GREEN STEEL
FOR EUROPE

INVESTMENT NEEDS

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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 the “Technology Assessment and Roadmapping” report (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 conventional blast furnace-blast oxygen furnace-route (BF-BOF-route), on direct reduction (DR), on smelting reduction and on iron ore electrolysis. The related investments needs are shown in Table 1.

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.

As shown in Table 1, 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 2050*: 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 CO_2 mitigation potential of up to 95%. However, its success in the European steel industry depends on the availability and cost of ‘clean’ energy (hydrogen and electricity). Therefore, starting with Natural Gas-based Direct Reduction (NG-DR) is a plausible and more realistic first step for industrial deployment, which would still enable high CO_2 mitigation. In any case, 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) to 9 (first industrial deployment); and
- *up to 2050*: 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 coke making 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 2050*: industrial investment in the progressive replacement of BFs and related plants and, subsequently, for industrial deployment in the European industry.

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

Technology routes based on iron ore electrolysis

These routes comprise two technologies mentioned in Table 1 - alkaline iron electrolysis (AIE) and molten oxide electrolysis (MOE) (under the ‘single decarbonisation technologies’ section), which both reduce iron ores through direct use of electricity but 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 2050*: 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 2050*: 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 full industrial plants**: these are the investment needs for a full-scale industrial production plant (normalised to 1 M t production capacity).

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.

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[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 of steel industry)		200	-
Water electrolysis	5–8	7–9	9 (ind. depl.)	Not evaluated (independent of 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.*

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[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.

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. In each part, the investment needs for TRL8, TRL9 and full industrial plants are presented. 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 and the time to achieve such abatement.

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.

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.

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[4] 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).

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, [5] 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 GREENSTEEL report (D1.7 – Decarbonisation Pathways 2030 and 2050).

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 “Technology assessment and roadmapping” report and the “Collection of possible decarbonisation barriers” report (deliverables D1.2 and D1.5 of the GREENSTEEL project), new markets and business models for clean steel must be established.

The above constraints impact the financial scenario, and the significant investment needs call for a public support to foster the stakeholders’ effort. 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

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[5] Source: EUROFER, www.eurofer.be

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 also provided inputs for the impact assessment under work package 3 of the GREENSTEEL project, which analyses and recommends different policy options.