, 2020)**). Note: the unit is million tonne.*

Figure 7: Total EU exports



Source: *EUROFER* (EUROFER, 2020)*). Note: the unit is million tonne.*

The European steel market has been experiencing difficult times since early 2019, before the onset of the COVID-19 pandemic. Final data available for 2019 (EUROFER, 2020)) show that the EU28 steel market (i.e. apparent steel consumption) dropped by 5.3%. In particular, safeguard measures proved somewhat effective, as imports from third countries in 2019 decreased by 11.5%, thereby reducing the pressure on EU steel producers, which was stemming from low-priced imports from outside the EU. However, in historical terms, imports remained at rather high levels, particularly for some flat products.

Meanwhile, in the first quarter of 2020 (EUROFER, 2020), the COVID-19 outbreak across the EU and all the world regions has slashed steel consumption forecasts, as well as the overall economic outlook. Shutdown measures implemented by governments starting from March 2020 have hugely impacted manufacturing activity and steel-using industrial sectors. As a result of the dramatic deterioration in economic prospects and steel consumption outlook since March 2020, the outlook for this year and for 2021 is obviously particularly affected by the disruption caused by the pandemic and is likely to be revised significantly over the course of the year, depending on the length and magnitude of the crisis. The extension of the containment measures that have been put in place in EU Member States, the subsequent lockdown of industrial activity, and the unprecedented nature of this crisis, are not without consequence. Because of the uncertainty and volatility surrounding possible developments in future months, no forecast could be considered reliable. Therefore, EUROFER has not produced forecasts for 2020 and 2021 in the latest market report on the second quarter of 2020, being confident that more clarity during the third quarter of 2020 will make it possible to issue forecasts in the framework of the next report.

The outlook for the global economy has been hugely impacted by the COVID-19 pandemic. The outbreak has resulted in the shutdown of major economic activities, particularly the manufacturing and automotive sectors. It is almost certain it will lead to the worst economic recession ever recorded for the EU, as well as other advanced economies. The downturn is likely to be far larger than the Great Recession of 2009-2012, which was triggered by the financial crisis. In its latest Economic Outlook (April 2020), the International Monetary Fund (IMF) has predicted an unprecedented global recession of -3%, with the US economy experiencing a recession of -5.9% and the euro area of -7.5%, all followed by a rebound in 2021. With the number of infected people rising across the continent and partial or full lockdown measures in place in most European countries, the economic impact of the health crisis is going to be massive, with the EU heading for an historically deep recession in the first half of the year. Eurostat's preliminary figures for the first quarter of 2020 already show a drop of -3.5% quarter-on-quarter in the EU. Even after the return to normal business conditions, the EU economy will still be particularly vulnerable, as it is exposed to fluctuations in international trade. As the largest contribution to growth during the previous cycle came from exports, a slowdown in export markets will further exacerbate the difficulties that EU economies will face as the lockdowns become a thing of the past.

Total production growth in EU steel-using sectors cooled further: in the fourth quarter of 2019 it was negative (-1.6%), resulting in the first annual drop, albeit very modest, since 2013 (-0.2%). The steepest fall was recorded in the automotive sector, followed by the mechanical engineering sector, the steel tube industry and the metal goods industry. Meanwhile, production activity in the construction sector continued to prove resilient, albeit slowing down compared to preceding quarters.

As in preceding quarters, developments in total imports in the fourth quarter of 2019 continued to conceal distortions at the individual product level. These are essentially caused by the design of the current safeguard mechanism, and which has resulted in a rush to maximise quarterly quota allowances by several key exporters to the EU such as Turkey and China. Despite the current uncertainty on the magnitude and the length of the COVID-19 outbreak, it is expected that once normal market conditions will be restored and steel demand will pick up again persisting import pressure – resulting from continued stockpiling and capacity expansion by major non-EU exporting countries – will, in essence, penalise EU steel producers.

Apparent steel consumption in the EU fell by -10.8% year-on-year in the fourth quarter of 2019, after a drop of 1.6% in the third quarter, resulting in yearly fall of -5.3% for the entire year 2019, which was the worst performance in EU steel demand since 2012. The negative trend in steel demand seen in the fourth quarter of 2019 is the result of the continued slump in EU's manufacturing sector due to weakened exports and investment that has become more pronounced during the second half of last year, coupled with escalating trade tensions between the US and its major trading partners. Equally, data for the fourth quarter of 2019 continued to show growing import distortions as well as higher volatility as a result of the increase of safeguard measures' quota.

The dramatic consequences of the COVID-19-related shutdown in industrial activity do not affect Europe alone. They have reached a global scale, in terms of huge disruption of supply chains and supplies of input and raw materials. This will probably have unprecedented repercussions on output in the second and third quarters of 2020. Against this background, a substantial rebound is not in sight before the first quarter of 2021. Even after the end of the pandemic, external risks will continue to cast a shadow over steel-using industrial sectors, even in 2021. This will likely seriously hamper investment. However, the extent remains difficult to predict. Much will depend on other, non-COVID-19 related factors that were already in place before the outbreak. Whether global trade fundamentals will improve – which is fundamental given the large exposure of EU's export-oriented industrial economies to changes in global trade – is unclear at this stage. Other sources of uncertainty exist, such as a no-deal Brexit – as the final agreement with the EU must be reached before the end of 2020 – and a new escalation in protectionist trade measures would also contribute to a sustained negative outlook.

The onset of the COVID-19 pandemic is expected to dramatically impact the already challenging steel market situation, with unprecedented consequences for the steel industry. Capacity idling, reduction in workforce and cuts in production are already taking place at an unprecedented scale and it is unknown, at the time of writing, as to when – or whether – normal economic activity will be fully restored. We assume that, according to confinement and lockdown easing schemes that have been set out by most EU governments, from the beginning of the third quarter production should have restarted again in almost all industrial sectors. The coming quarters will nevertheless be determined by some global restrictions on economic activity.

As previously mentioned, market conditions are not expected to improve up to early 2021. Much will depend on the length of the industrial lockdown in steel-using sectors that has almost put a stop to new steel orders (on the supply side) – although there are already signs of some restart in automotive and other sectors - as well as on governments' ability to alleviate the huge economic and social costs of the pandemic so as to support demand. However, if and when the economy returns to normal conditions, all the downside risks that had considerably weakened steel-using sectors and steel demand during 2019 will still be there, namely import distortions and continued global overcapacity and weakness in the global manufacturing cycle. Restarting normal industrial activity after the end of the pandemic will not lead to a rapid return to usual output volumes. Consumer demand, due to the huge social disruption caused by the pandemic, is set to remain depressed throughout 2020; therefore, it will take time before the end of industrial lockdown leads to substantial output increases.

The production of clean steel, at least for the foreseeable future, will go along with (much) higher costs for several reasons, thus, as already discussed in D1.2 (Technology assessment and roadmapping), new markets and business models for clean steel have to be established. The extremely high importance of this need was confirmed by the first part of the GREENSTEEL stakeholder consultation: The steel producers ranked "unknown market conditions for clean steel" as one of the top three barriers hindering the decarbonisation of steel production. In order to create a proper market context for clean steel and related products, incentives for users to use clean steel (and related products), promotion of clean steel products in public procurement and adaption of standards are discussed (Agora-Energiewende, 2019); (Wijns, Khandekar, & Robson, 2018).

5. Conclusions

The present report shows the main features of the investment needs for the most relevant steel production technologies and technology routes aimed at reducing CO_2 emission by at least 80% and representing complete process chains, based on the implementation of specific technologies. These technologies were identified through the technological assessment of the decarbonisation technologies carried out in the project Deliverable D1.2. For the economic assessments, considering the content of Tables 1, 3 and 4 of the report and the data discussed in Chapter 3, the following conclusions can be reached:

- many breakthrough decarbonisation technologies are not available for industrial deployment in the short term (until 2030),
- there are some decarbonisation technologies currently available which enable short-term deployment with limited R&D needs and investment effort, but their mitigation potential is also limited;
- all decarbonisation technologies need certain framework conditions, with the most important one being sufficient CO_2-free energy[37] at competitive costs; and
- there is no single technology which fulfils all demands, considering the different framework conditions within the European steel industry and the pressure to mitigate increasing percentages of CO_2, starting from now until (almost) complete mitigation in 2050. Hence, parallel investments in the development and deployment of several technologies are needed. These technologies can either be combined or represent alternatives with individual advantages for different framework conditions and different time scales.

Overall, there is a wide variety of investment needs. The technology-specific investment needs comprise investments either to further improve the technologies to full technological maturity, or to enable the subsequent deployment for industrial production. The investments required for improving technological maturity range from €5 M (for some biomass applications) up to €1,000 M (for MOE). Technologies with currently low technological maturity and high CO_2-mitigation potential typically require higher investment:

[37] In particular electricity and hydrogen and, in some cases, biomass.

- €5 to 400 M with typically around €300 M for one demo plant (TRL 8), with a peak of €1 B for the not yet mature MOE;
- generally, from €500 M to €1 B (maximum €4 B for BF-BOF- HR route) for deployment and industrialisation; and
- generally, around €1 B (referring to a capacity of 1 M t CS/a) for deployment as full industrial plant.

As can be expected, considering the sheer size of the plants, the costs raise considerably with the TRL. Although all the presented technologies should reach an industrial deployment latest by 2050, only some of them (H_2-DR, CCUS, gas injection on BF, increased scrap usage) are expected to achieve a TRL level of 9 close to 2030. Therefore, summarising the overall investments needed for all relevant technologies, the main investments for development (including demonstration) are needed before 2030, whereas most investments for industrial deployment will occur between 2030 and 2050, leading to most part of the overall investment needs from 2020 onwards, to be concentrated in the period 2030-2050. However, the DR technology provides a different opportunity: industrial plants based on natural gas could be built and successively further developed for increasing hydrogen usage. This would require large investments in the short term (up to €1-2 B, see Table 1 in the executive summary) but would enable a significant short-time mitigation and also a flexible and highly efficient mitigation on the medium term.

The efforts invested in developing the new technologies with dedicated projects all across Europe are encouraging, yet how much of the steel production will really be involved in the options identified within the GREENSTEEL project will depend on several factors (enablers, legal framework, especially public financial support for R&D&I and upscaling of the current demo).Moreover, local conditions, as seaport storage ad green-energy availability, can foster the deployment of some of the presented technologies. Changing all opportunities into reliable pathways will also depend on other external aspects (e.g. financial support or policies). A thorough analysis of the most promising pathways, together with a general indication of the expected positive effect on the investment needs, will be detailed in a dedicated report.

The huge investment needs and the related technical-economical risks call for adequate financial support of the development activities, in particular considering the current economic and market scenario. Parallel to financial support, there are regulatory initiatives needed to support clean-steel markets, with the objective of propelling the technology development and the industrial deployment towards the CO_2-mitigation targets. Consequently, the results of this report will be used within the upcoming work within the project Green Steel for Europe in work package 3 “Impact Assessment”, which will analyse and recommend related policy options.

Bibliography

Agora-Energiewende. (2019). *Klimaneutrale Industrie Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement.* Retrieved from 164/04-S-2019/DE Version: 1.1: , https://www.agora-energiewende.de/fileadmin2/Projekte/2018/Dekarbonisierung_Industrie/164_A-EW_Klimaneutrale-Industrie_Studie_WEB.pdf

Agrawal, A.-K., Peters, K. K., Rösner, B., Kappes, H., Bermes, P., Micheletti, L., . . . Oliveira, A. (2019). The blast furnace in view of past, current and future – CO2 saving technologies. *49º Seminário de Redução de Minério de Ferro e Matérias-Primas e 7º Simpósio Brasileiro de Aglomeração de Minério de Ferro.* São Paulo: ABM.

ArcelorMittal. (2019). *https://www.greencarcongress.com/2019/12/20191215-arcelormittal.html.*

ASCOPE. (2011). *French National Research Agency project: Acier sans CO2 par electrolyse - ANR-09-EESI-0002*. Retrieved from https://scanr.enseignementsup-recherche.gouv.fr/project/ANR-09-EESI-0002

Behera, P., Bhoi, B., Paramguru, R., Mukherjee, P., & Mishra, B. (2019). Hydrogen Plasma Smelting Reduction of Fe2O3. *Metallurgical and Materials Transactions B, 50*, 262–270.

Bhaskar, A., Assadi, M., & Nikpey Somehsaraei, H. (2020). "Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen". *Energies, 13*(3), 758.

Bioenergy International. (2018, June 18). *Swedish Energy Agency awards record funding to HYBRIT.* Retrieved from https://bioenergyinternational.com/research-development/swedish-energy-agency-awards-record-funding-to-hybrit

Budinis, S., Krevor, S., MacDowell, N., Brandon, N., & Hawkes, A. (2018, November). An assessment of CCS costs, barriers and potential. *Energy Strategy Reviews, 22*, 61-81. Retrieved from https://www.researchgate.net/publication/328664843_An_assessment_of_CCS_costs_barriers_and_potential

Bui, M. (2018). *Carbon capture and storage (CCS): the way forward.* Retrieved from https://doi.org/10.1039/C7EE02342A

CARBALYST. (2015). *https://corporate.arcelormittal.com/corporate-library/reporting-hub/carbalyst-capturing-carbon-gas-and-recycling-into-chemicals.*

COM. (2019). *640: Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions – The European Green Deal .* Retrieved from https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf

CORDIS. (2020, April). *Advanced Carbon Capture for steel industries integrated in CCUS Clusters*. Retrieved from https://cordis.europa.eu/project/id/884418.

Dahlmann, P. (2019). *Update of the Steel Roadmap for Low Carbon Europe 2050 - Part I: Technical Assessment of Steelmaking Routes - Final Report.* Institute VDEh.

DEEDS. (2020). *Dialogue on European Decarbonisation Pathways.* Retrieved from https://www.iamconsortium.org/resources/project-resources/deeds/#:~:text=DEEDS%20(Dialogue%20on%20European%20Decarbonisation,(EDPI)%20and%20its%20High%2D

EUROFER. (2019). Retrieved from https://www.eurofer.eu/assets/Uploads/EUROFER-Low-Carbon-Roadmap-Pathways-to-a-CO2-neutral-European-Steel-Industry.pdf

EUROFER. (2020). Retrieved from https://www.eurofer.eu/assets/Uploads/REPORT-Economic-and-Steel-Market-Outlook-Quarter-2-2020.pdf

EUROFER. (2020). EUROFER's Quarterly Economic and Market Outlook 2/2020. Retrieved from Quarterly Economic and Market Outlook 2/2020: https://www.eurofer.eu/assets/Uploads/REPORT-Economic-and-Steel-Market-Outlook-Quarter-2-2020.pdf

European Commission. (12 December 2019). European Council Conclusions EUCO 29/19.

Fischedick, M., Marzinkowsk, J., & Winzer, P. (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Cleaner Production, 84*, 563–580.

FReSMe. (2017, June). *From Residual Steel Gases to Methanol,.* Retrieved from http://www.fresme.eu

Ghenda, J.-T. (2013). *A Steel Roadmap for a Low Carbon Europe 2050 - A Global Industry Dialogue and Expert Review Workshop - Paris.* Retrieved from https://iea.blob.core.windows.net/assets/imports/events/205/NEWSteelRoadmappresentation_IEA_20131007.pdf

Hiebler, H., & Plaul, J.-F. (2004). Hydrogen plasma smelting reduction – an option for steelmaking in the future. *Metallurgija, 43*(3), 155-162.

Hisarna. (2020). *http\\Tatasteeleurope.com/static_files/Downloads/Corporate/About%20us/hisarna*.

IGAR. (2020). https://www.ademe.fr/sites/default/files/assets/documents/igar.pdf. ArcelorMittal funded by french agency ADEME: IGAR: Validation pré-industrielle de l'injection de gaz réducteur dans un haut-fourneau sidérurgique, [online].

IndWEDe. (2018). *Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme.* Berlin.

Ito, A., Langefeld, B., & Goetz, N. (2020, May 2020,). *The future of steelmaking / How the European steel industry can achieve carbon neutrality",.* Retrieved 17 July, 2020, from https://www.rolandberger.com/nl/Publications/Europe's-steel-industry-at-a-crossroads.html

Lavelaine de Maubeuge, H. v. (2016). *IERO.*

Lechtenbommer, S., Nilsson, L. J., Åhman, M., & Schneider, C. (2015). Decarbonising the energy intensive basic materials industry through electrification - implications for future EU electricity demand. *SDEWES2015.* Dubrovnik - Croatia.

Minh-Ho, T., Bustamante, A., & Wiley, D. E. (2013, November). Comparison of CO2 capture economics for iron and steel mills. *International Journal of Greenhouse Gas Control, 19*, 145-159.

Sabat, K. C., & Murphy, A. B. (2017). Hydrogen Plasma Processing of Iron Ore. *Metallurgical and Materials Transactions B, 48*(3), 1561-1594.

Sadoway, D. (2019). Decarbonizing the Production of Steel. *Webinar*. LowCarbonFuture Project, EU Grant Agreement N. 800643.

SALCOS. (2020). SALCOS official project website, [online] salcos.salzgitter-ag.com.

Schutti, G. (2013). *Nachhaltigkeit in Zeiten des Wachstumsdilemmas: - Von der ungebrochenen Beschwörung eines brüchigen Paradigmas.* Südwestdeutscher Verlag für Hochschulschriften.

SIDERWIN. (2020). *SIDERWIN official project website, [online] www.siderwin-spire.eu [01.06.2020].*

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

STEELANOL. (2015). *http://www.steelanol.eu/en.*

ThyssenKrupp. (2020). *https://www.thyssenkrupp.com/en/newsroom/content-page-162.html*.

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

ULCOS. (2011). *Ultra-Low CO2 steelmaking, Funded FP6-NMP, Grant Agreement 515960, 2004 - 2010.* Retrieved from testlink

VALORCO. (2014). *https://www.ademe.fr/valorco.*

Vogl, V., Åhman, M., & Nilsson, L. J. (2018, December). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production 203*, pp. 736 - 745.

Wijns, T., Khandekar, G., & Robson, I. (2018). *Industrial Value Chain: A Bridge Towards a Carbon Neutral Europe, Europe's Energy Intensive Industries contribution to the EU Strategy for long-term EU GHG emissions reductions, IES-VUB.* Retrieved from www.ies.be/files/Industrial_Value_Chain_25sept.pdf

worldsteel. (2020). *2020 world steel in figures.* Retrieved from (https://www.worldsteel.org/en/dam/jcr:f7982217-cfde-4fdc-8ba0-795ed807f513/World%2520Steel%2520in%2520Figures%25202020i.pdf

Wörtler, M., Schuler, F., Voigt, N., Schmidt, T., Dahlmann, P., Lüngen, H. B., & Ghenda, J.-T. (2013). *Steel's Contribution to a Low-carbon Europe 2050.* Boston Consulting Group.