European Commission

Climate-neutral Steelmaking in Europe

Decarbonisation pathways - Investment needs - Policy Conditions - Recommendations

Written by Hien Vu, Francesca Cecchin
Edited by Nadina Iacob, Cristian Stroia
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European Commission
Directorate-General for Research and Innovation
Directorate C - Clean Planet
Unit C.3 - Low Emission Future Industries
B-1049 Brussels

European Research Executive Agency (REA)
Directorate B - Green Europe
Unit B.1 - Future Low Emission Industries
Contact Sebastiano Fumero
E-mail REA-RFCS@ec.europa.eu

EUROPEAN COMMISSION

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Acknowledgements

This document reports on the results of the RFCS project 'Green Steel for Europe'. Thus, the first to acknowledge are all the scientists and researchers involved, ensuring excellent research. The document also summarises the discussions at the conference "Climate-neutral steelmaking in Europe: Technology, financing and policy conditions". We would therefore like to extend our thanks to the speakers and stakeholders who actively participated and provided inputs to this event.

Finally, our special thanks go to Sebastiano Fumero, Michael Laubenheimer, Vasiliki Kosiavelou and Gelsomina Fasano (European Research Executive Agency), who have provided valuable review and guidance which helped us complete the report.

List of abbreviations

AIE	Alkaline iron electrolysis
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CAPEX	Capital expenditures
CBAM	The Carbon Border Adjustment Mechanism
CCfDs	Carbon Contracts for Difference
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
CO_2	Carbon dioxide
CSP	The Clean Steel Partnership
DR	Direct reduction
ETS	Emission Trading System
EU	European Union
GDP	Gross domestic product
GREENSTEEL	The Green Steel for Europe project
GVA	Gross value added
H_2	Hydrogen
H2-DR	Hydrogen-based direct reduction
HE	Horizon Europe
HPSR	Hydrogen plasma smelting reduction
IBRSR	Iron bath reactor smelting reduction
IF	Innovation Fund
IPCEI	Important Projects of Common European Interest
MOE	Molten oxide electrolysis
OPEX	Operating expenses
R&D	Research and Development
R&D&I	Research, Development and Innovation
RFCS	The Research Fund for Coal and Steel
TRLs	Technology Readiness Level
WTO	World Trade Organisation

1. About the Green Steel for Europe project

The steel industry is responsible for around 7% of the global CO2 emissions; hence the decarbonisation of this sector plays a key role in achieving the European Union's (EU) climate goals for 2050. With more than 330,000 directly employed workers and over 2.67 million people working in and around the industry, the European steel industry produced an average of 170 million tonnes of steel per year, having created around €140 billion of Gross Value Added (GVA) in 2019.

The sector is highly exposed to international trade and global excess capacity. The European steel industry needs operational changes in the short-term and strategic decisions towards economically viable and climate-neutral transformation in the long term. This requires the alignment of steelmakers, steel value chains, policymakers and investors towards finding effective solutions to decarbonise the steel industry.

In this context, the Green Steel for Europe (GREENSTEEL) project provides insights and recommendations for effective solutions for clean steelmaking suitable for the EU to achieve the 2030 climate and energy targets and implementing the 2050 long-term strategy for a climate-neutral Europe.

With ten partners (including a think tank, research and technology organisations, a European industrial association, and a European technology platform), the project consortium relies on the best mix of skills and expertise and allows for full coverage of the EU Member States and steelmaking installations. The key outcomes of GREENSTEEL include:

- An analysis of the technologies aiming at decarbonising the steel industry and a proposal for framework conditions to reach this goal;
- A proposal for blending and sequencing of public and private funding sources for the decarbonisation of the EU steel industry;
- Policy recommendations to foster the decarbonisation of the EU steel industry; and
- The active engagement of relevant EU stakeholders and dissemination of the project findings to the public.

"The GREENSTEEL project has significantly contributed to identifying the challenges and proposing solutions towards reducing greenhouse gas emissions in the steel industry."

Jonas Fernandez*, Member of European Parliament, Socialists and Democrats*

2. Summary of the final conference of GREENSTEEL

The conference "Climate-neutral steelmaking in Europe: Technology, financing and policy conditions" highlighted the project's assessment of promising technologies, investment needs and funding opportunities, discussed policy options and their impacts, and outlined the way towards climate-neutral steelmaking in Europe.

The conference was held on 9 and 10 November 2021. A total of 227 participants joined the conference, representing European institutions, national and regional public authorities, steel and other industries, non-industrial enterprises, research institutes, academia and civil society.

This report summarises the discussions at the conference (Section 2). It also provides links to relevant studies carried by the GREENSTEEL consortium (Annex 1) and presents the biographies of the speakers (Annex 2). In addition, the executive summaries of the key reports of GREENSTEEL are presented in Annex 3.

A complete set of detailed information, i.e. all project reports can be found on the project's web page.

CONFERENCE AGENDA

Day 1: Technology, investment and financing for decarbonising steelmaking

Conference Chair: Cristian Stroia, Researcher, Centre for European Policy Studies CEPS

14:00	***Welcome*** Michael C. Laubenheimer, Project Adviser, REA.B1 – Future Low Emission Industries, European Research Executive Agency (REA)
14:05	***Keynote speech*** Jonas Fernandez: Fernandez, Member of European Parliament, S&D
14:20	**Session 1 - The Right Technology Pathways** Presentation of GREENSTEEL analysis: • Thorsten Hauck, Head of Department, BFI • Monika Draxler, Project Manager, K1-MET Metallurgical Competence Centre Reactions: • Klaus Peters, Secretary-General, ESTEP European Steel Technology Platform • Lena Sundqvist-Öqvist, Associate Professor, Luleå University of Technology, Sweden Discussion and Q&A moderated by Jean Borlee, Unit Manager Energy and Low-Impact Industry, CRM Group
15:30	***Video Message*** Maria da Graça Carvalho, Member of European Parliament, EPP
15:35	***Session 2 – Investment Framework and Financing Options*** Presentation of GREENSTEEL analysis: • Michele de Santis, Senior Researcher, Rina Consulting – CSM SpA • Simona Pace, Industry Relations, Rina Consulting – CSM SpA Reactions: • Stéphane Tondo, Climate Change & Government Affairs, ArcelorMittal Europe • Erik van Doezum, Director - Metals, Mining & Fertilisers EMEA, ING Discussion and Q&A moderated by Paula Queipo, Director of Business Operations, IDONIAL Centro Technologico
16:50	***Concluding Remarks*** Sebastiano Fumero, Head of Unit, REA.B1 – Future Low Emission Industries, European Research Executive Agency (REA)

Day 2: Policy options & the way forward towards climate-neutral steelmaking in Europe

Conference Chair: Hien Vu, Researcher, CEPS & GREENSTEEL Project Coordinator

10:00	***Welcome*** Jane Amilhat, Head of Unit, RTD.C3 – Low Emissions Future Industries, DG Research and Innovation, European Commission
10:05	***Introductive remarks*** Peter Dröll, Director, Directorate E - Prosperity, DG Research and Innovation, European Commission
10:20	***Highlights of Day 1 – Technology Pathways, Investment & Financing*** Hien Vu, Researcher, CEPS & GREENSTEEL Project Coordinator
10:30	***Session 3 – Policy Conditions for Clean Steelmaking in Europe*** Policy options emerging from the GREENSTEEL project: • Milan Elkerbout, Research Fellow, CEPS Panel discussion: • Maria Spyraki, Member of European Parliament, EPP • Gabriele Morgante, Policy Officer DG GROW, European Commission • Axel Eggert, Director General, EUROFER • Niklas Johansson, Senior Vice President, LKAB • Suzana Carp, EU Climate Policy Specialist Discussion and Q&A moderated by Christian Egenhofer, Associate Senior Research Fellow, CEPS, Brussels & Senior Research Associate, School of Transnational Governance, European University Institute, Florence
11:45	***Session 4 - The Way Forward Towards Climate-Neutral Steelmaking in Europe*** Panel discussion: • Alejandro German Gonzalez, Project Adviser, REA.B1 – Future Low Emission Industries, European Research Executive Agency • Jonas Fernandez: Fernandez, Member of European Parliament, S&D • Johanna Lehne, Senior Policy Advisor, E3G • Thorsten Hauck, Head of Department, BFI • Pietro Gimondo, Manager, Research Affairs, Rina Consulting – CSM SpA • Milan Elkerbout, Research Fellow, CEPS Discussion and Q&A moderated by Andrea Renda, Senior Research Fellow, CEPS
13:00	***Concluding Remarks*** Rosalinde van der Vlies, Director, Directorate C - Clean Planet, DG Research and Innovation, European Commission

2.1. Decarbonisation pathways

2.1.1. Decarbonisation technologies

The decarbonisation of the EU steel industry will take place gradually, beginning within the next years and extending probably until 2040 or longer. Such a long transition will require an adequate mix of technologies, and these integrated technology routes will also have to be optimised for the cycles of material and the gas.

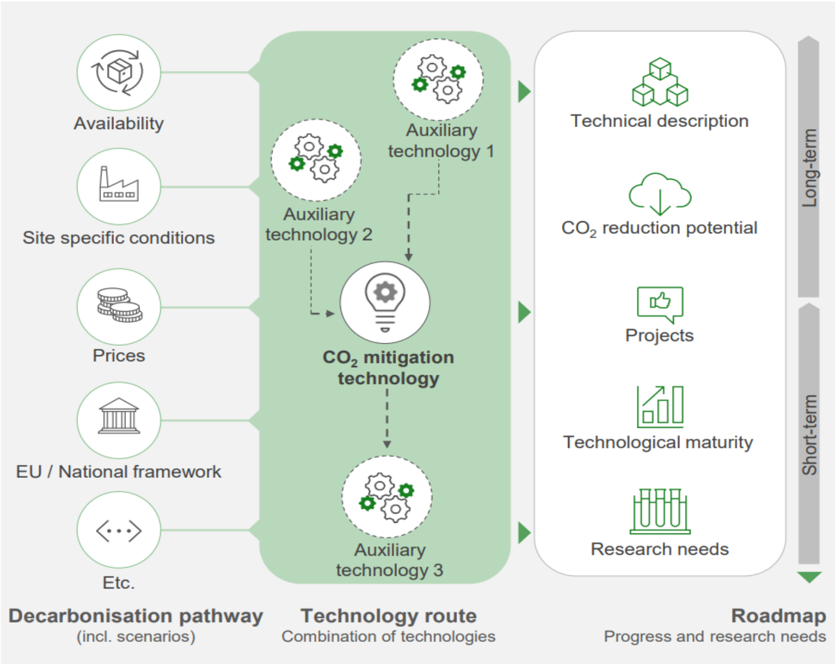


Figure 1: From decarbonisation technologies to decarbonisation pathways

Note: The nine CO_2 mitigation technologies in this figure include: (i) hydrogen-based direct reduction, (ii) hydrogen plasma smelting reduction, (iii) alkaline iron electrolysis, (iv) molten oxide electrolysis, (v) carbon oxide conversion, (vi) iron bath reactor smelting reduction, (vii) gas injection into the blast furnace, (viii) substitution of fossil energy carriers by biomass, and (ix) high-quality steelmaking with increased scrap usage. Auxiliary technologies include CO_2 capture and hydrogen generation. For further analysis of the mitigation technologies, refer to the Technology Assessment and Roadmapping Report (Deliverable D1.2) of GREENSTEEL mentioned in Annex 1 and Annex 3 of this report.

Figure 1 illustrates the process to define the decarbonisation technologies, technology routes, technology roadmaps and decarbonisation pathways under the GREENSTEEL project.

First, promising **decarbonisation technologies** were identified through desk research, stakeholder consultation and findings of the LowCarbonFuture project.

Second, these technologies were integrated into a full system (process chain), forming the so-called **technology routes**.

Third, these technology routes were assessed based on their potential progress and research needs along a timeline, leading to the development of the **technology roadmaps**.

Finally, three decarbonisation **pathway scenarios** for 2030 and three for 2050 were developed.

In developing the scenarios, several relevant factors were taken into account, including the availability of resources and infrastructure, technology maturities, specific site conditions, production costs, and the regulatory framework. The decarbonisation pathway scenarios define possible shares of different technology routes in industrial production and the potential CO_2 mitigation which can be reached in each scenario.

Following the process described in the previous paragraph, in the first step, the following **decarbonisation technologies** were identified:

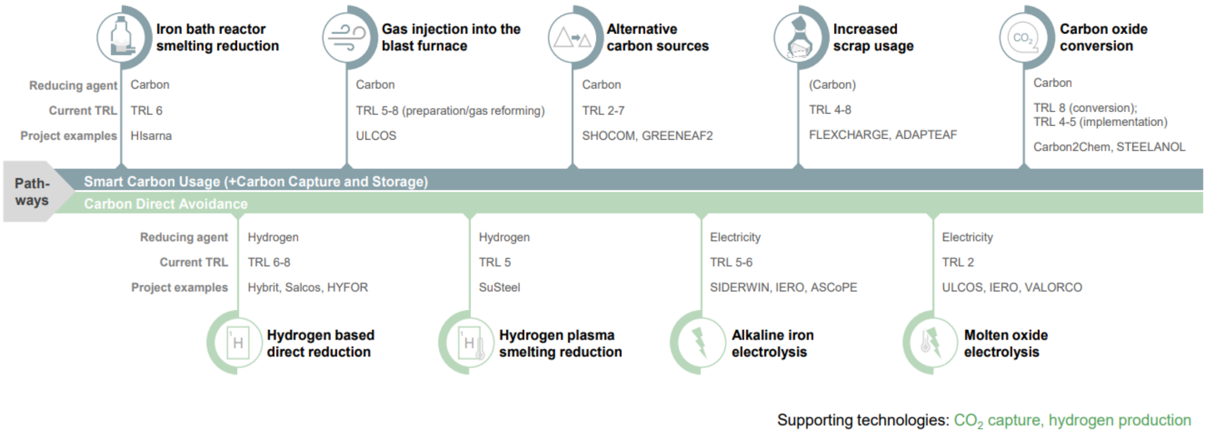


Figure 2: Decarbonisation technologies

Next, four promising **technology routes** for climate-neutral steelmaking were identified: optimised Blast Furnace - Basic Oxygen Furnace (BF-BOF) (Route 1), direct reduction (Route 2), smelting reduction (Route 3) and iron ore electrolysis (Route 4) (Figure 3 to Figure 6[1]).

The first technology route (Figure 3) is based on conventional BF-BOF plants (blast furnace, basic oxygen furnace), into which a number of add-on CO_2 mitigation technologies (process integration, carbon capture and usage) are incorporated. This route can be considered a short-term solution.

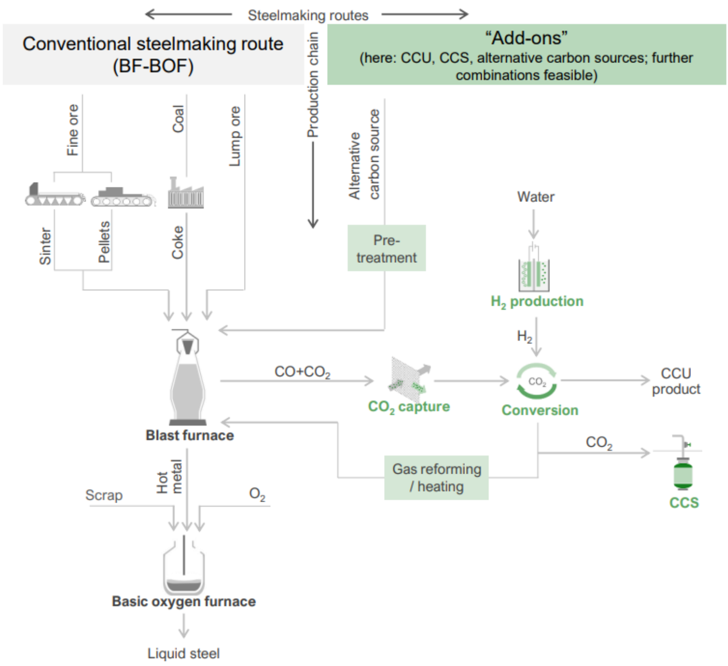


Figure 3: Route 1 - Optimised BF-BOF

[1] Note that in Figures 3 to 6, the green components of the flow diagram capture the changes or additions to the existing process, whereas the grey-coloured components depict unchanged procedures.

The second technology route (Figure 54) uses direct reduction based on natural gas or hydrogen, in which all ironmaking and steelmaking units are replaced by new production methods.

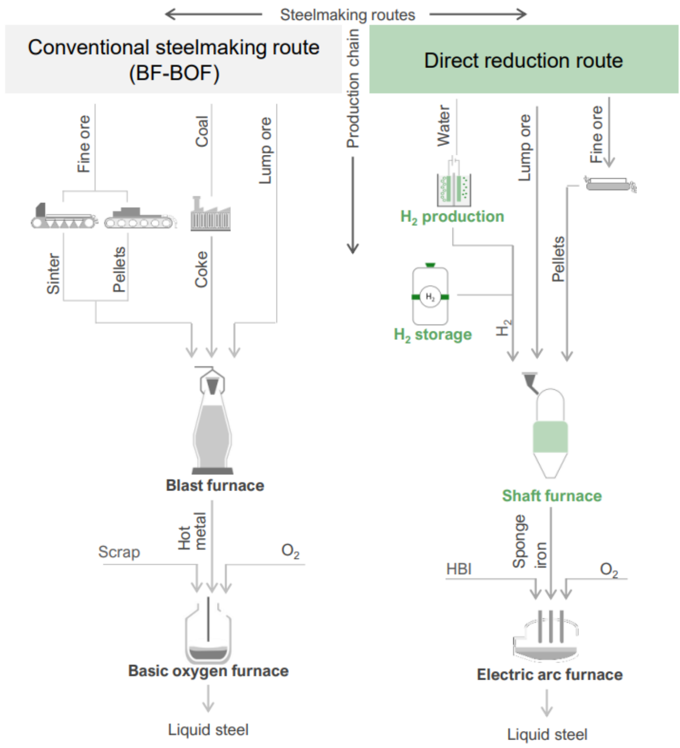


Figure 54: Route 2 - Direct reduction

The third technology route (Figure 5) comprises technologies based on smelting reduction. This includes, on the one hand, the iron bath reactor smelting reduction option, in which the ironmaking part is replaced and, on the other hand, hydrogen plasma smelting reduction, which enables the direct transformation of iron ore into liquid steel.

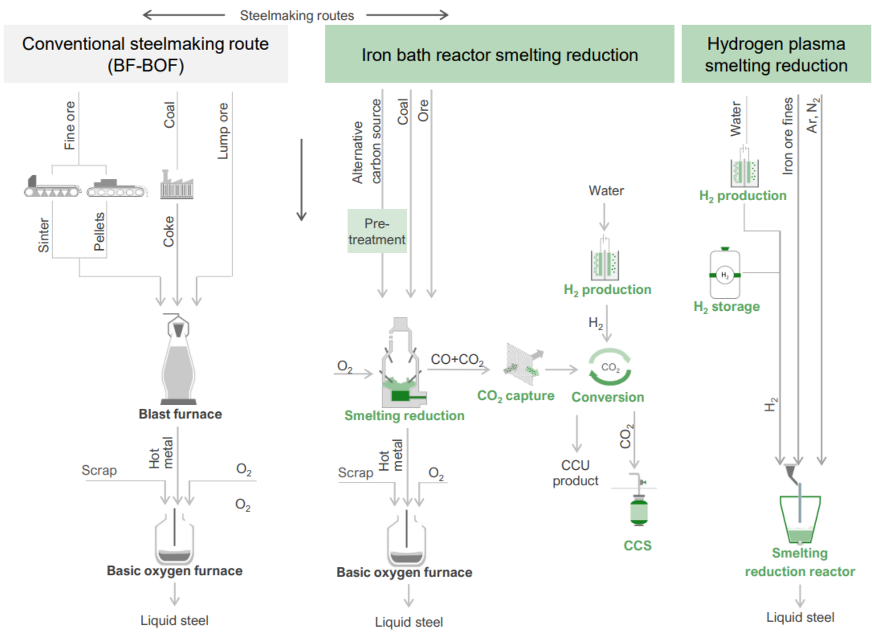


Figure 5: Route 3 - smelting reduction routes

The fourth technology route (Figure 6) refers to the electricity-based steelmaking by iron ore electrolysis. It can either be carried out at low temperatures (alkaline iron electrolysis, replacement of the iron making part) or at high temperatures (molten oxide electrolysis, direct production of liquid state metal from oxide feedstock).

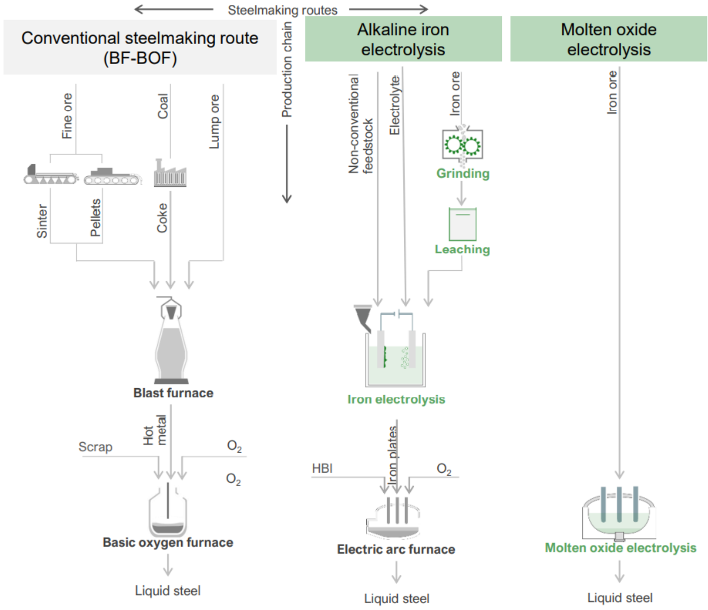


Figure 6: Route 4 - iron ore electrolysis

Starting from the identification of individual iron and steelmaking technologies, a **roadmap** for the proposed breakthrough technologies was created (Figure 7). This roadmap indicates the progress and the research needs for each technology involved along the timeline.

The needs for integrating the technologies into a complete breakthrough process chain are also visualised. Each line describes one technology. Starting in 2020 (current technology readiness level), the technology readiness level development is shown from left (short-term) to right (long-term) both graphically (grey shaded area) and numerically.

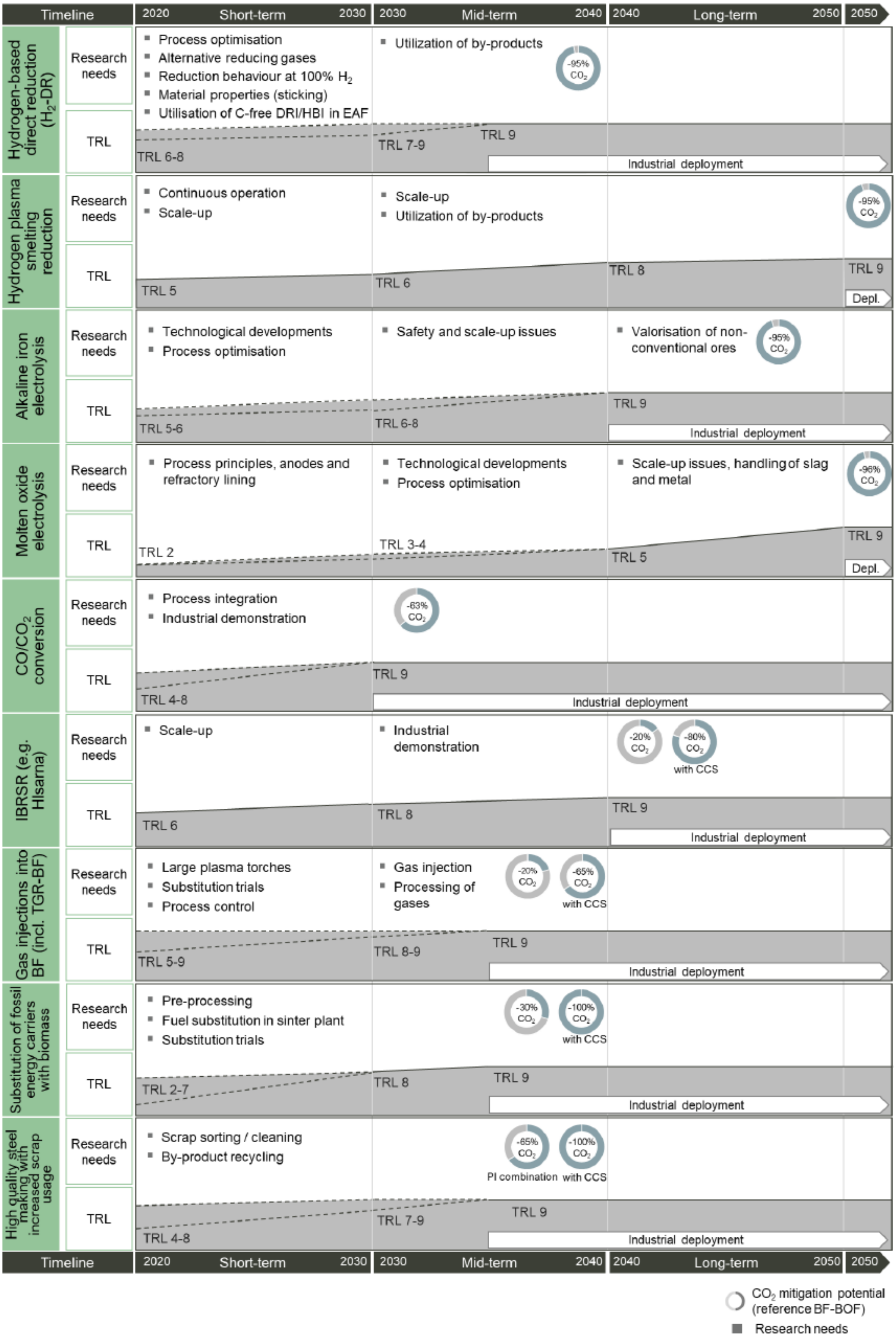


Figure 7: Roadmap of CO2 mitigation technologies

Finally, the **decarbonisation pathways** define possible industrial production shares of different technology routes in **six scenarios** (three for 2030 and three for 2050), and their CO_2 mitigation potentials.

In Figure 8 to Figure 13, the pie charts present the share of each technology route in the total steel production, the bars in the top right corner show the share of hydrogen (H_2) and natural gases (NG) in the energy use, the bars in the bottom right corner show the share of alternative carbon sources (ACS) and CCUS, and the bars in the middle present the CO_2 mitigation potential of each pathway.

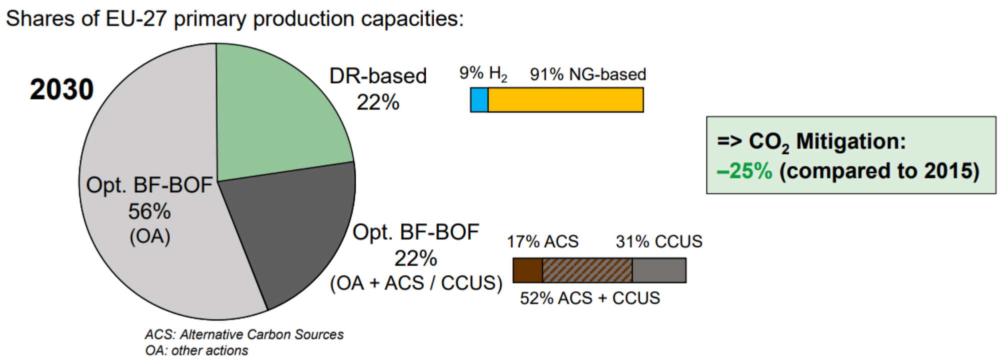


Figure 8: Pathway 2030 scenario – "Mixed implementation"

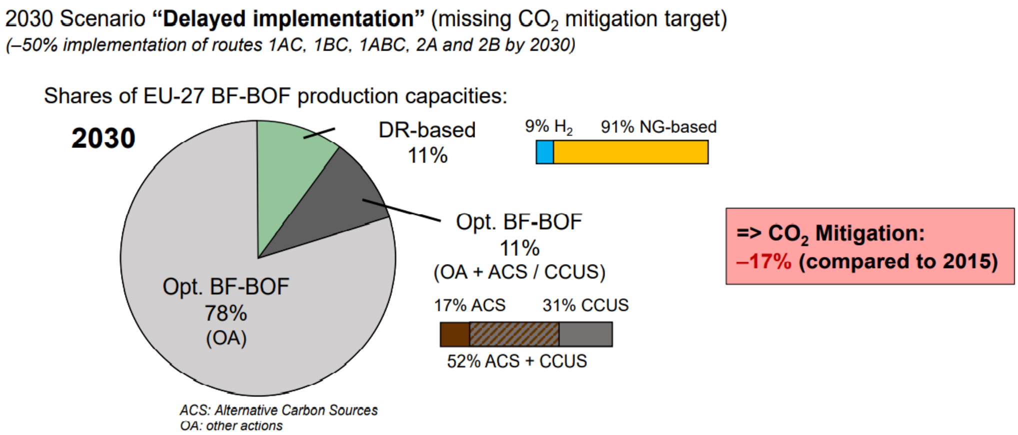


Figure 9: Pathway 2030 scenario – "Delayed implementation"

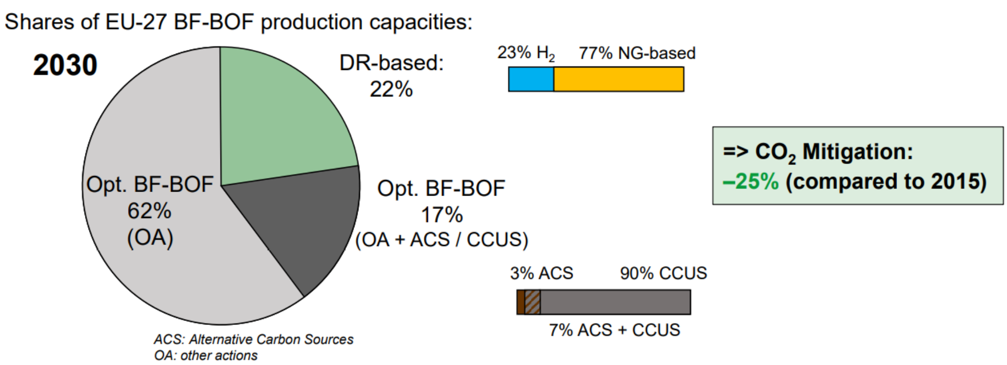


Figure 10: Pathway 2030 scenario – "Increased hydrogen availability"

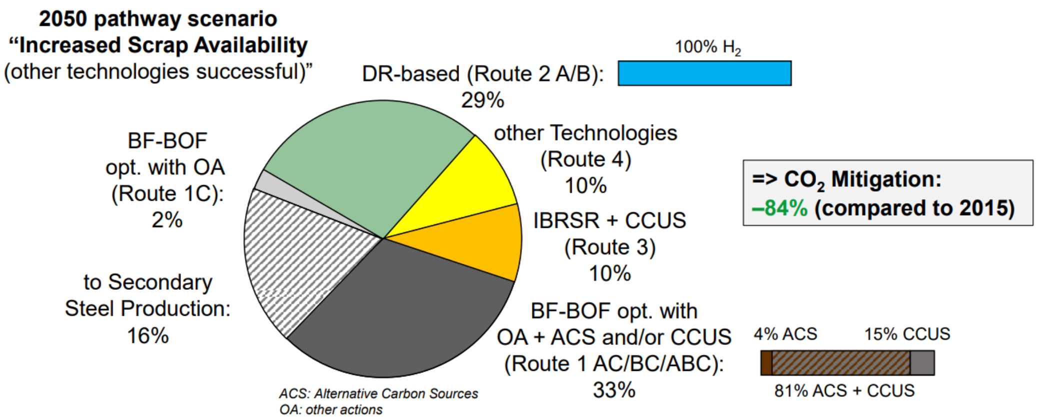


Figure 11: Pathway 2050 scenario – “Increased scrap availability”

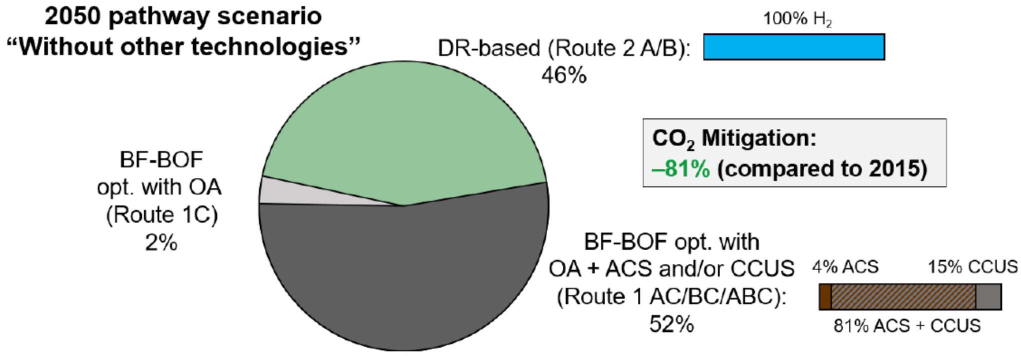


Figure 12: Pathway 2050 scenario - "Without other technologies"

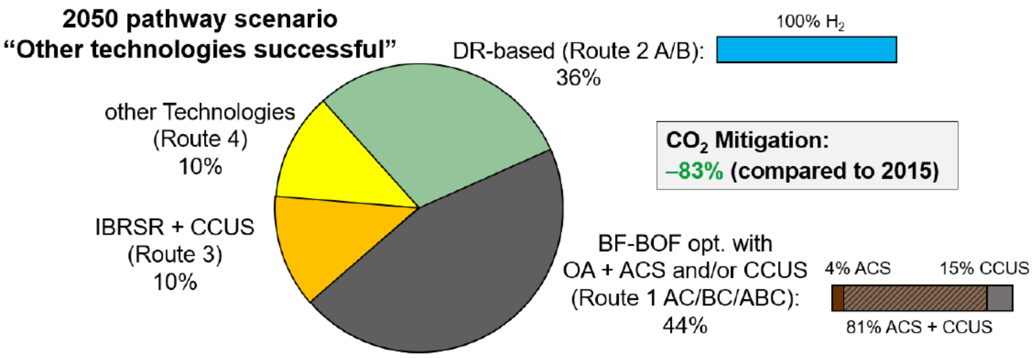


Figure 13: Pathway 2050 scenario - "Other technologies successful"

2.1.2. Integration of decarbonisation into existing steel plants

Besides the identification of decarbonisation technologies and decarbonisation pathways, another important technology-related aspect is the integration of new technologies into existing plant systems.

Due to the long investment cycles, almost all integrated plants will consist of mixed (transient) technology routes within the next 10 years. A smooth and efficient transition must take into account the massive existing assets of the steel industry.

A crucial next step is to ensure energy, material and cost efficiency for these “mixed” integrated plants.

Sweden: Examples of hydrogen-based projects

Sweden has two examples of using hydrogen for direct reduction, the HYBRIT and the H2 Green Steel.

In these projects, renewable energy, high-quality iron ore and scrap play a central role. In addition, bio-gases or liquid fuels produced from e.g. black liqueur, lignin residue, food residue, agriculture products, forest residue, etc. can be reducing agents that are CO2 neutral and hence another potential source for decarbonising the steelmaking process.

Sweden has carried out theoretical research, pilot and industrial tests on this topic, and has proven that using bio-coal of various types can lower the fossil CO2 emissions, thus making the best use of existing infrastructure.

In addition, the combination of three methods (bio-coke, bio-agglomerates and injection of bio-coal) can achieve the emission reduction potential of 20-40 %.

2.2. The investment needs and funding opportunities

2.2.1. The investment needs

The decarbonisation of the steel industry will require massive investments.

The decarbonisation technologies would create additional production costs of at least EUR 20 billion per year compared to the retrofitting of existing plants (i.e. existing plants that are upgraded with Best Available Techniques), 80% of these additional production costs would be accounted for by OPEX (e.g. increased use and higher prices for CO_2-lean energy).

Depending on the decarbonisation technologies, the primary steel cost/tonne would likely increase by 35% to 100% compared to the baseline. The investments for adequate maturity would range from around EUR 5 million (biomass) to EUR 1,000 million (Molten oxide electrolysis - MOE).

Table 1: Investment roadmapping per decarbonisation technology

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

*Note: Data refer to a crude steel capacity of 1 Mt/a as a reference. * €500 M including EAF. ** Excluding CO2 transport and storage. *** From greenfield (brownfield CAPEX costs 40% with respect to BF-BOF). For full spelling of the technologies in the first column, refer to the List of Abbreviation*

"The Clean Steel Partnership marks a big step in the EU's support to move carbon-neutral steel technologies from research to demonstration phase".

Peter Dröll*, Director for Prosperity, DG Research and Innovation, European Commission*

2.2.2. Funding opportunities

The funding opportunities have multiplied significantly in the last three years in a direction that supports more the green transition in the EU steel sector. Different EU, national, regional public funding and private funding programmes can be mobilised to support the decarbonisation of the steel industry.

At the EU level, the most remarkable programmes and initiatives are the Clean Steel Partnership, the Just Transition mechanism (first and second pillars), and the Carbon Border Adjustment Mechanism (CBAM).

Other important funding instruments for the steel industry include the Innovation Fund (IF), IPCEI, InvestEU, and the NextGenerationEU including the Recovery Plan.

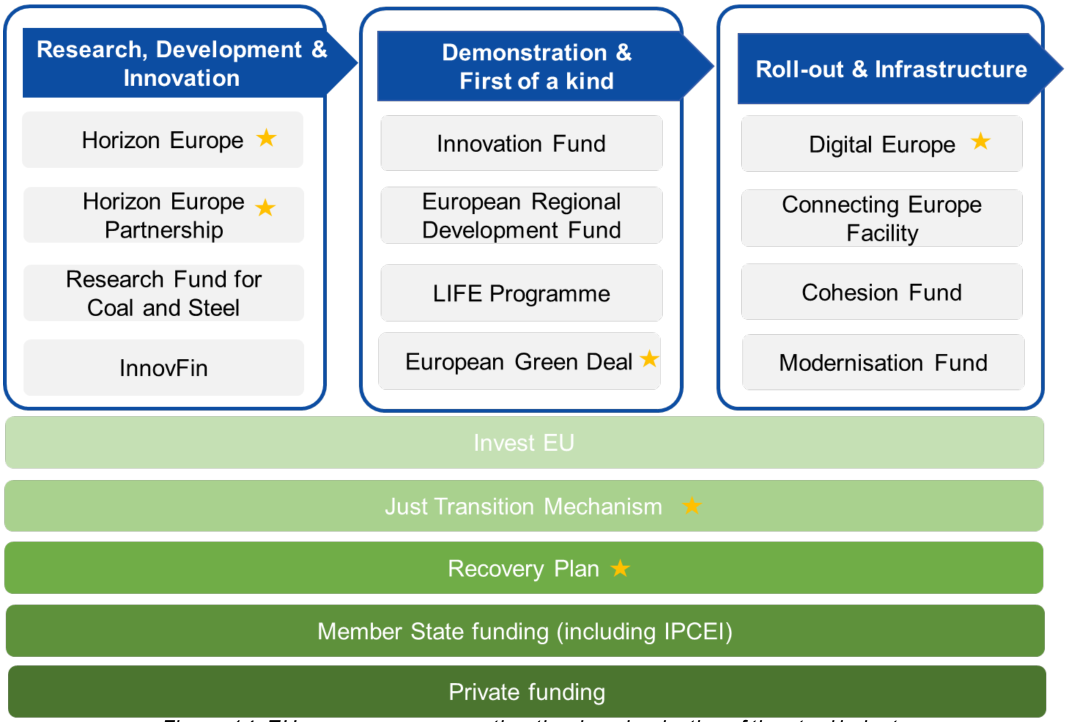


Figure 14: EU programmes supporting the decarbonisation of the steel industry

Note: ★ = new initiatives since 2019.

Meanwhile, the analysis of EU funding programs available as grants (combining HE, CSP, RFCS and IF) shows that only about EUR 2 billion of financial support would be effectively available for CO_2 emission reduction in the steel sector for the period 2021-30.

During 2021-22, national and regional funding instruments would contribute approximately EUR 400 million per year[2] to support decarbonisation projects in the steel sector.

Therefore, while new funding opportunities have been created, there is still a significant gap between the available funding and the investment needs to support the decarbonisation of the steel industry.

2.3. Policy conditions for clean steelmaking in Europe

Both the speakers and stakeholders who participated in the consultations under GREENSTEEL agreed that the framework conditions create a bigger barrier to decarbonising the EU steel industry than the technical challenges to developing the technologies.

To date, there is a lack of enabling frameworks to provide adequate funding, send signals to investors and create a market for low-carbon steel.

2.3.1. Availability of renewable electricity

The decarbonisation of the steel industry, regardless of the technologies routes, will require enormous volumes of clean electricity at an affordable price. There has been a boom in investment in renewable energy in recent years, and some investment conditions have started materialising, such as the creation of the taxonomy and the availability of funds for the green transition.

Nevertheless, several challenges remain unaddressed. The burdensome permitting procedures and the lack of a framework supporting electricity storage (due to the variability of renewable sources) hinder the expansion of renewable capacities in the EU.

Besides, local conditions can influence the price of electricity, impacting steel producers' choice of decarbonisation technologies. By way of example, the north of Sweden has a relatively high capacity for electricity generation, but it is challenging to transfer electricity from the north to the south of the country, resulting in a big difference in the electricity prices between the two regions.

"The provision of renewable energy is a big challenge to decarbonising the EU industry, and this will come with significant costs. Funding support, public-private partnerships and cross-sectoral cooperation can play a key role in overcoming this challenge."

Sebastiano Fumero, *Head of Unit, REA.B1 – Future Low Emission Industries, European Research Executive Agency (REA)*

The increased use of renewable electricity in steelmaking will entail a significant increase in operational costs compared to the conventional steelmaking process using fossil fuels. Meanwhile, the current design of the electricity market (e.g. the marginal system) does not optimise the investment in renewable energy.

[2] This estimate is based on the analysis of national and regional funding instruments in 11 EU member states, which account for at least 90% of the EU steel production and 80% of the CO_2 emissions from all EU steel plants.

The recent challenges related to high energy prices explain why legislators in some countries are arguing in favour of doing more with average pricing. At the same time, we also need to consider the investment signals in the renewable energy sector with the need to provide flexibility services by utilities, and a lot of them are based at very high marginal prices.

It is also necessary to look at the distributional impacts but acknowledge that marginal pricing can also be an important price signal to actually deliver investments in the electricity system with a high share of renewables.

2.3.2. Carbon capture, utilisation and storage

The decarbonisation scenarios are a mix of many solutions. While technologies like direct reduction would allow for deep decarbonisation, solutions like carbon capture, utilisation and storage (CCUS) need to be considered given that many old blast furnaces are still operating in the EU.

The current regulatory frameworks and national legislation constrain the expansion of CCUS technologies. The EU is lacking a concrete and flexible regulatory framework for carbon capture and storage (CCS) and carbon capture and utilisation (CCU), particularly CCS and CCU in industrial hubs and clusters.

The challenges are associated with different parts of the value chain: the CO_2 capture rates have to be high enough to avoid residual emissions, and there must be infrastructure for transportation and storage. In several pilot CCU projects in Germany and Sweden, the costs of products from the captured carbon are still very high to make the projects economically viable. Besides, not enough effort has been made to increase public awareness and knowledge about the safety of CCS and CCU technologies[3].

Finally, the United Kingdom's recent legislative decision not to give public funding for early CCU projects (due to delaying risks, a lack of evidence on costs and market potential, and the complexity arising from applying the business model to CCU) might call for some further consideration of the EU on this issue.

2.3.3. Carbon Border Adjustment Mechanism

The speakers agreed that Carbon Border Adjustment Mechanism (CBAM) is an important instrument to support the decarbonisation of the industry. It creates demand for low-carbon steel in Europe, provides a long-term price signal and establishes a level playing field when the EU advances substantially towards its green targets. In addition, the CBAM can generate a revenue stream to repay the Next Generation EU debt.

> ***"One big challenge to the decarbonisation of the steel industry is the steel global excess capacity. China, for instance, has started to increase its domestic and offshore capacity after leaving the Global Forum on Steel Excess Capacity."***
>
> ***Gabriele Morgante,*** *Policy Officer, DG GROW, European Commission*

3 Norway shows a good practice in raising the public acceptance of CCUS solution.

"The EU must advance its decarbonisation process while maintaining the competitiveness of its industry and mitigating the impacts on prices and income distribution."

Jonas Fernandez, *Member of European Parliament, Socialists and Democrats*

However, speakers' views were more divergent when it comes to the testing and implementation of the CBAM.

Regarding the **free allocation of emission allowances**, the steel industry proposed that the current system should be maintained while testing CBAM in 2026-2030. Otherwise, companies that export to the EU can either shift their export or absorb the CBAM costs to keep the market share.

It is important to note that those companies usually export between 1-5% of their entire production to the EU, which is a relatively small share. Meanwhile, the EU market holds a larger share in the total production of EU steel companies, making it more challenging for them to absorb the carbon price.

The carbon price has significantly increased in the past three years and the free allocation plays an important role in avoiding a substantial increase in the steel production costs. It is possible to test the CBAM while maintaining free allocation and being WTO-compatible at the same time.

The Parliament and other speakers representing research institutes and non-steel industries however suggested phasing out the free allocation to the steel industry when the CBAM is implemented, in compliance with WTO regulation.

In recent years, the steel sector has received around 100 million of the Emission Trading System (ETS) allowances per year to mitigate the carbon leakage risk. With the current carbon price, around EUR 6 billion of assets are being transferred from the public funds to the steel industry every year.

The rationale of free allocation is to support emission reductions. Some research however finds that the current way in which free allocation works prevents some of the emission reductions that could have already happened. The European Commission must rethink the free allocation and its interaction with tools such as Carbon Contracts for Difference (CCfDs) and CBAM (e.g. CCfDs interact and operate differently when there is a CBAM in place than where there is free allocation in place).

The steel sector also recommended maintaining the current **benchmark** system to support the free allocation. This proposal was challenged by research institutes, who argued that the benchmark system is not working in favour of decarbonisation at the speed required.

The EU ETS proposal gives free allocation to green hydrogen, which proves to be a departure from the traditional free allocation mechanism. In offering this financial support to green hydrogen, the Commission is opening up a pathway different from the traditional benchmark approach.

2.3.4. Green procurement

Public procurement represents around 14% of the GDP of the EU. The size of public procurement is therefore important for competitiveness. Hence, there is an incentive to make public procurement 'green', i.e. applying environmental criteria to energy-intensive materials.

Despite enormous challenges such as information asymmetries, knowledge gaps or complex administrative procedures, public procurement is nevertheless a promising area to create demand for low-carbon steel.

Both the Commission and the Parliament support initiatives, which contribute to the promotion of green public procurement. The European Commission has been working on the Sustainable Product Initiative and the revision of the Energy Performance of Buildings Directive.

The Commission might adopt a life-cycle approach from the raw materials to final products and recycling (building upon the experience of the Product Environmental Footprint pilot project).

> ***“The Parliament sees its role in pushing for green public procurement to create a market for green products.”***
>
> ***Maria Spyraki,*** *Member of European Parliament, EPP*

Besides public procurement, research institutes suggested that private procurement could be an important component to create a market for green steel. For instance, companies that have substantial profit margins and want to decarbonise their supply chain can procure low-carbon steel.

2.3.5. Availability of high-quality steel scrap

Up to 2050, almost 50% of the emissions reduction would come from material efficiency and circularity at a global level. In the steel industry, increased scrap availability for scale recycling will be a critical factor, as secondary steel production requires a higher volume of high-quality scrap. However, the availability of steel scrap of appropriate quality is still strongly limited in the EU.

Currently, there is a lack of an enabling policy framework for the circular economy, particularly in heavy industries. Public support for R&D to increase the quality of scrap recycling and limit the exports of scrap to non-EU countries are therefore desirable.

2.3.6. Survey

A *Mentimeter* poll was launched during the conference, asking the audience “which elements play the most crucial role in the decarbonisation of the EU steel industry?”.

The audience could rank the following elements in terms of their importance in reducing the emissions in the steel industry: innovation, market creation, corporate responsibility, funding, sector coupling, carbon pricing, CBAM, renewable energy, green hydrogen, scrap, and CCUS. Answers from the stakeholders showed that renewable electricity would play the most crucial role in cutting emissions in steel production.

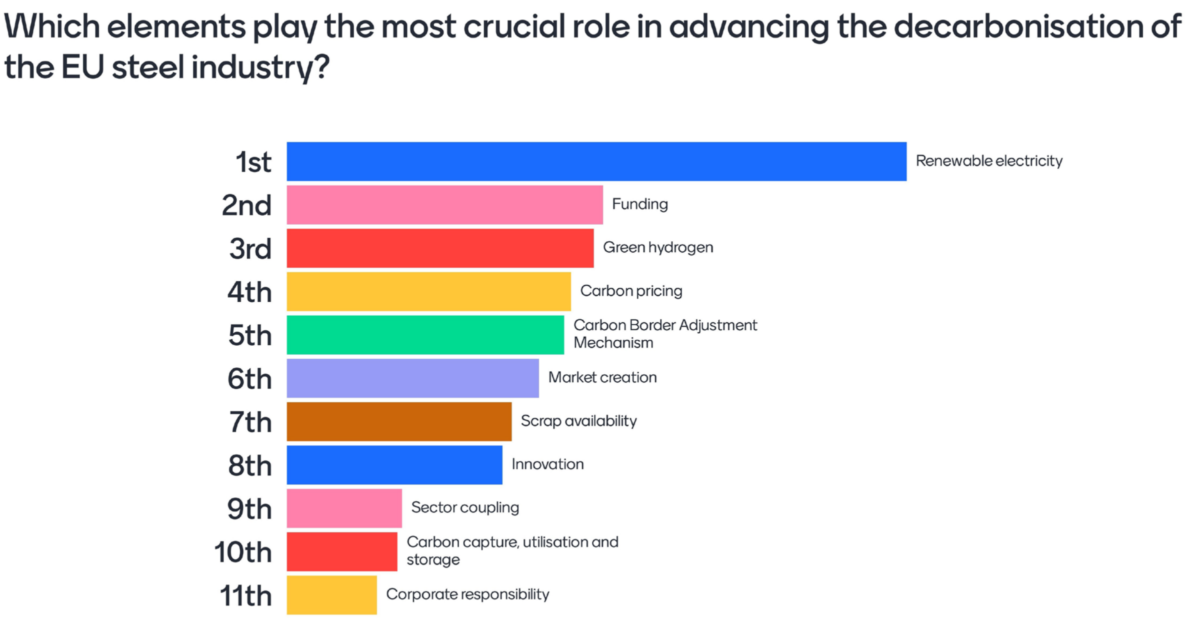


Figure 15: Poll results

2.4. The way forward

Policy intervention and collaboration at different levels are crucial to create enabling framework conditions for the decarbonisation of the steel industry. This section summarises the key recommendations by the speakers to support the green transition in the industry.

2.4.1. Synergies of funding

"At all levels, we must ensure that public and private funding can have combining impacts, and that the European Commission provides support to make full use of the different synergies."

Maria da Graça Carvalho, *Member of European Parliament, EPP*

Synergies of funding instruments at EU, national and regional levels play a vital role in meeting the investment needs to decarbonise the steel industry.

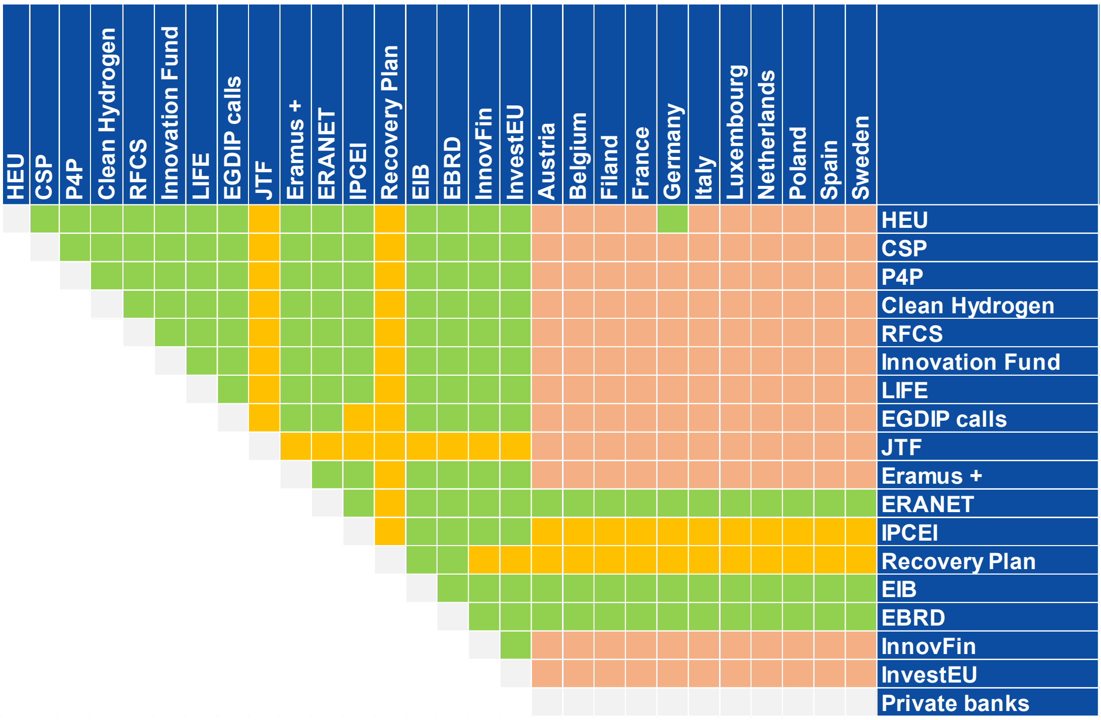
Each funding mechanism has its own framework in terms of TRL maturity or technology type; hence the synergies of funding instruments can help navigate the technologies from low to higher TRLs.

There are several examples of technologies that are very close to maturity (TRL8). The sequencing of funding is important to move these technologies from TRL8 to TRL9, and to further support the deployment and exploitation of these technologies.

The blending of funding is also important to avoid overlaps in investments. Furthermore, public funding must be combined with private funding to support sizable projects. Finally, an initiative in the form of Important Projects of Common European Interest (IPCEI) for low-carbon industries is desirable, following the good example of the established IPCEI for hydrogen.

Table 2 below presents potential blending of the main European funding programmes and selected national and regional funding instruments.

Table 2: Potential blending opportunities of R&D&I funding instruments



*Note: **green**: synergies are possible between the instruments; **yellow:** to be specifically defined; **red**: synergies are generally not allowed; and **grey**: information is currently not sufficient*

2.4.2. Upskilling and re-skilling of the labour force

Operating steel plants using innovative decarbonisation technologies requires new skills to manage much more complex processes and connections. The upskilling and re-skilling of the labour force in the steel sector, therefore, plays a crucial role. The EU should support learning and new training programmes to overcome the shortage of qualified staff in this sector.

2.4.3. R&D support beyond TRL9

Most decarbonisation technologies have obtained TRLs of 5-7 and need support to reach the demonstration scale (i.e. TRL 9). However, considering the huge steel plant sizes, obtaining TRL9 does not allow new technologies to achieve the same level of maturity as conventional steelmaking technologies, which have been established for decades.

R&D support beyond TRL9 is therefore vital to ensure that decarbonisation technologies reach the deployment phase and are commercially used.

2.4.4. Cooperation at different levels

"Collaboration is key to making progress towards decarbonising the steel industry and building a zero-carbon society."

Rosalinde van der Vlies, *Director for Clean Planet, DG Research and Innovation, European Commission*

- ***Public-private collaboration***

Decarbonisation technologies need to be taken up by the market. It is therefore crucial that the EU develop these technologies together with the industry and put in place the right framework to bring these technologies to the market.

Public-private partnerships play a central role in steering research and innovation and bringing innovative solutions to the market: the partnerships co-funded via Horizon Europe (HE) might have a very important role as they have the merit of implementing common strategic agendas. They can leverage public funds to make sure that key private players increase their investment in technology and research, helping the EU reach its policy goals and maintain competitiveness and jobs.

For example, the Clean Steel Partnership can validate promising technologies able to reduce emissions by 50 to 80 per cent by 2035. However, it is not the single initiative that will become decisive.

The EU should consider the combined effect of putting together activities resulting from other partnerships and other projects, e.g. the Clean Hydrogen Joint Undertaking, the EIT RawMaterials, the Horizon Europe collaborative projects, and projects under the European Innovation Council.

- ***Collaboration among industries***

The decarbonisation of the steel sector strongly depends on several other sectors, e.g. the energy sector. In an intervention at the COP26, the former Swedish environment minister, Mr Per Bolund, emphasised the three 'F's that support industrial decarbonisation, which are: 'framework, financing, and friends'.

The steel industry can start by making 'friends', i.e. collaborating with the renewable industry because the resource constraints will persist both in the short and medium-term.

In addition, the EU must support the development of an industrial technology roadmap at the EU level, which brings member states and industrial players together to i) reap technology spill-over across industrial sectors and ii) inform potential investors (e.g. commercial banks) and help them align their lending portfolios towards supporting the net-zero targets.

Industries must cooperate through industrial symbiosis and take full advantage of EU-level hubs such as the Innovation Hubs or the Hubs for Circularity.

- ***Engagement of the society***

It is crucial for policymakers, steel companies, energy suppliers and the research community to work together. But more importantly, the users and the civil society must be engaged to get the transformation of the steel sector done, e.g. through improving consumer awareness and increasing the demand for products made of low-carbon materials.

- ***International cooperation***

The steel sector is highly exposed to international trade and competition, making it challenging for EU steel companies to be the first movers in deploying decarbonisation solutions while still maintaining their competitiveness. Trade policy plays a key role in this respect.

There has been recently some progress in the international cooperation to decarbonise the steel sector, e.g. the EU-US carbon-based sectoral agreement on steel and aluminium trade, or the UK-India-led initiative on industrial deep decarbonisation. However, these initiatives tend to be driven mostly by European and North American companies and countries. It is critical to include other key players (e.g. China) in these initiatives. Besides, these ambitions need to be accompanied by concrete targets e.g. around phasing out blast furnaces or funding support.

The EU can take leadership in this process as there are a large number of steel producers headquartered in Europe, and there have been many innovations in this area in the EU so far.

2.4.5. Cross-cutting areas

Besides policies that are specific to the steel sector, the EU must consider cross-cutting policies that support the decarbonisation of different industries. These options include public and private procurement, Carbon Contracts for Differences, and mitigation of carbon leakage risk.

2.4.6. Reconsideration of the timeline

Research institutes recommended a reconsideration of the timeline to achieve the EU's emission reduction targets. The EU should use 2025 as the short-term window and 2035 as the long-term window instead of 2030 and 2040. 2025 is an important milestone used by other stakeholders around the world.

More importantly, almost 50% of the steel capacity in Europe will be reinvested in the next decade. Therefore, the EU has a short policy window to take advantage of this upcoming reinvestment cycle in the steel industry, rather than being locked in 20-25 years of carbon-intensive production.

The 2035 milestone allows the EU to have some time to adjust before getting the final outcomes in 2040 when the ETS cap would reach net zero (with the proposed linear reduction factor).

Across this timeline, ensuring the competitiveness of the industry will be a continuous process. Therefore, it is important to use those earlier milestones to track the decarbonisation progress.

2.4.7. Follow-up of GREENSTEEL

Stakeholders representing research institutes in the steel sector asked for the continuation of the research work carried out under GREENSTEEL.

Since the development of techniques, mitigation targets and framework conditions progress fast and GREENSTEEL mainly focused on upstream steel production, a follow-up of the project is needed to guide the way forward.

"We have come from far, and we will go very far if we are smart in cooperating.

A strong industrial base is good for cohesion, cohesion is good for democracy, democracy is good for peace.

Peace among us and peace with nature."

***Peter Dröll**, Director for Prosperity, DG Research and Innovation, European Commission*

Annexes

Annex 1 - Useful links

Rewatch the conference in YouTube

- Day 1: Technology, investment and financing for decarbonising steelmaking
- Day 2: Policy options & the way forward towards climate-neutral steelmaking in Europe

Links to the presentations at the conference:

- The Right Technology Pathways (Thorsten Hauck and Monika Draxler)
- Right Technology pathways – some reflections (Lena Sundqvist Öqvist)
- Investment framework and financing options (Michele De Santis and Simona Pace)
- ArcelorMittal Europe' journey to decarbonization: Investment Framework and Financing Options (Stéphane Tondo)
- Policy options coming from GREENSTEEL (Milan Elkerbout)

Links to key reports and studies carried out under the GREENSTEEL project:

- Technology assessment and roadmapping (Deliverable 1.2)
- Collection of possible decarbonisation barriers (Deliverable 1.5)
- Decarbonisation pathways 2030 and 2050 (Deliverable 1.7)
- Investment needs (Deliverable 2.2)
- Funding opportunities to decarbonise the EU steel industry (Deliverable 2.4)
- Guidelines and approaches for using funding in line with technological developments (Deliverable 2.5)
- Impact assessment (Deliverable 3.2)
- All the public reports of GREENSTEEL can be found here.

Annex 2 - Speakers' biographies

The order of the speakers' biographies reflects the order of their intervention in the Conference.

Michael Christian Laubenheimer, Project Adviser, European Research Executive Agency REA.

Michael is an electrical engineer, specialised in energy and economy. He joined the European Commission in September 2015. He was in charge of a series of research projects linked to mobility and smart grids. He was also in charge of a free-of-charge service for research projects in the field of energy aiming to support the exploitation of research results – the "Support Services for Exploitation of Research Results SSERR".

He joined REA in April 2021, where he manages a portfolio of projects from the Research Fund for Coal and Steel RFCS, in particular projects related to Post-Mining Issues, Safe and Productive Coal Mining Operations. Before, Michael worked at the Common Support Centre of the University of Duisburg-Essen (DE), supporting the researchers to develop and submit research projects and to manage EU-funded research projects.

From 2005-2013, he worked as a senior consultant, developed and managed European projects within the INTERREG, CIP and FP7 programmes, mainly related to sustainable transport. Before, he worked in Madeira (PT), Montpellier (FR) and Cologne (DE) for technology parks and research institutes where he coordinated research and demonstration projects in tourism, telework, distant training, telecommunications and urban development.

Jonás Fernández Álvarez (Oviedo, 1979) is a MEP in the Progressive Alliance of Socialists and Democrats.

He is member of the Committee on Economic and Monetary Affairs, where he acts as coordinator for the European socialist party. In addition, he is a substitute member of the Budgets Committee.

Jonás Fernández Álvarez holds an Executive MBA from IESE Business School (2010-12), a M.A. in Economics and Finance from CEMFI-Bank of Spain (2002-04) and an undergraduate degree in Economics from the University of Oviedo (1997-2001). He has completed his training with a program of Advanced Econometrics at the London School of Economics and Political Science (2006) and the Senior Executives in National and International Security at Harvard University (2016).

Professionally, Jonás joined as an analyst in economics and international politics in the consultancy firm Solchaga Recio & Asociados in 2005, chaired by former Spanish finance Minister Carlos Solchaga. Three years later he was promoted to the company´s board and later on, appointed as Chief Economist in 2014. Jonás has combined his work activity with teaching at the Universidad Carlos III (2007-10) and various entrepreneurial activities. In addition, he is a regular op-ed contributor to the main Spanish newspapers (El País, Cinco Días, La Nueva España, etc.).

Politically, Jonás Fernández was Secretary General of the Socialist Youth in Oviedo (1998-2000) and served on the executive board of the Socialist Youth in Asturias (2000-01). During the college years he was also a member of the Senate of the Universidad de Oviedo as a student representative. More recently, he has participated in the design of the electoral programs in the 2008 and 2011 legislative elections and was a policy advisor of PSOE (2004-05).

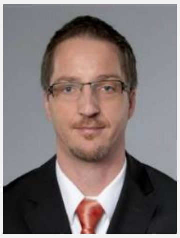
Moreover, he is an associate in various national and international foundations. Jonás is also a participant of the Political Leadership Program of the Aspen Institute, chaired by Javier Solana, former EU Higher Representative and the Workshop in Global Leadership 2016 at Harvard University.

Jean Borlée is Unit Manager Energy and Low-Impact Industry, CRM Group.

In 1990 he Graduated in Chemical Engineering from the University of Liège and started at CRM at the cokemaking department, then moved to other fields of activity such as sintering, blast furnaces, direct and smelting reduction, steelmaking, continuous casting and environment.

From 2000 to 2004, Jean coordinated the FP5 "Avoid Solid ByProducts and CO2" project dedicated to the smelting reduction of various steel plant wastes and the reduction of CO2 emissions. Between 2005-2007 he led the iron and steel production department at CRM, and between 2007-2012 he was seconded to ArcelorMittal to coordinate all the contributions of ArcelorMittal in the large FP6 ULCOS project. Jean was notably involved in all blast furnace, smelting reduction and electrolysis developments, including the erection and operation of pilot plants

His current positions include: i) at CRM Group, leads the ELIMIN ("Energy and Low Impact Industry") unit and coordinates the technological platform on "Energy Shift"; ii) chairman of the TGA2 Expert group "Iron and steelmaking" of the RFCS programme, and iii) member of the "Clean Steel Partnership" board.



Dr. Thorsten Hauck has 21 years of experience in process research and development of steel production processes in different positions at BFI. He was responsible for 22 international and several national research projects.

Since 2011 Dr. Hauck is head of the department "Process Optimisation Iron and Steel Making" at VDEh-Betriebsforschungsinstitut GmbH (BFI). The work of his department is focused on the development and optimisation of processes and process chains with respect to digitisation, productivity, quality, energy supply and environmental issues and cooperates with all main European production companies and research institutes on the subject of iron and steel making.

Monika Draxler is a Researcher and Project Manager at K1-MET in charge of national and international projects.

She is currently working in the field of CO2 mitigation technologies and decarbonisation of the iron and steel industry. She analyses the technical framework conditions to successfully implement the new technologies. Her main responsibilities are in the area of carbon direct avoidance. Another focus of her work is the treatment of steelmaking slag. Based on the reachable saving potential concerning a replacement of primary resources, the goal is to develop processes for metal recycling and the utilisation of the low metal fraction as a secondary raw material.

Her work includes mass and energy models as well as the calculation of theoretical energy consumption concerning the treatment of slag. Monika completed her studies in Industrial Environmental Protection with a focus on process engineering at the Montanuniversitaet in Leoben (AT). Her master's thesis dealt with the sinter process and the associated emissions.

Dr. Klaus Peters is Secretary-General at ESTEP European Steel Technology Platform.

He qualified as Doctor of Engineering in 1993 and as state doctorate (Habilitation) in 1998, started his industrial career with thyssenkrupp Steel Europe (tkSE). His senior experiences include production, sales, quality and R&D both on national and international level.

From 2011, Dr. Peters joined several working groups and committees of the European Steel Technology Platform (ESTEP) and was in charge of international research projects and European funding of tkSE. He became in July 2015 Secretary General of ESTEP.

Amongst others, he is member of the Steel Advisory Group (SAG) of the Research Fund for Coal and Steel (RFCS) and vice-president of the public-private partnership Processes4Planet, which is an evolution of the H2020 SPIRE partnership. He is the Executive Director of the Horizon Europe Clean Steel Partnership. In 2021, ESTEP was again appointed as member of the High-Level Group on Energy Intensive Industries.

Maria da Graça Carvalho is currently a member of the European Parliament.

She was a senior advisor of Commissioner for Research, Science and Innovation, Carlos Moedas, from November 2014 to December 2015.

Previously, she was a member of the European Parliament, between July 2009 and May 2014. In that capacity, she was one of the rapporteurs of Horizon 2020. She was also Principal Adviser to President Barroso in the fields of Science, Higher Education, Innovation, Research Policy, Energy, Environment and Climate Change from 2006 to 2009.

She served as a Minister of Science and Higher Education of the XV Constitutional Government of Portugal and Minister of Science, Innovation and Higher Education of the XVI Constitutional Government. She is a Full Professor at Instituto Superior Técnico (University of Lisbon).

Dr. Paula Queipo is the Director of Business Operations at IDONIAL Technology Centre and deals with innovation management, international project coordination communication strategy, networking and technology transfer activities.

With a degree in chemistry, she obtained the PhD degree in Materials Science and Technology in 2003 from the University of Oviedo (Spain). She has more than 20 years' experience as researcher in academic and industrial contexts in several European entities such as Abo Akademi, VTT and Technical University of Technology (Finland), University of Leeds (UK), and CSIC and PRODINTEC (Spain). She belongs to the Management Boards of the European Technology platforms on additive manufacturing "AM-Platform" (Platform Deputy Coordinator) and innovation in nanotechnology "NANOfutures" (platform co-chair).

Michele De Santis, Principal Consultant, Process & Control Systems, Rina Consulting – CSM SpA.

Degree in physics, over 30 years of experience in steel process modelling and problem-solving. His activity has been focused on thermofluid-dynamics modelling along all the steelmaking route and also to the related environmental aspects.

Since 1991, he has been project leader in about 50 industrial & institutional projects in Italy & abroad. He has been member of the European Commission Technical Group Steel 3 (since 2008), the AIM Environment & Safety Technical Committee since 2016 and the Scientific Committee of Congresses (STEELSIM) in several editions.

A reference for CSM of the Green Steel for Europe- GREENSTEEL project. Currently, he is vice-chairman of the RFCS TGA2 'downstream processes' group, author of more than 60 publications and patents and referee for Journals and expert evaluator for the European Commission Funding Programmes.

Simona Pace, Industry Relations & Financed Projects Team Member, Rina Consulting – CSM SpA.

Simona Pace is member of the Financed Research team at Rina Consulting – Centro Sviluppo Materiali with over 10-year experience in material research and development. She gained her PhD in 2015 at Imperial College London in Material Science and Engineering and worked in several research laboratories in Europe and UK.

She recently joined the Financed Research team at Rina Consulting – Centro Sviluppo Materiali, where she focuses on Industry relations and European funding programs & opportunities.

Erik van Doezum, Director - Metals, Mining & Fertilisers EMEA, ING.

Erik acts as Director within ING's Metals, Mining & Fertilisers sector coverage team. In addition, he is Steel Lead and as such is responsible for ING's strategy towards steel. He joined ING in 2010 and the sector coverage team in 2013, where he has structured and executed various large syndicated transactions in the metals and mining sector and for the steel sector specifically.

Being responsible for steel, he has been significantly involved in ING's reporting on the carbon intensity of its lending portfolio, Terra. Seeing the energy transition as the largest challenge for the steel sector, Erik is now leading a new multi stakeholder working group under the flag of the Net Zero Steel Initiative, which will draft a climate aligned finance agreement for the steel sector based on a net zero scenario.

Stéphane Tondo, General Manager of ArcelorMittal is currently technical head for governmental affairs and climate change.

In that function, he contributes to the decarbonisation roadmap of European entities and its financing. Stéphane joined Sollac, a former company of ArcelorMittal in the automotive sales division in 1998 where he held several positions, from market development engineer, through key account manager and finally heading an automotive sales area.

Since 2013, he has been Chief Marketing Officer in charge of Packaging, Oil and gas, and Electrical Steel segments within ArcelorMittal Europe Flat Products. Additionally, in March 2020, he took the role of Chief Executive Officer of ArcelorMittal Avelino & Canossa in Italy.Stéphane holds a degree as sales engineer from the Esidec business school in Metz (France) and he is a graduate in mechanical engineering.

Dr Sebastiano Fumero, Head of Unit, REA.B1 –Future Low Emission Industries, European Research Executive Agency (REA).

He has been working for European Institutions since almost 30 years. He served the European Commission in several Directorates General (SecGen, DG EMPL, DG Transport and Energy, and DG RTD), occupying several management positions. He has been Member of Ms Emma Bonino's Cabinet from 1995 to 1999 and has worked also at the European Parliament for the Regional Development Committee.

As of April 2021, he re-joined the European Research Executive Agency REA, where he had been managing the 'Experts, Participant and Validation Support' unit from 2008 to 2016, and currently, as Head of Unit B1 for 'Low Emission Future Industries', he manages the Research Fund for Coal and Steel RFCS.

Sebastiano Fumero is a Political Scientist, with a major in international politics.

Jane Amilhat, Head of Unit, RTD.C3 – Low Emissions Future Industries, DG Research and Innovation, European Commission.

She took over the management of unit Low Emission Future Industries in the Directorate General for Research and Innovation (DG RTD) of the European Commission in April 2021 after coming from Directorate General for Energy (DG ENER) where she was 3 years Deputy Head of Unit in charge of Energy infrastructures and Regional cooperation.

Jane Amilhat worked in the private sector after her engineer/economist study in France and Germany. She started her career in the industrial/energy sector (Danone, Gaz de France/Engie, RWE Trading). She joined the European Commission in Directorate General for Environment (previously DG ENV, now DG CLIMA) from 2006 until 2008, where she was responsible for international climate change negotiations and sectorial climate policies.

She has been dealing with Energy and industrial issues when she started at Directorate General for Trade (DG TRADE) at the end of 2008. She was responsible for Russia and the Eastern Partnership but also the Western Balkans and Switzerland when she became Deputy Head of Unit at DG TRADE in 2014.

Dr Peter Dröll, Director, European Commission, Directorate General Research and Innovation, Prosperity Directorate.

Peter has been working in the European Commission for more than 20 years with positions in environment, enlargement negotiations, industry policy, innovation and research. He was a Cabinet member of Enlargement Commissioner Günter Verheugen and Head of Cabinet of the Science and Research Commissioner Janez Potočnik.

Since 2010 he is at Directorate-General Research and Innovation where he was first responsible for Innovation then for Industrial Technologies. Following the re-orientation of DG Research and Innovation towards sustainability, his competences have been enlarged to include industrial R&I agendas and business intelligence as well as knowledge valorisation policies. Before joining the European Commission in 1991, Peter worked as a lawyer in a German law firm. Peter is a lawyer by training with a doctorate degree in German constitutional law and European law.

Christian Egenhofer is an Associate Senior Research Fellow at the Centre for European Policy Studies (CEPS) in Brussels and Senior Research Associate at the School of Transnational Governance at the European University Institute (EUI), Florence. He is also Visiting Professor at the Paris School of International Affairs (PSIA) in SciencesPo, at the College of Europe in Natolin/Warsaw.

Expert in energy, climate change, and issues of European Integration with over thirty years of professional experience, Christian provided research and advisory services to various public institutions.

He has published 8 books on energy, climate change, resources and issues of European integration in addition to more than 160 reports, articles and book chapters. Selected articles and book chapters have been translated into 12 languages. He is a professional policy analyst, competent in data analysis and visualisation, conferences and workshop organisation and moderation, lecturing and training students and government officials, as well as project management.

Milan Elkerbout is a Research Fellow at CEPS Energy Climate House.

His research focuses on EU climate policy, in particular industrial decarbonisation and the EU Emissions Trading System. In 2019 and 2020 he spent a year in Stockholm at IVL Swedish Environmental Research Institute as a visiting Mistra Fellow for the Carbon Exit research programme, which focuses on material value chains and climate neutrality policy challenges.

He has been closely involved in analysing the EU ETS Phase 4 revision processes. He frequently participates in events on these topics, together with policy makers and civil society stakeholders, both at CEPS as well as at EU institutions and in other EU member states. Other topics of interest include industrial transformation and the bioeconomy, mobility, state aid control, Energy Union governance, and the impacts of Brexit.

His academic background is in Political Economy and European Studies. Before starting at CEPS in 2014, Milan Elkerbout studied at the London School of Economics, SciencesPo Paris, and Maastricht University

Maria Spyraki is a MEP in the Group of the European People's Party (Christian Democrats).

At the European Elections of 2014 she was elected first Member of the European Parliament with Nea Demokratia and she joined the European People's Party. She is a member of the Committees on Regional Development (REGI) and on Industry, Research and Energy (ITRE), as well as a member of the EUFYROM Joint Parliamentary Committee. She is also a member of the Nea Demokratia Executive Board after Kyriakos Mitsotakis was elected in the presidency of the party.

Maria Spyraki has worked for 22 years as a journalist in the private sector and she is a member of the Union of Editors of Macedonia and Thrace (ΕΣΗΕΜΘ). Since 1992 she worked at the newspapers «Ependitis», «Exousia», «Thessaloniki», «Aggelioforos», «Imerisia tou Savvatou» and at the TV Stations SKAI, STAR, ALTER, and MEGA, from where she resigned on April 4th of 2014 when the former Prime Minister Antonis Samaras asked her to run for office with Nea Dimokratia at the upcoming European Elections of the 25th of May.

As a journalist she has participated in missions to Southeast Europe (Skopje, Cyprus, Albania, Bulgaria, Serbia, Montenegro). Since 1998 and until March 2014 she worked as a political reporter. She has also worked in the Press Office of the European Parliament in Athens during the period of 2003-2004, as well as the office of Greek Commissioner to the EU, Mr. Stavros Dimas, for the period 2004-2009.

Gabriele Morgante, Policy Officer DG GROW, European Commission.

After his degree in law, two years of traineeship as a lawyer and 13 years spent in the Italian public administration as a public official, Gabriele Morgante joins the European Commission in 2013, where he starts to work as policy officer in the energy intensive team of DG GROW as responsible in particular for the steel sector.

In this position, he contributes to the definition and implementation of policy instruments in several policy field, e.g.: climate policy ("fit-for 55" Package, Emission Trading System), Research and Development (clean steel partnership, research fund for coal and steel), trade (G20 working group "Global Forum on Steel Excess Capacity", OECD Steel Committee meetings, trade-defence instrument cases, foreign direct investment cases), competition (revision of the Energy and Environmental State aid guidelines, of the Regional Aid Guidelines, and of the revision of guidelines for compensation of ETS indirect cost; merger and state aids cases), environment (aspects relating to circular economy for steel), skills (Roundtable for Skills in the energy-intensive industries). Gabriele Morgante is also member of the scientific committee and lecturer at the Eurosteelmaster.

Axel Eggert is the Director General of the European Steel Association (EUROFER), a position he has held since 2014. He initially joined the association in 2007 as Director of Public Affairs and Communications.

Mr Eggert has over twenty years of experience in EU affairs, having worked for eight years in the European Parliament prior to his role at EUROFER. In addition to his EUROFER leadership, Mr Eggert is also Vice-President and Member of the Board of the European Steel Technology Platform (ESTEP).

Mr Eggert holds Master's degree in Modern History, Economics and Law from the University of Darmstadt and the State University of New York at Buffalo.

Niklas Johansson is Senior Vice President of the Communication and Climate Unit, LKAB, Sweden. Niklas is also a member of the Group Management at LKAB.

Niklas holds an MBA and has a broad experience from both government and industry, with previous positions including Deputy CEO and Head of Communications for a small international industrial group.

He joined the company from the post of State Secretary, where he was first of all State Secretary to Mikael Damberg when he was Minister for Enterprise and Innovation, and then State Secretary to Ann Linde when she was Minister for Foreign Trade.

Suzana Carp is an EU Climate policy specialist advising EU institutions and NGOs across a range of climate policies.

Suzana has led the EU engagement strategy of several European think tanks and NGOs and has most notably delivered effective civil society campaigns around the EU ETS, the EU Climate law, the Climate Action regulation implementing the Paris Agreement, and NECPs.

For several years now Suzana has been involved in research concerning heavy industry decarbonisation and her ambition is to see the "hard to abate" sectors becoming supported with the right policy ecosystem and infrastructure to become less difficult to decarbonise.

Her academic background entails graduate studies at the College of Europe in Warsaw and at the University of Oxford (Climate & Energy focus and Migration, respectively) and her university degree in International Studies was completed in the United States.

Andrea Renda is a Senior Research Fellow and Head of the CEPS Unit on Global Governance, Regulation, Innovation and the Digital Economy (GRID), and Professor and holder of the "Google Chair" for Digital Innovation at the College of Europe in Bruges (Belgium).

He is a non-resident Senior Fellow at Duke University's Kenan Institute for Ethics. For 2018/2020, he was also a Research Fellow of the Columbia Institute for Tele-Information (CITI) at Columbia University, New York. In August 2019, he was names Fellow of the World Academy of Art and Science.

A very prolific author and keynote speaker, Andrea provides regular advice to several institutions, including the European Commission, the European Parliament, the OECD, the World Bank, the Inter-American Development Bank, and many more. He was the main author of key studies on better regulation for the European Commission, the OECD and the World Bank. He sits in the Board of the journals Telecommunications Policy (Elsevier), and European Journal of Risk Regulation (Cambridge).

He is currently a member of the EU High Level Expert Group on Artificial Intelligence. His current research interests include regulation and policy evaluation, regulatory governance, innovation and competition policies, and the ethical and policy challenges of emerging digital technologies, in particular Artificial Intelligence.

Alejandro Gonzalez, Project Adviser, REA B.1 "Future Low Emissions Industry".

Alejandro has been working in the European Commission since 2018 managing Iron- and Steelmaking Technical Group TGA1. In charge of steel related policies, Alejandro was the EC representative during the inception of the Clean Steel partnership.

Since 2021, he continues his activities at the European Commission Research Executive Agency (REA). Prior to joining the European Commission, Alejandro gained over 15 years of technical and managerial experience in industry, transport, mining and infrastructure in multinational companies in Spain, Germany and Australia. Alejandro is mechanical engineer, MSc electrical engineering.

Johanna Lehne is a Senior Policy Advisor in E3G's Brussels office.

She works on industrial decarbonisation, competition policy and EU climate politics. Johanna works with NGO partners, industrial stakeholders and policymakers on issues relating to decarbonising energy- and resource-intensive sectors. Her expertise includes industrial policy, circular economy, built environment and trade and competition policy.

Before joining E3G in August 2019, Johanna was a research associate in the Energy, Environment and Resources Department at Chatham House. Her research, while at Chatham House, covered industrial decarbonisation, the circular economy, low-carbon innovation in the built environment, chokepoints in global food trade, natural resource governance in China and energy for displaced populations.

She holds an MPhil in International Relations from the University of Oxford, where her thesis focused on the role of oil-abundance and water-scarcity in interstate conflicts in the Middle East. Johanna also has a BA in European Social and Political Studies, with a specialisation in economics, from University College London.

Dr. Pietro Gimondo, Head of Relations with Industry, Tender, Funded Research, Rina Consulting – CSM SpA.

Dr. Pietro Gimondo has worked for the European Commission in the 2002-2006 period as Programme Officer of the Directorate General for Research and Development.

Has a wide experience in the EU frame especially having worked for various Public-Private Partnership among those SPIRE PPP, Process4Planet PPP and various others. He is the Head of the Dept. Relations with Industry and Financed Projects at RINA-CSM, and he is one of the father founders of ESTEP the European Steel Technological Platform. The HYDRA Project is inserted in the IPCEI Hydrogen for the Italy MS.

Rosalinde van der Vlies, Director, European Commission, Directorate-General Research and Innovation, Clean Planet Directorate.

Ms Rosalinde van der Vlies, is the Director of the Clean Planet Directorate in the European Commission's, Directorate General for Research and Innovation. Before her appointment as Director, Ms van der Vlies was the Head of Coordination & Interinstitutional Relations Unit, and acting Head of Communication & Citizens Unit.

Previously she held positions in Directorate-General Environment, Directorate-General Justice and Home Affairs, and in the private office of Janez Potočnik, the European Commissioner for the environment. Before joining the European Commission, she worked as a competition lawyer in an international law firm in Brussels and was a part-time teacher at the Catholic University in Brussels.

Hien Vu is a Researcher in the Global Governance, Regulation, Innovation and the Digital Economy (GRID) unit at CEPS.

Her expertise and publications cover regulatory policy and better regulation, in particular in the area of sustainable development, industrial decarbonisation, research and innovation, renewable energy, and the circular economy. Hien is also affiliated with the EU-ASEAN Think Tank Dialogue, a research programme supporting the strategic partnership between the EU and ASEAN.

Prior to these positions, Hien was a Team Assistant at the World Bank in Vietnam. She gained experience with managing transport development projects, working with local governments, and coordinating with research institutes. Hien was also a Junior Policy Analyst at the Organisation for Economic Cooperation and Development (OECD) in Paris.

Besides, Hien was the co-founder and coordinator of a project on the circular economy in Douala, Cameroon. Hien holds a Master in Development Economics and International Project Management at the University of Paris-East Creteil.

Cristian Stroia is a Researcher in the Energy, Resources and Climate Change Unit at CEPS.

An experienced professional in European policy and international relations, he has over 6½ years of multidisciplinary experience in stakeholder engagement, project management, policy analysis, strategic communication, event management and capacity building. He has covered policy topics ranging from the EU Green Deal, energy transition, climate change, smart cities and sustainable urban development, to circular economy, regional cooperation, and sustainability

He was involved in over 16 European and international projects that dealt with the decarbonisation of urban economies, circular economy, regional energy cooperation, renewable energy, climate change mitigation and sustainable consumption and production.

Cristian was part of the consortiums that developed the EU Circular Cooperation Hub (a circular economy platform for R&I joint programming in Europe), and the EU Smart Cities Information System (a knowledge platform for exchanging data, best practices, know-how and improved collaboration on the creation of smart cities in Europe, now part of the EU Smart Cities Marketplace). His previous experience is in the NGO sector, academia, business and entrepreneurship programs, and non-formal education initiatives.

He is the winner of a 2013 national competition on renewable energies and smart cities planning in Italy, and he holds a Master of Science Degree in European and International Studies (Italy), a Bachelor Degree in International Relations and European Studies (Romania) and academic courses in Political Science in the USA.

Annex 3 - Executive summaries of key reports of GREENSTEEL

Technology Assessment and Roadmapping (Deliverable D1.2)

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

This report, which is Deliverable D1.2 of the GREENSTEEL project, provides the technological foundation for the evaluation of CO_2 mitigation strategies with specific low-carbon technologies, and for implementing complete technology routes in the European steel industry. It summarises iron and steelmaking technologies, supporting technologies and technology routes, describing their technological approaches, their current maturity (in terms of readiness level) and their expected development, as well as the influencing framework conditions. The technological foundation provided by this report is used for the development of scenarios as reported in the report Decarbonisation Pathways 2030 and 2050 (Deliverable D1.7 of the GREENSTEEL project).

The CO_2 mitigation pathways, which are currently being addressed in the European steel industry, are carbon direct avoidance (CDA), process integration (PI) and carbon capture and usage (CCU). The parallel circular economy strategy targets a 'zero waste' concept and complements the above-mentioned pathways as an overarching approach.

- The CDA pathway primarily focuses on the development of new steelmaking processes using fossil-free reductants and (renewable or clean) energy sources to produce steel from virgin iron ore, thereby avoiding the generation of carbon oxides and its emissions.
- The PI pathway concerns possible modifications or adaptations to existing steel plants in order to reduce greenhouse emissions and can be complemented by CCU and/or carbon capture and storage (CCS).
- The CCU pathway consists of the capture of CO_2 or CO from steel production process gases and the production of further valuable carbon-based products from captured fossil carbon, thus mitigating emissions caused by fossil resources in their conventional production chains.

The following nine iron and steelmaking technologies were identified as the most relevant within these pathways:

- hydrogen-based direct reduction (H2-DR)
- hydrogen plasma smelting reduction (HPSR)
- alkaline iron electrolysis (AIE)
- molten oxide electrolysis (MOE)
- carbon oxide conversion
- iron bath reactor smelting reduction (IBRSR)
- gas injection into the blast furnace
- substitution of fossil energy carriers by biomass
- high-quality steelmaking with increased scrap usage

The selection of iron and steelmaking technologies is based on desktop research of various global publications, a comprehensive stakeholder survey and the outcomes from the previous RFCS Project LowCarbonFuture - Exploitation of projects for Low-Carbon Future Steel Industry (Grant Agreement No. 800643). Table 1 provides an overview of the technologies and their main data.

Table 1: Overview of low-carbon iron and steelmaking technologies

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

[4] The list comprises national and international projects (not exhaustive).

Substitution of fossil energy carriers by biomass	TRL 2-7	TRL 8	TRL9 (ind. depl. in 2035)	CAPEX relatively low and OPEX depends mainly on the raw materials	SHOCOM, GREENEAF2, ACASOS
High-quality steelmaking with increased scrap usage	TRL 4-8	TRL 7-9	Ind. deployed	OPEX: significant depending on the scrap price	FLEXCHARGE, ADAPTEAF, SSIA, LCS

CS - crude steel; ind. deployed - industrially deployed; CAPEX - capital expenditure; OPEX - operational expenditure; impl. - implementation; neg. – negative
Source: authors' own composition.

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

Several technologies can be combined in order to raise the overall CO_2 mitigation potential above their individual limits. CO_2 capture and H_2 generation are the main auxiliary processes connected to several of the technologies. As H_2 can be extracted from fossil fuels and biomass, water, or a mix of both, there are multiple production processes available such as reforming of gas, gasification (biomass, waste etc.) or water electrolysis.

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

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

The iron and steelmaking technologies within each pathway (CDA, PI, CCU) can be considered as individual modular components (mitigation options) within the complete steel production chain. Technology routes integrate these components into a full system (process chain), which includes upstream operations (transformation of raw materials into intermediate steel products) and downstream applications (production of final shaped and coated products). When projecting the development and research needs of the technologies as well as technology routes onto a time frame, a corresponding roadmap is created. The compilation of technologies to technology routes including the integration into existing/new production chains needs substantial additional effort (both with respect to R&D activities and to accompanying investments needed) as all material and gas flows including upstream and downstream processes and infrastructures are affected. Combining mitigation technologies in technology routes is by essence not limited to a specific mitigation pathway (CDA, PI, CCU) but may include elements from all of them. This correlation between technologies and technology routes, as well as the approach within the report, is shown in Figure 1.

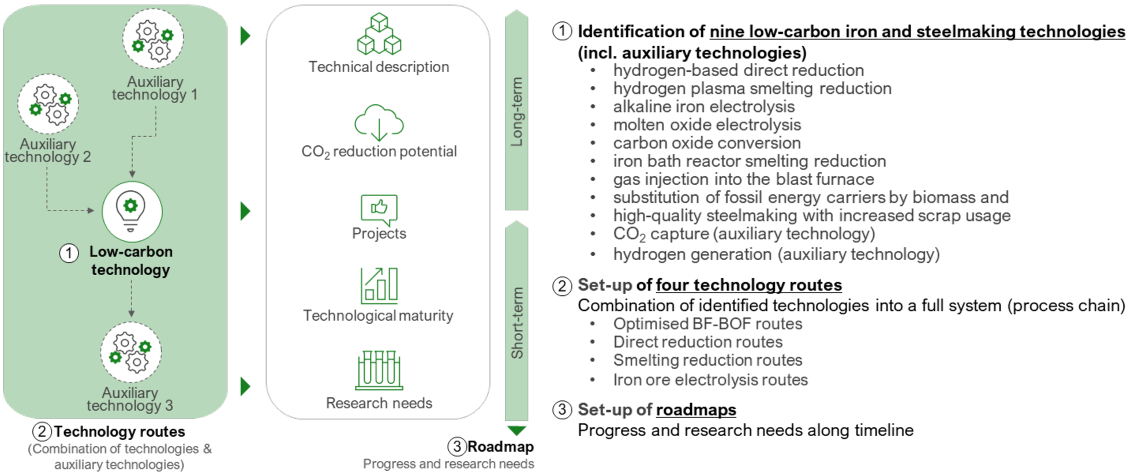


Figure 1: Link between technologies and technology routes

Source: author's own composition.

The CO2 emission of downstream processes is much lower than from ore-based upstream processes. Therefore, the focus lies on upstream applications and scope 1 (direct emissions) and scope 2 (indirect emissions from the production of required energy) emissions.

Four promising technology routes (Table2) were identified within the project work as highly relevant (but non-exclusive) examples. The first one is based on conventional BF-BOF plants (blast furnace, basic oxygen furnace), into which a number of add-on CO2 mitigation technologies are incorporated (PI, CCU). This route can be considered a short-term solution. The second is based on the utilisation of direct reduction based on natural gas or hydrogen, in which all ironmaking and steelmaking units are replaced by new production methods. The third technology route comprises technologies based on smelting reduction. This includes, on the one hand, the iron bath reactor smelting reduction option, in which the ironmaking part is replaced and, on the other hand, hydrogen plasma smelting reduction, which enables the direct transformation of iron ore into liquid steel. The fourth technology route refers to the electricity-based steelmaking by iron ore electrolysis. It can either be carried out at low temperatures (alkaline iron electrolysis; replacement of the iron making part) or at high temperatures (molten oxide electrolysis; direct production of liquid state metal from oxide feedstock).

The advantages and disadvantages of a technology route are strongly related to the associated framework conditions and the considered facility since each plant entails different possibilities and hurdles. The adequacy of a technology route must be assessed on an individual basis. The following table (Table 2) summarises necessary framework conditions for each technology route.

Table 2: Technology routes and their associated framework conditions

Technology route	Framework conditions
Technology route 1 Technology routes based on optimised BF-BOF	• Technologies to upgrade alternative carbon sources • Transportation, storage, price and availability of alternative carbon sources • Possibility of integrating upgrading technologies at the steelmaking sites • Energy efficient separation and purification technologies • Availability and price of low-CO_2 hydrogen production • Availability and volatility of renewable energy • CO_2, process gases and hydrogen transport system • Marketability and price of CCU products • Social acceptance
Technology route 2 Technology routes based on direct reduction	• Price and availability of natural gas • Process gases transport system • Availability and price of low-CO_2 hydrogen • Energy system without (or with minimum) carbon input • Strengthening of high-voltage grids • Hydrogen transport and storage infrastructure
Technology route 3 Technology routes based on smelting reduction	• Carbon capture, usage and storage technologies have to be used in combination with IBRSR to attain sufficient mitigation • Pre-treatment processes for alternative carbon sources (IBRSR) • Price and availability of alternative carbon sources (IBRSR) • O_2 production and CO_2 capture and compression (IBRSR) • Social acceptance (IBRSR) • Availability and price of low-CO_2 hydrogen production (HPSR) • Energy system without (or with minimum) carbon input (HPSR) • Strengthening of high-voltage grids (HPSR) • Hydrogen transport and storage infrastructure must be provided (HPSR)
Technology route 4 Technology routes based on ore electrolysis	• Energy system without (or with minimum) carbon input • Strengthening of high-voltage grids

Source: own composition by the authors of the report

The illustration below (FigureFigure 2) provides a comparative view of the technology routes (green) and the integrated primary steel production route (grey). The process chain is visualised from top to bottom of the figure. The objective is to demonstrate to which extent alterations occur.

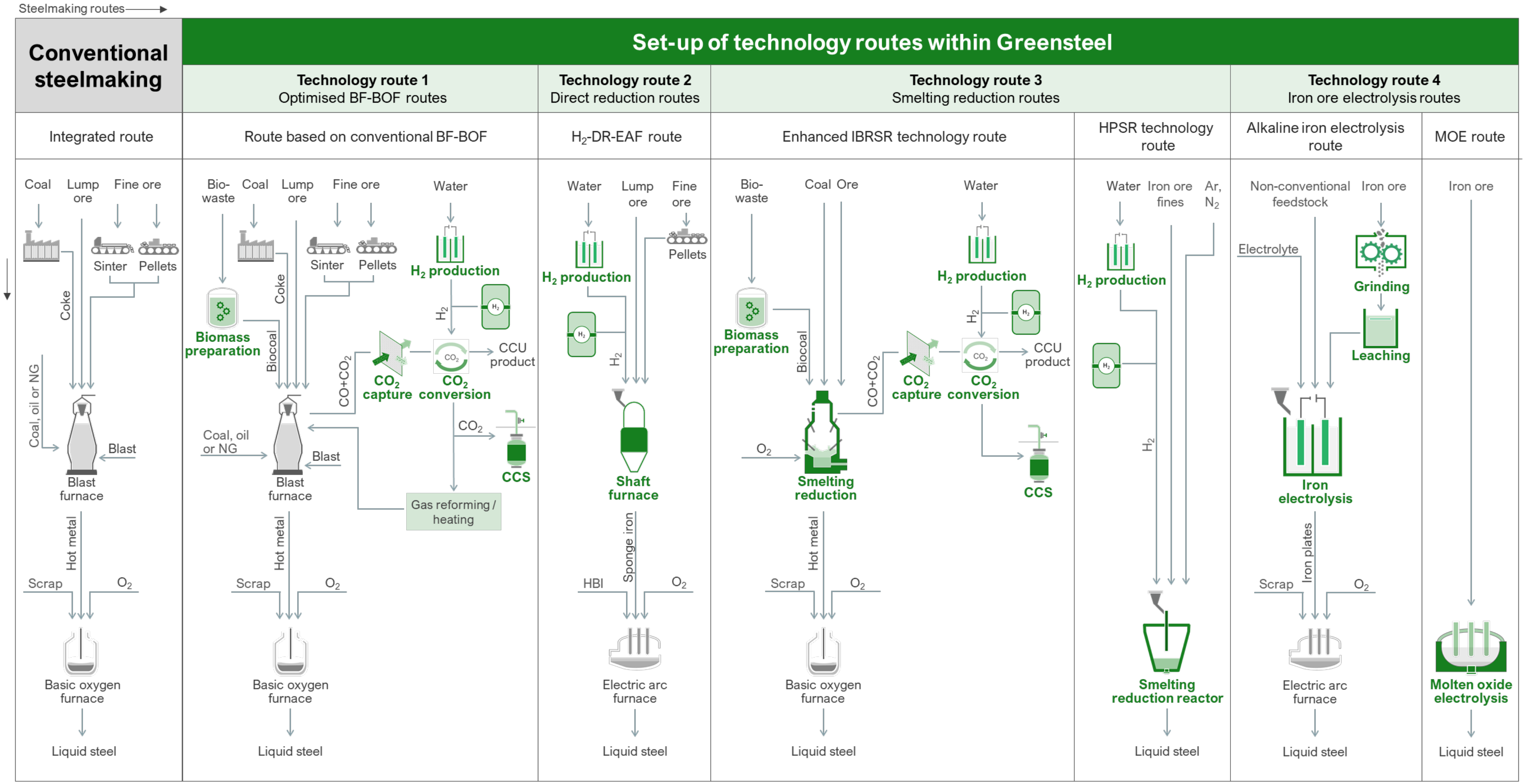


Figure 2: Overview of the set-up of technology routes in comparison to the integrated steelmaking route

Source: own composition by the authors of the report

The route based on conventional BF-BOF and the enhanced iron bath reactor smelting reduction technology route show a horizontal change (i.e. with remaining BOF) as opposed to a widespread vertical alteration within the hydrogen-based direct reduction - electric arc furnace (H2-DR-EAF) route and the electrolysis-based technology route. The green indications within the flow diagrams show the modifications, whereas the grey-coloured depictions symbolise unchanged procedures. Although the main existing process units are not replaced with new technologies for the proposed CO2 mitigation route based on conventional BF-BOF, considerable changes must be carried out in conventional plants. To reach significant mitigation through this technology route, considerable investments are required for the add-on technologies (e.g. carbon capture, usage and storage, biomass preparation, gas preparation and blast furnace gas injection systems). For the H2-DR-EAF route, the technology route based on hydrogen plasma smelting reduction and the technology routes based on iron ore electrolysis, the full ironmaking and steelmaking capacities of existing BF-BOF plants have to be replaced. The effort is almost comparable to greenfield conditions. The data provided in the figure regarding this route refer to the breakthrough technology with (almost) complete usage of hydrogen as reducing gas for direct reduction. The smelting reduction technology route replaces the full ironmaking process in conventional plants; further significant investments are required for add-on technologies (e.g. carbon capture, usage and storage and biomass preparation) to achieve extensive CO2 mitigation.

Starting from the identification of individual iron and steelmaking technologies, a roadmap for the proposed breakthrough technologies has been created (Figure 3). This roadmap indicates the progress and the research needs for each technology involved along the timeline. The needs for integrating the technologies into a complete breakthrough process chain are also visualised. Each line describes one technology. Starting in 2020 (current technology readiness level), the technology readiness level development is shown from left (short-term) to right (long-term) both graphically (grey shaded area) and numerically.

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

A promising short-term option regarding CO2 mitigation is to replace part of the fossil coal used in different plants (e.g. coking plant, sinter plant and blast furnace) with biomass. This can further be combined with recycling the remaining CO and hydrogen from the blast furnace top gas back into the process, effectively decreasing CO2 emissions. CO and hydrogen can be recovered with a CO2 separation step, such as recycling fumes in blast furnace hot stoves or some new, in process, capture technologies. Several gaseous streams in steel plants have rather high concentration of CO2, therefore offering a great potential for specific/integrated capture processes.

Besides possible replacement of energy carriers with biomass, the replacement of primary raw materials with increased scrap utilisation according to the circular economy strategy (creating a closed loop system) is another measure for CO2 mitigation. In direct comparison, secondary steel production via the scrap-EAF route makes use of recycled steel scrap and results in about 80% less CO2 emissions than with the primary BF-BOF-route. Nonetheless, the potential for scrap utilisation is strongly restricted under the requirements for steel product quality. More specifically, the metallurgical requirements for high-quality steel, which is often produced via the primary BF-BOF-route, demand the processing of virgin material and will limit the scrap utilisation significantly for the foreseeable future. A clear R&D demand for improved scrap processing in order to ensure better scrap quality was identified. Indeed, this would alleviate the limitations of scrap utilisation to some extent.

An important intermediate step towards the deployment of the H2-DR-EAF technology route is the direct reduction with natural gas, which has been an industrially established technology for a long time. Also, with natural gas the direct reduction technology (NG-DR) provides a significant CO2 mitigation potential compared to the conventional BF-BOF-route, and thus, a promising short-term option. The share of hydrogen as a partial substitute for natural gas can be increased stepwise towards the possible later target of complete hydrogen-based reduction. This allows a gradual enrichment with hydrogen on industrial scale and enables a flexible increase of hydrogen concentration depending on availability, price, and technical requirements. Regarding the time scale for industrial deployment, this results in the option of direct reduction plants being built as of now (depending on the individual investment cycles of the respective plants) and their shift towards increased hydrogen usage as soon as possible depending on its availability. Natural gas-based direct reduction can be complemented by CCU and/or carbon capture and storage; the realisation relies on the specific situation of the individual steel production site.

To realise the crucial next step of demonstration and completion in operational environment (TRL 7–8) and to enable the European climate and energy targets to be met, the R&D actions need to be taken immediately. Since the needed R&D actions are widespread and the effort by far exceeds usual R&D needs, international collaborative research could be useful for effective progress. It can be stated that the four proposed technology routes have a CO2 mitigation potential up to 100%, but not all technologies can be industrially deployed in the short term (by 2030). Some technologies are available, which enable short-term deployment with limited R&D need and investment effort. The technologies need certain framework conditions, the most important one being the availability of sufficient clean energy at costs that are competitive with worldwide levels.

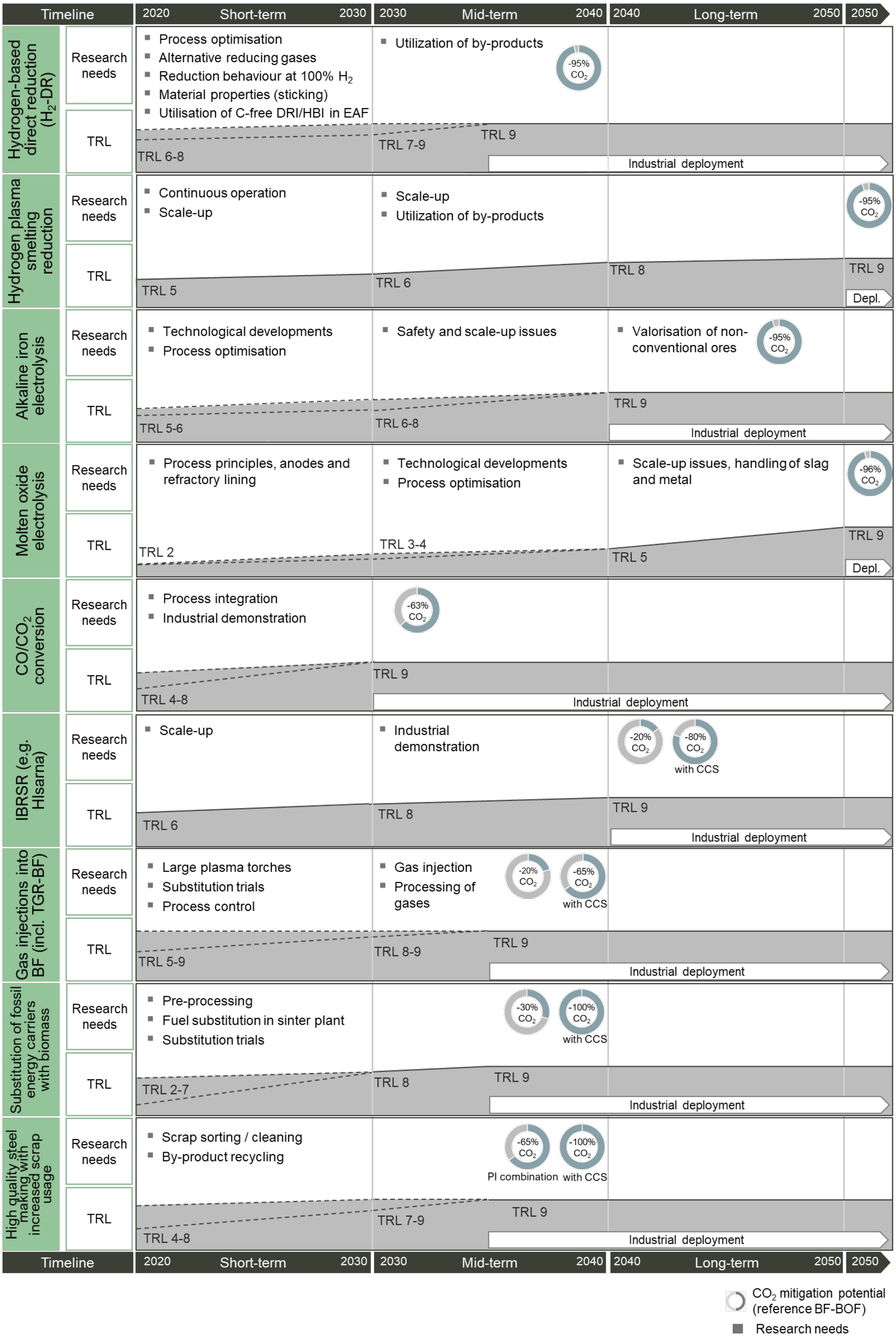


Figure 3: Roadmap of selected CO_2 mitigation technologies

Source: own composition by the authors of the report

Collection of possible decarbonisation barriers (Deliverable D1.5)

This 'Collection of possible decarbonisation barriers' report (D1.5) aims to give a comprehensive overview of all major barriers to the decarbonisation process in the iron and steel industry. It does not assess the specific severity or offer possible solutions to overcome these barriers.

Less serious barriers may slow down or limit the development and deployment processes; more serious barriers may block them completely.

The findings of this report are based on desk research evaluating academic and industrial publications, as well as on input provided by EU steelmakers via a scoping questionnaire.

Based on the desk research conducted, four different categories of decarbonisation barriers have been identified:

1. technical barriers caused either by the technological development of decarbonisation technologies or by the required mass and energy flows;
2. organisational barriers caused by the organisation of technology development or deployment in terms of management, administration or personnel;
3. regulatory or societal barriers caused by externally set framework conditions, policies or social acceptability; and
4. financial barriers caused by limitations to the economic operation of the iron and steel production.

For each category, four to five specific barriers have been identified and analysed in more detail. Besides the assessment of the barriers themselves, their specific relevance to the stakeholders of the EU iron and steel production is assessed through an evaluation of the consultations with steel producers covering more than 80% of the European steel industry's CO_2 emissions.

The definition, background and potential impacts of these barriers can be summarised as follows.

1. Technical barriers

Within the technical barrier category, four specific barriers affecting the decarbonisation of the EU steel industry have been identified:

- limited availability of raw materials
- limited availability of renewable energy
- limited technical integration potential into existing plants, and
- risk of unsuccessful development.

The main input materials for steel production are iron ore as the primary raw material (processed into sinter or pellets), and steel scrap as the secondary raw material. A replacement of the primary raw materials (i.e. ores) by scrap would avoid the energy- and CO_2-intensive step of ironmaking; however, this is strongly limited by scrap availability and product quality issues due to residual impurities from scrap. Additionally, the higher costs of scrap are extremely relevant; the price is expected to further increase as the demand for high quality scrap rises. A shift towards direct reduction plants (to replace the blast furnace-basic oxygen furnace [BF-BOF] route) would result in a high demand for iron ore pellets. The current sintering plants, which allow the use of a wide variety of iron-bearing raw materials and the recycling of most internal residuals, probably have to be replaced in the long-term. This would need new material cycles and new raw material supply chains. New pelletising plants would have to be built on site (causing high investments and space problems for brownfield installations) or an external pellet supply would be necessary (causing a risk of carbon leakage and decreasing flexibility).

The deployment of decarbonisation technologies results in an increased substitution of fossil energy carriers with renewable energy sources (including secondary biomass and waste materials). The renewable energy supply will have to be delivered mainly by electricity, which will be consumed either directly (electrification) or indirectly via hydrogen production (e.g. by water electrolysis). Only a smaller part can be supplied by secondary biomass and combustible wastes. The CO_2-free electricity demand of the EU iron and steel industry in 2050 is estimated at 400 TWh per year, corresponding to about half of today's total electricity production from renewable sources. Additionally, fluctuations in renewable electricity production should be considered. These may require, for instance, the implementation of large-scale storage systems (e.g. for electricity or gas) or new approaches to increase demand-response flexibility.

The technical integration of a new technology into pre-existing physical plants (brownfield sites) at industrial level requires available space for the new equipment and a connection to the existing material and energy flows. In practice, any steelworks would need comprehensive individual planning and to find room for new installations as well as for their servicing within an already limited physical space. Additionally, production would have to stop (at least partially) while the new equipment is incorporated. Longer downtimes of large parts of a plant can cause a loss of production worth several million euros. A further important aspect is the influence of the new technologies on energy flows, as currently heat and power production relies on gases generated by the processes of the plants (BF gas, BOF gas and coke oven gas) as the main energy sources.

The risk of unsuccessful development refers to failures in achieving either the technical objectives itself or in achieving an economically sound and sustainable result. While the technical functionality of a process is developed during the technical development phase, the economical operation and sustainability is developed at a later stage in the industrial deployment phase. Due to this, a risk of unsuccessful development must be considered for all stages of development and for all technologies, as in all R&D activities. In terms of decarbonisation of the iron and steel industry, due to the fluctuating quality of the raw materials and the huge size of steel production plants, the technical risks of unsuccessful development are still very present during the final stages of development.

2. Organisational barriers

The category of organisational barriers consists of four specific decarbonisation barriers relevant to the EU steel industry:

- limited availability of qualified staff
- administrative requirements
- issues related to the management of industrial transformation
- issues related to intellectual property management (intra- & inter-firm).

As in any large-scale production process, the planning and operation of (integrated) plants for iron and steel production require significant human resources. Thus, the availability of qualified staff is a precondition to pushing forward the development of decarbonisation technologies, including the necessary technical development of new technologies. In the first phase, the development and operation of new technologies need more personnel than usual commercial processes. Additional personnel are necessary when the new technology is installed in addition to the existing ones. Challenges arise with regard to the long-term perspective for the workforce, however.

Administrative requirements may also hinder the development and deployment of low-CO_2 technologies. Authorities may demand proof of compliance with relevant standards, which may be lacking at the time of first implementation. Regarding collaborative research and the funding of projects, internal and external bureaucracy could impose an additional burden.

Considering the fundamental changes of process chains, including energy and raw material supply chains, the decarbonisation of industrial production is a revolutionary transformation process whose different phases are extremely difficult to manage. It starts with the efforts and issues related to the research and demonstration of the new technologies. Managing the deployment of new technologies in the existing brownfield plants while usual production goes on might be even more important. The related effort significantly exceeds ‘normal’ business since the scope and time pressure of the changes are fundamentally larger than usual.

Intellectual property management refers to the management of intellectual property (IP) rights. Extraordinary intensive research and development (R&D) activities are needed within the coming decades to decarbonise the steel production. In this context, the use of exclusionary rights generates burdens and limitations for the competitors. This might lead to a delayed or altered implementation of decarbonisation technologies, possibly resulting in less CO_2 mitigation achieved or higher costs. Additionally, the information exchanged between competitors outside of the regulated environments may be decreased, leading to slower technological progress overall.

3. Regulatory/societal barriers

Among the regulatory or societal barriers to the decarbonisation of the EU steel industry are five specific ones:

- limited availability of permanent CO_2 storage
- limitations stemming from emissions-related legislation (e.g. pricing in EU ETS system)
- limitations associated with social acceptability and environmental protection
- burden by local taxes and fees, and
- uncertainty related to carbon contracts for difference.

For the abatement of remaining CO_2 emissions that cannot be mitigated in the process, Carbon Capture and Storage (CCS) is an option, in particular in the medium-term when not enough renewable energy sources are available yet replace all fossil energy sources. The capacities for CO_2 storage in Europe are limited. Current cumulative storage resources are in the range of 10,000-30,000 Gt CO_2, including 1,000 Gt in depleted oil and gas reservoirs. The main share of these capacities is restricted by national legislations due to public concern. Thus, the significance of this barrier is highly depending on the national and regional framework conditions related to CCS.

The economic viability and competitiveness of decarbonisation technologies is subject to emissions-related legislation as the carbon pricing in the EU emission trading system (ETS). Meanwhile, substantial increases in carbon price and/or changes in mitigation measures could ultimately result in carbon leakage. This is especially true if one considers that production costs for green steel are expected to be substantially higher than costs for conventional steel. Steel imported from third countries with less stringent climate rules than the EU could be sold at a lower price, while generating comparable or often higher carbon emissions than those linked to EU steelmaking. The magnitude of the carbon leakage challenge is increased by the global overcapacity and heavy competitive pressure from the global steel markets.

Technologies that are technically and economically viable may not be successfully implemented due to limited social acceptability. Such issues have already occurred to CCS and renewable energy installations (e.g. windmills or power supply lines). Other decarbonisation technologies may suffer from similar issues in the coming years (e.g. pipelines for hydrogen or CO_2).

Decarbonisation actions can be subject to additional or changing local taxes and fees. One example is that of feed-in tariff schemes, which several member states have unilaterally changed to support renewable energy. However, in doing so, they have generated economic uncertainty and increasing investment risks. Specifically, the German Renewable Energies Act (*Erneuerbare Energien Gesetz*, EEG) plays a significant role in local electricity costs. As a matter of fact, under its provisions steelmakers may have to pay additional taxes and fees if they acquire renewable electricity externally instead of producing it internally.

The current set of national framework conditions is not fixed for a longer term but is subject to change in coming years. This may for instance be a barrier with respect to the currently discussed implementation of carbon contracts for difference (CCfD): A 'strike price' is agreed upon between a state and a producing company over a defined period, which anticipates the expected future increase of certificate prices. The aim of these contracts is to hedge the higher future prices. If the 'strike price' is higher than the market price, the state covers the difference. In the opposite case, the company covers the difference. This would guarantee producers of low-carbon steel a fixed future CO_2 emission price, decrease their investment risks and make their decarbonisation projects financially viable already in short-term. However, if national framework conditions in this respect are unknown, precarious and heterogeneous, this may become a barrier.

4. Financial barriers

Besides the aforementioned non-financial barriers, five specific financial decarbonisation barriers relevant to the EU steel industry have been identified:

- increased operational expenditure
- additional capital expenditure for demonstration plants
- additional capital expenditure for industrial deployment
- limited access to funding and financing, and
- unknown market conditions for clean steel.

The implementation of a technology is highly dependent on its competitiveness. Therefore, attention must be paid to the operational expenditure (OPEX) which includes costs for energy, material, operation and maintenance. The OPEX related to energy and material inputs generally make up over half of the total steel production cost. The price of electrical energy is significantly higher than for thermal energy provided by fossil fuels (e.g. seven times higher for coal). It is expected that the electricity prices will significantly rise in almost every EU member state up to 2050. Additionally, new raw material demand (e.g. high-quality scrap for increased scrap usage or pellets for direct reduction [DR] plants) may significantly raise the OPEX.

Most breakthrough decarbonisation technologies currently have technology readiness levels (TRLs) in the range of 7, meaning that the important step of demonstration in an operational environment still has to take place. High capital expenditure for demonstration plants is due to the fact that the scale of steel demonstration plants is considerable compared to process industries, with capacities ranging from 10 to 100 t per day. Usual demonstration project budgets are between 100 and 200 million euros.

Additional capital expenditure for the industrial deployment of decarbonisation technologies depends on the extent to which the new technology calls for new asset expenditure. This includes not only the investment in the decarbonisation technologies themselves, but also the effort to adapt the existing assets to integrate the new technologies into the brownfield plants. Generally, the costs must be evaluated in relation to the corresponding mitigation potential and vary among plants depending on the local conditions (e.g. investment cycles, availability of secondary biomass).

The high demand in terms of capital expenditure (CAPEX) clearly shows that the development and deployment of decarbonisation technologies need additional financial investments. Thus, the limited access to funding is a concern and does not encourage the desired actions. This applies not only to the high investments in demonstrations plants, but also to the even more expensive industrial deployment of decarbonisation technologies.

The production of clean steel, characterised by zero or low CO_2 emissions, will go along with (significantly) higher costs, at least for the near future. To cover these additional costs, the implementation of new markets and business models for clean steel is a promising option. In such an approach, 'clean steel' would be characterised as a different product than conventionally produced steel (premium product), with higher pricings to cover the higher production costs. If such a market for clean steel were created, it would strongly depend on European and worldwide policies. These may include public support (currently unknown), e.g. for public procurement. Additionally, the customer acceptance of higher prices for clean steel-based end products is unknown and may need support by legislative actions.

Evaluation of the specific importance of the barriers to stakeholders

To gain insight into the significance of the identified barriers and their impacts on the overall decarbonisation process, the barriers were the subject of a scoping questionnaire in the first step of the stakeholder consultation. Stakeholders were asked to rate on a scale from 1 (not important) to 5 (very important) the importance of pre-selected barriers to the activity of their respective companies in the short term (2020-30) and in the long term (2030-50). The results presented in this report reflect the situation as of 30 August 2020, thus incorporating preliminary names and categorisation of the barriers. The evaluation is based on detailed responses from 15 stakeholders, which together account for 71% of CO_2 emissions (based on 2020 EU ETS allocations).

The results were further assessed in two different ways: as a general average rating and as a CO_2-weighted average. The CO_2-weighted average takes into account the stakeholders specific CO_2 emissions based on EU ETS data. Thus, stakeholders emitting larger amounts of CO_2 are weighted correspondingly higher. Based on these methods, the barriers were ranked to identify the main barriers to decarbonisation. In Table 1 the rankings are presented based on the short-term average (2020-30). Table 1 displays both the average and the CO_2-weighted importance ratings for both periods (2020-30 and 2030-50). In this table, the categories were abbreviated as 'TEC' for technical barriers, 'ORG' for organisational barriers, 'FIN' for financial barriers and 'POSO' for policy or societal barriers.

It is striking that six out of the seven most significant barriers are financial ones. The only exception are the framework conditions created by national or local taxes or fees (ranking 6th) which, however, have financial implications too. Most organisational barriers can be found at the bottom of the table due to the low ranking by the stakeholders. Most rankings – for the average evaluation and the CO_2-weighted evaluation – follow the same trend.

Table 1: Ranking of decarbonisation barriers by steel producers (sorted by 2020-30 average)

	Decarbonisation Barrier	Cat.	2020-2030		2030-2050	
			Avg.	CO_2	Avg.	CO_2
1	Investments for industrial deployment	FIN	4.80	3.76	4.50	4.51
2	Increase in OPEX (energy/renewable energy)	FIN	4.50	4.75	4.30	4.25
3	Unknown market conditions of clean steel	FIN	4.50	3.85	4.30	3.85
4	Investments for demonstration plants	FIN	4.40	4.59	4.11	3.11
5	Limited access to funding opportunities	FIN	4.30	4.65	4.20	4.06
6	Local taxes and fees (e.g. German EEG)	POSO	4.22	4.19	4.00	4.13
7	Other increase in OPEX (materials, CCS, CCU, etc.)	FIN	4.20	4.49	4.00	3.98
8	Availability of renewable energy	TEC	4.00	4.24	3.90	4.79
9	Bureaucracy and other administrative burdens	ORG	4.00	2.98	3.50	2.66
10	Emission-related legislation (e.g. EU ETS)	POSO	4.00	4.59	4.10	4.70
11	National implementation of other framework conditions (e.g. contract for difference)	POSO	3.63	3.17	3.50	3.17
12	Risk of unsuccessful deployment	TEC	3.60	2.00	3.40	1.90
13	Social acceptance of certain technologies	POSO	3.60	3.92	3.30	3.86
14	Integration of new technologies in existing plants	TEC	3.40	2.64	3.30	2.74
15	Information exchange with other parties, collaborative research	ORG	3.20	3.26	2.90	3.00
16	Management of industrial transformation	ORG	3.10	2.22	2.90	2.21
17	Intellectual property management	ORG	3.10	2.99	2.90	2.99
18	Availability of qualified staff	ORG	2.90	2.60	2.60	2.66
19	Issuing of CO_2 storage permits for CCS	POSO	2.89	3.48	2.67	3.48
20	Availability of raw materials	TEC	2.40	3.28	3.10	3.98

Source: own formulation by the authors of the report based on stakeholders' consultation.

Concluding remarks regarding decarbonisation barriers

Different plants will be in different starting positions to integrate new technologies (regarding e.g. the availability of space, the possibilities for industrial symbiosis or even government permits). Therefore, it is extremely difficult to identify any single technology that could be fitted into all existing European steelworks as the best solution. Careful consideration of specific and general conditions is needed to enable the transition towards carbon neutrality. In this context, the stakeholders clearly rated the financial aspects as the biggest barrier to decarbonisation.

In more detail, especially high investment costs for industrial and demonstration plants, increasing OPEX and unknown market conditions for clean steel in particular were assessed as having the highest impact on decarbonisation for both periods under investigation (2020-30 and 2030-50). Also limited funding opportunities and local taxes and fees had average ratings between 'high' (4) and 'very high' (5). These findings are used as basis for the more detailed impact analysis and discussion of policy options in work package 3 of the Green Steel for Europe project (refer to the Impact Assessment Report – Deliverable D3.2 of the project).

Decarbonisation Pathways 2030 and 2050 (Deliverable D1.7)

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

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

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

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

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

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

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

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

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

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

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

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

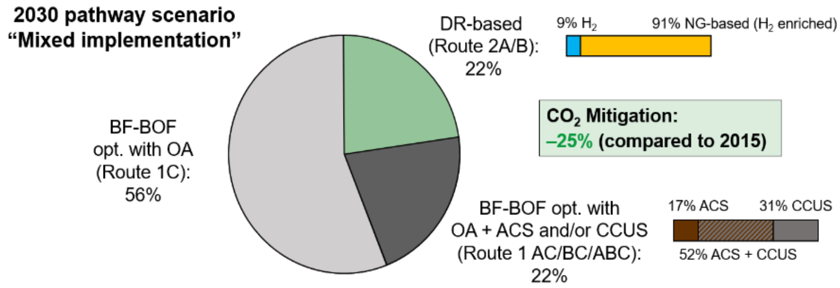
The pathway scenarios show the shares of the considered primary steel production routes in the EU-27. The pathway scenarios focus on primary steel production, as this is responsible for an estimated 87% of current CO_2 emissions of the European Steel Industry. This is consistent with the scope of this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

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

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

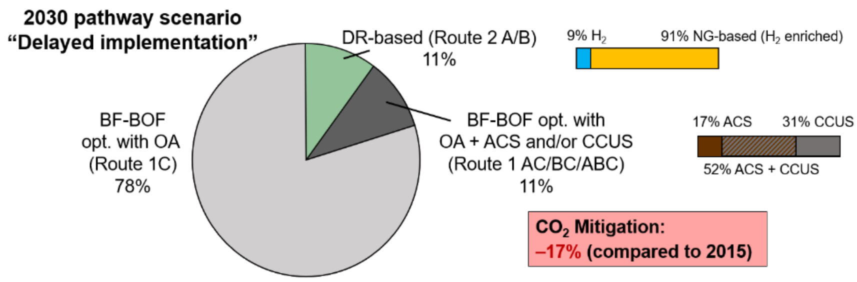
This assessment of national / regional framework conditions was fused with estimations of blast furnace relinings in the EU-27 by 2030. It was estimated that at least 46% of primary steel production capacity in the EU-27 will not be subject to major technology switches by 2030 based on their investment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

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



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

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

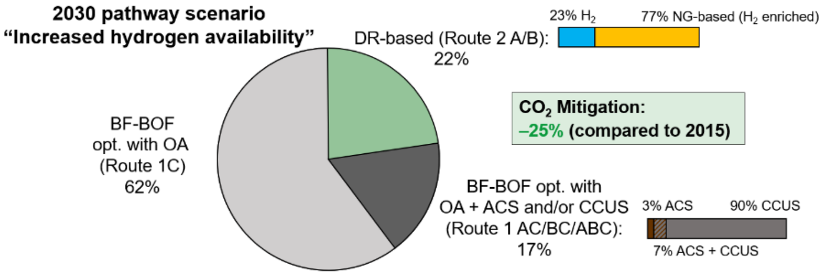


Main examples are:

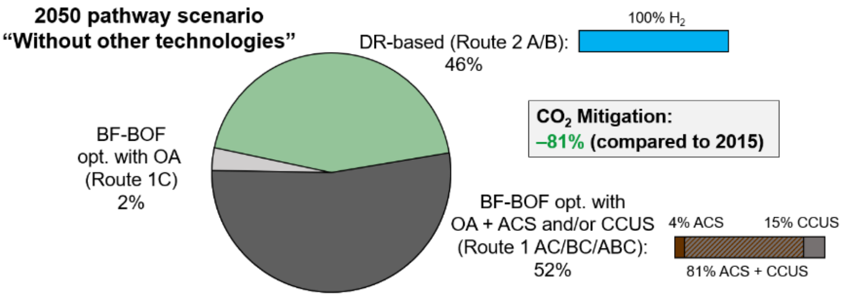
1. Significantly decreasing CO_2 emissions in secondary steel production by extensive use of renewable power. This can be rated as a preferable option since no adaption of steel production sites needing costly investments and involving technical risks is necessary.
2. Increasing hydrogen enrichment for new direct reduction plants.
3. Decreasing energy demand and emissions by increased use of scrap. This approach is however strongly limited for 2030 by the shortage of scrap of sufficient quality.

4. Another option is that primary steel production sites are shut down. However, due to the most probable consequences of carbon leakage and steel quality issues this option can be rated as the worst-case scenario for the European steel industry, for the European economy and for the global climate.

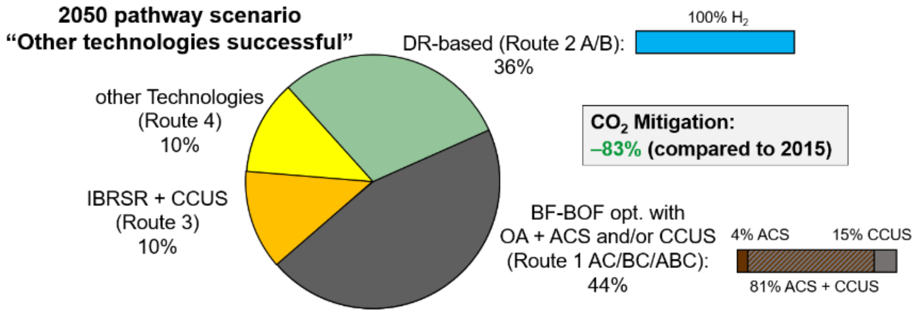
The third 2030 scenario "Increased hydrogen availability" reflects the more extensive use of hydrogen in the steel industry by 2030 (+0.2 million tons resp. +25% was assumed to be utilised). Since the availability of alternative carbon sources in 2030 is not yet clear, it was also assumed that fewer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



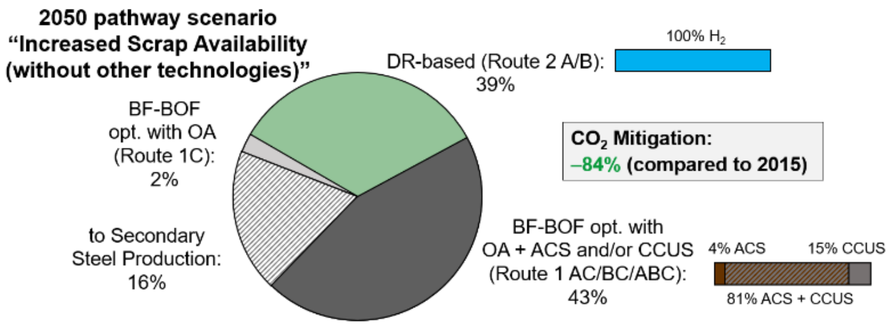
Analyses covering a forecast of almost 30 years obviously include huge uncertainties and a large variance of possible framework conditions and resulting industrial scenarios. To illustrate the range of options three 2050 scenarios were selected which all realise the targeted CO_2 mitigation of >80% but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



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



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



It can be concluded that:

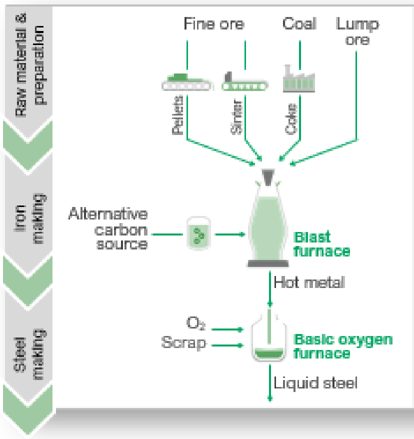
- framework conditions such as production costs as well as the availability of resources and infrastructure dominate the industrial implementation of breakthrough decarbonisation technologies;
- the framework conditions are currently far from positive for decarbonisation investments;
- policy actions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

The next few years will be decisive in achieving the European CO2 mitigation targets with many influential factors also changing in an unpredictable fashion. The Green Steel for Europe consortium is thus strongly in favour of continuing the interdisciplinary roadmapping and assessment work in a follow-up project with consideration to the actual framework conditions and targets and to provide a deeper investigation of aspects which have only been touched upon in this project: secondary steel production including downstream processes and decarbonisation during the decisive years 2030-2040.

Technology Routes based on Optimised BF-BOF Utilisation of Alternative Carbon Sources

Development of effective Solutions towards a Low-CO_2 Steel Production

Fact Sheet



Technical description

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

Framework conditions

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

Economic assessment*

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

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

Feedstock

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

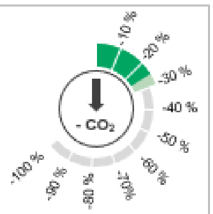
Iron ore

Coal

Alternative carbon source

CO_2 mitigation potential

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



TRL development

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

Geographical information

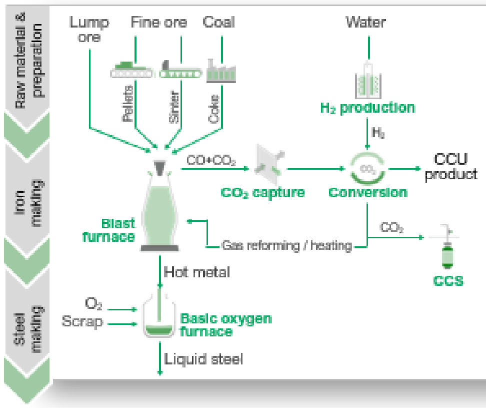
- ☐ Key projects for utilisation of alternative carbon sources in primary steel production in:
  - ☐ Ghent (Belgium)
  - ☐ Dunkerque, Fos-sur-Mer (France)
  - ☐ Bremen (Germany)
  - ☐ Dabrowa Gornicza (Poland)

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

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

DEVELOPMENT OF EFFECTIVE SOLUTIONS TOWARDS A LOW-CO_2 STEEL PRODUCTION

FACT SHEET



Technical description

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

Framework conditions

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

Feedstock

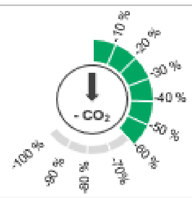
As CCU is an extension of the conventional blast furnace – basic oxygen furnace (BF-BOF) route usual blast furnace feedstock (ores, coke, lime…) is utilised within this technology route. The conversion process further requires hydrogen. In addition, the replacement of certain amounts of coal with alternative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

Iron ore

Coal

CO_2 mitigation potential

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



TRL development

TRL 4 - 8	2020	▮▮▮▮▯▯▯▯▯
TRL 9	2030	▮▮▮▮▮▮▮▮▮
Industrially deployed	2050	▮▮▮▮▮▮▮▮▮

Economic assessment*

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

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

Geographical information

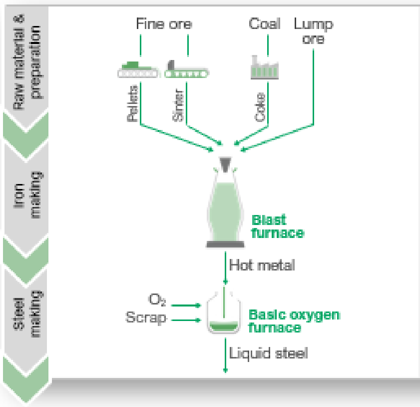
- ☐ CCU projects in primary steel production as indicated in the map in France, Belgium, Netherlands, Germany and Poland
- ☐ CCS projects in primary steel production: Ghent (Belgium), Dabrowa Gornicza (Poland), Bremen (Germany), Eisenhüttenstadt (Germany), Dunkerque (France), Fos-sur-Mer (France)

Optimised BF-BOF with CCUS (Route 1B) factsheet

Technology Routes based on Optimised BF-BOF Other Actions (gas injection, sinter plant,…)

Development of effective Solutions towards a Low-CO_2 Steel Production

Fact Sheet



Technical description

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

Framework conditions

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

Economic assessment

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

Feedstock

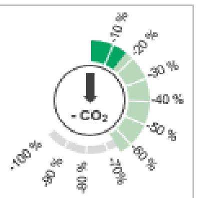
Beyond usual blast furnace feedstock (ores, coke, lime…), gases have to be injected. Either external (hydrogen or natural gas) either process gases, even BF ones after reforming and reheating.

Iron ore

Coal

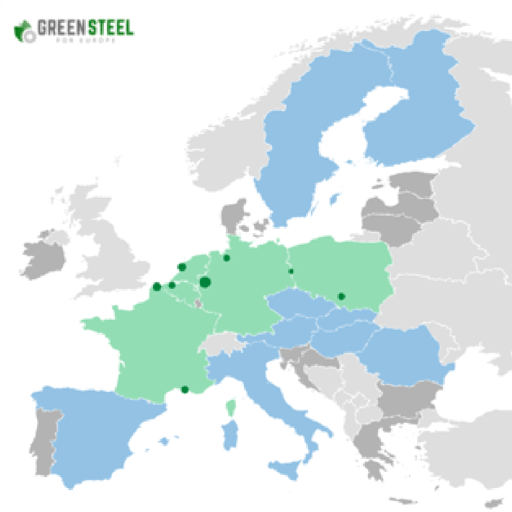
CO_2 mitigation potential

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



TRL development

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



Geographical information

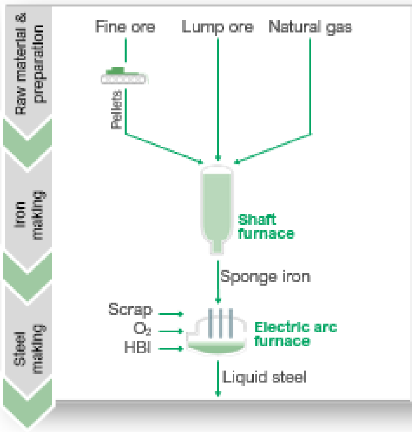
- Projects of further optimisation of BF-BOF routes are planned in
  - France (Dunkerque, For-sur-Mer)
  - Belgium (Ghent)
  - Netherlands (IJmuiden)
  - Germany (Duisburg, Bremen, Eisenhüttenstadt)
  - Poland (Dabrowa Gornicza)

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

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

DEVELOPMENT OF EFFECTIVE SOLUTIONS TOWARDS A LOW-CO_2 STEEL PRODUCTION

FACT SHEET



Technical description

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

Framework conditions

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

Economic assessment

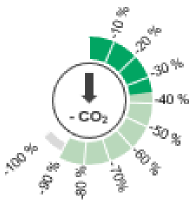
Cost for development up to **TRL 8**	50 M€
Cost for **first industrial deployment**	150 M€
Cost for **production plants**	500 M€

Feedstock

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

CO_2 mitigation potential

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

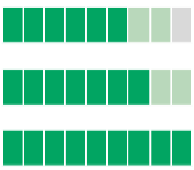


TRL development

TRL 6 - 8 ◂ **2020** ▸

TRL 7 - 9 ◂ **2030** ▸

Industrially deployed ◂ **2050** ▸



Geographical information

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

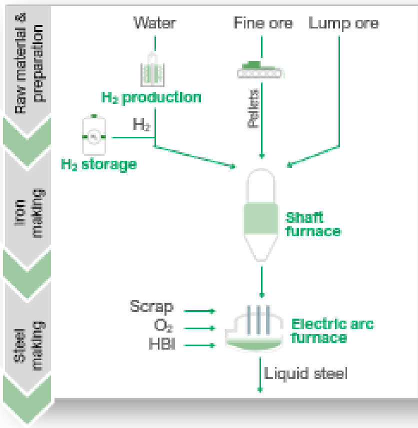
Natural Gas based Direct Reduction (Route 2A) factsheet

Hydrogen-based Direct Reduction (Route 2B) factsheet

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

DEVELOPMENT OF EFFECTIVE SOLUTIONS TOWARDS A LOW-CO_2 STEEL PRODUCTION

FACT SHEET



Technical description

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

Framework conditions

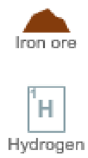
- Availability and price of low-CO_2 hydrogen production
- Energy system without (or with minimum) carbon input
- Strengthening of high-voltage grids
- Hydrogen transport and storage infrastructure must be provided

Economic assessment

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

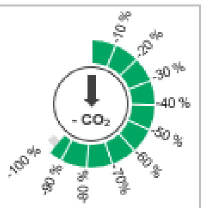
Feedstock

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



CO_2 mitigation potential

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



TRL development

TRL 6 - 8	**2020**	
TRL 7 - 9	**2030**	
Industrially deployed	**2050**	

Geographical information

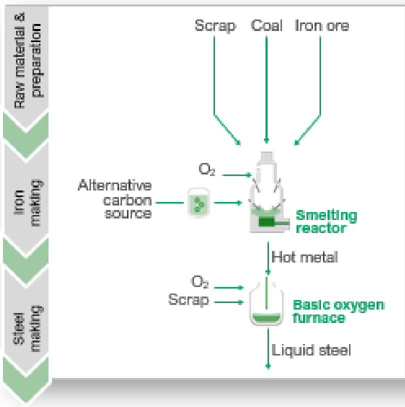
- As most planned Direct Reduction projects target the utilisation of hydrogen in the future, all current key Direct Reduction projects are included in the map
- Direct Reduction Plants in primary steel production are planned in Austria, Belgium, France, Germany, Poland and Sweden

Hydrogen-based Direct Reduction (Route 2B) factsheet

Technology Routes based on Smelting Reduction
Iron Bath Reactor Smelting Reduction

Development of effective Solutions towards a Low-CO_2 Steel Production

Fact Sheet



Technical description

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

Framework conditions

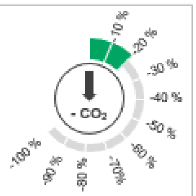
- Carbon capture, usage and storage technologies have to be used in combination with IBSR to attain sufficient mitigation
- Pre-treatment processes for alternative carbon sources
- Price and availability of alternative carbon sources
- O_2 production and CO_2 capture and compression
- Social acceptance

Feedstock

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

CO_2 mitigation potential

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



TRL development

TRL 6	2020
TRL 8	2030
Industrially deployed	2050

Economic assessment

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

Geographical information

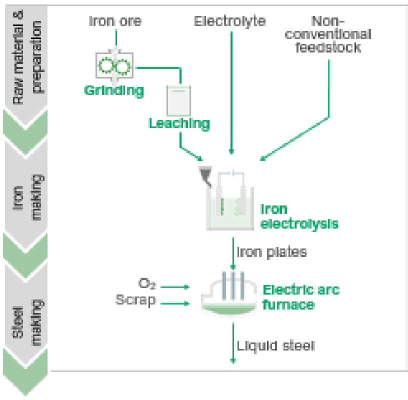
- This technology route (HISARNA) is developed at Tata Steel Europe Ijmuiden plant. All the related investment, energy, feedstock and infrastructures are therefore to be addressed first in the Netherlands.

Smelting Reduction (Route 3) factsheet

Technology Routes based on Ore Electrolysis
Alkaline Iron Electrolysis

Development of effective Solutions towards a Low-CO_2 Steel Production

Fact Sheet



Technical description

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

Framework conditions

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

Economic assessment

Cost for development up to **TRL 8** ▸ M€ 250

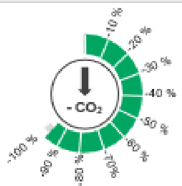
Cost for **first industrial deployment** ▸ M€ 500

Feedstock

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

CO_2 mitigation potential

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



TRL development

TRL 5 - 6 ◂ **2020** ▸

TRL 6 - 8 ◂ **2030** ▸

Industrially deployed ◂ **2050** ▸

Geographical information

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

Iron Ore Electrolysis (Route 4) factsheet

Investment Needs (Deliverable D2.2)

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:

- the current technology developments in the field of CO_2 reduction in the steel industry, with a focus on their related investment needs;
- an investment roadmap, describing the investment needs for the technologies up to industrial deployment; and
- 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:[5] routes based on the optimised conventional blast furnace-

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

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.

- 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 is 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;[6]
3. the cost for full industrial plants: these are the investment needs for a full-scale industrial production plant (normalised to 1 Mt 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.

[6] 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: own composition by the authors of the report 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[7]. * €500 M including EAF. ** Excluding CO_2 transport and storage. *** From greenfield (brownfield CAPEX costs*

[7] 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.

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. 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.[8]

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.

[8] 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, 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 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

Funding Opportunities to Decarbonise the EU Steel Industry (Deliverable D2.4)

Climate neutrality by 2050 is one of the main policy priorities of the European Union (EU), as outlined in the December 2019 European Commission (EC) communication on the European Green Deal (EGD). In addition to being the EU's response to challenges related to climate and the environment, the EGD is also a growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy.

The transition to a climate-neutral society is not only an urgent challenge but also an opportunity to build a better future for all economic sectors. By aligning actions in critical industrial areas through policy, the EC can lead the way to achieving climate neutrality while continuing to drive new business models, guiding private investment, especially in new technological solutions. Developing such solutions, however, will not be easy.

The Covid-19 health crisis has hit the European economy hard, causing a sharp technological slowdown, a fall in the EU's gross domestic product (GDP) and an unprecedented situation of uncertainty. The severe lockdown restrictions imposed to contain the spread of the virus have slowed down the EU's industry, supply chains and production lines, with serious economic implications. In particular, consumption has dropped as jobs have been lost, income has fallen and the public's appetite for buying has declined because of confinement measures closing shops.

Energy-intensive industries (EIIs), among others, the steel sector provide materials and goods that are necessary for the European way of life, and significantly contribute to GDP and employment. EIIs require a considerable amount of energy, directly or indirectly producing greenhouse gases (GHGs), and are responsible for at least 15% of the EU's emissions. Carbon dioxide (CO_2), the GHG most relevant to the steel industry, is difficult to mitigate with conventional technologies.

Consequently, research and innovation (R&I) are fundamental for the development of 'breakthrough technologies' that would allow for compliance with the climate change targets of the EGD while maintaining global competitiveness. Creating the conditions for such innovations at the industrial and commercial scale, however, requires political support and important investments by industry. In other words, a coordinated approach is needed to change production routes, trade and consumption. This implies an unprecedented technological transformation and substantial funding. To bolster this effort and foster innovative approaches, in May 2020, the EC presented a wide-ranging package for the period 2021-27 combining the future multiannual financial framework (MFF, €1,074.3 B) and a specific recovery effort under Next Generation EU (NGEU, €750 B).

The purpose of this report is to analyse all main, relevant financial instruments for an overview of the funding available to reach the zero GHG emissions target in the steel sector set by the EU for 2050. In particular, this report considers a wide range of programmes relevant to the steel sector, both public and private: 25 EU programmes (19 public and 6 private), 24 private funding opportunities (mainly from banks, including both conventional instruments and green bonds), and 81 national and regional instruments (from 11 countries). The member states involved in this research and mapping exercise (Austria, Belgium, Finland, France, Germany, Italy, Luxembourg, the Netherlands, Poland, Spain and Sweden) account for at least 90% of the EU steel production and 80% of CO_2 emissions from all EU steel plants.

EU public funding opportunities

Of all the public funding instruments available at European level, the following are significant:

- Horizon Europe (HE, €100 B), the EU's main funding programme for R&I;

- the Clean Steel Partnership (CSP), the key alliance for CO2 emission reduction in the steel sector, supported by the EU with funding from HEU;
- the Research Fund for Coal and Steel (RFCS), providing funding for generally smaller R&I breakthrough projects in clean steelmaking;
- the LIFE programme, an environment and climate initiative that may provide additional support to the transformation of EU production and distribution, including the steel sector, into a clean, circular, energy-efficient, low-carbon and climate-resilient economy;
- the Innovation Fund (IF), the funding programme for the demonstration of innovative low-carbon technologies; and
- the European Green Deal Investment Plan (EGDIP), the Just Transition Mechanism (JTM) and various other EU instruments, not only for research, development and innovation (R&D&I) but also for first-of-a-kind and infrastructure and skills projects.

The funding programmes dedicated to the specific investment needs of the EU steel industry (see GREENSTEEL D2.2 Report on Investment needs) are not sufficient. Overall, only about €2 B of available EU public funding would be usable for activities aiming to reduce CO_2 emissions in the steel sector for the period 2021-30. An overview of the EU programmes supporting steel sectors is sketched in Figure 1.

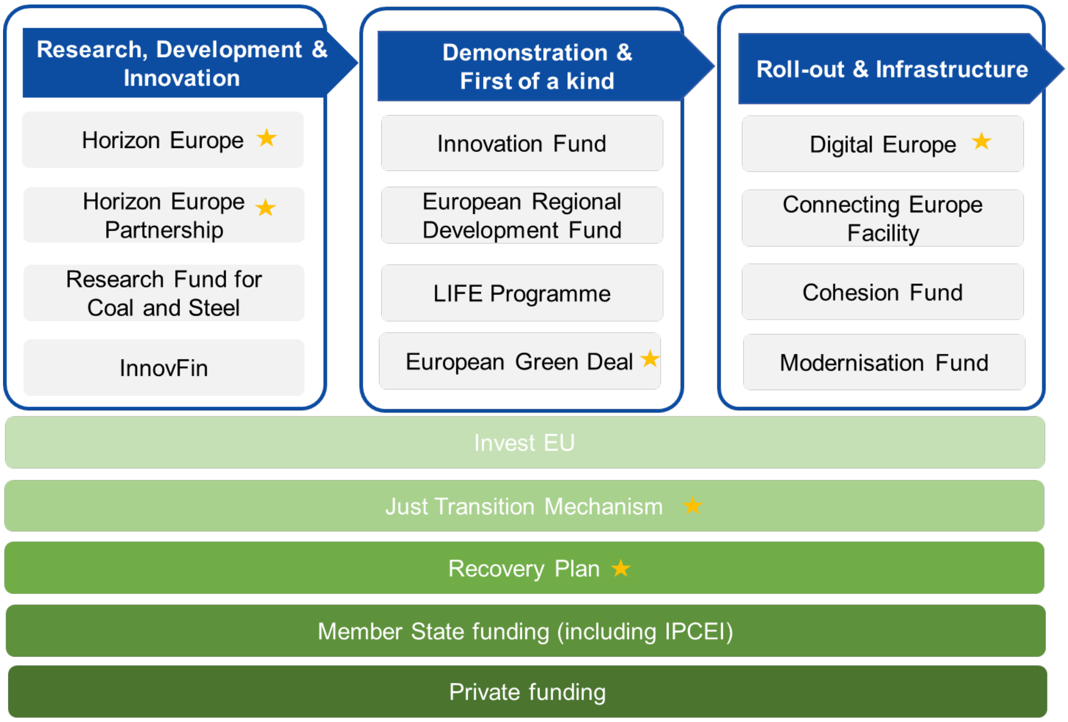


Figure 1 EU programmes supporting the decarbonisation of the steel industry

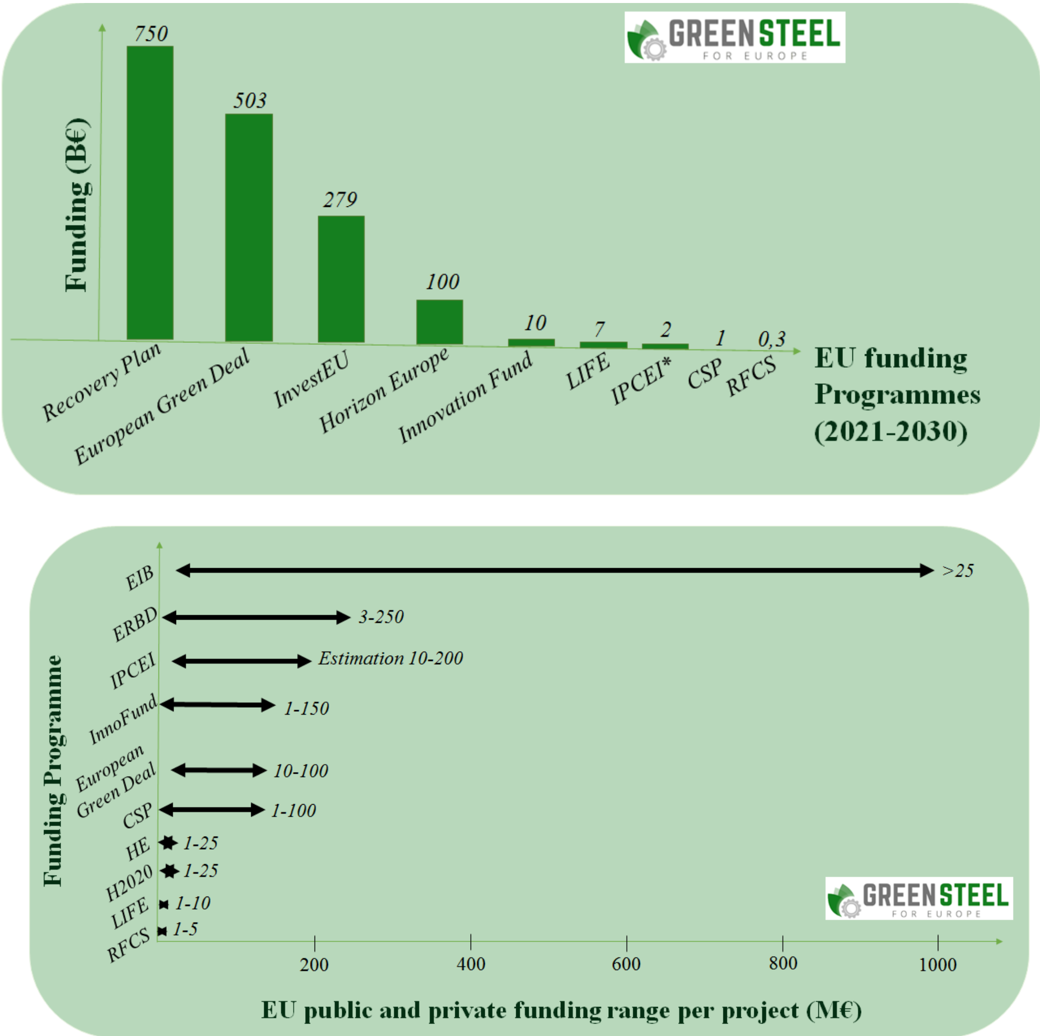


Figure 2 Top: Funding available per programme (2021-30). Down: Estimated range of funding available per project

The above-mentioned estimate does not take into account the possible implementation of an important project of common European interest (IPCEI) in the steel sector, which is still under discussion. Based on the existing IPCEIs (microelectronics and batteries), additional funding could total around €2 B.

Moreover, additional funds could come from initiatives that are either new or under development, such as the EGDIP, the JTM and InvestEU. The EGDIP has a total budget of €503 B (of which InvestEU amounts to €279 B).

As an example, Table 1 shows an overview of European public funding opportunities.

Table 1: Overview of European public funding opportunities

EU Programme	Scope and objective	Funding available in total	Estimation of funding available for decarbonisation of steel	Beneficiaries	Type of action	Blending with other instruments	TRL
Horizon Europe (HE)	Driving economic growth and creating jobs	€100 B (2021-27)	€80 M (2021-30)	Undertakings and individuals	R&D&I RIA, IA, CSA	CSP, RFCS, IF, LIFE	1-9
Clean Steel Partnership (CSP)	Supporting the decarbonisation of the steel industry	€700 M (2021-27)	€975 M (2021-30)	Undertakings and individuals	R&D&I small-scale demonstration projects	RFCS, HE, IF, LIFE	5-8
Research Fund for Coal and Steel (RFCS)	Supporting R&I in coal and steel sectors. Projects cover: (I) production processes; (ii) application, utilisation and conversion of resources; (iii) safety at work; (iv) environmental protection; <u>(v) reduction of CO_2 emissions from steel production</u>	€ 40 M per year (€30 M for steel)	€300 M (2021-30)	Undertakings and individuals	R&D&I Research projects (up to 60%), pilot and demonstration projects (up to 50%) and accompanying measures (up to 100%)	HE, CSP, IF, LIFE	3/5-7
Innovation Fund (IF)	Supporting the demonstration of innovative low-carbon technologies and promoting GHG emission avoidance	€10 B (2021-30)	€500 M (for 20 different sectors) (2021-30)	EII, renewable energy, IT	Demonstration & first-of-a-kind big (€>7.5 M) or small (€<7.5 M) projects. Big projects: up to 60% of additional costs related to innovative technologies; small projects: up to 60% of CAPEX	HE, CSP, RFCS, LIFE	7-9
LIFE	Promoting environment and climate actions	€5.4 B (2021-27)	€50 M (2021-30)	Climate, environment, nature	Demonstration & first-of-a-kind projects	HE, CSP, RFCS, IF	6-9

EU Programme	Scope and objective	Funding available in total	Estimation of funding available for decarbonisation of steel	Beneficiaries	Type of action	Blending with other instruments	TRL
European Green Deal Investment Plan (EGDIP)	Helping the most vulnerable regions deal with the socio-economic impacts of the green transition	€503 B (2021-27)	Currently under evaluation at EU level	Climate, environment	Demonstration & first-of-a-kind projects	HE, CSP, RFCS, IF	7-9
Digital Europe (DE)	Building the strategic digital capacities in the EU and facilitating the wide deployment of digital technologies	€9.2 B (2021-27)	Not directly contributing to CO_2 emission reduction	Undertakings and individuals	Roll-out & infrastructure digitisation projects	Draft orientation	Draft orientation
Connecting Europe Facility (CEF)	Promoting growth, jobs and competitiveness through targeted infrastructure investment at European level (to support the development of high-performing, sustainable and efficiently interconnected trans-European networks in the fields of transport, energy and digital services)	€28.7 B (2021-27)	Not directly contributing to CO_2 emission reduction	Undertakings and individuals	Roll-out & infrastructure projects in energy, telecom and transport sectors	CF	Infrastructure networks
Erasmus+	Supporting education, training, youth and sport in Europe	€14.7 B (2021-27)	Not directly contributing to CO_2 emission reduction	Undertakings and individuals	Projects aimed at skills, mobility, cooperation, and policy reform	Not applicable (co-financing up to 100%)	Education, skills and training
ERA-NET	Supporting the preparation and establishment of networking structures, and the design, implementation and coordination of joint activities	Depending on the amount allocated by each region	Indirect contribution to CO_2 emission reduction	Depending on the specific call	SMEs, depending on EC and regional criterial	EC	Depends on the specific call

EU Programme	Scope and objective	Funding available in total	Estimation of funding available for decarbonisation of steel	Beneficiaries	Type of action	Blending with other instruments	TRL
		and the EC					
SME Instrument	Supporting high-risk, high-potential SMEs to develop and bring to the market new products, services and business models that could drive economic growth	1.2 B€	Estimated not directly contributing to CO_2 emission reduction	SMEs	Dedicated to SMEs COSME, INNOSUP, EUROSTAS, SME instruments	Regions	4-9
Important project of common European interest (IPCEI)	Providing a contribution to Union objectives and significant impact on economic growth, sustainability or value creation across the EU	Agreement among at least three MSs	Around €2 B (based on the two existing IPCEI for R&D)	By sector	R&D&I	National funding, structural funds and central EU funding programmes	5-9

Source: own composition by the authors of the report

Figure 3 shows the distribution of the 81 national and regional public instruments analysed by member states and region. The figures demonstrate the interest of member states and regions in supporting industrial transformation. The number of national instruments is consistently higher than that of regional ones. However, regions also are demonstrating growing support. That said, rules tend to differ significantly.

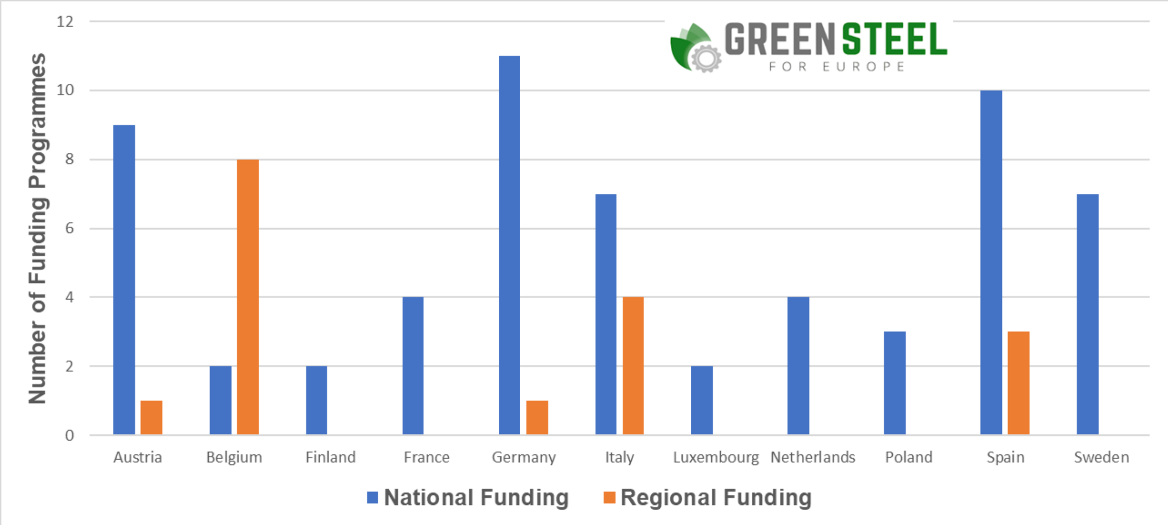


Figure 3: National & regional funding programmes supporting the decarbonisation of steel industry

Source: own calculation by the authors of the report.

Quite often, national and regional programmes are insufficiently coordinated in terms of scope, timeline and funding availability. Long-term visibility and stability must also be ensured to allow for blending with the new set of EU initiatives, in order properly to support CO_2 emission reduction in the steel sector.

Based on the information currently available on national and regional funds, approximately €400 M per year would be available for CO_2 emission reduction in the steel sector for all 11 European countries considered in the analysis for the period 2021-22. This amount is in addition to the amount cited above for EU instruments.

The report also present details on private instruments available at the European, national and regional levels, including from banks, highlighting, whenever possible, synergies such as:

- involvement of public and private investors, increasing the total amount of financing available to projects compared with support through grants only;
- greater and more extensive support to beneficiaries that may not be supported by a single grant at EU or national level, also taking into consideration state aid rules;
- risk reduction and bridging the so-called “innovation valley of death” (the gap between academic-based innovations and their commercial application in the marketplace); and
- better alignment of company interests with the successful outcome of the project.

In this context, every year all main development banks (World Bank, International Finance Corporation, European Bank for Reconstruction and Development, European Investment Bank, Asian Development Bank and African Development Bank) renew their commitment to sustainability by launching new green bond emission plans (see figure 4).

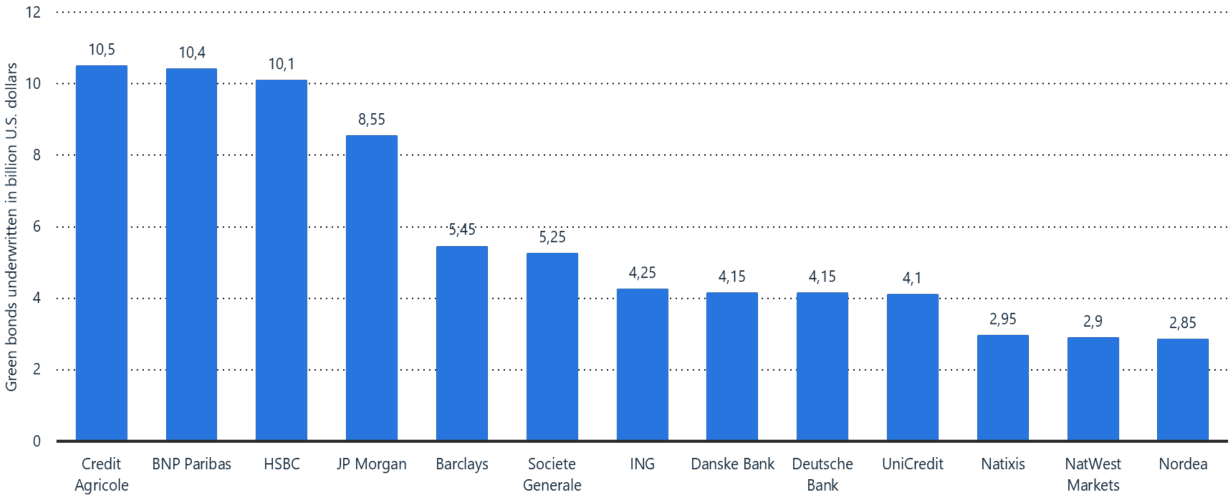


Figure 4: Leading European banks for green bond underwriting in 2019, by value of bonds (B $)

Source: Climate Bonds Initiative – Statista.

Sequencing is the possibility to continue sustaining an ongoing project through the same or a similar funding mechanism. Based on the information collected here, sequencing has not generally been highlighted as a key bottleneck to be addressed in the rules, either at the EU level or at national/regional levels.

In very few cases is sequencing regulated by rules associated with the funding source. Consequently, even though sequencing is important for supporting long-term technological development, the use of the tool depends much more on the specific technical nature of the project and its own evolution than on the detailed definition of rules for the funding instrument.

Conclusions

The 2050 climate stabilisation challenge can be met only if private capital is sufficiently supported by a consistent and coordinated framework of public funding opportunities at the EU, member state and regional levels. Both EU and national/regional financial support schemes for the decarbonisation of industrial installations must be made available at sufficient scale for the entire transition period from 2021 to 2050. In addition, the steel industry and other stakeholders will need to cooperate to overcome the technological and economic challenges they face with regard to the implementation of low-carbon production technologies.

However, the analysis of EU financial support conducted in the framework of this report has found that even by combining significant financial mechanisms—such as HE, CSP, RFCS, LIFE and IF—only about €2 B would be available as grants for CO_2 emission reduction in the steel sector for the period 2021-30. This is, of course, a large amount of money but unfortunately far from enough to turn breakthrough technologies into technically achievable and economically viable solutions, which would allow the sector to do its part toward achieving the objective of a climate-neutral EU by 2050. In addition, based on currently available information, the analysis of national and regional funding instruments has found that approximately €400 M per year would be available for reducing CO_2 emissions in the steel sector in the period 2021-22, for all 11 of the European countries considered. These amounts are insufficient to meet the investment needs of the steel sector

Guidelines and approaches for using funding in line with technological developments (Deliverable D2.5)

Huge investment in innovation and breakthrough technologies are crucial if the European steel industry is to meet EU climate and energy targets, boost its competitiveness and give stakeholders a 'first-mover' advantage on the global scene.

This report provides guidelines to EU and national policymakers and industry players on how to harness existing and forthcoming funding opportunities to decarbonise the EU steel industry and achieve the EU energy and climate targets. The guidelines are developed based on the main findings of the report on Funding Opportunities to Decarbonise the EU Steel Industry[9].

D2.4 finds that the financial support relevant to the steel sector consists of 25 EU programmes (19 public and 6 private), 24 private funding opportunities (mainly from banks, including both conventional instruments and green bonds; 13 with specific tables) and 81 national and regional instruments (from 11 countries). All the main relevant financial instruments are analysed based on the information currently available, including blending and sequencing options, to enable a global view of funding to reach the 2050 European zero greenhouse gases (GHG) emission target. Findings of the Funding Opportunities to Decarbonise the EU Steel Industry report and the Investment Needs report[10] also show that the support ensured by the funding programmes dedicated to the investment needs of the EU steel industry is currently not sufficient. Considering the significance and key role of the European emissions reduction target for future generations and the high impact of the steel industry on overall CO_2 emissions, an enormous effort is required from steel stakeholders.

To achieve the challenging CO_2 reduction objectives, a strong collaboration and joint commitment of the private and public sector are needed at EU, national and regional level (see Figure 1).

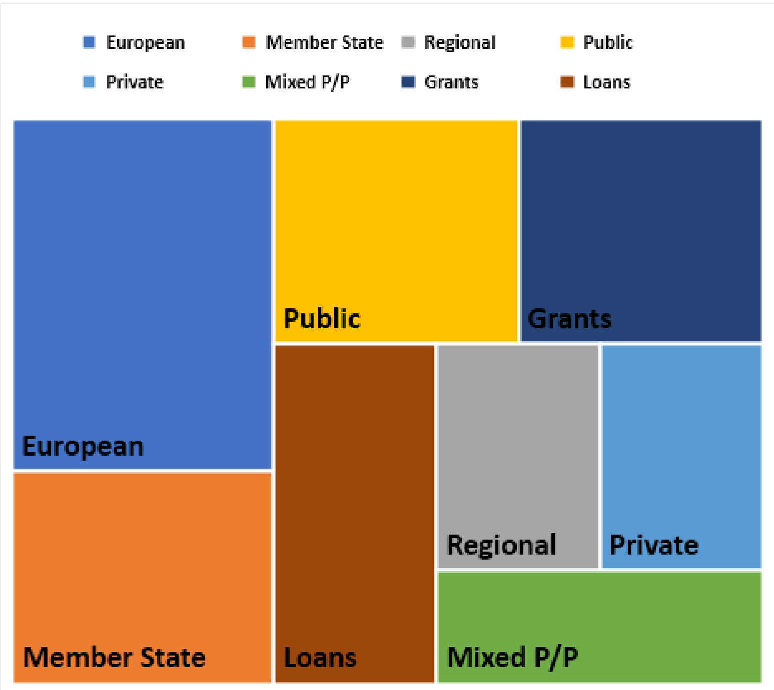


Figure 1 - Main funding elements of the blending framework

[9] Deliverable D2.4 of the 'Green Steel for Europe project'- GREENSTEEL

[10] Deliverable D2.2 of GREENSTEEL

Source: authors' own compilation.

At European level, the following synergies of funding programmes are suggested:

- Combining Research Fund for Coal and Steel (RFCS) and Horizon Europe (HE). To better achieve the synergies at European level, three options could be considered:
    - Combining HE and RFCS funds and assets under the same Clean Steel Partnership (CSP) call for proposals (the so-called 'one-stop shop approach') to ensure synergies at European level;
    - Presenting the call as a single package (the so-called 'single package approach'); and
    - Publishing at least (RFCS and HEU) CSP calls with the same deadline.
- Combining RFCS and HE with the Innovation Fund (IF):
    - HE and IF: HE can support innovation up to the pilot phase and IF can support innovation in the demonstration and scale-up phases;
    - RFCS and IF: RFCS can support innovation for the research phase and up to the pilot and demonstration phase, and IF can support innovation for the scale-up phase.
- Combining RFCS and HE with LIFE program:
    - HE and LIFE: the E is now working to provide more support through the LIFE Climate Action financial instrument to have a basis for a larger number of projects.
    - RFCS and LIFE: the LIFE Climate Action sub-programme supports projects to develop innovative ways to respond to the challenges of climate change in Europe. In particular, one of the main objectives of the sub-programme is to contribute to the shift towards a low-carbon and climate-resilient economy. Importantly, this objective can be reached through synergies with the RFCS.
- Combining RFCS and HE with IPCEI:
    - Member states, the EU steel industry and other actors (under the supervision of the CSP) could explore the possibility to table a proposal for setting up an IPCEI on Green Steel. This IPCEI would create a legal framework allowing the combination of EU, national, regional and private funding in compliance with state aid rules.
    - In this respect, the European Commission may consider an 'integrated project', i.e. a group of single projects inserted in a common roadmap or programme aiming at the same objective and based on a coherent systemic approach. The individual components of the integrated project may relate to separate levels of the supply chain but must be complementary and necessary for the achievement of the important European objective.
- Combining HE with ESIF:
    - Over the next budget cycle, the Cohesion Fund and the structural funds aim at supporting the green transition. In this respect, the combination of funding among HE and ESIF for ambitious industrial projects is especially concerning. In this report an extensive analysis of this two instruments' combination, an overview of the differences between H2020 and structural funds and finally, on the practical side, a real industrial case of combination between ESIF and EIB loans are presented.

Synergies and blending of funding program at national and regional level is also necessary to achieve the abovementioned objectives. Current national and regional instruments are often insufficiently coordinated in terms of their scope, timeline and funding availability. Since there are potentially €800 M available from national and regional instruments to support the CO_2 emissions reduction in the steel sector for the period 2021-22[11] in the 11 EU countries considered, full knowledge of those instruments is needed to create synergies with the EU instruments. In this case, the general aim is to establish formal and informal mechanisms of cooperation with member states to create additional synergies with national and regional policies and programmes.

Finally, synergies at project level can be achieved through a combination of:

- funding related to the same project idea;
- inter-related or successive projects,
- parallel projects;
- projects at different Technology Readiness Levels (example of 'vertical' synergies in Table 1).

Table 1: Synergies among projects in terms of Technology Readiness Level (TRL)

TRL	Funding instrument
TRL 1 – Basic principles observed	HE, RFCS, regional funds
TRL 2 – Technology concept formulated	HE, RFCS, regional funds
TRL 3 – Experimental proof of concept	HE, RFCS, regional funds
TRL 4 – Technology validated in lab	HE, RFCS, regional funds
TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	HE, RFCS, IF
TRL 6 – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	HE, RFCS, IF
TRL 7 – System prototype demonstration in operational environment	HE, RFCS, IF
TRL 8 – System complete and qualified	HE, InvestEU
TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)	HE, InvestEU

Source: own compilation by the authors of the report.

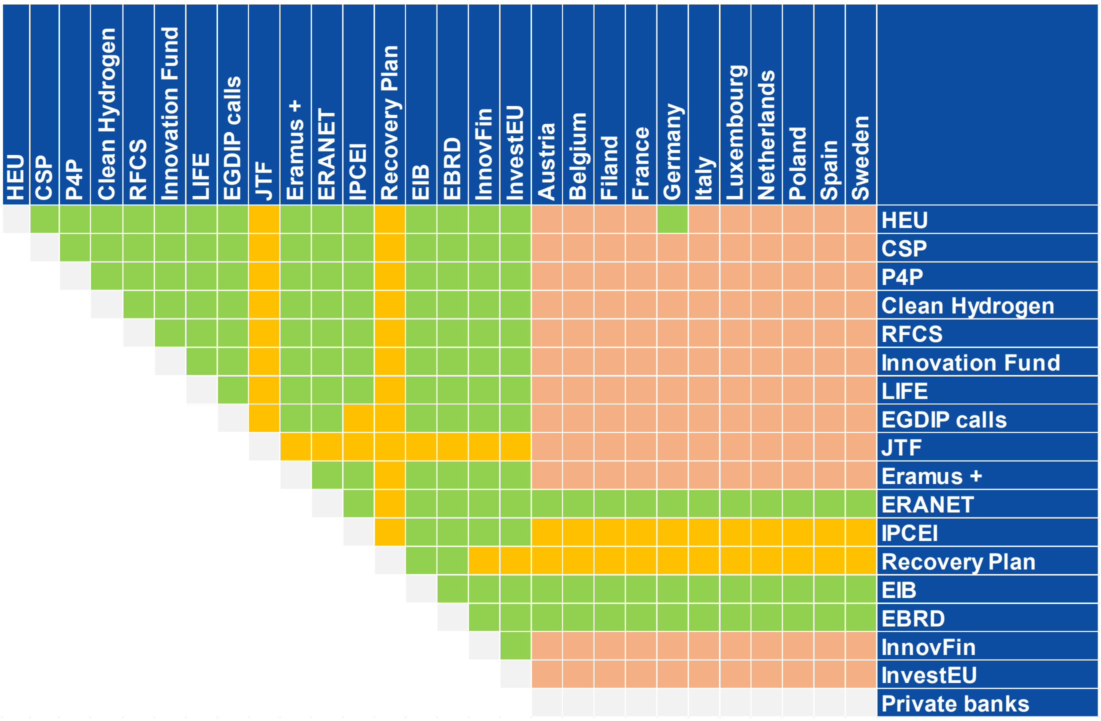
From the analysis of private instruments at European, national and regional level, including banking instruments, several possible synergies between public and private sectors have emerged:

- involvement of public and private investors to increase the total amount of financing available to projects as compared to support through grants only;

- greater and more extensive support to beneficiaries that may not be supported by a single grant at EU or national level, also considering state aid rules;
- risk reduction and bridging over the 'innovation valley of death'; and
- higher alignment of company interests and the successful outcome of the project.

Several possible blending scenarios are shown in Table 2.

Table 2 - R&D&I funding instruments – Blending



Source: own composition by the authors of the report.

*Note: **green**: synergies are possible between the instruments; **yellow**: to be specifically defined; **red**: synergies are generally not allowed; and **grey**: information is currently not sufficient*

Finally, Table 3 evidences in a comprehensive way the possible synergies existing between the main European funding programmes, national and regional funding opportunities. While at European level the various programmatic resources can generally be combined (left side of the table), synergies between EU and national/regional instruments are generally not allowed, except for a small number of cases (right side of the table).

Besides suggestion for synergies of funding, the report also presents several 'success stories' - examples of funding instruments used by steel companies to support their decarbonisation technologies. Several examples of funding instruments used by the steel sector are EIB's loan to Arcelor Mittal, Marcegaglia Group and Aperam; EIB, H2020 and national instrument's financing and guarantee for Salzgitter AG; and the Swedish Energy Agency's funding support for SSAB, LKAB and Vattenfall.

As a final comment, to reach the 2050 climate objectives, private and public funding must join forces within a consistent and coordinated framework. The steel industry and other stakeholders will need to cooperate to overcome the technological and economic challenges regarding the implementation of CO_2-low production technologies.

Table 3 - Main financial instruments available to the steel sector by project size

	Project with funding <7.5 M€	Project funding between 7.5 and 100 M€	Project funding between 100-250 M€	Projects with funding > 250 M€
Horizon Europe (HE) and related relevant PPPs (P4P, Clean Hydrogen)	Pillar 2 calls to be published at the beginning of 2021.			
Clean Steel Partnership (CSP)	Expected calls in April/May 2021;			
Research Fund for Coal and Steel (RFCS)	Usual call every year; Average project dimension 1.5 M€ funding.			
Innovation Fund (IF)	IF small-scale instrument (no calls currently open. Calls expected to be launched on beginning 2021).	- Budget up to 150 M€ - Calls published on 3rd of July 2020. Deadline 29th October - At least 7.5 M€ CAPEX. - A single legal entity, as well as consortium, can apply. - Breakthrough projects; it is funded the innovation gap respect to conventional plant. - Maximum grant 60% of the relevant costs. - Payments against GHG emissions avoidance. - Cost incurred prior of the signature of the GA are not included in the calculation of the relevant cost. - IF grant is not considered to be State aid - A project that has received the IF support may also receive a contribution from any other Union programme.		

European Green Deal (EGD) Calls	CSA projects starts from 2 M€	Topic Area 3 (of interest of the Steel Sector). Work Programme available. 10 -40 M€ project dimension. Deadline on January 2021		
InvestEU	The InvestEU Fund is expected to mobilise more than 372 B€ of public and private investment through an EU budget guarantee of 26,2 B€ that backs the investment of financial partners such as the EIB Group and others.			
Important Projects of Common European Interest (IPCEI)	- Two types of IPCEI actions interesting for the GREENSTEEL project: 1. IPCEI - Hydrogen for climate action 2. IPCEI – Low carbon industries (still in preparation) - Currently the maximum amount for a single MS, based on the two already active IPCEI (Microelectronics and Batteries), amount to 400 M€. - Funding up to 100% of the relevant cost, even if industry co-financing is highly expected. - IPCEI follows the State aid rules (2014/C 188/02).			
National and Regional	Considering the wide variety of rules, these instruments have to be specifically verified on a case-by-case base.			
EIB		Loans > 25M€, e.g. InnovFin Energy Demonstration Projects up to 75M€	No defined upper limit	
ERBD	Loans available in the range 3-250 M€ (average amount €25 M). Full details are negotiated with the client on a case-by-case basis-			
Banks	Conventional instruments and green bonds			

Source: own composition by the authors of the report.

Note: green = funding available; yellow = funding rules under definition; red = funding not available.

Impact Assessment (Deliverable D3.2)

Green steel can be achieved through various technological pathways, some of which may be more suitable for specific producers and regions, depending on local factors related to energy infrastructure and demand. EU policy has an important role to play in the decarbonisation of the steel industry. Nevertheless, member state environmental, energy and industrial policies can also affect the prospects for certain industrial decarbonisation pathways. In the long term, some decarbonisation technologies may end up being more successful and competitive than others. This summary examines some of the most promising policy options that can support the technological pathways[12] and leverage the funding opportunities[13] identified in the project.

It includes policy options directly linked to specific technologies, such as green hydrogen, CCUS, renewables and scraps, but also options related to specific policy strategies such as carbon pricing – which is strengthened by the EU's Fit-for-55 package – and funding, which applies horizontally across the policy areas. Some options aim to address specific problems related to the individual technologies, while others could support industrial decarbonisation or emission reductions more generally. A number of cross-cutting policy options that can contribute to all policy areas have also been identified.

Below, the six policy areas (funding, carbon pricing, renewable electricity, green hydrogen, CCUS, scraps) are discussed separately, covering the specific policy problems, policy objectives, and policy options as well as the expected results from the most promising options.

1. Funding

The general problem for funding is the limited amount of funding flowing towards decarbonisation technologies in the steel industry. This does not necessarily mean there is an insufficient amount of potential funding, but rather that the business case for individual transformational investments in (costlier) green steelmaking production capacity is still missing.

Specifically, the funding challenges of green steel are also rooted in the – as of yet – higher costs of green steelmaking, both with regard to CAPEX and OPEX. In addition, green steelmaking technologies are unproven at scale (although there is rapid progress in some technologies, such as hydrogen-based steelmaking) and therefore carry greater risk. While some public funding is available to be invested in emission reduction technologies for the industrial sectors, they are not sufficient considering the transformational investment needs. Moreover, funding is especially required to fill the gap between R&D and commercial deployment at scale. Investments will also depend on there being a market for green steel specifically.

Therefore, green steel funding should cover a wide range of drivers that lead to an increase in costs and investment needs. This includes new low-carbon production plants that replace existing blast furnaces, as well as low-carbon energy sources and infrastructure (e.g. hydrogen and CCUS). While public funding is inevitable to a degree, private funding would ideally constitute the biggest share of green steel investments. However, the market conditions for green steel will be a key driver for such private investment. The risk of carbon leakage can negatively impact it all. Competition from non-EU producers that face lower carbon costs can deter investments in green steel. Policy interventions aimed at creating a market – for example through green public procurement

[12] See Work Package 1 of GreenSteel

[13] See Work Package 2 of GreenSteel

(GPP) – can, nevertheless, improve the business case for such green steel investments. However, knowledge about green steel, and demand for it, should be present throughout the whole steel value chain.

There are also several challenges related to combining various public and private funding mechanisms to ensure that their impact is maximalised. It is not always possible to blend different sources of funding, even if that would increase the impact. Furthermore, steel investments have long lead times and require lengthy financial commitments, even if some funding instruments operate on shorter-term project bases. Furthermore, in the wake of the Covid-19 pandemic, the capacity of member states to provide funding (i.e. State aid) may be constrained due to budgetary pressure.

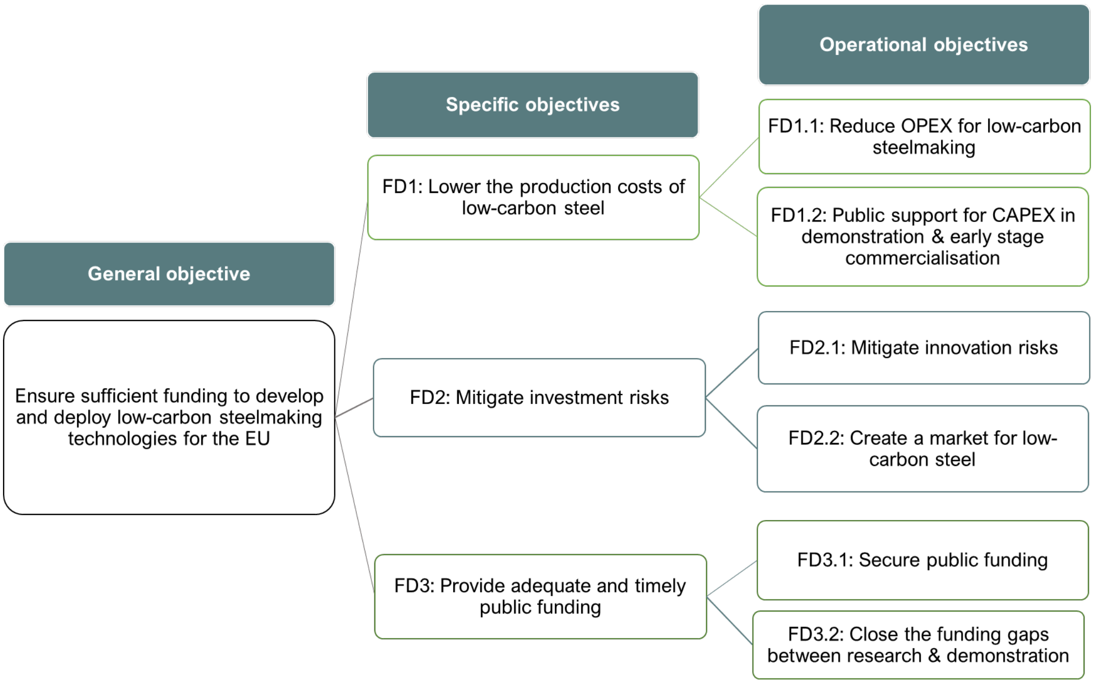


Figure 1: Policy objectives of funding (FD) for decarbonisation technologies in the steel industry

Source: own composition by the authors of the report.

The objectives of funding policies are threefold in light of the above problems: the production costs of green steel need to decrease (specific objective FD1), investment risks should be mitigated (specific objective FD2), and funding should be aligned with the needs of the steel industry in terms of timing and scale (specific objective FD3) (see Figure 1). Some problems require specific and dedicated solutions.

- To address the greater OPEX costs of green steel, the use of EU funding programmes such as the ETS innovation fund is recommended. The large CAPEX requirement cannot be fully covered with public funds, it therefore requires the mobilisation of private funds (see specific objective FD1).
- Public support could also go beyond direct funding, using tools such as risk mitigation instruments and loan guarantees to lower capital costs. Besides 'technology-push' measures, policies that result in 'demand-pull' for green steel are also important. These measures, such as GPP, green labels and standards, are not classic funding instruments but can nevertheless address some of the gaps in the current steel investment landscape. In fact, these three policy tools can often address multiple policy objectives at once, going beyond funding goals. They are therefore also reviewed separately as cross-cutting policy options, together with the impact of higher carbon prices and carbon contracts for differences (CCfDs) (see specific objective FD2).

- Finally, synergies between funding instruments are important. Initiatives such as the Clean Steel Partnership (CSP) can play an important role here, as well as coordination instruments such as the Important Projects of Common European Interests (PCEIs), as they could target technologies that enable green steelmaking (as is already happening with hydrogen) or the steel value chain as a whole (see specific objective FD3).

Table 1: Overview of policy solutions[14] – Funding

	Effectiveness	Efficiency	Feasibility	Coherence
Option FD1: promoting the use EU funding programmes to finance OPEX of low-carbon steel	green	green	green	green
Option FD2: mobilising private funding to support CAPEX of decarbonisation technologies	green	green	green	green
Option FD3: ensuring public support for CAPEX beyond direct public funding	green	yellow	green	green
Option FD4: introducing risk mitigation and loan guarantee instruments for investments in decarbonisation technologies	green	yellow	orange	green
Option FD8: ensuring that EU resources will support the green transition in the steel industry	green	green	green	green
Option FD9: identifying pathways (2030 & 2050) for decarbonisation technology routes and ensuring that EU & national policy makers account for them	yellow	yellow	yellow	green
Option FD10: creating synergies in EU level funding via the Clean Steel Partnership	green	green	yellow	green
Option FD11: creating additional synergies in EU level funding via blending & sequencing of different opportunities	yellow	green	yellow	green
Option FD12: establishing an IPCEI for low-carbon steel	yellow	green	green	yellow

*Note: This table presents the policy options in the funding area that would support the decarbonisation of the EU steel industry. The options are assessed based on the four criteria under the Better Regulation guidelines: their effectiveness, efficiency, feasibility and coherence. Colour legend: **orange** - low, **yellow** – moderate, **green** – high. For instance, a policy option that has a green cell in the Effectiveness column is considered to be "highly" effective. Source: own composition by the authors of the report*

2. Carbon pricing

The EU's main carbon pricing policy – the EU ETS – also applies to steel sector emissions. However, the EU ETS is insufficient, on its own, to fully decarbonise the sector. This is partly because carbon prices are too low compared to the abatement costs in the steel sector, but also because there are other economic and non-economic barriers to the deep decarbonisation of energy-intensive industries that make carbon pricing on its

[14] Policy options FD3-5 have not been included in this overview as these options are assessed in the cross-cutting policy chapter

own insufficient. In addition, the steel sector is considered at risk of carbon leakage, which may deter private investment in climate-neutral technology.

Several specific issues hinder the ability of the EU ETS to contribute to the decarbonisation of the steel sector. The supply of allowances in the ETS is relatively rigid, even if it has become more responsive to fluctuations in demand after the introduction of the Market Stability Reserve. Demand is more volatile, however, which has led to supply-demand imbalances in the ETS, and with it, to carbon price volatility. This volatility undermines predictability and deters investment. While the ETS price increasingly reflects future scarcity, this is insufficient, in the short term, to drive the investments the steel sector requires. The long lead times of the steel sector's investments exacerbates this issue. Furthermore, so long as the market for green steel remains limited, private investments may likewise lag.

The risk of carbon leakage can hinder the effectiveness of carbon pricing not just because of the purported threat to competitiveness, but also because of the measures that are taken to mitigate said carbon leakage risk. Free allocation can support the bottom line of steel companies, but it also dampens the carbon price signal. The suggested alternative, i.e. the Carbon Border Adjustment Mechanism (CBAM), can have many different designs, each with significant impacts on investment signals and competitiveness. Beyond direct carbon costs, the carbon leakage risk may also arise through indirect costs, i.e. higher energy prices (mostly for electricity) due to the pass-through of the carbon price in energy prices. Finally, the competitiveness of the steel industry is affected by many more (global) factors beyond climate policy. This too, will affect the capacity and willingness to invest in green steelmaking.

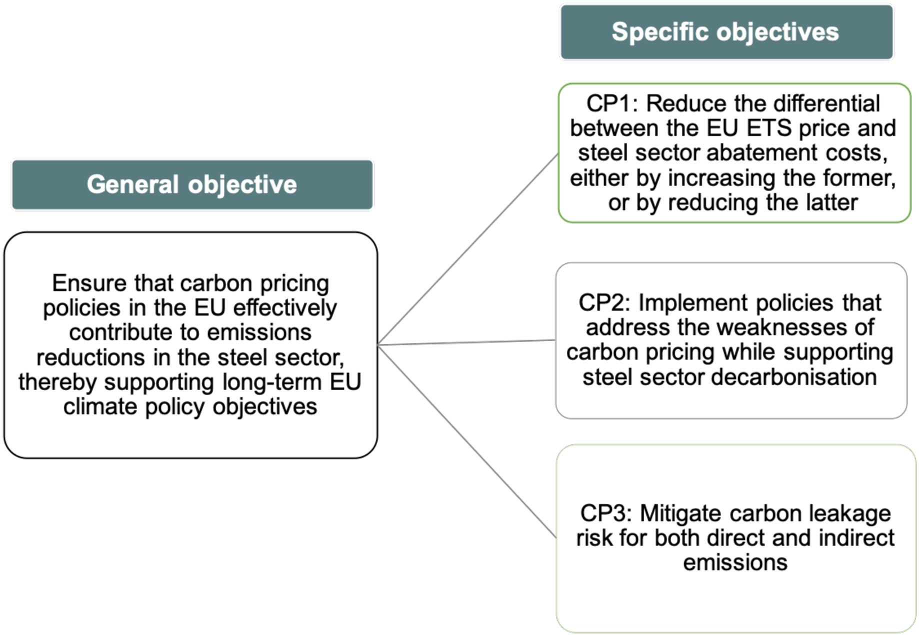


Figure 2: Policy objectives on carbon pricing (CP) to decarbonise the EU steel sector

Source: own composition by the authors of the report.

The general objective of policy interventions should be to make carbon pricing contribute effectively to the steel sector's decarbonisation. To achieve that, the carbon pricing instruments themselves could be strengthened, but, as an alternative, policies that reduce abatement costs in the steel sector could be implemented instead. Once abatement costs are lower and green steelmaking is more competitive, the impact of a carbon price signal increases. Some additional policies that address the inherent weaknesses of carbon pricing are nevertheless recommended. This includes, for example, demand-side policies that can support an increased market for green steel. Finally, the carbon leakage risk should be mitigated for both direct and indirect carbon costs. However, mitigating carbon leakage risk is not always the same as supporting industrial competitiveness, and vice versa.

The most promising policy option is the introduction of CCfDs. CCfDs specifically address a key weakness of current carbon pricing policies in the EU: carbon prices are too volatile and too low to trigger investments in green steel. By agreeing on a ‘strike price’ that would enable a producer to invest in green steelmaking capacity, a variable subsidy could be agreed. CCfDs work in tandem with the EU ETS: if the carbon price gets closer to the agreed strike price, the subsidy payments can be lowered.

In general, policies (such as public investments) aimed to lower the steel sector’s abatement costs would be effective, as the ETS price level at which carbon-intensive steelmaking would be discouraged and made less competitive will decrease as well. The CBAM can also make investments in green steelmaking more attractive, although much depends on the design of the mechanism and what happens to existing free allocation.

Table 2: Overview of policy solutions[15] – Carbon pricing

	Effectiveness	Efficiency	Feasibility	Coherence
Option CP1: adopting a hybrid MSR design				
Option CP2: reducing steel sector abatement costs				
Option CP5: introducing CCfDs				
Option CP6: implementing a CBAM				
Option CP7: introducing a separate industrial competitiveness policy for the steel industry				

*Note: This table presents the policy options in the carbon pricing area that would support the decarbonisation of the EU steel industry. The options are assessed based on the four criteria under the Better Regulation guidelines: their effectiveness, efficiency, feasibility and coherence. Colour legend: **orange** - low, **yellow** – moderate, **green** – high. For instance, a policy option that has a green cell in the Effectiveness column is considered to be “highly” effective. Source: own composition by the authors of the report.*

3. Renewable electricity

Renewables can contribute to the decarbonisation of the steel industry in two ways: directly, using electricity to power electric arc furnaces; or indirectly, due to electrification through hydrogen-based steelmaking. In both cases, vast additional volumes of renewables are needed, ranging up to 400TWh by 2050 (up from 55TWh today – which is a little more than Romania’s total annual electricity demand). The general problem is therefore the gap between demand and supply of renewable electricity (RES-E) for the steel industry.

There are three specific reasons for this gap:

[15] Policy options CP3 and CP4 have not been included in this overview as these options are assessed in the cross-cutting policy chapter

I. the first is the insufficient installed capacity of renewables – a challenge for the whole economy, as electrification and renewables are the preferred decarbonisation option in many sectors. Volatile and occasionally low electricity prices can, nonetheless, deter further investment in renewables deployment. In addition, the deployment of some RES-E projects is sometimes hindered by administrative or local barriers;

II. the second is increasing network costs and unharmonised rules on RES-levies for the industry, which affect industrial power prices and can also deter investment. Furthermore, indirect carbon costs are compensated unequally, while Power Purchase Agreements (PPA) may also have divergent rules across MS;

III. the third is the inherent variability of renewable electricity, which is a challenge per se. To this end, increased investments in electricity storage and balancing, or in demand-side responses are needed.

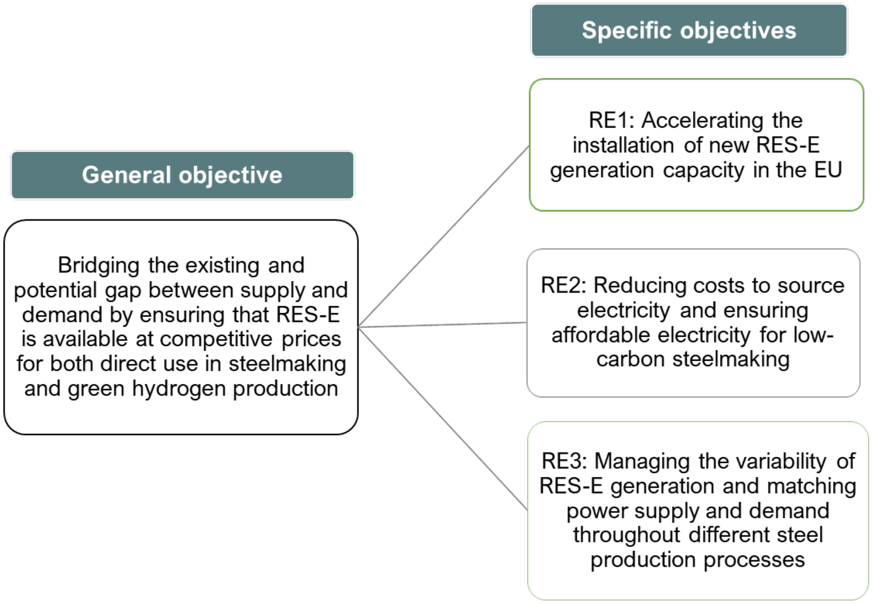


Figure 3: Policy objectives on the availability of renewable electricity (RE)

Source: own composition by the authors of the report

The EU's policy interventions to bridge the gap between RES-E supply and demand from the steel sector can be supported by: (i) accelerating the installation of new RES-E generation capacity; (ii) reducing costs to source electricity and ensuring affordable electricity for green steelmaking, and (iii) managing the variability of RES-E generation and matching power supply and demand in steelmaking.

The proposed policy options would affect the availability of RES-E for the steel industry by facilitating RES-E investments (through funding, better permitting rules, better rules on PPAs) and addressing the variability of RES-E supply (through an increase in RES-E storage capacity and better balancing services). EU policies can also lead to lower energy costs for the EU steel industry through a lower levelised cost of electricity (LCOE) of RES-E, improved mechanisms for indirect carbon costs, updated rules on demand-response measures and PPAs. The most promising policy interventions are to continue to financially support RES-E technologies, support PPAs and green energy offers (e.g. a reformed guarantees of origin system), and to improve the availability of energy storage solutions.

Table 3: Overview of policy solutions – Renewable electricity

	Effectiveness	Efficiency	Feasibility	Coherence
Option RE1: EU funding for RE technologies				
Option RE2: EU guidelines on permitting process for RE projects				
Option RE3: compensation of indirect emission costs				
Option RE4: EU guidelines on demand-response measures				
Option RE5: PPAs or green energy offers				
Option RE6: balancing and shaping costs in national markets				
Option RE7: policies on energy storage				

Note: This table presents the policy options in the energy area that would support the decarbonisation of the EU steel industry. The options are assessed based on the four criteria under the Better Regulation guidelines: their effectiveness, efficiency, feasibility and coherence. Colour legend: ***orange*** *- low,* ***yellow*** *– moderate,* ***green*** *– high.For instance, a policy option that has a green cell in the Effectiveness column is considered to be "highly" effective. Source: own composition by the authors of the report.*

4. Green hydrogen

Green hydrogen – i.e. hydrogen produced through electrolysis powered by RES-E – can be used in certain green steelmaking pathways. Today, however, there is only limited availability of green hydrogen, nor is it competitively priced. This limited availability of green hydrogen is driven by a limited production capacity, i.e. lack of installed electrolyser capacity. The technological readiness of electrolysers running on variable electricity is still improving, therefore funding and projects may be risky and low in number. In addition, green hydrogen is not the only type of hydrogen, nor even the only type of hydrogen that can deliver significant emissions reductions. Green hydrogen, therefore, needs to compete with these other hydrogen types such as blue and grey hydrogen[16], which for now are more cost competitive. Finally, there is a poor link between the supply and demand for green hydrogen. The use of green hydrogen in the steel industry requires significant capital investments in production facilities that can produce steel this way. Furthermore, infrastructure is required to match supply and demand.

[16] Grey hydrogen is hydrogen produced through the steam methane reforming of natural gas without carbon capture

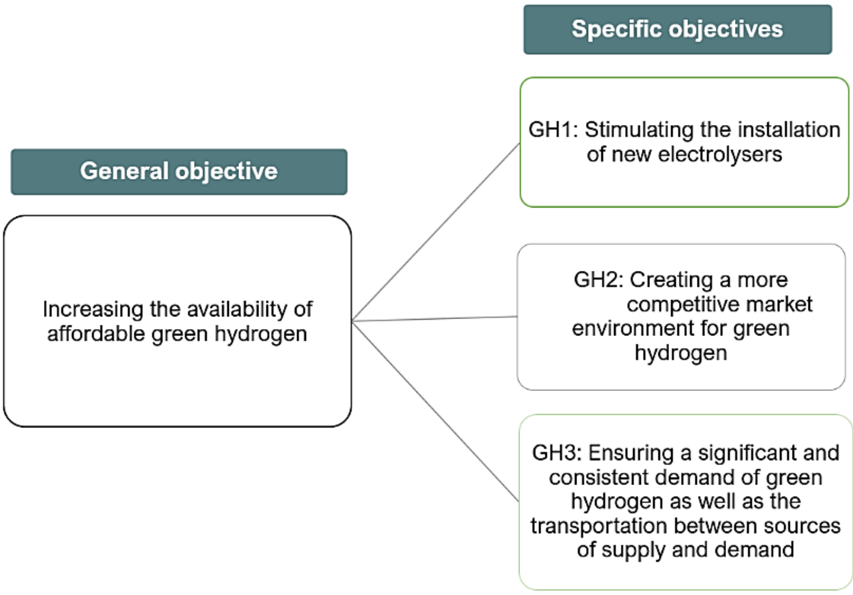


Figure 4: Policy objectives on availability of green hydrogen (GH) to decarbonise the EU steel sector

Source: *own composition by the authors of the report.*

To increase the availability and competitiveness of green hydrogen, EU policies should foster the installation of new electrolyser capacity, create a more competitive market environment for green hydrogen specifically and support a wider demand for green hydrogen as well as the infrastructure to transport it.

The most promising policy options to support green hydrogen availability are a more widespread availability of CCfDs to green hydrogen producers and a wider support to MS initiatives – in particular through State aid guidelines. EU funding support for electrolysis and investment in transport infrastructure can also be worthwhile options.

Table 4: Overview of policy solutions – Green hydrogen

	Effectiveness	Efficiency	Feasibility	Coherence
Option GH1: supporting MS initiatives				
Option GH2: providing financing for electrolysers at EU level				
Option GH3: improving the GOs framework				
Option GH4: offering a premium such as CCfDs				
Option GH5: financial support for hydrogen transport infrastructure				

*Note: This table presents the policy options in the green hydrogen area that would support the decarbonisation of the EU steel industry. The options are assessed based on the four criteria under the Better Regulation guidelines: their effectiveness, efficiency, feasibility and coherence. Colour legend: **orange** - low, **yellow** – moderate, **green** – high. For instance, a policy option that has a green cell in the Effectiveness column is considered to be "highly" effective. Source: own composition by the authors of the report*

5. Carbon capture and use or storage (CCUS)

CCUS provides another technological pathway for the steel sector's decarbonisation. While CCUS has been deployed at small scale throughout the world, there is not yet widespread deployment of CCUS infrastructure, especially as part of industrial clusters. The specific reasons for this limited availability of CCUS solutions for the steel industry are related to the individual parts of the CCUS value chain: (i) CO2 storage sites are not yet available; (ii) CO2 capture is energy-intensive, faces challenges with capture rates and is costly, and (iii) many use-cases for CO2 (CCU) are incompatible with climate neutrality. In addition, there are also cross-chain issues, such as the underinvestment in CO2 transport infrastructure so long as CO2 capture and storage remain limited.

The different parts of the CCUS value chain are often interdependent, which raises coordination challenges. CO_2 purity levels, expected volumes, or the availability of other low-carbon infrastructures may all affect the choices of other decision-makers in the value chain. To improve the availability of CCUS solutions for the steel industry, EU policies should: (i) target an improved access to safe CO_2 storage sites; (ii) improve the business case for CO_2 capture at high capture rates; (iii) develop a market for CCU products that is compatible with climate neutrality, and (iv) support coordination efforts along the value chain.

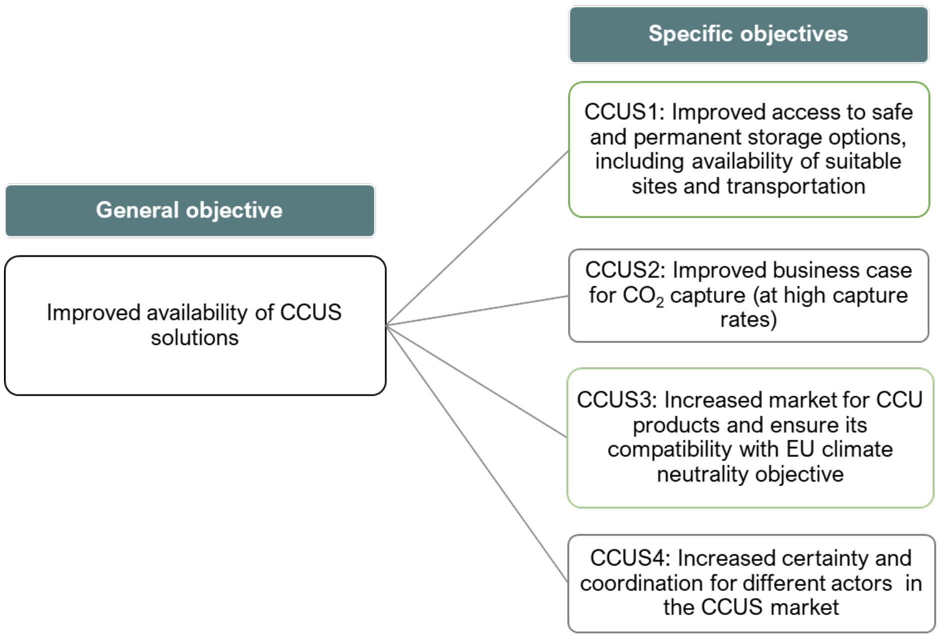


Figure 5: Policy objectives on availability of CCUS solutions to decarbonise the EU steel sector

Source: *own composition by the authors of the report.*

The most promising policy options are to provide increased public funding for R&D to optimise CO_2 capture rates; foster the use of climate-neutral CCU applications under the EU ETS; provide a coordination platform; and focus public support on entire industrial clusters, as CCUS solutions could provide decarbonisation options for (industrial) sectors beyond the steel sector, thereby increasing the efficiency of decarbonisation efforts.

Table 5: Overview of policy solutions[17] – CCUS

	Effectiveness	Efficiency	Feasibility	Coherence
Option CCUS2: supporting other CO_2 transport methods beyond pipelines, as well as recognising and promoting negative emissions technologies in ETS				
Option CCUS3: providing funding (CAPEX and OPEX) for CO_2 storage and transport infrastructure				
Option CCUS5: providing increased public support and funding for R&D&I to optimise capture at high rates				
Option CCUS6: promoting the use of climate-neutral CO_2				
Option CCUS7: providing a platform where different actors in the value chain meet and coordinate				
Option CCUS8: supporting clusters/industrial symbiosis				

Note: This table presents the policy options in the CCUS area that would support the decarbonisation of the EU steel industry. The options are assessed based on the four criteria under the Better Regulation guidelines: their effectiveness, efficiency, feasibility and coherence Colour legend: ***orange*** *- low,* ***yellow*** *– moderate,* ***green*** *– high. For instance, a policy option that has a green cell in the Effectiveness column is considered to be "highly" effective. Source: own composition by the authors of the report.*

6. Iron and steel scraps

Increasing the reuse of ferrous scrap in steel production is effective in reducing CO2 emissions from steelmaking. However, the EU steel industry can count on only limited amounts of steel scrap, particularly high-quality scrap for steelmaking with electric arc furnaces (the EAF route). There are two reasons for this: the first one is that a large share of steel scrap generated in the EU is exported to third countries, first because scrap processing in third countries costs less, and secondly because scrap prices there are high enough to cover transport costs. The second reason is that steel scrap is lost during the steel's life cycle and end-of-life scrap contains high level of impurities that reduce the quality of steel produced in the EAF route.

[17] Options CCUS1 and CCUS4 have not been included in this overview as these options are assessed in the cross-cutting policy chapter

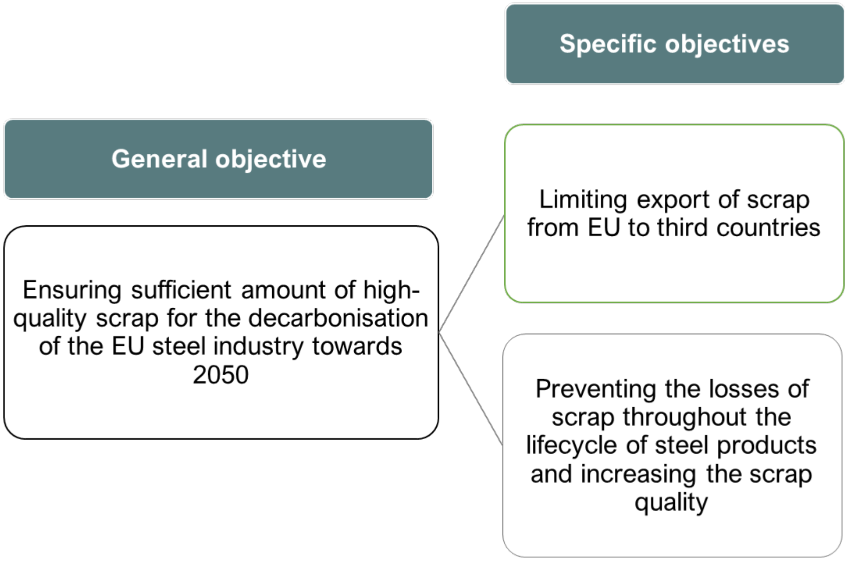


Figure 6: Policy objectives on the availability of steel scrap in the EU

Source: own composition by the authors of the report.

Policy measures should therefore ensure the availability of a sufficient amount of high-quality scrap in Europe, either through limiting the export of scrap to non-EU countries or preventing the loss of steel throughout the use cycle and increasing the scrap quality. The most promising policy options could have positive impacts on increasing the quality of steel scrap for EU steelmakers through promoting the use of best available technologies (BATs) and fostering innovation of scrap refining solutions. Reducing illegal scrap export, or increasing the recyclability of steel-contained products, can also be useful means to increase the availability of steel scrap in the EU.

Table 6 Overview of policy solutions – Iron and steel scrap

	Effectiveness	Efficiency	Feasibility	Coherence
Option SC1: revision of the EU regulatory framework on scrap exports				
Option SC2: improving the quality of scrap available in the EU				
Option SC3: ensuring that final products are recyclable				

Note: This table presents the policy options linked to steel scrap that would support the decarbonisation of the EU steel industry. The options are assessed based on the four criteria under the Better Regulation guidelines: their effectiveness, efficiency, feasibility and coherence. Colour legend: ***orange*** *- low,* ***yellow*** *– moderate,* ***green*** *– high. For instance, a policy option that has a green cell in the Effectiveness column is considered to be "highly" effective. Source: authors' own composition.*

7. Cross-cutting policy options

Several policy options were identified separately in the individual chapters and are considered to have the potential to contribute to many different problem areas at the same time. These include GPP, labels for green steel, CCfDs, increased ETS scarcity and low-carbon standards. These options also represent policy approaches that could be applied to other industrial sectors as well – which often face similar decarbonisation challenges as the steel industry. As such, these options could constitute a particularly coherent set of policy measures to support the industrial dimension of the European Green Deal.

Increased ETS scarcity is a given with the Fit-for-55 package. A higher ETS price will further deter carbon-intensive steel production, and it may also support other policy proposals. A higher ETS price would reduce the subsidy payments made through CCfDs, while the latter could still provide crucial funding for specific green steel investments. The EU carbon price can also be used in GPP projects as a guiding factor for investments. Green labels could also support a market for green steel by making it easier for steel customers to choose climate-neutral products. Longer term, low-carbon standards could harmonise the playing field and protect EU producers of green steel, as such standards would apply to both domestic producers and importers.

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