SRIA Update Draft Version 2 – 15 September 2023

CLEAN STEEL PARTNERSHIP STRATEGIC RESEARCH AND INNOVATION AGENDA

This document is the Strategic Research and Innovation Agenda of the Clean Steel Partnership and is the updated version of the Clean Steel Partnership Roadmap that was issued in November 2020 by ESTEP AISBL. It is to be used for that purpose only. Nothing in this document or parts of it may be used for other purposes without written permission of ESTEP.

This Roadmap is a living document and can be subject to further revision and updates.

Table of contents

List of acronyms and abbreviations

AiSBL	International non-profit association under Belgian law
BB	Building block
BF	Blast Furnace
BOF	Basic Oxygen Furnace
BTX	Benzene Toluene Xylene
CCU	Carbon Capture and Usage
CCUS	Carbon Capture, Utilisation and Storage
CDA	Carbon Direct Avoidance
CE	Circular Economy
cPPP	Contractual public-private partnership
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSP	The Clean Steel Partnership
DG CLIMA	Directorate-General for Climate Action
DG ENER	Directorate-General for Energy
DG ENV	Directorate-General for Environment
DG GROW	Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs
DG R&I	Directorate-General for Research and Innovation
DR	Direct Reduction
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
ESTEP	The European Steel Technology Platform
ETS	The EU Emissions Trading System
EU	The European Union
European Green Deal	Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions,
EUROFER	The European Steel Association

FB	Fluidised bed
FG	Focus Group
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GVA	Gross Value Added
H_2	Hydrogen
HBI	Hot-briquetted Iron
HM	Hot metal
ICT	Information and communications technology
IoT	Internet of Things
KPI	Key Performance Indicator
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
MG	Monitoring Group
Mt	Million Metric Tonne
N_2	Nitrogen
NH_3	Ammonia
NOx	Nitrogen oxides
PI	Process Integration
PPP	Public-Private Partnership
R&D&I	Research, Development, and Innovation
RES	Renewable Energy Sources
R&I	Research and Innovation
RFCS	The Research Fund for Coal and Steel
SCU	Smart Carbon Usage
SDGs	The Sustainable Development Goals
SPIRE	The contractual Partnership "Sustainable Process Industry through Resource and Energy Efficiency"

SRIA	Strategic Research and Innovation Agenda
TRL	Technology Readiness Level
UN	United Nations

Executive summary

The Clean Steel Partnership is developed in the context of the EU goal and policies to **achieve climate neutrality by 2050 - the European Green Deal, the Clean Planet for All strategy and the Paris Agreement.** It will thus contribute to **fighting climate change** and moving towards climate neutrality by 2050, a zero-pollution ambition for a toxic-free environment and a circular economy using digital technologies as a driver and new forms of collaboration. Steelmakers are committed to reducing their emissions and energy intensity, and thereby contributing to the achievement of the EU climate targets.

The steel industry is an important engine of **sustainable growth**, **value-added** and **high-quality employment** within the EU, both directly and indirectly as discussed below. Steelmakers participate in wider value chains including sectors which are crucial for the **EU competitiveness**, like construction, automotive, mechanical engineering, energy generation and networks, mobility, and defence. Also, steel is a material enabling the deployment of green energy technologies, and thereby vital in the path to a climate-neutral EU. Finally, steel is infinitely recyclable, and its residues and waste energies can become valuable resources, thus contributing to a **circular EU economy.**

The Clean Steel Partnership nurtures the **long-term vision** of supporting the European leadership in the transformation of the steel industry into a **climate-neutral sector**. The steel industry has set itself the following vision for **CO_2 emissions reductions compared to 1990 levels**:

- Develop technologies reducing CO_2 emissions from steel production by 50% by 2030; and
- Develop deployable technologies that can reduce CO_2 emissions by 80-95% by 2050, ultimately achieving climate neutrality.

Therefore, the **general objective** of the Partnership is to develop technologies at TRL8 to reduce CO_2 emissions stemming from EU steel production by 80-95% compared to 1990 levels, ultimately leading to climate neutrality. This will contribute to the EU effort towards a climate-neutral continent. At the same time, this objective is to be achieved while **preserving the competitiveness** and viability of the EU steel industry and making sure that EU production will be able to meet the growing demand for steel products. This general objective is in line with the climate ambitions and commitments set by the **European Green Deal**, the UN's 2030 **Sustainable Development Goals**, and the **Paris Agreement**.

The decarbonisation efforts made so far by the steel industry need to be stepped up and integrated into a single-minded and coherent framework by a renewed research, development, and innovation (R&D&I) strategy for clean steel. An essential element of such a strategy will be to move from lower technology readiness levels (TRLs) to an **industrial-scale deployment**. This entails coordinating the research, sharing the risk that certain technologies do not prove effective, and contributing to offset the higher production costs that come with the deployment. **A partnership** is therefore needed to overcome the barriers to R&D&I investments in the steel industry and ensure that available technologies are deployed.

R&D&I activities supporting the achievements of the Clean Steel Partnership's objectives can be classified according to two different levels:

- **Six areas of interventions** comprising different technological pathways (and combinations thereof) to decarbonise the EU steel industry as well as enablers and support actions. Hydrogen and/or electricity will be considered to replace fossil carbon in steelmaking. If fossil carbon is used, CO_2 emissions will be captured and processed for utilisation or storage. In addition, higher levels of circularity will be explored by focusing for instance on the recycling of steel, the usage or recycling of residues, and resource efficiency.

- **Twelve technology building blocks**, which can contribute separately to the areas of intervention, or jointly to enable a higher level of CO_2 emission reduction in steel production.

The Clean Steel Partnership proposes a **three-stage R&D&I approach** to accelerate carbon mitigation in the steel industry:

- Stage 1 targets projects that generate 'immediate' CO_2 reduction opportunities;
- Stage 2 focuses on those projects that may not be 'immediately' implemented in the installed base, but allow for a quick evolution towards improved processes; and
- Stage 3 looks at those projects that can 'revolutionise' the steel industry through breakthrough development, and require significant capital investment in new processes.

Based on the estimated industrial efforts from the steel sector in R&D&I projects falling within the scope of this Roadmap, the total resource requirement is estimated at around **EUR 3** billion between 2021 and 2030. Due to the collaboration among steel producers, reasonable synergies are expected compared to the company-by-company approach, thus reducing the **investment need** to approximately **EUR 2.55 billion** for the next decade (up to 2030). For the Partnership period of 2021 to 2027, the **'wider boundary',** i.e., the estimated collective investment needs, amounts to **EUR 2 billion**, and the remaining funding (estimated to be EUR 0.55 billion) will be allocated to the period immediately after the Clean Steel Partnership, i.e., **2028-30**, where some projects will still be completed. The collective investment managed within the **scope** of the Clean Steel Partnership will be at least **EUR 1.4 billion**. The overall budget is expected to finance at least 16 projects resulting in building blocks at TRL7, 12 projects resulting in building blocks at TRL 8 and 4 demonstration projects. The Clean Steel Partnership is expected to generate both **direct and indirect leverage effects** for additional investments.

A strong effort will be required by sectoral players even beyond the Clean Steel Partnership to realise its potential of drastically reducing CO_2 emissions while ensuring that the EU steel industry remains a global leader in clean technologies. The resources deployed via the Clean Steel Partnership and the subsequent investments will ensure the delivery of demonstrators combining several building blocks in the various areas of intervention.

The objectives and impacts of the Clean Steel Partnership are in line with the pathways of Horizon Europe and will generate a number of results in different spheres, namely:

- **CO_2 reduction.** The steel sector will be able to develop, upscale and roll out new technologies that could reduce CO_2 emissions from EU steel production by 50% by 2030, compared to 1990 levels.
- **Industry and EU competitiveness**. The support for the deployment of the decarbonisation technologies will allow the EU to remain a global leader in the steel industry and to reinforce its knowledge-based competitive advantage.
- **Resource efficiency**. The partnership enables the coordination of technological progress in the use of steel scrap and by-products, leading to an enhanced, larger use of those resources.
- **Jobs and skills**. the Partnership will support the preservation of high-quality jobs in the steel making value chain.

Significant EU added value in the Clean Steel Partnership is generated by the new coordinated framework towards a modern and sustainable steel industry. In this context, the Partnership will ensure a strong commitment from all actors of the steel value chain in all Member States towards decarbonisation, thus leading to synergies and a **high degree of additionality**. Furthermore, the Partnership's openness and transparency can generate additionality by **cross-fertilising both suppliers and customers**. To achieve these results, the Partnership will collaborate with other Horizon Europe Partnerships as well as other funding programmes.

The Clean Steel Partnership has been established between the European Commission (public side) and the European Steel Technology Platform (ESTEP) on behalf of the entire European steel value chain community (private side). It is centred around the so-called '**Partnership Board**' featuring representatives from both the public and private side and in charge of discussing and approving the periodic Work Programmes and ensuring compliance with the vision, ambition, objectives, and research programme laid down in the Roadmap. The so-called '**Implementation Group**' is the general assembly of the Clean Steel Partnership. Decisions made by the Implementation Group are being discussed and proposed to the public side of the Partnership and finally approved by the Partnership Board. The work of the Implementation Group relies, among others, on the inputs of **specific 'Task Forces'** composed of technology experts from organisations that are members of the Partnership as well as external experts. The Implementation Group is supported by **two external bodies**:

- Monitoring Group, composed of technical experts of steelmaking and related technologies, including, among others, academics and leading researchers, and representatives from the public side;
- Stakeholder Forum, including relevant stakeholders that are not members of the Partnership but may contribute to the successful implementation of the Partnership.

The decarbonisation of the steel industry requires a **coordinated approach across all countries, technologies, and steel plants**. Therefore, the impact of the Partnership is maximised by involving all relevant stakeholders and remaining open to new partners. ESTEP and the Clean Steel Partnership are **open to the entire European steel value chain community**, i.e., to all EU based steel stakeholders comprising steel producers, steel processors, customers, suppliers, plant builders, research and academia, and civil society representatives.

Chapter 1: Vision

Summary

Context

- The Clean Steel Partnership is designed to tackle two major challenges: fighting against climate change and ensuring sustainable growth for the EU. In line with the European Green Deal, the Clean Planet for All strategy and the Paris Agreement, it takes an integrated approach to fight climate change and aims at moving towards climate neutrality by 2050, a zero-pollution ambition for a toxic-free environment and a circular economy.
- Decarbonising the steel sector is vital to a thriving, sustainable, and circular EU economy. The steel sector made a strong commitment to reducing its emissions and thereby contributing to the achievement of the EU energy and climate targets.
- A European partnership offers a wide range of opportunities:
  - Achievement of an EU climate-neutral steel production;
  - Export of low-carbon steel making technologies to external markets;
  - Less dependence on fossil energy and feedstock;
  - Securing of the EU strategic industry's value chains;
  - Know-how spill-overs to other industries; and
  - Smart use of resources and realisation of a circular economy model.

R&D&I issues and the need for a partnership

- Hydrogen and/or electricity will be considered to replace fossil carbon in steel making. If fossil carbon is used, CO_2 emissions will be captured and processed for utilisation or storage. In addition, higher levels of circularity will be explored by focusing for instance on the recycling of steel, the usage or recycling of residues, and resource efficiency.
- A partnership is needed to ensure that available technologies are deployed by overcoming the following barriers to R&D&I investments:
  - Key bottlenecks: the transition from pilot phase to industrial-scale deployment, long investment cycle, high capital intensity and competitive global market;
  - The 'funding gap' between research and deployment of technologies calling for significant support of the public sector;
  - External and wider industry factors: requirement of zero-carbon electricity and hydrogen, availability of geological storage of CO_2, carbon leakage outside the EU.

Vision and ambition

- The long-term vision of the Partnership is to support the European leadership in the transformation of the steel industry into a climate-neutral sector:
  - Intermediate step: developing technologies reducingCO_2 emissions from steel production by 50% by 2030 compared to 1990 levels;
  - Final ambition: reducing CO_2 emissions by 80-95% by 2050, ultimately achieving climate neutrality.

Objectives

- General objective: to develop technologies at TRL8 to reduce CO_2 emissions stemming from EU steel production by 80-95% compared to 1990 levels by 2050, ultimately leading to climate neutrality.
- Six specific objectives, to be achieved in 7 to 10 years, will support the obtainment of the general objective.

1.1 Context

The Clean Steel Partnership is developed in the context of the European Union (EU) goal to achieve climate neutrality by 2050 and to move towards a zero-pollution ambition for a toxic-free environment and circular economy. This policy entails two major challenges: on the one hand, **climate change** must be tackled, by reducing the amount of CO_2 emissions and/or the energy intensity; on the other, this must be done by ensuring that our society continues benefiting from **sustainable growth.** The Clean Steel Partnership can contribute to both accounts, as described in the remainder of the Section, while at the same time ensuring that several opportunities are grasped, for the competitiveness of both the industry and the EU.

The Strategic Research and Innovation Agenda (SRIA) of the Clean Steel Partnership (CSP) accompanied the proposal for a Partnership on Clean Steel to the European Commission.

It was issued in November 2020 by ESTEP AISBL after a public consultation aimed at gathering feedback from stakeholders to improve and enrich different areas of the CSP SRIA.

The Memorandum of Understanding (MoU) , which constitutes an agreement in which the Partners will undertake all efforts necessary to achieve the objectives that are described in the SRIA. The starting date for the Partnership is 09/08/2021, date of the signature of the MoU, and its end date is 31/12/2030.

1.1.1 Climate change

The EU has since long acknowledged the need for substantive and timely measures to combat climate change and stressed its commitment to do so through several increasingly ambitious frameworks, agreements, and policies. The latest step has been the **European Green Deal**[1] presented by the European Commission in December 2019, following and further deepening previous visions, such as the 'Clean Planet for All' Commission strategy.[2] The European Green Deal also reaffirms the EU's vision of a global effort against climate change, which is exemplified in commitments like the United Nations (UN) Sustainable Development Goals (SDGs) or the Paris Agreement.

Partnerships are one of the tools that the Commission intends to deploy to achieve the European Green Deal targets.[3] Therefore, the CSP is firmly embedded in the European Green Deal, and designed in line with its approach and targets. At the same time, and again in line with the EU strategy, the Partnership pays special attention to the global competitiveness of the EU steel industry.[4]

[1] European Commission (2019), the European Green Deal, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, 640. Hereinafter also: 'European Green Deal'.

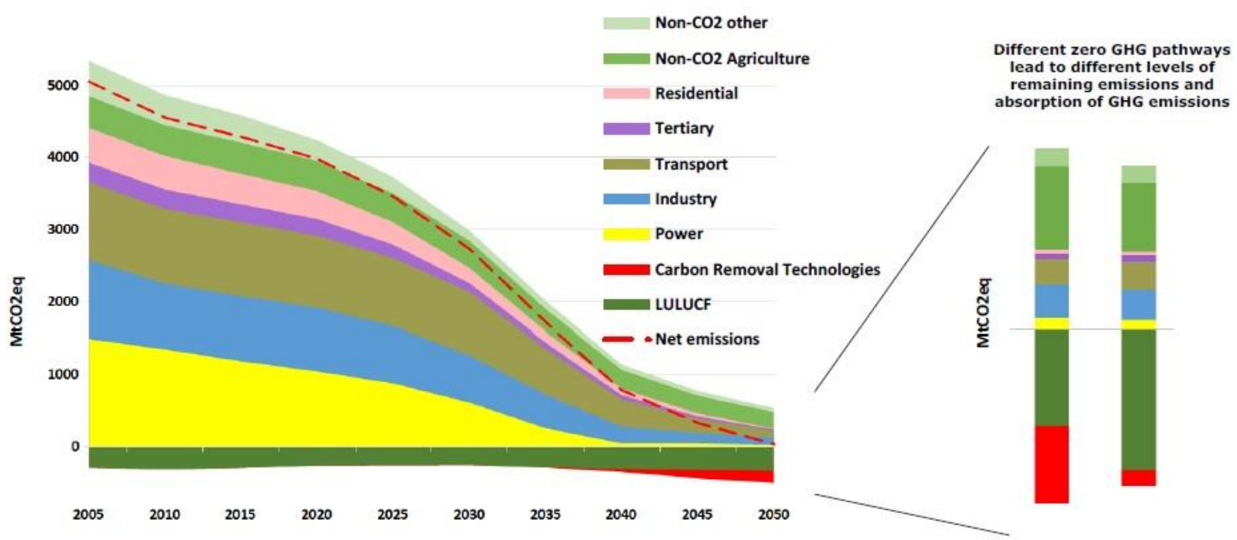
[2] European Commission (2018), A Clean Planet for All: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral company, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank, 773.

[3] European Green Deal, p. 8.

[4] European Green Deal, p.2.

The European Green Deal is an integral part of the EU strategy to achieve the UN's 2030 Agenda and SDGs. The Agenda aims to provide a global blueprint for peace and prosperity and consists of 17 goals. Among those, **the Partnership can contribute to the Sustainable Development Goals** related to sustainable production and consumption, and in particular to the urgent fight against climate change.[5] Under the Paris Agreement, the EU has committed to limit the temperature rise well below 2°C, and to pursue efforts to limit the temperature increase to 1.5°C, a commitment that will require pursuing the ultimate goal of climate neutrality by 2050. Figure 1 illustrates the necessary reduction of greenhouse gas (GHG) emissions to meet the targeted temperature rise. Furthermore, the figure shows the significant share of emissions caused by the European industry sectors and thereby stresses the role industry must play in a collaborative effort to reduce CO_2 emissions. Such a **collaborative effort will be necessary**, as the European Green Deal underlines that current policies will not suffice in reaching the targets. Figure 2, on the other hand, shows the different global temperature warming scenarios in relation to the level of annual CO_2 emissions. Further underlining the need for urgent and significant action.

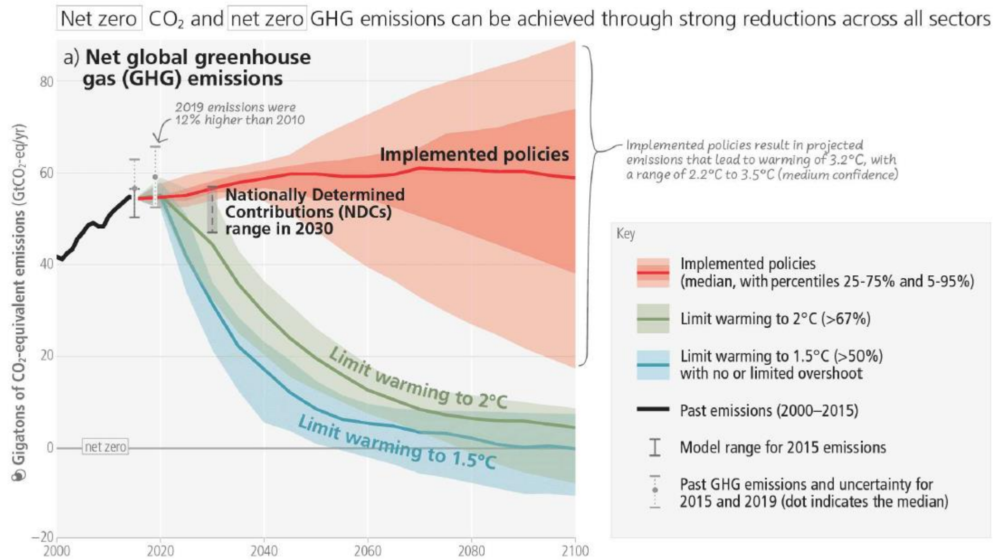
Figure 1 GHG emissions trajectory in a 1.5°C scenario



Source: 'A Clean Planet for All' Commission Strategy.

Figure 2 Scenarios of global warming depending on CO_2 emission levels

[5] The SDGs to which the Partnership can contribute include: SDG 8 – promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for, SDG 9 – build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation, SDG 12 – ensure sustainable consumption and production patterns, and SDG 13 – take urgent actions to combat climate change and its impacts.



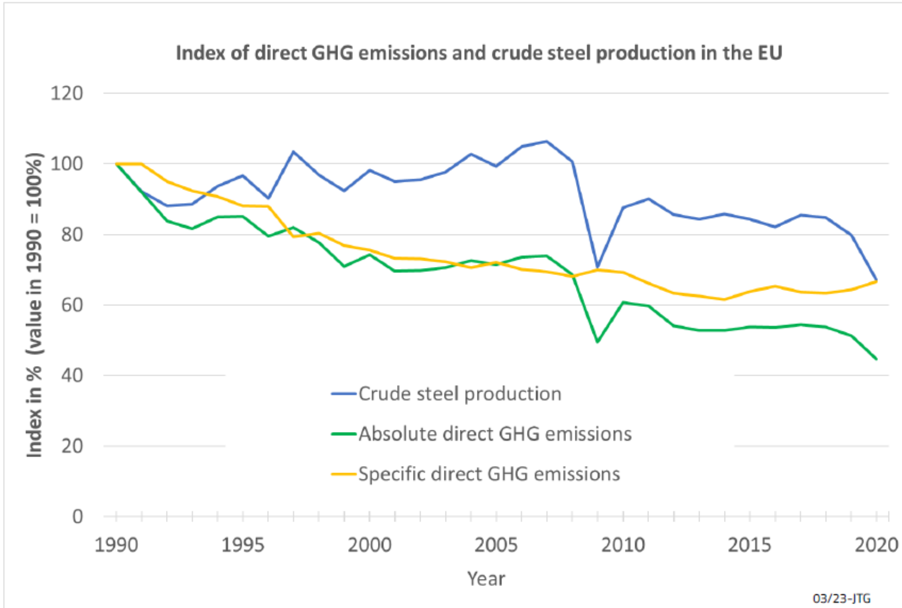
Projected emissions for implemented policies and scenarios in line with limiting global warming to 2C and 1.5C (Source: IPCC AR6 Synthesis Report SfP 2023)

As a significant contributor to those emissions, **the steel sector must play a key role** in such collaborative efforts. Looking at the EU Emissions Trading System (ETS), the steel industry is responsible for about 20% to 25% of industrial CO_2 emissions covered.[6] Steelmakers have a high commitment to reducing their emissions and thereby contributing to the achievement of the EU energy and climate targets. The steel industry commitment has been shown by the sector's position at the forefront of Research and Development and Innovation (R&D&I) into breakthrough technologies to reduce the climate footprint for many years.[7] Figure 3 shows the past industry efforts in reducing CO_2 emissions, without reducing production. The blue line shows the approximate crude steel production, while the yellow and green lines indicate respectively the specific (per tonne of produced crude steel) and absolute GHG emissions. The precise numbers are varying on the source and way of measurement, but the figure presents very well the decreasing CO_2 intensity of steel production. The efforts made so far, however, need to be stepped up and integrated into a single-minded and coherent framework, which can be better managed via a partnership. EUROFER estimates that in 2022, CO_2 specific emissions were 35% lower compared with 1990 levels.

[6] There is diverging data on the exact share. Under the EU ETS, "production of pig iron and steel" accounted for 122 Mt CO_2 out of 587 Mt CO_2 for all industrial installations in 2018. Additional 11 Mt CO_2 have been emitted by "production of coke", and 13 Mt CO_2 by "production or processing of ferrous metals". For further details, please see: eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1. Other sources estimate the share of the iron and steel industry to be somewhat higher at about 30% of all industrial emissions, for further details, please see: Herbst *et al.* (2018), Low-carbon transition of EU industry by 2050: Extending the scope of mitigation option, Available at: set-nav.eu/sites/default/files/common_files/deliverables/wp5/Issue%20Paper%20on%20low-carbon%20transition%20of%20EU%20industry%20by%202050.pdf

[7] European Commission (2018), European Steel: The Wind of Change.

Figure 3 CO_2 in steel production



Source: EUROFER calculations, based on Eurostat data

1.1.2 EU sustainable growth

While working on achieving its climate targets, the EU is aiming to foster the sustainable growth of the European economy. The European Green Deal underlines this goal by outlining an economic transition that is not only ecologically sustainable but also socially just.

The competitiveness of the steel industry must be preserved as an important engine of sustainable growth, value-added and high-quality employment within the EU, both directly and indirectly as discussed below. This is because steelmakers participate in wider value chains including sectors which are crucial for the EU competitiveness, like construction, automotive, mechanical engineering, energy generation and networks, mobility, and defence. Also, steel is a material enabling the deployment of green energy technologies, and thereby vital in the path to a climate-neutral EU. Finally, steel is infinitely recyclable, and its residues and waste energies can become valuable resources. In a nutshell, **steel is vital to a thriving, sustainable, and circular EU economy**, as repeatedly recognised in EU policies.[8] Some of these aspects can be evidenced with the following **key facts on steel**:

- The steel sector represents around 95% of all metals produced;[9]

[8] European Commission (2013), Action Plan for a competitive and sustainable steel industry in Europe, COM/2013/0407 final, available at: eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52013DC0407; European Commission (2017), Steel: Preserving sustainable jobs and growth in Europe, COM(2016)155, Available at: eesc.europa.eu/en/our-work/opinions-information-reports/opinions/steel-preserving-sustainable-jobs-and-growth-europe; and European Commission (2017), A renewed EU Industrial Policy, COM(2017)479, available at: ec.europa.eu/transparency/regdoc/rep/1/2017/EN/COM-2017-479-F1-EN-MAIN-PART-1.PDF

[9] For further details, please see: greenspec.co.uk/building-design/steel-products-and-environmental-impact/

- In 2019, the production of crude steel in the world was 1 870 Mt of which Europe produced approximately 8.5% (World Steel Association, 2020). This took place mostly in Germany, Italy and France where half of the steel within Europe was manufactured;
- With an output of 168 million tonnes of crude steel per year (level year 2018), the EU is the second-largest producer in the world;[10]
- The steel sector in Europe has an annual turnover of EUR 166 billion and is responsible for 1.3% of EU GDP;[11]
- Steel is a genuine EU industry with 500 production sites across 23 EU countries and employed 320,000 people directly in 2018. The total number of jobs enabled by the steel industry is 7.9 times the steel industry's own employment (i.e., around 2.6 million EU jobs are supported in total);[12]
- The Gross Value Added (GVA) of steel production is EUR 20.7 billion. Total GVA supported by the steel industry is 5.8 times the steel industry's own GVA;[13]
- Europe's competitive position has deteriorated in recent years and prices worldwide have dropped, partly due to global steel overcapacity;
- The steel industry in Europe recycles about 90 Mt of scrap (20Mt in BOF and 70Mt in EAF) with a high recycling rate for relevant EU industrial sectors; construction 90%, automotive 85%, packaging 75%.

The steel production in the EU today adopts different routes with differing technologies. The production process can be broadly distinguished by two main routes:

- the so-called integrated **blast furnace (BF)-basic oxygen furnace (BOF)** route ('integrated route');
- the **electric arc furnace (EAF)** route ('scrap route').

The **viability of both the BF-BOF and EAF production routes must be preserved**, as they remain necessary to ensure the EU steel sector's capacity of delivering high-quality steel grades using different raw materials, thereby ensuring strategic capability. Hence, R&D&I needs to focus on both production routes[14]. Box 1 briefly describes the two routes.

---

[10] EUROFER (2019), 2019 European Steel in Figures, eurofer.org/News%26Events/PublicationsLinksList/201907-SteelFigures.pdf; p. 13.

[11] European Commission (2017), Steel: Preserving sustainable jobs and growth in Europe, COM(2016)155, Available at: eesc.europa.eu/en/our-work/opinions-information-reports/opinions/steel-preserving-sustainable-jobs-and-growth-europe; and European Commission (2017), A renewed EU Industrial Policy, COM(2017)479, available at: ec.europa.eu/transparency/regdoc/rep/1/2017/EN/COM-2017-479-F1-EN-MAIN-PART-1.PDF

[12] EUROFER (2019), 2019 European Steel in Figures, eurofer.org/News%26Events/PublicationsLinksList/201907-SteelFigures.pdf; p. 7.

[13] Ibid.

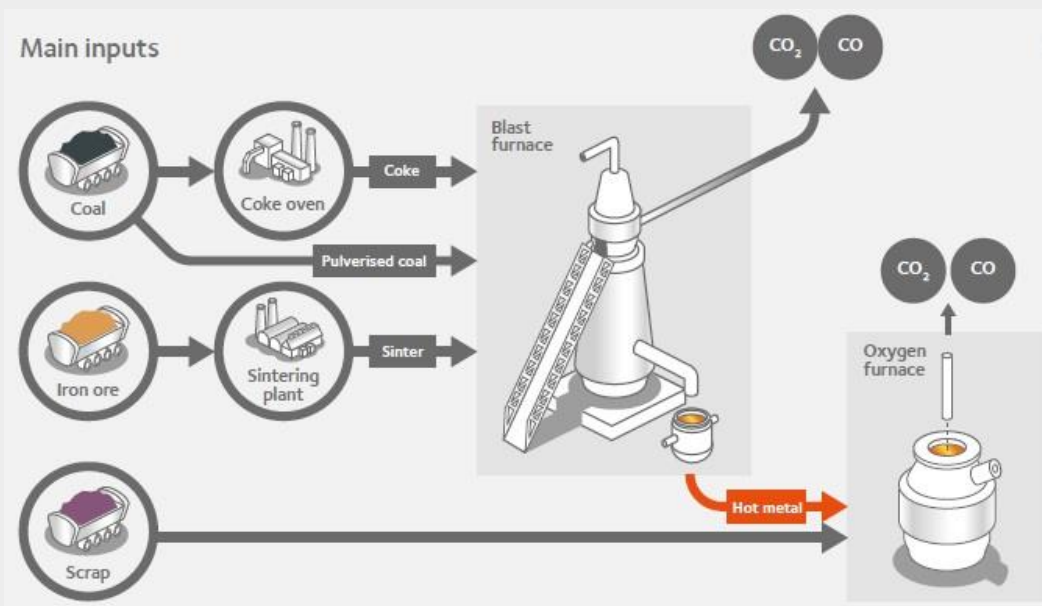
[14] In the addition to the two routes with a limited diffusion worldwide and not diffused in the EU: Smelting reduction (Corex, Finex with about 7,5 million hot metal worldwide) and Direct reduction of iron ores and the use of DRI/Hot Briquetted Iron with 87 million t worldwide for steelmaking, predominantly in EAF.

***Box 1 Steel production routes: BF-BOF and EAF.*[15]**

A general feature in steelmaking is the necessity to separate iron (Fe) from oxygen (O) in the iron ores and to remove impurities when processing hot metal to steel, and to control the carbon, and sometimes other metals in the final alloy. The impurities referred to here are primarily carbon, phosphorus, and sulphur. Not all steel is the same and its strength and ductility and specific qualities depend on production procedures. After the removal of impurities, specific qualities can be adjusted through the addition of metals like nickel, chromium, manganese, silicon, and others, thereby creating alloys.

Primary steelmaking requires the preparation of the materials that are then loaded into the blast furnace, namely coke and sinter. In the BF-BOF route, coke and sinter, together with pellets and lump ore, are placed into the top of the blast furnace and in the bottom hot air is injected. Additionally, pulverised coal is injected. A reaction of the hot air with the coke and coal leads to the formation of carbon monoxide (CO), the main agent to reduce iron oxides by extracting oxygen from iron ore. Thereby, CO_2 is formed. iron ore, supplied with coke and flux from the BF top, is reduced and melted, whereby hot metal is achieved as the final product at the BF bottom, as well as slag. In the process of making steel and removing impurities, liquid hot metal together with selected scrap is charged in the BOF, where oxygen is blown and limestone and other flux are furthermore added, which leads to slag and molten steel. BF-BOF slag can be reused in other sectors. Figure 4 illustrates the integrated steelmaking route or BF-BOF route.

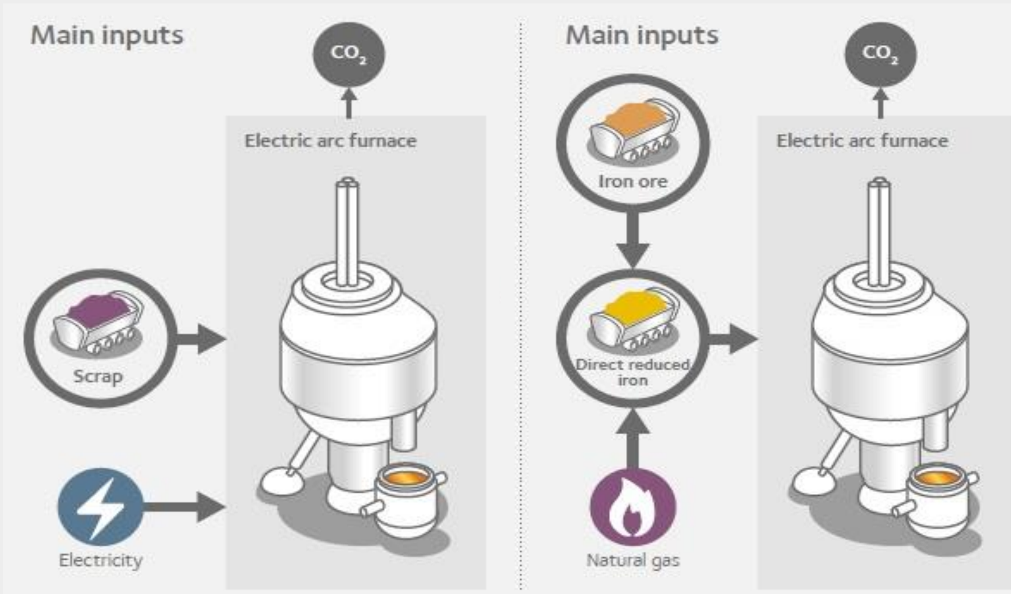
Figure 4 Integrated BF-BOF steelmaking route



Source: ArcelorMittal (2019), Climate Action Report 1: May 2019.

The EAF route relies on the recycling of steel by using scrap, which may be comprised of scrap from inside the steelworks (own scrap), cut-offs from steel product manufacturers (e.g. vehicle builders) and capital or post-consumer scrap (e.g. end-of-life products, obsolete scrap). Electric energy and additional energy from natural gas and coal are used to melt scrap within the EAF. The scrap route consists primarily of melting scrap and not extracting oxygen from iron, which makes carbon less important in this route. The consumption of carbon electrodes is the main source of direct CO_2 emissions in the EAF. As scrap may contain so-called tramp metals that would lower the metallurgical quality of the final steel product, the furnace can be charged further with pig or sponge iron to dilute them. Direct reduced iron (DRI) and Hot-briquetted iron (HBI) is also increasingly being used as a feedstock due to its lower content of undesirable metals (e.g., Cu). Similar to the BF-BOF route, slag is produced by the insertion of limestone and other flux to the EAF and thereby removing the undesirable impurities. Figure 5 shows the steelmaking route via EAF, using either scrap or DRI.

Figure 5 EAF steelmaking route, using scrap (left) or DRI (right)



Source: ArcelorMittal (2019), Climate Action Report 1: May 2019.

At this stage, process operation is involved to set the steel composition and temperature at the desired target to fit with the production needs. These actions involve alloying, heating, and also melt stirring with inert gas or Electromagnetic tools to attain steel homogenisation as quickly as possible to favour productivity.

Next, the newly formed molten steel from BOF or EAF needs to be adjusted to make the perfect steel composition. This is done by either manipulating the temperature and/or removing certain elements in the so-called secondary steelmaking, that includes processes such as degassing, stirring, ladle injection, or argon bubbling. These processes are mainly based on electric energy and produce slag that today is sometimes internally reused. Liquid steel from secondary steelmaking (subsequent secondary steelmaking is a common step) is then cast to certain shapes, dimension, and weights of crude steel (billet, blooms, slabs, ingots). These semi-finished products are formed through "hot rolling" at a temperature of about 1,300 °C. Hot rolled steel may afterwards go through various processing steps such as heat treatment, cold rolling, or surface treatment. These two steps can be integrated into the production process or can be stand-alone and are presently based on a gas combustion process using both steelmaking gaseous residues (BF, BPF of COG gases) and natural gas.

At the moment, the share of production between the two routes is split roughly 60% produced via BF-BOF route to about 40% via the EAF route in the EU.[16] Production using the EAF route is less CO_2 intensive than the BF-BOF route. For each tonne of crude steel produced with the BF-BOF process, about 1.3 to 1.8 t of CO_2 are created. One tonne of steel produced with the EAF process requires about 400-500 kWh (kilowatt-hour) electricity, 80-120 kg CO_2 direct and 250-350 kg CO_2 indirect emissions.[17]

[15] Description source: CEPS & Economisti Associati (2013), Assessment of cumulative cost impact for the steel industry – Final Report, Report for European Commission – DG Enterprise and Industry, p. 79-80; & Steel Institute VDEh (2019), Update of the Steel Roadmap for Low Carbon Europe 2050, Part I: Technical Assessment of Steelmaking Routes, p. 7-10; & ArcelorMittal (2019), Climate Action Report 1: May 2019, p. 42-43.

[16] Steel Institute VDEh (2019), Update of the Steel Roadmap for Low Carbon Europe 2050. Part I: Technical Assessment of Steelmaking Routes, p. 40; European Commission (2018), European Steel: The Wind of Change, p. 19.

[17] Ibid.

1.1.3 Opportunities

A partnership developed in the context of tackling climate change and ensuring sustainable growth will provide a framework under which a **range of opportunities** can be embraced, such as:

- supporting a climate-neutral and competitive steel production in the EU;
- exporting successful EU technologies for low-carbon steel making to large markets outside the EU (e.g., China, India, Japan, US);
- making the steel sector less dependent on fossil energy and feedstock;
- securing the presence of a strategic industry in Europe as a key part of important (future) value chains;
- enabling know-how spill-overs to other industries;
- enhancing processes for smart use of resources, which potentially further enable the contribution of the steel sector to the EU circular economy strategy.

Despite these opportunities for the steel sector, industry actors cannot address the challenges ahead and bear the necessary R&D&I alone. On one hand, the steel market is globalised and highly competitive, with EU competitors facing declining prices in recent years. On the other hand, the EU production is scattered across several Member States and plants, bearing the risk of individual results and innovations not being aligned. Indeed, the scale of the challenge, the need to coordinate a plethora of private and public actors in a workable multi-stakeholder environment, and the amount of resources envisaged suggest that any uncoordinated approaches or efforts would risk missing the objective. The Clean Steel Partnership will allow the realisation of the outlined opportunities and presents a roadmap under which the shared visions of a **climate-neutral steel sector** and a **sustainable and competitive EU economy** can be aimed for.

1.1.4 European policies – International developments

Since the start of the Clean Steel Partnership, important developments took place in Europe and the rest of the world, leading to new or re-oriented European policies regarding energy, climate and competitiveness issues. The vision and mission of the Clean Steel Partnership fit in seamlessly with these developments.

The **'fit for 55' package**, presented in July and December 2021, is designed to realise the European Climate Law objectives: climate neutrality by 2050 and a 55 % reduction of net greenhouse gas (GHG) emissions by 2030, compared with 1990 levels. It consists of 13 interlinked proposals to revise existing EU climate and energy laws, and six proposals for new legislation.

The proposals aim to accelerate emission reductions in the sectors covered by the EU emissions trading system (ETS) and the sectors covered by the Effort-sharing Regulation.

Russia’s unprovoked and unjustified military aggression against Ukraine in 2022, has massively disrupted the world’s energy system. It has caused hardship as a result of high energy prices and it has heightened energy security concerns. In March 2022, EU leaders agreed in the European Council to phase out Europe’s dependency on Russian energy imports as soon as possible. They invited the Commission to swiftly put forward a detailed **REPowerEU plan**.

Building on the Fit for 55 package of proposals and completing the actions on energy security of supply and storage, this **REPowerEU** plan puts forward an additional set of actions to:

- save energy;
- diversify supplies;
- quickly substitute fossil fuels by accelerating Europe's clean energy transition;
- smartly combine investments and reforms.

RePower EU includes a decarbonisation pathway for low carbon primary steelmaking based on renewable electricity and green hydrogen. However, the anticipated speed of implementation depends on a high rate of additional capacity for renewable electricity and green hydrogen, which is currently not in line with the future needs of the steelmaking industry.

In February 2023, the Commission presented a **Green Deal Industrial Plan** to enhance the competitiveness of Europe's net-zero industry and support the fast transition to climate neutrality. The Plan aims to provide a more supportive environment for the scaling up of the EU's manufacturing capacity for the net-zero technologies and products required to meet Europe's ambitious climate targets.

The Plan builds on previous initiatives and relies on the strengths of the EU Single Market, complementing ongoing efforts under the **European Green Deal and REPowerEU**. It is based on four pillars: a predictable and simplified regulatory environment, speeding up access to finance, enhancing skills, and open trade for resilient supply chains.

1.2 R&D&I issues and the need for a partnership

On the path to achieving clean steel production within the EU, there are important R&D&I challenges lying ahead. These challenges concern both the life cycle of technologies and external factors influencing technological development and the steel sector as a whole. The capital-intensive nature of steel production, the global competition, and the long investment cycle are challenges that need to be addressed immediately and in a coordinated and cooperative manner. The successes of the EU steel industry in decoupling growth from CO_2 emissions and electricity use are promising that the challenges can be overcome. The Clean Steel Partnership will provide a single-minded and coherent framework that allows the coordination and upscaling of technological efforts.

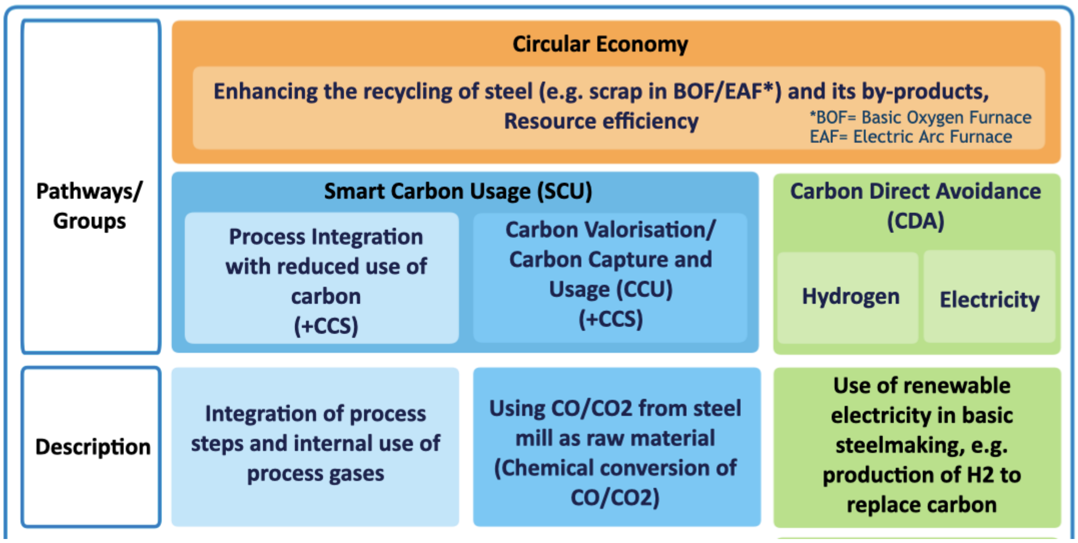
1.2.1 <u>R&D&I general strategy</u>

To achieve significant reductions of CO_2 emissions in the steel industry, there are **two general technological pathways** for decarbonisation:

- **Carbon Direct Avoidance** (CDA), covering technologies to avoid emitting carbon during steelmaking;
- **Smart Carbon Usage** (SCU), consisting of ways to use the carbon from steel production for other applications, via carbon capture, utilisation, and storage (CCUS) and process integration (PI);

Overarching these two general pathways are **circular economy** (CE) projects, working for example on the recycling of steel, the usage or recycling of residues, and resource efficiency.[18] Different groups of technological approaches can be found in each pathway, illustrated in Figure 6 below.

***Figure 6 Technological Pathways and technologies to reduce CO_2 emissions of the EU steel industry*[19]**



Source: Low Carbon Roadmap: Pathways to a CO_2-Neutral European Steel Industry, EUROFER, November 2019.

There is no shortage of promising technologies on which an R&D&I strategy for clean steel can focus. An essential element of a renewed R&D&I strategy will be to move from lower technology readiness levels (TRLs) to an **industrial-scale deployment**. This entails coordinating the research, sharing the risk that certain technologies do not prove effective, and contributing to offset the higher production costs that come with the deployment.

1.2.2 R&D&I commitment, issues and need for partnership

Under the Horizon Europe framework, there are three types of partnerships proposed to support the wider research and innovation (R&I) framework.[20] The main idea behind all partnerships is to coordinate efforts in R&D&I in order to better address global challenges. Co-programmed partnerships, such as the Clean Steel Partnership, function on the basis of memoranda of understanding or other contractual arrangements and aim to ensure higher coordination and continuity among individual R&D&I efforts. Besides coordination and continuity via specified objectives and roadmaps, the funding opportunities of R&D&I initiatives is naturally at the heart of such partnerships as well.

The Clean Steel Partnership follows and build upon a series of existing cooperation frameworks, Public-Private Partnership (PPPs), and other research efforts, which not only underline the high **commitment** of all parties to tackling the challenges at hand but also show the fruitful **potential** of such initiatives.

[18] Ibid, p.43.
[19] Pre-conditioning (cleaning, separation, concentration) of steel mill gas streams for PI, carbon storage and carbon use is very specific for the steel sector, furthermore the upgrade of the purified CO/CO_2 streams for CCU can be steel sector specific.
[20] More information available at: ec.europa.eu/info/horizon-europe-next-research-and-innovation-framework-programme_en#european-partnerships-in-horizon-europe.

Currently, steelmaking R&D&I supported by the EU is mainly covered by the **Research Fund for Coal and Steel (RFCS)** Big Tickets programme and by the Horizon Europe 2021-2027 framework, under the Work Programme Cluster 4 Digital, Industry and Space.

The following are only a small number of past and ongoing projects and programmes that have contributed to important technological developments and signify the commitment of different stakeholders:

- **ULCOS (Ultra Low-CO_2 Steelmaking)** has been a key R&D&I project financed by the European Commission between 2004 and 2010, which enabled some breakthrough technologies such as BF with top-gas recycling, a new smelting reduction process, advanced direct reduction, and electrolysis of iron ore.
- More than 150 projects in 5 different technical groups on steel under the RFCS annual funding calls.
- 10 projects under the Horizon Europe Cluster 4 2021-2022 funding calls
- 4 projects under the RFCS Big Tickets funding call 2022
- **PPPs at the national level**, for example **HYBRIT**, a joint venture between three companies (SSAB, LKAB, Vattenfall), co-sponsored by the Swedish Energy Agency.
- The **"Green Steel for Europe"** project[21], which is being funded by the European Parliament and administered by the European Research Executive Agency (REA)Despite the commitment of the actors involved and the described successes in developing breakthrough technologies, significant efforts and a holistic framework are required to meet the targets. A first R&D&I issue is that the optimisation of current processes is already very high, and the production processes are close to their thermodynamic limits. This leads to a situation where no significant emission reduction can be expected anymore under the current baseline scenario. **In this baseline scenario, the total CO_2 emissions of the steel industry would be only 10-15% lower in 2050 than in 1990**, accounting for the estimated growth in production.[22] This estimation is based on demand and production of steel increasing and therefore, despite efficiency gains, overall emissions from steel production increasing compared to today and slightly decreasing in comparison to 1990.

A partnership is needed to overcome the barriers to R&D&I investments in the industry and ensure that available technologies are deployed. **Investment cycle in the steel industry takes between 20 and 30 years**.[23] As the steel sector is very **capital intensive** and operates in a **highly competitive global market**, immediate intervention and financial certainty are necessary. A key financial R&D&I challenge right now is the so-called valley of death between research and deployment of technologies. Research financing currently focuses on primary R&D&I, while support towards industrial deployment is lacking. On one hand, research organisations do not have the scale to fully shoulder the cost of deployment;[24] on the other hand, commercial companies cannot bear the high technological and economic risks. Therefore, in the valley of

[21] Climate Neutral Steelmaking in Europe, Green Steel for Europe Final Report, November 2021

[22] Namely, the business-as-usual trajectory would cause reduction of about 10% compared to 1990 levels; a reduction of 15% compared to 1990 would be achieved with retrofitting technology and low-carbon electricity being available. For further details, please see: EUROFER (2019), Low Carbon Roadmap: Pathways to a CO_2-Neutral European Steel Industry.

[23] See 'European Green Deal', p.7.

[24] European Commission (2018), European Steel: The Wind of Change, p. 28.

death a **'funding gap'** emerges. The sharing of financial burdens and risk will be essential to enable test and approval phases by value chain partners and allow technologies to mature.

Two further major challenges in connection with the technology life cycle described above are:

- The **'adoption gap**', that is the commercial diffusion of technologies that have already been deployed at industrial scale**.** The funding and adoption gaps can hit simultaneously very promising technologies, thus stifling some of the best opportunities to address the decarbonisation challenge;
- **Integration of technologies into the production system remains a challenge**. Even if the low-CO_2 technologies reach maturity, their market uptake will depend on their operational costs. On one hand, minimising those costs will have to become one of the main areas for further R&D&I; on the other hand, some form of cost compensation for green projects up to the first production and political guidelines for the use of climate-neutral steel are essential for overcoming this barrier.

The final main systemic issues that explain why a partnership is needed consist of **external factors and wider industrial challenges** surrounding the steel industry and market. These factors and challenges include both inputs that the steel sector requires to produce clean steel and the overall framework of international competition. The most important are the following:

- The production of clean steel will require the high availability of **zero-carbon electricity and carbon-free hydrogen** produced from this electricity in both CDA and SCU pathways. Despite steel production became considerably more energy-efficient in recent decades, the transformation to clean steel will require a significantly higher availability of green electricity.
- The availability of CCS, for example through **geological storage of CO_2,** will be another essential external factor, related to several technologies in the SCU pathway.
- Clean steel is expected to cost substantially more than conventional steel. In a competitive and global market environment, in which not all competitors face similar environmental regulation, the lack of public support would **put EU steelmakers at a serious competitive disadvantage**. Without a joint public-private endeavour, the path towards decarbonisation may end up in **carbon leakage**, i.e., in shifting steel production outside of the EU, resulting in a loss of jobs and growth and a negative impact on global emissions.

1.3 Vision and ambitions

The Clean Steel Partnership nurtures the long-term vision of supporting the European leadership in the **transformation of the steel industry into a climate-neutral sector.** Underlining its commitment to contribute to a common EU transition to green economic growth, the steel industry has set itself the following **long-term vision** for CO_2 emissions reductions compared to 1990 levels:

- Develop technologies reducing CO_2 emissions from steel production by 50% by 2030[25] compared to 1990 levels; and

[25] Letter to Frans Timmermans from EUROFER, dated 21 February 2020

- Reduce CO_2 emission by 80-95% by 2050 compared to 1990 levels, ultimately achieving climate neutrality.[26]

This vision implies that the sector will help remove more carbon than it emits itself. Provided that the EU steel sector reduces its own emissions up to 95%, its clean steel products replace more CO_2-intensive products, and it is a global leader in low CO_2 steelmaking, combined emission from steel making and downstream products will result in **negative CO_2 emission after 2050**.

To reach the steel industry's long-term visions, its **immediate and intermediate ambitions** consist of **piloting and demonstrating breakthrough technologies** that can significantly reduce the impact of steel production on the climate footprint.

This vision matches the EU ambitions of significantly reducing CO_2 emissions and building a sustainable and green economy in Europe. Furthermore, as the steel industry is a centrepiece of the European economy, this vision has the potential of contributing to the EU aspirations in industrial policy and economic growth.

1.3.1 A system-level vision: sustainable growth and renewable energy networks

Beyond the steel industry, other industries within the EU will also contribute to pursuing a sustainable economy. **Steel plays an important role in many industrial value chains**, such as construction, mobility, energy, or mechanical engineering.[27] The European steel industry is already a global leader in environmental sustainability and highly technologically specialised products.[28] A coordinated framework can thus entail the spreading and exchange of knowledge from the steel sector to other industries. For the EU to remain a **global leader in sustainable economic growth**, the steel industry's ambitions must, therefore, be not only to reduce its footprint by producing steel with low carbon emissions, but also to share its technological knowledge along industrial value chains. For this ambition to realise, geographical proximity is key, as the cross-industry spill-overs, for instance to the casting sector, can take place only if a strong presence of the steel industry in the EU is preserved.

The achievement of sustainable growth will depend largely on the EU spearheading global efforts on **renewable energy**. Steel is an essential material in modern energy solutions, which is why clean steel will be instrumental to reach this common vision. Figure 7 portrays how modern green electricity technologies are more steel-intensive that vintage ones.

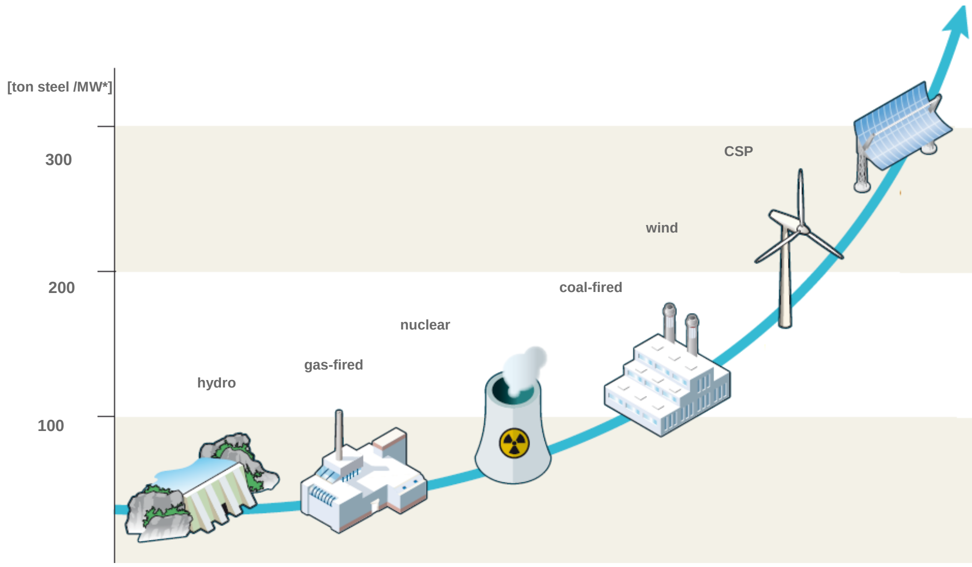
---

[26] Under the condition that the right political conditions are implemented. For further information see EUROFER "A Green Deal on Steel".

[27] EUROFER (2019), 2019: European Steel in Figures, p. 25.

[28] Steel: Preserving sustainable jobs and growth in Europe, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank, COM(2016)155, 16.3.2016.

Figure 7 Steel intensity of modern electricity solutions (tonnes of steel/MW installed capacity)



Source: De Maré, C. (2019), The Circular Economy in 2050 – Challenges and opportunities for EAF route (keynote speech).[29]

1.3.2 The European Green Deal as a just transition

Finally, the European Commission has stressed that its vision of a sustainable economy must not come at the expense of citizens and workers, as it should be **a just transition**.[30] A strong and competitive clean steel industry will contribute to the achievement of the just transition in several ways. The European steel sector is highly important for **employment and GVA** within the EU.[31] However, the steel industry is also under heavy competitive pressure from global markets and imports to the EU from regions with less immediate decarbonisation efforts. It will be vital to ensure a competitive steel sector to secure economic growth, high-quality employment, and innovation throughout industrial value chains in the EU. The challenging tasks ahead will further require highly skilled workers, but in reverse will offer those workers employment opportunities. Furthermore, European society is currently changing, and steel is playing a crucial role in such a change. Further to CO_2-free energy production and distribution, another example is the changing mobility of citizens within urban areas, which will require the extension of **affordable urban transport infrastructure**. Steel is essential for such infrastructure, as it represents a strong, fire-resistant, and anti-corrosive material, needed for underground and open-air railway systems[32].

1.4 Objectives

The **general objective** of the Partnership is to develop technologies at TRL8 to **reduce CO_2 emissions stemming from EU steel production by 80-95% compared to 1990 levels by 2050**, and to close the feedstock and energy loops (circularity), ultimately leading to climate neutrality. This will contribute to

[29] See reported also in: ESTEP (2014), Sustainable steel production for the 2030s: the vision of the European Steel Technology Platform's Strategic Research Agenda (ESTEP's SRA).
[30] European Green Deal, p. 15.
[31] See Section 1.1 above.
[32] Navigant Netherlands B.V. (prepared for EUROFER) (2019), Update of the Steel Roadmap for low-carbon Europe 2050,

the EU effort towards a climate-neutral continent. At the same time, this objective is to be achieved while **preserving the competitiveness and viability of the EU steel industry** – both for BF-BOF and EAF routes and including the wider steel value chain – and making sure that EU production will be able to meet the growing EU demand for steel products. This general objective is in line with the climate ambitions and commitments set by the European Green Deal (as discussed in Section 1.1 above), and in particular with its pledge to promote the decarbonisation and modernisation of energy-intensive industries, including steel, in a time frame that goes beyond the remit of this Partnership. Furthermore, the general objective is in line with the UN's 2030 SDGs (discussed more in detail in Section 3.2), and the Paris Agreement with its associated pledges.

Against this background, the Clean Steel Partnership has set specific and operational objectives that are to be **achieved in 7 to 10 years**. This timeframe is determined in accordance with the framework of the Horizon Europe Programme, which runs from 2021 to 2027. Three more years are added to the end year of the programme, as approval of new project calls can still be expected in the last years of the programme, and then followed by project completion up to 2030.

There are six specific objectives to the Partnership, each of which entails one or more operational objectives. As further discussed in Chapter 3, the operational objectives are linked to key performance indicators (KPIs) to monitor and assess their progress/achievement. The potential contribution of the projects towards the zero-pollution ambition for a toxic-free environment as expressed in the European Green Deal communication will be taken into account. The specific objectives are listed below.

- **Specific objective 1:** Enabling steel production through carbon direct avoidance (CDA) technologies at a demonstration scale;
- **Specific objective 2:** Fostering smart carbon usage (SCU – Carbon capture) technologies in steelmaking routes at a demonstration scale, thus cutting CO_2 emissions from burning fossil fuels (e.g. coal) in the existing steel production routes;[33]
- **Specific objective 3:** Developing deployable technologies to improve energy and resource efficiency (SCU - Process Integration);
- **Specific objective 4:** Increasing the recycling of steel scrap and residues, thus improving smart resources usage and further supporting a circular economy model in the EU;
- **Specific objective 5:** Demonstrating clean steel breakthrough technologies contributing to climate-neutral steelmaking;
- **Specific objective 6:** Strengthening the global competitiveness of the EU steel industry in line with the EU industrial strategy for steel.[34]

[33] This specific objective exclusively focuses on the steelmaking process. By way of example, it does not cover projects that aim to use gases from steelmaking as a feedstock in processes of other sectors; by contrast, it does cover projects aiming to prepare/treat such gases to meet the requirements of other sectors.

[34] European Commission (2013), Action Plan for a competitive and sustainable steel industry in Europe, COM/2013/0407 final, available at: eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52013DC0407; European Commission (2016), Steel: Preserving sustainable jobs and growth in Europe, COM(2016)155, Available at: eesc.europa.eu/en/our-work/opinions-information-reports/opinions/steel-preserving-sustainable-jobs-and-growth-europe

Box 2 The Steel sector's CO_2 emissions – definition of system boundaries

The **specific and total CO_2 emissions for the EU steel industry** can be calculated using various approaches resulting in different values for CO_2 emissions and energy consumption. To be able to compare and assess data of any publication, the system boundaries have to be known. In the Clean Steel Roadmap, the same system boundaries are applied as in previous steel studies and roadmaps published by EUROFER. The numbers calculated represent the total carbon footprint of the EU27/28 steel industry. The footprint can be understood as equating to all CO_2 emissions that would not take place if there was no steel industry. The steel industry has established a **standardised method of calculating emissions** in a constituent way. Figure 8 and Figure 9 show the CO_2 emissions of a steel producer following the concept of reporting on scope I, scope II, and scope III CO_2 emissions.

Figure 8 Overview on scope I, scope II, and scope III emissions of a steel producer within the Clean Steel Partnership Roadmap

Scope I Direct CO_2 emissions from facilities of the steel producers			
Sinter Plant	Ironmaking (e.g.: Blast Furnace, Direct Reduction Plant, Smelting Reduction Plant)	Steelmaking	Casting Plant
Pellet Plant			Hot Rolling Mill
Coke Oven			Cold Rolling Mill and Downstream Plants

Scope II Indirect CO_2 emissions from purchased energy
Electricity

Scope III: Indirect CO_2 emissions from the value chain (upstream and downstream), which are not included in Scope I and II purchased materials				sold materials
Pellets	DRI / HBI	Pig Iron	Graphite Electrodes	Process Gases[1]
Oxygen	Natural Gas	Coke	Lime	Slag[2]
Hydrogen	Steam	Scrap	Biomass	

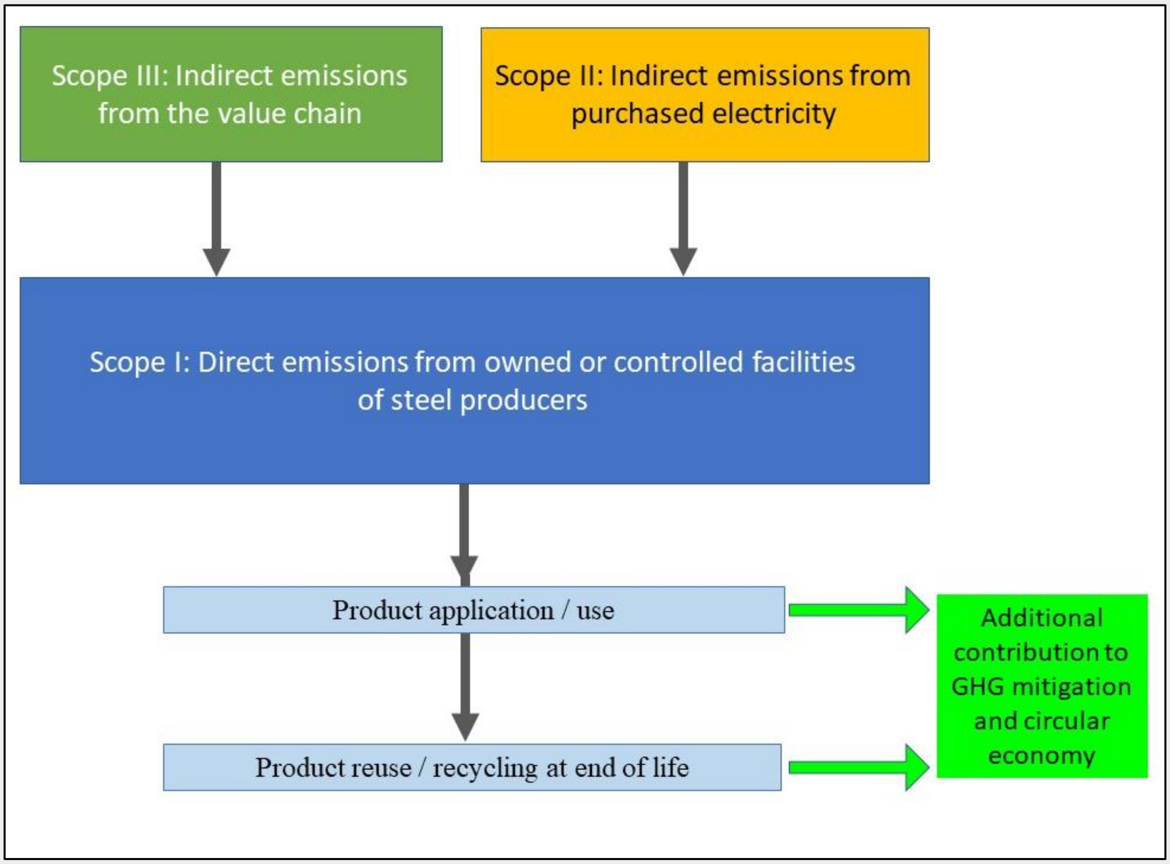
1. The utilisation of byproducts, such as process gases or waste heat, is not counted as credit because such use helps reduce the energy consumption of facilities. Only byproduct gases, that are sold to a second party can be counted as a credit, because they help to reduce emissions of a different sector.
2. Currently no credits are given for the CO2 savings through slag usage in cement production.

Source: Authors' elaboration.

CO_2 emissions were determined by the amount of **input material consumed and output material produced** within each process step attributed to each material's carbon content. Netting input with output CO_2 flows (carbon balance) yields the direct CO_2 emissions for each step. Emissions from previous process steps are included in the next step as upstream emissions ("backpack") weighted with the amount of material needed.

Despite the high dependency on company-specific product portfolios, cold rolling and further processing of steel are also included in the system boundaries applied for the Clean Steel Roadmap. Emissions associated with the mining and transportation of raw materials are not included. By increasing the level of circularity more complex systems (e.g. industrial symbioses) will be created, which are likely to initiate a re-evaluation of the system boundaries.

Figure 9 Scheme of CO_2 emissions calculation of a steel producer and the wider perspective of product application/use and re-use/recycling



Source: Authors' elaboration.

Most emissions are generated directly by **production processes**:

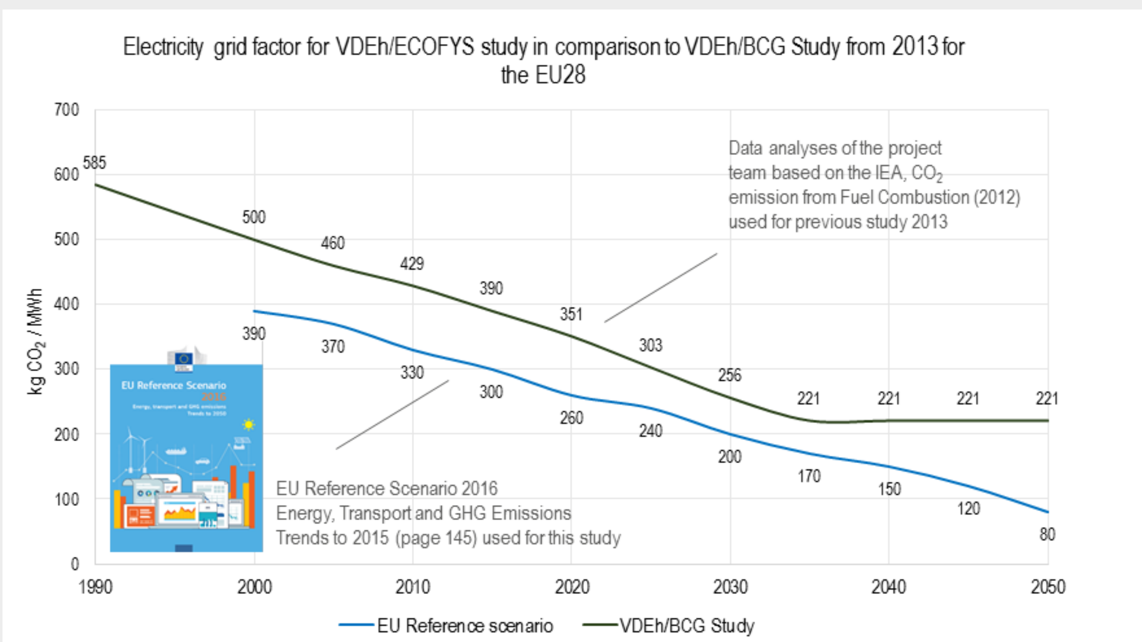
- The aggregates of the BF-BOF iron and steelmaking processes are closely intertwined, making synergies possible. Most of the residues can be recycled within the integrated steel plants (for example, oil-free mill scale, flue dust etc. can be fed into the sinter plant), making efficient use of residues.
- For Scrap-EAF, only around half of the CO_2 emissions are generated by steelmaking production processes, with the remainder coming from indirect emissions. Direct emissions are due to feedstock that contains carbon such as coal and natural gas, electrodes, and fluxes. Indirect emissions stem from purchased electricity needed for steel making in EAF, casting and hot rolling
- Works arising gases/process gases are essential for the energy management of the iron and steel production. These gases are recovered and used to save natural resources and thus contribute to reducing CO_2 emissions:
    - In the BF-BOF route, process gases occur at the coke plant, blast furnace and basic oxygen furnace. In the Smelting Reduction-BOF route, they occur at the smelting facility and BOF. Because of their calorific value, those process gases are recovered and used to substitute for natural gas in the furnaces or to generated electricity and steam.

- In EAF route, off-gases occur containing both chemical and latent high-temperature heat (residual heat called "waste heat") that can be recovered and used to pre-heat the feedstock before charging in EAF or to generated steam.
- Slag is a by-product created by chemical reactions during ironmaking or steelmaking. Its composition is adjusted through the addition of fluxes:
  - Granulated slag from the BF is used in the cement industry, where it replaces materials that are CO_2 intensive (Portland clinker).
  - EAF slag is used in agglomerate for road construction.
  - Second Metallurgy Slag is used directly in the EAF melting process in substitution of virgin lime or in the cement industry, where it replaces materials that are CO_2 intensive (Lime).
- Indirect emissions from purchased materials, such as coke, burnt lime and O_2, are considered for both routes.

The change from integrated carbon-based blast furnace/converter route to **hydrogen DRI/EAF route** would result in no further need of coke and sinter, but instead the need for hydrogen and pellets. Hence for comparison purpose, some additional assumptions can be made regarding the system boundaries. One main assumption is that there will be no carbon leakage for the steel industry in Europe. This means that the whole agglomerated iron ore burden materials for the processes should be produced within Europe and accounted as direct emissions. This effects mainly the pellet production for DRI plants. Therefore, the calculations are done considering a pellet "backpack" (upstream emission) for the routes where pellets are used. Also, the use of **HBI** if produced by natural gas as reductant got a backpack load.

Alternative routes to the conventional blast furnace will include CDA technologies (Carbon Direct Avoidance) and CCU technologies which all need electricity with a low CO_2 footprint for massive CO_2 mitigation in their processes. Hence, an assumption of the development of the electricity mix is needed. Figure 10 shows the CO_2 intensity of the electricity grid in the EU 28 up to 2050. Using, for example, the EU reference scenario, the CO_2 intensity of the EU 28 is 300 kg/MWh in 2015, 200 kg in 2030 and 80 kg in 2050. In the Clean Steel Roadmap, the EU reference scenario is used.

Figure 10 Electricity CO_2 intensity of EU 28 (grid mix factor)



Source: Steel Institute VDEh (prepared for EUROFER) 2019, Update of the Steel Roadmap for low-carbon Europe.

Assessing the contribution of steel to climate change mitigation requires to consider the **lifecycle of the steel value chain**.

- Steel is an essential material for low carbon manufacturing and technology, and without steel, the climate change mitigation in many other sectors could not be realised. Therefore, the whole supply chain has to be recognised as being 'environmentally sustainable' for the low carbon activity to be fully supported, as one part cannot exist without the other. Examples of steel as an enabler to low carbon manufacture and technology include:
    - Use of Advanced High Strength Steels (AHSS) to reduce the weight of vehicles in the transport sector and therefore reduce fuel consumption and CO_2 emissions
    - The use of grain-oriented electrical steel in transformers to minimise power distribution losses.
    - The use of high alloyed steel like stainless steels for corrosion protection, thus multiplying the service life of an installation or product and reducing maintenance.
    - The use of steel in key infrastructures such as high-speed rail, bridges, and tunnels, enables faster transport links, which can reduce the amount of driving and flying.
    - Steel is an essential material for renewable energy technologies such as wind, tidal, solar and wave power.
    - The production of steel also produces valuable by-products that are used in other sectors, which contributes to the reduction of natural resource use and emissions in those sectors.
    - Steel is a highly recycled material, contributing to a more circular economy and saving CO_2 from recycling by reducing the need for primary material.
- The reuse and recycling of steel products at the end of life contribute to increase resource efficiency and thus bring essential contribution to the reduction of CO_2 emissions.

By increasing the **level of circularity** more complex systems (e.g., industrial symbioses) will be created, which are likely to initiate a re-evaluation of the system boundaries.

Chapter 2: Research and Innovation Strategy

Summary

Activities

- R&D&I activities supporting the achievement of the Partnership's objectives are classified according to two levels:
  - Six areas of intervention:
    - Two technology pathways: carbon direct avoidance and smart carbon usage, which is further divided into carbon capture, utilisation and storage, and process integration.
    - Circular economy projects overarching the technology pathways.
    - Possible combinations of the different pathways and CE projects.
    - Enablers and support actions, i.e., activities that can support the successful implementation of solutions developed under the other five areas of intervention as well as the global competitiveness of the EU steel industry.
  - Twelve technology building blocks:
    - One building block can be integrated into different technological pathways and can contribute to one or more areas of intervention.
    - Only the combination of building blocks will provide impactful solutions to mitigate CO_2 emissions.

Timeline and budget distribution

- A multi-stage R&D&I approach is applied to accelerate carbon mitigation in the steel industry:
  - Stage 1 targets projects that generate 'immediate' CO_2 reduction opportunities;
  - Stage 2 focuses on those projects that may not be implemented 'immediately' in the installed base, but allow for a quick migration (evolution) towards improved; processes;
  - Stage 3 (medium- to long-term impact measures) looks at those projects that can 'revolutionise' the steel industry through breakthrough development, and require significant capital investment in new processes.
- This multi-stage approach provides the rationale behind the budget split over time and areas of intervention.
- Between 2021 and 2030, the total resources needed to implement the Roadmap are estimated at about EUR 2.55 billion. During the timeframe covered by the Clean Steel Partnership (2021-27), the wider boundary of the investment needs is estimated at EUR 2 billion.
- The proposed budget withing the scope of the Clean Steel Partnership is around EUR 1.4 billion during 2021-27, including both public and private funding. To implement the Roadmap in full, the Partnership's activities will mobilise further resources from other EU funded programmes and Member States.
- The budget is expected to finance 16 projects resulting in building blocks at TRL7, 12 projects resulting in building blocks at TRL 8 and 4 demonstration projects.

2.1. Activities

As further detailed in this Section of the Roadmap, R&D&I activities supporting the achievements of the Clean Steel Partnership's objectives can be classified according to two different levels. The first level covers **six areas of interventions** representing different technological pathways (and combinations thereof) to decarbonise the EU steel industry. The second level includes **12 technology building blocks**, which can contribute separately to the areas of intervention, or be combined with other building blocks within a certain area of intervention to enable a higher level of carbon reduction in steel production. The building blocks are core technology elements to define collaborative projects on low-CO_2 steelmaking, allowing to break down the emission reduction challenge into manageable activities and relevant projects.

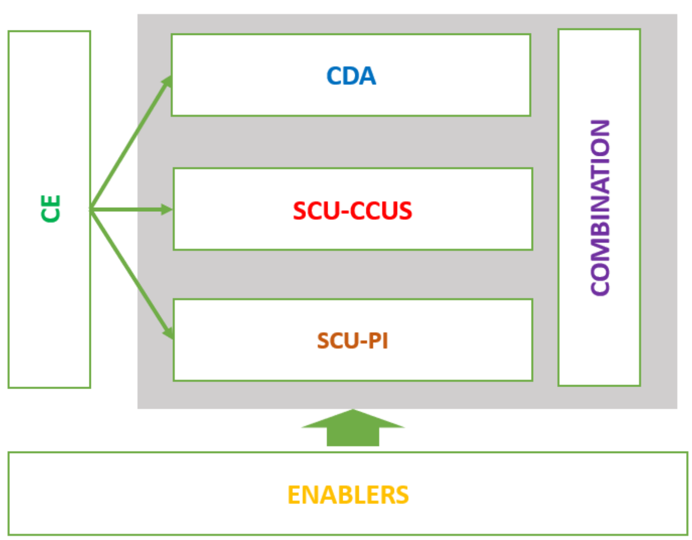
Different optimal technological solutions can be applied in the various regions of Europe, taking into account local availability problems, energy issues, environmental issues, current practices and political aspects.

2.1.1. Areas of intervention

To achieve the objectives identified in Chapter 1 and reduce CO_2 emissions stemming from EU steel production by 80-95% compared to 1990 levels by 2050 - ultimately leading to climate neutrality, R&D&I activities funded by the Clean Steel Partnership will revolve around **six main areas of interventions** comprising (Figure 11):

- Two technology pathways: CDA and SCU, which is further divided into SCU-CCUS and SCU-PI (see Section 1. 2.1).
- CE projects overarching the technology pathways.
- Possible combinations of the different pathways and CE projects.
- Enablers and support actions, i.e. activities that can support the successful implementation of solutions developed under the other five areas of intervention as well as the global competitiveness of the EU steel industry.

Figure 11 Interaction among the areas of intervention



Source: Author's elaboration on consultation with ESTEP members.

Each area of intervention is **linked to one or more specific objectives** of the Partnership as shown in Table 1 and is expected to generate certain impacts, as further discussed in Chapter 3.

Table 1 Links between areas of intervention and specific objectives of the Clean Steel Partnership

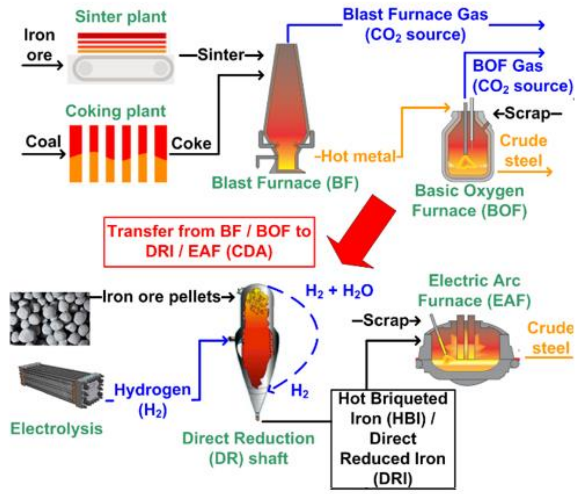
Areas of intervention	Specific objectives
Carbon direct avoidance (CDA)	1: Enabling steel production through carbon direct avoidance (CDA) technologies at a demonstration scale
Smart carbon usage via carbon capture, utilisation, and storage (SCU-CCUS)	2: Fostering smart carbon usage (SCU – Carbon capture) technologies in steelmaking routes at a demonstration scale, thus cutting CO_2 emissions from burning fossil fuels (e.g., coal) in the existing steel production routes
Smart carbon usage via process integration (SCU-PI)	3: Developing deployable technologies to improve energy and resource efficiency (SCU - Process Integration)
Circular economy (CE)	4: Increasing the recycling of steel scrap and residues, thus improving smart resources usage and further supporting a circular economy model in the EU
Combination of pathways	5: Demonstrating clean steel breakthrough technologies contributing to climate neutral steelmaking
Enablers & support actions	6: Strengthening the global competitiveness of the EU steel industry in line with the EU industrial strategy for steel

Source: Author's elaboration on consultation with ESTEP members.

2.1.1.1. Carbon Direct Avoidance

CDA includes technologies that **avoid carbon emissions during steelmaking**. CDA mainly relies on steel production processes based on **hydrogen and green electricity**. For instance, carbonaceous sources can be switched to green hydrogen-based sources. Figure 12 illustrates an example of how the substitution of the BF-BOF route by the EAF route for crude steel production may contribute to CDA. Hydrogen can be produced via water electrolysis powered by green electricity. The resulting green hydrogen is then used to reduce iron ore in a DR shaft or other breakthrough technologies and the green electricity is used also for the EAF. Another example is the direct use of green electricity for ore reduction (iron ore electrolysis). A positive side effect of these electrolysis processes is the production of oxygen, which can then be directly used inside the steel mill e.g., as an oxidiser for internal combustion/heating processes.

Figure 12 Carbon direct avoidance



Source: LowCarbonFuture[35]

2.1.1.2. Smart carbon usage via process integration (SCU-PI)

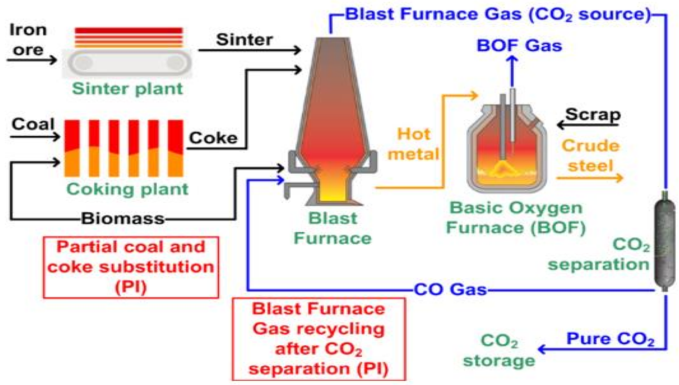
SCU-PI allows **reducing fossil fuel** (coal, natural gas, etc.) used in both BF-BOF and EAF steel production and, in turn, **curtailing CO_2 emissions** generated by the steel industry. Several technology options may contribute to the SCU-PI in conventional steel plants, including the (partial) replacement of coal by natural gas[36], biogas, biomass[37], hydrogen, or even electricity, the increase of the scrap/hot metal ratio, the replacement of iron ore or scrap by available hot briquetted/direct reduced iron, and the advanced management of the energy streams and process gases (e.g., off gases released from EAF/BF-BOF). Figure 13 illustrates examples of solutions for SCU-PI in BF-BOF plants, namely the recycling of CO recovered from Blast Furnace gas back into the Blast Furnace for metallurgical use, to avoid the CO_2-intensive usage for electricity production.

[35] For further details, please see: lowcarbonfuture.eu/projects-area

[36] In the CSP roadmap "natural gas" means a future orientated concept, that includes natural gas (transition period), natural gas enriched by/blended with hydrogen and hydrogen rich gas. The latter are in any case typical process gases from steelmaking: Coke oven gas (COG) for example is composed of at least 60% H_2.)

[37] In the CSP roadmap "biomass" means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin as defined in the Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources(EU, 2018).

Figure 13 Smart carbon usage via process integration

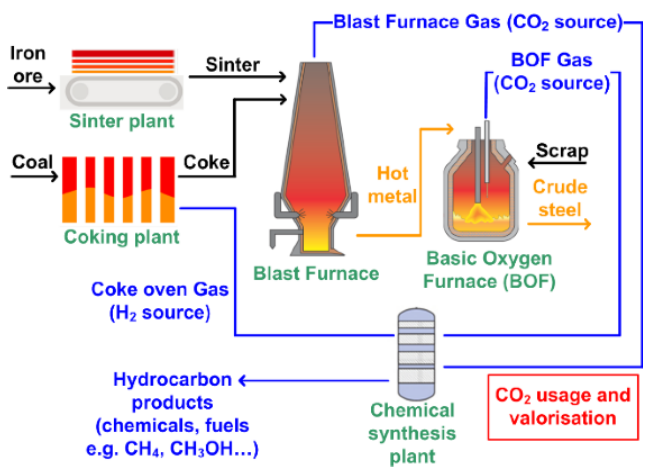


Source: LowCarbonFuture

2.1.1.3. Smart carbon usage via carbon capture, utilisation, and storage (SCU-CCUS)

SCU-CCUS encompasses technologies that help **avoid carbon emissions to the atmosphere**. This pathway supports all the options for **utilising the CO and CO_2 in steel plant gases or fumes as raw material** for the production of/integration into valuable products. SCU-PI-related projects can be often combined with SCU-CCUS. Figure 14 shows one possible application of SCU-CCUS solutions to the BF-BOF route, i.e., the production of fuels or base chemicals from steel mill gases. CO_2 originates from the BF and the BOF gases and hydrogen from coke oven gas can be used for hydrocarbon production, through a chemical hydrocarbon synthesis process. The final products can be chemicals and fuels that can be used by other industries.

Figure 14 Smart carbon usage via carbon capture, utilisation, and storage



Source: LowCarbonFuture

2.1.1.4. Circular Economy

To achieve a sustainable steel industry, CE must be addressed by different technical solutions contributing to European initiatives, such as the European Green Deal (EGD) and the New EU Circular Economy Action

Plan (CEAP), which were launched by the EU in 2020. There are several main actions envisaged under the umbrella of the EGD and the CEAP and appear particularly significant for the steel sector. These are the introduction of a sustainable product policy framework supporting the design of sustainable products, the empowerment of consumers in the selection of “green” products, strengthening circularity in production processes, the enhancement of a waste policy oriented toward prevention, the circularity and elimination of toxic compounds, and the enforcement of a market for secondary raw materials. Steel fits well with this ambition due to its inherent properties and because the steel industry established circular practices decades ago.

CE approaches **enhance the recycling of steel** (e.g., scrap in BOF/EAF and residues) **and resource efficiency**. CE promotes the scrap utilisation through scrap sorting and improved removal of scrap pollution with new detecting technologies. It also includes process related to the utilisation of all residues from steel production internally or in other sectors like dust in the non-ferrous sector or slags in the cement sector. Besides, CE supports the substitution of fossil materials with alternative carbon-bearing materials and alternative reductants (e.g., biomass[38], plastic, rubber, syngas from wastes). Finally, CE approaches encompass technologies that identify and make use of waste heat sources. Several activities under this area of intervention are directly linked to other areas of interventions such as SCU-PI/CCUS and CDA.

In the CE EU context, the steel sector is covered by several EU Directives and regulations as a relevant stakeholder:

- Waste Framework Directive: Steel promotes measures to reuse products, reduce waste generation and increase preparation for reuse;

- Waste Shipment Regulation: tackling illegal shipments of waste overseas in countries with less stringent environmental and social policies is supported by well-defined procedures and audits to avoid these shortcuts;

- End-of-life Vehicles (ELV): given the importance of scraps as input for secondary steel making, expanding the quantity of material that can be utilised is crucial to avoid the waste of such an important source

- Regulation of Ecodesign requirements for sustainable and green products: the complexity of the definition about what sustainable and green means and related implications allows space for proposals for more precise definitions

- Industrial Emissions Directive (IED): this is one the most critical aspects that via the wider framework of the EU Green Deal needs to be tackled to take into consideration an integrated way to couple the goals, avoiding focusing on specific aspects at the expenses of others

[38] Here "biomass" means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin as defined in the Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (EU, 2018).

•	Water Framework Directive: the steel sector promotes measures to protect water bodies and prevent their deterioration by preventing harmful emissions (including relevant thermic impacts) and to improve water efficiency

These opportunities need to be materialized and some priorities defined to be capable of fully exploiting such chances.

2.1.1.5. Combination of technological pathways

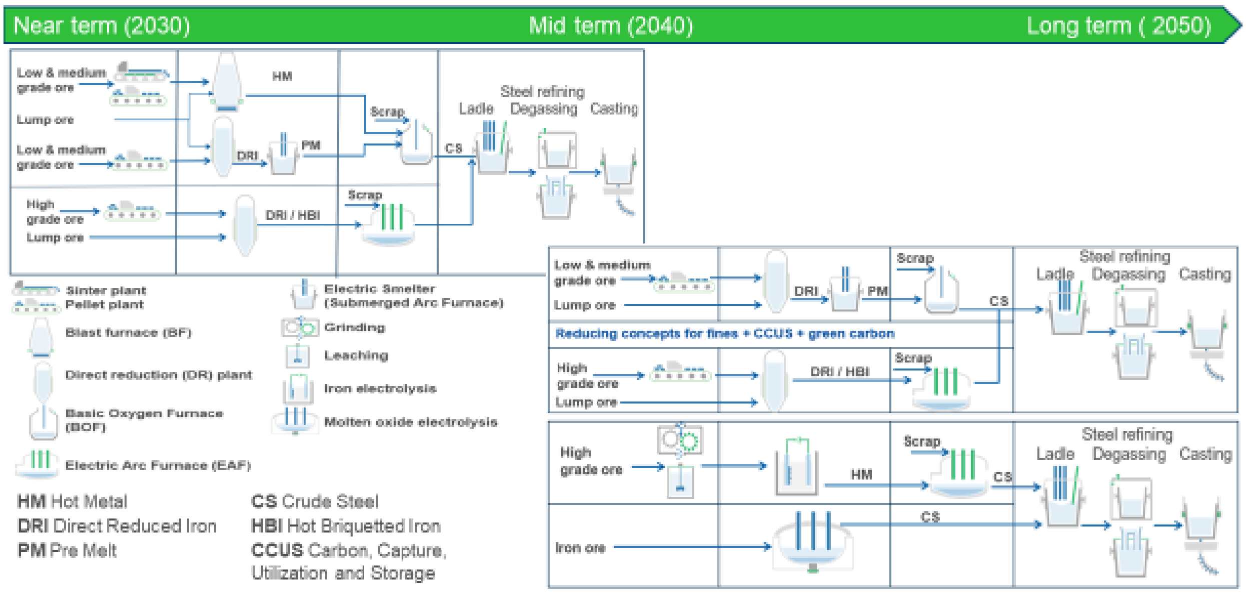
There is no single solution to decarbonise the steel sector. Rather, many different technical pathways and approaches must be developed to achieve a climate-neutral EU steel industry by 2050. The Clean Steel Partnership will play a crucial role in bringing together, coordinating, and making the most of different solutions and technologies. This area of intervention focuses on the **combination of different technologies** and has the full potential to generate larger CO_2 reduction than any single pathway or technology. It is important for the steel sector to investigate possibilities to combine the technologies options to achieve higher CO_2 reduction potential. By way of example, SCU-PI technologies alone can help reduce CO_2 up to 65%. However, if they are combined with CCUS technologies, the total CO_2 mitigation value can be up to 100%.[39]

Figure 15 illustrates a general view of co-existence of traditional steelmaking progresses with new breakthrough steelmaking progresses and integration between SCU-PI and SCU-CCS, namely during the transition to net zero scenario, that could include the partial substitution of coal with biomass[40] together with the CO_2 separation and internal recycling of CO as an auxiliary reducing agent.

Figure 15a Example of the integration between SCU-PI and SCU-CCUS pathways in a co-existence of new breakthrough and traditional steelmaking progresses

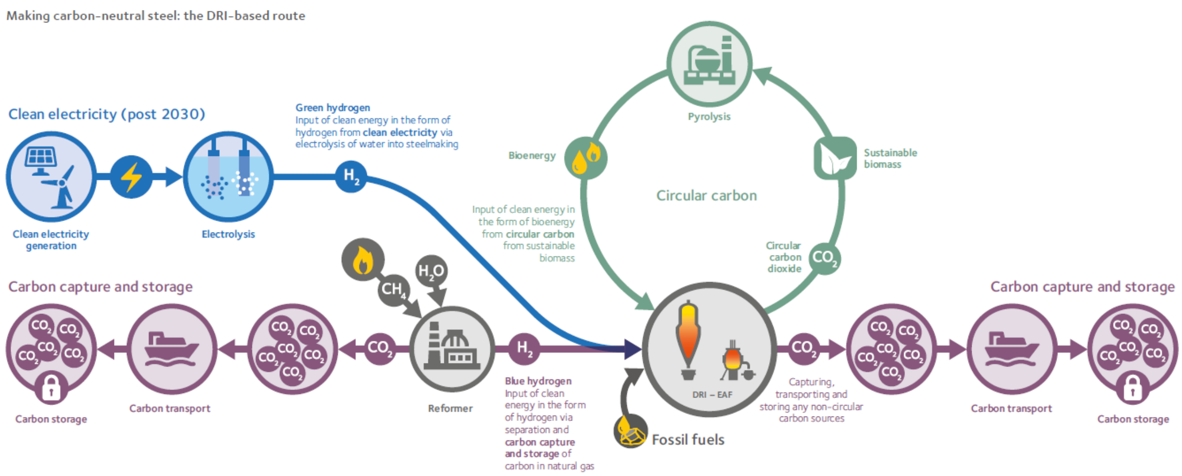
[39] For further details, please visit: LowCarbonFuture.eu

[40] Here "biomass" means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin as defined in the Directive EU 2018/2001 of the European Parliament and the Council on the promotion of the use of energy from renewable sources : Forest sustainability Art.29 paragraphs 6-7 and Agricultural biomass, biogas and bioliquids Art.29 paragraphs 2 to 5. Feed- and food crops are not used.



Source: LowCarbonFuture[41]

Figure 15b Example of integration between the CDA, SCU-CCUS and SCU-PI pathways in the DRI based route



Source : Arcelor Mittal Climate Report 2 - June 2021

41 For further details, please see: lowcarbonfuture.eu/projects-area

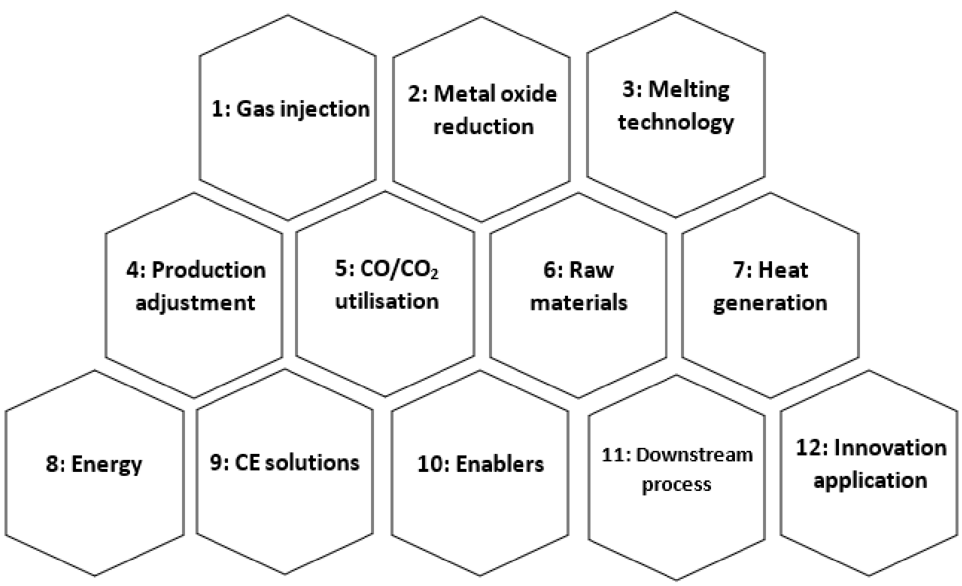
2.1.1.6 Enablers and actions supporting the global competitiveness

To properly implement R&D&I activities under the above-mentioned areas of intervention, enablers and support actions are required. This area of intervention includes, *inter alia*, the integration of the latest technologies such as **artificial intelligence and digital solutions** into the industrial production. This encompasses the development of new measurement technique and digital tools for monitoring and control in the new steel production processes; in addition, new predictive and dynamic models will be developed, as well as strategic scheduling tools, which will ensure the planning, assessment and optimisation of the industrial transition process. Enablers and support actions may also include the creation of synergies with EU and national programmes that enable the **upskilling of the steel workforce**, activities aiming at **fostering R&D&I collaboration between EU companies** participating in the clean steel value chain as well as broader initiatives supporting the **creation of a new market for clean steel products**, the **uptake of successful technology** developed in the EU and, more generally, the **global competitiveness of the EU steel industry**.

2.1.2. Building blocks

R&D&I activities contributing to the above areas of intervention will focus on 12 technology building blocks (listed in Figure 15) and/or combination thereof. Only the combination of building blocks will provide impactful solutions to mitigate CO_2 emissions. One building block can be integrated into different technological pathways and can contribute to one or more areas of intervention, as summarised in Table 2. This section of the Roadmap takes **a closer look into the technical specification of each building block**, and how they contribute to the six areas of intervention. The order of presentation of the building blocks does not reflect the importance nor prioritise R&D&I activities carried out in the context of the Clean Steel Partnership.

Figure 15 The 12 building blocks covered by the Clean Steel Partnership



Source: Author's elaboration on consultation with ESTEP members.

Table 2 Building blocks' contribution to the six areas of intervention

	CDA	SCU-CCUS	SCU-PI	CE	Combination	Enablers
1. Gas injection technology	Major	Minor	Major	Minor	Major	Minor
2. CO_2-neutral iron-ore reduction	Major	Minor	Major	Maj/Minor	Major	Minor
3. Melting of pre-reduced and reduced ore, scrap, and iron-rich low-value residues	Major	NA	Major	Major	Major	Minor
4. Adjustment of today's production to prepare for the transition towards climate neutrality	Major	Major	Major	Major	Major	Major
5. CO/CO_2 utilisation, CO_2 Capture, and storage	Major/minor	Major	Major	Minor	Major	NA
6. Raw material preparation	Major	NA	Minor	Major	Major	Major
7. Heat generation for processes	Major	Minor	Major	Minor	Major	Minor
8. Energy management / Energy vector storage (H_2, electricity, intermediate materials)	Major	Minor	Major	Major	Minor	Major
9. Steel specific circular economy solutions	Minor	Minor	Major	Major	Major	Major
10. Enablers (skills, digitalisation)	Major	Minor	Major	Minor	Major	Major
11. Low CO_2 emissions downstream processes	Major	Major	Major	Minor	Major	Major
12. Innovative steel applications for low CO_2 emissions	Major	Minor	Minor	Minor	No	Minor

Source: Author's elaboration on consultation with ESTEP members.

The activities introduced via the building blocks of the Clean Steel Partnership will mainly focus on the facilities of **steel production**. The CO_2 emission of the steel sector can be measured as the average value between the primary and secondary route. Today, the EU is in a good position when compared to other regions outside the EU. Values in the EU are 1300 -1800 kg CO_2/tonne of liquid steel produced via the BF-BOF route, and 80-120 kg CO_2 direct and 250-350 kg CO_2 indirect emissions from steel production under the EAF route. The BF-BOF route accounts for around 60% of EU steel production, while the EAF route accounts for around 40%. The main CO_2 emissions of steel production originate from **primary steelmaking**, transforming iron ore via BF and BOF into steel. Therefore, the challenge for the Clean Steel Partnership lies in solutions to transform this route to become climate neutral.

At the same time, the use of CO_2-free fuels or CO_2-free electricity could lead to CO_2 emissions as low as 60 kg CO_2 /t tonne of liquid steel in the **scrap-based EAF** as well as for purely green hydrogen/electricity iron-ore based CDA.[42] The level of 60 kg CO_2/tonne of liquid steel is an operational minimum as long as the EAF uses graphite electrode and some carbon dioxide is coming from the additions and the alloying material consumption.[43] This very low CO_2 emission level if reached for about 50% of the steel production in the EU can contribute to reducing the very challenging target of integrated BF-BOF route.

The decarbonisation of the EU steel industry thus requires a combined approach aiming to reduce CO_2 emissions in both production routes. The contribution to the CO_2 emissions of the **downstream processes** (in particular hot rolling) to the CO_2 emissions is already comparable with that originated from the production of liquid steel in the scrap-based EAF route (about 150 kg CO2/ton of crude steel). It is apparent, therefore, that the downstream CO_2 emissions will also be relevant with respect to the final CO_2 reduction scenario (2050 and beyond).[44]

2.1.2.1. Building block 1: Gas injection technologies for clean steel production

Gas injection technology aims to **reduce the CO_2 footprint of the steel production**. In the coming years, the injection of gases needs to be adjusted, optimised, and/or developed in several steelmaking facilities. This building block focuses on all gases that contribute to a significant decrease in the steelmaking induced CO_2 emission. It encompasses **several activities with different timing in terms of industrial deployment**. The carbon footprint may be reduced moderately with rapid industrial deployment, for example through injecting natural gas[45], coke oven gas or BOF gas in the BF. Other gas injection options have the potential for very low CO_2 emissions but need intermediate steps before being ready for full industrial deployment (e.g. injection of high percentages of hydrogen in BF and EAF). Integration of gas injection with CO2 capture and storage technologies will also contribute to the transition towards CO2 neutral steelmaking.

From a technical standpoint, this building block covers **new process technologies for co-injection and new injection ports** e.g. for BFs, DRI plants but also for EAFs. **New control techniques** will also have to be developed taking into account process needs, safety issues and economic aspects. Further activities in this building block are related to **gas treatment:** advanced gas treatment solutions (purification, reforming, preheating) for steel plant process gases for the purpose of internal re-use. Finally, the influences on refractories and burner materials have to be investigated, in particular when injecting high percentages of hydrogen.

Table 3 summarises the contribution of gas injection technologies to the areas of intervention covered by the Clean Steel Partnership.

---

[42] Steel Institute VDEh (2019), Update of the Steel Roadmap for Low Carbon Europe 2050. Part I: Technical Assessment of Steelmaking Routes, p. 4

[43] Ibid.

[44] Ibid, p. 49.

[45] In the CSP roadmap "natural gas" means a future orientated concept, that includes natural gas (transition period), natural gas enriched by/blended with hydrogen and hydrogen rich gas. The latter are in any case typical process gases from steelmaking: Coke oven gas (COG) for example is composed of at least 60% H2.)

Table 3 Contribution of Building Block 1 to the six areas of intervention

CDA - Major contribution	• Injection will focus on hydrogen or at least hydrogen-rich gases or biogas to directly avoid the usage of fossil carbon as reducing agent in Blast Furnace, Direct Reduction or Fluidized Bed or as heat source in EAF operation. • Main focus is on injection in EAF and DRI plants but the injection of hydrogen in BFs can also be rated as the first step towards hydrogen-based DRI • The technologies provide important know-how and concrete technologies for the future use of hydrogen-based (resp. almost carbon-free) ironmaking • The process involving H_2 results in the formation of water vapor. Focus on the effect of water vaporization on the metallisation process due to hydrogen resulting.
SCU-CCUS - Minor contribution	• Combination of gas injection with CCUS makes sense for fast industrial decarbonisation • Integration of gas injection with CO_2 capture and storage technologies for the transition to CO_2 neutral steelmaking
SCU-PI - Major contribution (in combination with BB5, and also BB4, BB6, BB7, BB8, BB9)	• PI through injection of metallurgical gases as well as natural gas and H_2 in the BF to * minimise the need for fossil carbon (meaning SCU), the same applies for the new developments regarding the related process technology and control technology * CO_2-intense use of metallurgical gases in power plants • Development and demonstration of gas injection technology for the BF (injection of hot reducing gases, of H_2 or biogas, etc, in tuyeres and/or in the shaft) • New process technologies for co-injection and new injection ports for BF and DRI plants and EAF technology
CE - Minor contribution	• Limited to the increased recycling of metallurgical gases for e.g. the injection in BFs instead of using them in power plants or flaring • Advanced gas treatment solutions (purification, reforming, separation, preheating) for steel plant process gases for the purpose of internal re-use
Combination - Major contribution	With BB5 and also BB4, BB6, BB7, BB8, BB9, • Combinations of technologies related to SCU-PI, CDA and SCU-CCUS (e.g. BF top gas recycling combined with CCUS).
Enabler & Support actions - Minor contribution	• The technologies provide important know-how and concrete actions which can partly be rated as enablers for future hydrogen-based ironmaking (e.g. measurement and control technologies) • Safety issues with H_2 and hot gas injections, and integration of gas injections and CO2 utilisation and storage in the BF • Evolution of BF control systems to integrate gaseous injections (predictive models, sensors, etc.)

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.2. Building block 2: CO_2-neutral iron-ore reduction for clean steel production

This building block includes R&D&I activities related to the metal reduction processes using hydrogen, renewable electricity, or biomass[46]. **Direct reduction with high amounts of hydrogen** will be a key component of this building block, in demonstration projects on industrial scale, if possible, on existing hardware. Impacts on the properties of reduced materials (e.g., mechanical and metallurgical properties, reactivity, and bulk behaviour) and the process conditions have to be carefully investigated. Thus, several activities will concentrate on the process and the product properties as well as on the impact of the product properties on the downstream processes (e.g., EAF or smelter). The process technology may have to be adapted to the new boundary conditions. The activities related to the **use of electricity** are widespread. They have to cover **plasma technology**, for example for smelting reduction processes or gas preheating. Advancing and validating the H2 plasma reduction method with demonstration in a H2-plasma reactor could be coupled with approaches to monitor and control the process. Furthermore**, electrolytic reduction of iron ore** at low or high temperature will be further developed, and integrated into new or existing steelmaking sites.

Concerning **secondary carbon sources**, different sustainable and circular sources will be investigated, for instance biomass, polymers, biochar, civil or industrial wastes including their adaptation to different processes. Several R&D aspects should be addressed referring to logistics, availability, environmental assessment on the long term, legislation and regulation, flexibility of infrastructures, digital tools for monitoring. Research is necessary on the need for biochar and biocoal providers as these are foreseeable sources of carbon that will replace fossil coal. The sources will cover carbonisation and pyrolysis processes and biomass use (lump or pulverised) and biogas injection technology. A significant part of the activities will furthermore focus on the **adaption of the process control**, considering both the single reduction processes and the control along the production chain (e.g., electrolyser, DR, EAF, smelter). A general horizontal objective is to ensure **high levels of safety** when operating with new/modified reducing agents.

Table 4 summarises the contribution of CO_2-neutral iron-ore and other metal oxide reduction technologies to the areas of intervention covered by the Clean Steel Partnership.

Table 4 Contribution of Building Block 2 to the six areas of intervention

CDA **Major contribution** (in combination with BB3, BB4, BB7, BB8, BB9, BB11)	**H_2 as reducing agent:** BB2 is the central BB for CDA. Development of new processing routes for iron and steelmaking, excluding fossil carbon: • Transition from traditional coal-based energy to renewable (hydro/wind/ solar) electricity in iron and steelmaking. • Transition to Hydrogen based reduction and melting processes. • Improved plasma melting processes (i.e. improved electrode technologies using a plasma torch, plasma smelting reduction). • Demonstration at industrial scale a direct conversion of iron oxide to crude steel by green H_2, if possible, also on existing hardware. • Advancing and validating the H_2 plasma reduction method with demonstration in a H_2-plasma reactor (for iron ores and possibly side-stream materials) and could be

[46] Here "biomass" means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin as defined in the Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (EU, 2018).

	coupled with approaches to monitor and control the process, obtain new sets of data and develop new models. **Electrons as a reducing agent** • Industrial development of the iron ore electrolysis process; this covers a wide range of technological developments (grinding and leaching of ores, harvesting and cleaning systems for the iron plates, purification of the produced oxygen, etc) • Progressive integration of water electrolysis systems for highly efficient hydrogen production in the environment of a steel plant • Valorisation of non-conventional ores in electrolysis processes • Integrate electrolysis of iron ore and or liquid metal into new or existing steelmaking sites.
SCU-CCUS **Minor contribution**	• Carbon remains a structural important alloying element in steelmaking. If fossil source is used, capture and reintroduction to minimise carbon footprint will be in any case necessary.
SCU-PI **Major contribution** (in combination with BB1, BB3, BB4, BB6, BB7, BB8, BB9, BB10)	• Integration in steel plants of carbonisation, pyrolysis and gasification processes designed for using biomass as coal and/or gas substitute in existing steel processes (coke plant, sinter plant, BF, BOF, EAF) • Adaptation of grinding, drying and pneumatic injection technologies to biomass and torrefied/carbonised biomass in BF and EAF • Gas utilisation and recycling/recovery within processes, e.g., utilisation of oxygen derived from water electrolysis
CE **Major/Minor contribution**	**Major** (with BB3, BB4, BB10)**:** Adjustment and processing of slag chemistry for H_2 metallurgy to make it useable in cement production and other resource-saving applications (NB: EAF melting is used in conventional plants, but is also an essential process in CDA routes (H_2-DR and alkaline electrolysis)) **Minor** (With BB7, BB10)**:** In a similar way to conventional processes, new steelmaking processes will have to be tailored to recycle internal residues. Moreover, external residues may also be considered, such as the valorisation of Fe-rich residues in electrolysis processes, e.g. red mud from Al production, wastes coming from the desalination of water for water electrolysis purposes. Such activities will be fostered in cooperation with the PPP Circular Industries (SPIRE)
Combination **Major contribution**	With BB4, BB6, BB9, BB11, BB12: • In particular combinations including SCU-PI, CDA and SCU-CCUS (see comments above). Integration in steel plants of the water electrolysis processes for producing H_2 and O_2: green H_2 (and O_2) are requested for all technological pathways, including PI (H_2 injection in BF, substitution of NG as fuel), etc, including CCUS (H_2 necessary for most CO_2 valorisation processes) and including electrolysis in CDA (H_2 can be used as fuel for reheating furnaces, for preheating ladles, flexible H_2 production compensating fluctuations in energy demand when operating an EAF)
Enabler & Support actions **Minor contribution**	• The technologies provide important know-how and concrete actions, in particular on safety, measuring and process control, which can partly be rated as enablers for future hydrogen-based ironmaking • Integration of steel plants (notably EAF/smelter, iron electrolysis and H_2 production processes) in smart electrical networks, as tools to mitigate network fluctuations (> to link with SPIRE) • Safety issues in electrolysis processes

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.3. Building block 3: Melting of pre-reduced, reduced ore and scrap for clean steel production

The building block covers low-carbon dioxide emission technologies for melting iron-bearing feed materials with variable content of carbon and variable metallisation, (e.g., low-value iron-based sources, such as but not limited to low- and medium grade ores).

Since the transformation to climate-neutral iron and steelmaking processes will run gradually over the next decade's integrating conventional as well as new process routes operated in parallel, it is necessary to make it sustainable by avoiding inefficiencies. In particular the effects of the properties of feed materials for technologies allowing low-carbon emission for melting in new and adapted processes required to be investigated in relation to the three technological pathways CDA (e.g., DRI produced by H2), SCU-PI (e.g., integration with raw material preparation), and CE (e.g., recycling of slags, mill scale, etc.)

The properties of the feed materials while melting will be investigated in new and adapted processes. Processes will be adapted and improved (e.g., to allow use of low-value iron-based sources). This considers the three technological pathways. The building block covers **low-carbon dioxide emission technologies** for melting iron-bringing feed materials with variable content of carbon and variable metallisation, including low-value iron-based sources. EAF melting adaptations are envisaged to **replace the traditional use of carbon and hydrocarbons** (e.g., for re-carburisation of the liquid, for promoting slag foaming or charge heating and melting) with climate-neutral substitutes and hydrogen. The reduction of the specific consumption by optimisation of energy inputs (electrical vs. chemical) depends on charge mix (scrap, DRI, HBI, HM, pig iron) and the pre-heating of the feedstock. Pre-heating technologies using waste heat in off-gas have to be focused, as pertinent to the EAF production technology in reducing CO2 emissions. Apart from that, available surplus BOF gas generated in integrated steel mills, could be used as fuel in the scrap preheating process, with an overall impact of (average) reduction of 0.1-tonne CO2/tonne of final steel product.

R&D&I activities will also have to consider the possibility of adding to the process variable percentages of steel scrap and/or a wide range of iron-bringing feed materials with variable content of carbon and variable metallisation, including low-value iron-based sources (i.e., >5% of acidic gangue) without prejudice to the yield of the metallic charge.

Electric smelting furnace (ESF) with different operation characteristics respect to EAFs can be considered. Main benefits of implementing the ESF into the iron and steelmaking process chains are among others an enlarged iron ore spectrum to produce a BF similar hot metal and to further use existing steel plant infrastructure (integrate new DR plants and link these to existing BOFs/EAFs for crude steelmaking). In the medium/long term ESF will create a link between new and existing installations for crude steelmaking (BOF/EAF) allowing the use of low/medium grade ores with Fe contents <60 wt.% (DR-EAF route requires high-grade pellets with a gangue <5 wt.%). Technological ESF developments currently ongoing are e.g., Submerged Arc Furnace (SAF) or Open Slag Bath Furnace (OSBF) that are already used for the nonferrous sector. However, since the melting performance (e.g., arc operation mode, hot metal yield, slag forming) is strongly linked to the feed mix (such as DRI with varying carbon and gangue content and metallization degree, scrap, by-products…) R&D&I activities are required to adapt and optimize ESF operation to be applied for the steel sector. One main aspect is related to the melting performance considering varying pre-reduced, reduced ore and scrap qualities being available in the future and different carbon carriers (also secondary carbon carriers) for liquid metal carburization (e.g., in case of melting DRI coming from 100% H2 DRP).

From a technical standpoint, this building block also covers the **demonstration of new reduction process technologies**, including the assessment of material quality and residue handling within new production chains, for the recovery of metal contents to be used as scrap replacement from low-value residues by pre-reduction or reduction smelting with H_2, biogas, CO_2-lean electricity and carbon-bearing residues.

The integration of new processes in the existing routes is envisioned to improve the process sustainability. Part of the activities will furthermore focus **on providing monitoring and data gathering supporting tools supported by the integration of new sensors** for in line up to real-time management inside the reactors of liquid metal and slag temperature and composition.

Table 5 summarises the contribution of technologies for melting of pre-reduced and reduced ore, scrap, and iron-rich low-value residues to the areas of intervention covered by the Clean Steel Partnership.

Table 5 Contribution of Building Block 3 to the six areas of intervention

CDA - Major contribution	• Replace traditional use of carbons and hydrocarbons by the hydrogen or biomass[47] in existing melting processes and advanced alternative smelting processes using electricity, H_2 and biomass • Melting of iron blocks from iron ore electrolysis
SCU-PI - Major contribution	• Processes (i.e., EAF, electric smelting furnace ESF) will be adapted and improved to achieve a low CO_2 process: ○ Design of new solid raw material injectors for use of alternative material (i.e. substitution of coal, lime) ○ Pre-heating the feedstock using melting/reducing furnace off-gas to achieve a low carbon process ○ Replacement of fossil natural gas with H_2 and/or CH_4 from renewable energy sources in the EAF ○ R&D&I actions related with oxidation kinetics of steel in H_2 combustion in comparison to natural gas and yield issues (loss of material) ○ Replacement of coke from coal by char/coke from renewable energy sources for the ESF ○ Graphite electrodes from renewable C carriers for the EAF and/or partial replacement of fossil C-carriers (pet coke, coal tar pitch) for Söderberg electrodes with renewable C carriers (biochar, biotar) for the ESF. Spill-over effects to the casting sector • Allow use of low-value iron-based sources
CE - Minor contribution	• Recovery of iron to be used as scrap replacement from low-value residues by reduction smelting • Refining of the melt with new approaches to remove impurities, such as copper • Removal of tramp elements e.g., through mechanical treatment or via solvents • Use of iron-rich secondary raw materials (e.g., scrap, dusts, slags, scale…) together with DRI/HBI (also originating from low/medium grade ores) to produce a low-carbon

[47] Here "biomass" means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin as defined in the Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (EU, 2018).

	hot metal using existing and new aggregates, such as BF or an electrical smelting furnace
Combination – Major contribution	With BB1, BB4, BB6, BB7, BB9, BB10, BB11: • The demonstration of new reduction processes technologies, includes assessment on material quality and residue handling within new production chains, for the recovery of metal contents to be used as scrap /pig iron/ DRI-HBI replacement from low-value residues by pre-reduction or reduction smelting with H_2, biogas, clean electricity and carbon-bearing residues.
Enablers & Support Actions - Minor contribution	• Part of the activities will furthermore focus on new sensors and models: ○ real-time measurement of liquid metal and slag temperature ○ reliable energy forecasting to optimal setup and process control ○ spill-overs to related industries e.g., the casting sector ○ specific instrumentation for harsh environments e.g., high temperature • Optimisation of energy input (electrical, chemical) depending on actual charge mix (scrap, DRI, HBI, HM solid/liquid)

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.4. Building block 4: Adjustment of today's production to prepare for the transition towards climate neutrality

Today's steel-producing sites have been optimised in the last decades with respect to cost and resource efficiency. The new low-carbon technologies bring along **substantial changes concerning the internal and external flows of energy and materials**. The internal and external ecosystems thus have to be adjusted to handle the new boundary conditions. This applies in particular for the most common integrated steelworks, based on the conventional BF-BOF route with its thoroughly coordinated gas and material network. The gases from coking plant, BF and steelworks are used all across the working processes as an energy source in several furnaces and in the power plant; and almost all residues, iron-bearing, carbon-bearing or slags are recycled in sinter plants or externally. If the components of such conventional BF-BOF sites are substituted for example by a hydrogen-based DRI/EAF-route, or by alternative smelting reduction processes most of the energy and material cycles will change substantially.

To enable such transformations, each intermediate stage has to be handled in a sustainable way during continuously ongoing industrial production. This is even more important since the transformation towards climate-neutral steelmaking asks for **a decade-long transition that requires in many cases a gradual or stepwise integration of the new technologies and the renewable energy** sources in the production chains.

This building block, therefore, encompasses R&D&I activities with different time frames. It considers techniques and tools which support the immediate decrease of the carbon footprint on the industrial level, for example by the integration of first shares of **hydrogen or renewable electricity** into already existing industrial plants. Reduction of carbon footprint can be implemented by incrementally adapting to hydrogen and biomass as reducing agents. It considers techniques and planning tools as well to support the later steps of decarbonisation on the industrial level.

The technical scope consequently covers a wide range of activities. By way of example, a strategic approach can involve **gas distribution systems** (including mixing stations, furnaces, and combustion technologies), with evolvement and management during the transformation to clean steel production, as well as the hydrogen and biogas enrichment. Zero flaring, with gases management and storage, can also be managed aimed at heat/power conversion. The **electricity networks** will also need to be adjusted to enable the gradual increasing integration of renewable energies. Finally, the technical scope also includes the necessary **adaption of material ecosystems** (e.g., iron sources, slags, residues, water) during the stepwise transition.

This building block can be exploited at the multi-fold level. In a nutshell, flexibility can involve the production cycle itself and the energy and materials supplied. Concerning the first item, of course, it is expected an **adaptation of process control** in view of the new conditions. Then, support is also given by **flexible technologies for heating processes**. From a combustion side, technologies such as O_2 use on-demand, high turndown burners, flexible fuel mixing stations, multifuel burners, play a crucial role. Flexible hybrid heating processes combining combustion and electric heating have to find its place to assist the construction of new steel mill ecosystems. The main goal should be to allow a flexible on-demand utilization of fuels (either process gases, H_2, or other green fuels) and direct use of electricity to guarantee a high overall efficiency of the plant. This is important either for downstream applications (reheating, annealing) but also for upstream processes (e.g., reducing gas preheating, plasma technology). Process flexibility includes as well optimum **coordination of clean carbon steel production chains with CCUS processes**. Generally, a variety of different input streams can be used in reduction and melting plants.

Concerning the flexibility actions involving materials and energy supplied, it is worth mentioning the use a **wide control range of heating capacity** by modular heating technologies such local regenerators, and a sort of hybrid heating, based on both fuel gases and electricity. Integration of fuel cells can also bring back energy into the system. Materials can involve the use of a**lternative coal-based products for non-fossil coke**, as well as increased use of **non-fossil energy and reactants** (e.g., green electricity for heat generation, biomass[48], green hydrogen) in downstream processes. Adaptation of the energy and materials flow in the existing steel installations allow for technically and economically feasible transition to reduce the use of fossil carbon as reducing agent.

Competitiveness, resilience and reliability of the steel manufacturing process can be enabled by promoting industrial synergies (e.g., engaging with H_2 producers) and expand H_2 supply chain possibilities and technological spectrum for CO_2 neutral steelmaking; this can include, for example, options such as ammonia (NH_3), liquid organic hydrogen carrier (LOHC), liquid H_2 as H_2 carrier.

Table 6 summarises the contribution of activities related to the adjustment of today's production to the areas of intervention covered by the Clean Steel Partnership.

[48] Here "biomass" means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin as defined in the Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (EU, 2018).

Table 6 Contribution of Building Block 4 to the six areas of intervention

CDA - Major contribution	• Flexible operation of pure hydrogen and hydrogen-rich gases into DRI plants as reductants as well as different iron-containing input streams (such as pellets, lump ore, scrap). • Reduction of carbon footprint by incrementally adapting to hydrogen and biomass as reducing agents • If the components of conventional BF-BOF sites are substituted by e.g., hydrogen-based EAF route, most of the energy and material cycles will be substantially influenced (e.g., gas and electricity networks). • The corresponding area of interest which enable the transition of the existing sites are considered by this building block. • Since the decarbonisation transition will need decades also intermediate states of coexisting conventional and breakthrough technologies have to be considered to enable sustainable production during these decades. • Adaptation of the energy and materials flow in the existing steel installations to allow for technically and economically feasible transition to reduce the use of fossil carbon as reducing agent, e.g., adaptation of refractories to be warmed up/pre-heated with hydrogen. • Utilization of H_2, NH_3, biofuels and/or electricity in a flexible manner to pave the way for a full decarbonization of the steelmaking process. Action will have to cover technical developments, ecological and economic evaluations as well as extensive work on standards concerning flexible combustion systems, emission legislation and measurement technology. • Enabling competitiveness, resilience and reliability of the steel manufacturing process by promoting industrial synergies (e.g., engaging with H_2 producers) and expand H_2 supply chain possibilities and technological spectrum for CO_2 neutral steelmaking; this can include, for example, options such as ammonia (NH_3) as H_2 carrier.
SCU-CCUS - Major contribution	• Mainly considering the integration of CCUS in current plants/production chains
SCU-PI - Major contribution	• Involve the production cycle, the energy, and materials supplied; demonstrate the integration of CO_2 neutral iron ore reduction, DRI smelting, and/or heating technologies in steelmaking at industrial scale, into new or existing hardware or steelmaking processes and sites. (e.g., tuning of gas distribution/combustion to new gas properties and amounts). Develop technological pathways to increase the reutilisation of internal metallurgical process gases by deploying advanced gas treatment solutions; • New or modified alloying concepts, downstream processing and manufacturing processes for new clean steel grades, as well as derivation of new test methods that are closer to reality into the industrial application; • Provide concepts addressing the re-optimisation of the process integration in future integrated steelworks based on clean steel production technologies and considering the stepwise transition of production lines from current conventional iron and steelmaking to future low carbon technologies including relevant intermediate states with mixed production chains; • Involve wide control range of heating capacity by modular heating technologies (e.g., local regenerators) and a sort of hybrid heating, based on both fuel gases and electricity. Integration of fuel cells can also bring back energy into the system.

	• Integration of novel materials and processes to efficiently transfer heat to semi-finished products from residual energy sources • Integration of novel technologies for recovery of high temperature waste heat from gases and intermediate products (e.g., slabs, slags, coke, sintered materials) for re-use in steel making operations • Introduction of innovative and improved continuous processes to replace more energy intensive batch or semi-continuous processes.
CE - Major contribution	• The impact of new technologies on material cycles (solid/liquid/gaseous) will need new CE solutions also considering the decade-long intermediate states • Both, internal and external, material flows are deeply influenced by the transition, thus CE is affected also beyond the steel industry (e.g., use of slags in the cement industry; and addressing the issue of water use and recovery related to the conversion of iron oxide to crude steel by H_2 and considering it as input material for further utilization. In this context, address solutions for water re-utilization, energy availability and energy efficiency) • Energy internal reuse via gas distribution systems, with evolvement and management during the transformation to low Carbon steel production, as well as the hydrogen and biogas enrichment. • Zero flaring, with gases management and storage aimed at heat/power conversion • Waste water recovering/recirculating and/or recovering of valuable material • Water efficiency
Combination – Major contribution	With BB1, BB3, BB4 (as intermediate step), BB5 (see contributions above), BB8, BB9, BB10, BB12: • Flexibility is relevant to all process aspects from injection techniques to resource and energy management along the whole route (up to downstream). Pertinent to increase of EAF production share (up to 50%) enabling high-quality production nowadays possible only with BF cycle)
Enablers & Support Actions - Major contribution	• Compared to the usually slow changes within steel production systems (due to long investment cycles), the decarbonisation transition implies fast changes including different intermediate states, new tools are needed to plan and handle those states • The decarbonisation transition of industrial plants needs substantial changes in the production chains which have to be to be more strictly integrated to lead to seamless through process data exchange and processing along a compact manufacturing chain while, at the same time, the steel production must go on in a sustainable way. Support actions are needed to enable this open-heart operation; for instance, evaluating techno-economical risks and benefits and demonstrate the efficacy and efficiency of H_2 supply chains (e.g., pure H_2, NH_3, etc) for steel manufacturing • The technologies provide important know-how and concrete technologies which can partly be rated as enablers for future hydrogen-based ironmaking (e.g., predictive instead of reactive though process management, extensive monitoring and analysis of measurement and AI-steered control technologies)

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.5. Building block 5: CO/CO_2 utilisation, CO_2 capture and storage in steelmaking

The utilisation of CO and CO_2 from steel plants can be done in different ways and for various applications. R&D&I is first necessary for the **preparation of the gaseous stream containing CO/CO_2**: depending on the envisioned use, the gaseous stream, either process gas or off-gas to be released to the atmosphere, must first be prepared, potentially involving cleaning, compressions, drying, sulphur removal, separation, conversion, reforming, concentration, etc. These steps are generally highly energy-consuming. It is therefore of first importance to optimise their integration in steel plants, making the best use of the available equipment and heat streams, exploiting synergies to limit the energy penalty. This potentially also includes substantial changes in the gas network of steel plants.

Significant efforts are then certainly necessary to improve the performances of the additional processes for allowing their utilisation of CO/CO_2 from steel plants and to establish the quality and marketability of the various products that can be obtained (chemicals, synthetic fuels, etc.) and all the necessary separation and purification steps required. Possible secondary residues also have to be marketed or recycled to ensure optimal environmental performances. In this field, the use of **life cycle impact assessment tools** will be of paramount importance to neatly compare potential solutions and to allow a full environmental assessment of the proposed technologies. Generally, these CO/CO_2 utilisation processes require some hydrogen. Hence, the building block applies both to SCU and CDA.

In this field, the use of **life cycle impact assessment (LCIA) tools** will be of paramount importance to neatly compare potential solutions and to allow a full environmental assessment of the proposed technologies. Since, comparative policy methods become of primary importance in directing the technological choices they should be based on agreed methodologies in order to address both potential benefits and related side effects in technology substitution. In this perspective LCIA should be linked with mitigation paths at sectoral level.

Finally, **CO_2 storage** is generally considered as a fall-back option with excessive costs and potential environmental and societal issues. It is, however, an option that potentially allows handling the large CO_2 volumes produced by the current steel plants. This option will also have to be considered in the portfolio of R&I.

Table 7 summarises the contribution of CO/CO_2 utilisation, CO_2 capture and storage to the areas of intervention covered by the Clean Steel Partnership.

Table 7 Contribution of Building Block 5 to the six areas of intervention

CCUS - Major/minor contribution	• **Major (with BB1, BB4, BB7, BB8):** - Integration of chemical and biological conversion of CO/CO_2 in steel plants, with full internal valorisation of residues, including biomass[49]; utilize CO/CO_2 streams to produce added value products and/or intermediates of wide industrial interest (e.g., polymers, resins, chemicals, feed/food ingredients, automotive, construction, etc.) • System impact analysis (e.g., cost/benefit, efficiency, reliability, sustainability, environmental impact, etc.) and demonstration for the use of synthetic fuels elaborated from CO/CO_2 capture, to be applied in steel thermal treatment processes. This area allows for the possibility to apply an industrial symbiosis approach. • **Minor (with BB9)**:

[49] Here "biomass" means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin as defined in the Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (EU, 2018).

	○ Evaluate the options for compression and transport of CO_2 streams from steel plants (technological and material aspects considering the concentration and minor compounds) ○ Evaluate the storage options for CO_2 streams from steel plants, considering the development of CO_2 networks and infrastructures (can potentially handle very large CO_2 volumes)
SCU-PI - Major contribution	• Energetic integration of end-of-pipe capture units in steel plants • Energetic integration of preparation steps in steel plants for reliable CCUS approaches for steel gases (cleaning, drying, sulphur removal, CO/CO2 scrubbing, conversion, compression, heating, reforming, etc.). • Develop mature technologies for separation/purification of CO/CO2 containing waste streams to allow the integration, in the targeted industry sector/sectors • In-process integration of CO_2 capture steps in BF-BOF plants; process significant amounts of CO/CO2 containing waste streams, including efficient approaches for the pre-treatment of the gaseous streams (e.g., compression, drying, concentration, etc.) if needed • Evaluation, validation and demonstration of the compatibility of metallurgical gas streams from steel plants with current and/or future CCUS infrastructures, including also compatibility with technologies for heterogeneous catalysis routes (thermal catalysis, electrocatalysis, photo-electrocatalysis) for CO2 conversion into chemicals and fuels. • Evaluation of compatibility of metallurgical gas streams from steel plants with current/future CCUS infrastructures. • Conditioning and separation of metallurgical gases (containing CO2, CO, CH4, etc.) to meet specifications for CCUS applications. • Energetic integration of preparation steps in steel plants for reliable CCUS approaches for steel gases (cleaning, drying, sulphur removal, CO/CO2 scrubbing, conversion, compression, heating, reforming, etc.). • Achieve GHG emissions mitigation in the overall lifecycle compared to existing processes for the same products (or relevant benchmarks)
CE - Major contribution (with BB10)	• Development of the carbonisation and mineralisation of steelmaking residues (e.g., slags, dust), and use of CO_2 as feed for plants (e.g., algae) as a mean to sequester CO_2 by steel specific activities • Enhance the market for CO/CO2 based products providing economically viable and sustainable alternatives to existing products with strong market interest in one or more applications (e.g., consumer products, feed/food ingredients, automotive, construction, etc.) • Consider clearly industrial specifications and relevant market requirements • Demonstrate that targeted products and/or intermediates can fully replace existing counterparts. The prevention of upcycling of hazardous substances, including their separation and disposal should be considered • Demonstrate the improved environmental footprint of the proposed products and processes, as well as other positive impacts using relevant methodologies (e.g., LCA, LCSA, etc.)
Combination – Major contribution	With BB1, BB2, BB3, BB4, BB8, BB9, BB10, BB12: • Development and energetic integration in steel plants of preparation steps for process gases (cleaning, drying, sulphur removal, CO_2 scrubbing, conversion, compression, heating, reforming, etc). • Separation of CO_2, CO, H_2, N_2, BTX, etc from steel process gases for dedicated valorisation/use

	• Contribution to standardisation and best practices, and future national and European directives related to residues, wastes, by-products valorisation (e.g., dust and slag mineralisation processes)
Enablers & Support Actions - Minor contribution	• Development of smart **life cycle impact assessment tools** to allow an environmental assessment of the proposed technologies. • Development of sensors supporting the preparation of the gaseous stream containing CO/CO_2

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.6. Building block 6: Raw material preparation for clean steel production

This BB is related to the two main raw-material in the iron and steelmaking route: the iron-ore and the scrap. As refer to **iron ore**, the availability of high-grade iron ores is expected to become a more critical factor, as demand will increase. Therefore, technologies for the upgrade and the use of low-quality iron ores are needed. This includes low carbon technologies for sintering/ pelletisation and/or cold bonded iron ore agglomeration.

Scrap is considered as a crucial resource by the EU steel strategy for the reduction of CO2 emissions and thus, the relevant demand coming from BF/BOF and EAF steel production routes is expected to increase. Its availability towards 2050 was modelled[50] by differentiating three sources of scrap: home scrap, prompt scrap and obsolete scrap. Home scrap and prompt scrap are expected to maintain their portion, while obsolete scrap is estimated to increase leading to a global increase of scrap availability. However, impurities accumulation during the whole recycling process, such as copper and tin, have been identified as barriers limiting the use of steel scrap for producing certain grades of steel product.

The research on scrap preparation will focus on the best available and applicable technologies to eliminate such detrimental effects. The aim is to remove impurities before melting considering physical separation and chemical treatments. Furthermore, the improved sorting of scrap to separate high-alloyed material from it leads to optimised scrap use and minimised need for primary alloying metals. In particular, 'Cleaner' scrap is reliable for challenging application as those for the automotive sector.

R&D&I activities in the frame of physical separation, in addition to regular shredding and magnetic separation, include the experimentation of expeditious analytical methods to identify impurities present in scrap and effective methods for their removal before loading into the furnaces.

Scrap cleaning actions, including metal, paints, impurity removal, by chemical treatment that can also lead to added value production require to evolve at high TRL, from laboratory scale to industrial applicability due to the involving either high temperature or vacuum or complex process.

---

[50] EUROFER, "European Steel in Figures 2020," 01 06 2020. [Online]. Available: https://www.eurofer.eu/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2020/#:~:text=European%20Steel%20in%20Figures%202020%20is%20EUROFER's%20statistical%20handbook%2C%20laying,Association's%20(EUROFER)%20statistical%20guide..

Iron-ore is the base material for traditional BF/BOF route and new DRI/EAF route. DRI/EAF technology is proven and in use today since the benefits on CO2 emission reduction level are immediate. However, it requires high-quality iron ore (DR-grade) with iron (Fe) content of 65% and above, which has lower levels of impurities. DR-grade iron ore currently makes up only about 4% of global iron ore supply. Therefore, the availability of high-grade iron ores is expected to become a more critical factor, as the demand will increase due to higher share of DR-based production being expected in the future. Therefore, technologies for the upgrade and the use of low-quality iron ores (Fe <65 wt.%) including iron ore fines are needed. This refers to beneficiation as well as low carbon technologies for pre-treatment, such as but not limited to calcination, pre-oxidation sintering/pelletisation and/or cold bonded agglomeration to be further used in different processes, such as existing installations (sinter plant, BF), but also new plants, such as DR reactors (shaft furnace, fluidized bed).

Finally, suitable process monitoring and control in real time or quasi-real time for the characterisation of raw-material pre-treatment steps, charging in EAF or ESF for dynamically adjustment of production chains due to new raw material circuits during the decarbonisation transition is required.

Table 8 summarises the contribution of raw material preparation to the areas of intervention covered by the Clean Steel Partnership.

Table 8 Contribution of Building Block 6 to the six areas of intervention

CDA - Major contribution	• First, post-consumer scrap improvement is beneficial compared to the use of pig iron. • Removing raw materials impurities before melting, as well as scrap management and charge optimisation, optimise the operation of the melting and treatment units to reduce unwanted substances, contributing to material and cost savings with rational use of resources, allowing CO_2 emissions reduction (e.g., scrap preheating is very effective in reducing CO_2 emissions. • Also, the development of Low Carbon technologies for pelletisation and sintering, as well as cold bonded iron ore agglomeration, supports the scope • Upgrading of low-grade iron ores and Fe-containing residues
SCU-PI - Minor contribution	• Cleaning actions, including metal, paints, waste removal, brings about added value production (e.g., 'cleaner' scrap is reliable for challenging application as those for the automotive sector): • Pre-heating technologies to be focused and integrated, as pertinent to the EAF production technology. • Expected suitable process control and monitoring strategies, either for characterisation of EAF, DR charge materials and for dynamically adjusting of production chains and pre-treatment steps on new raw material circuits due to decarbonisation transition. Pertinent to increase of EAF production share (up to 50%) enabling high-quality production nowadays possible only with BF cycle) • Upgrading of low-grade iron ores and Fe-containing residues
CE - Major contribution	• Use of secondary raw materials and/or biogenic carbon carriers as substitutes for slag forming and/or slag foaming to substitute injection of coal being beneficial to low CO2-emission raw material for steel production. • Surplus BOF gas available could be used as fuel in the scrap preheating process, with an overall impact of (average) reduction of 0.1-ton CO_2/tonne of final steel product. In general, the use of waste heat, and solutions using flare process gases, supports CE strategy in the steel production chain. • Upgrading of low-grade iron ores and Fe-containing residues using appropriate technologies, such as but not limited to calcination, pre-oxidation sintering/pelletisation and/or cold bonded agglomeration
Combination – Major contribution	With BB1, BB3, BB4, BB6, BB7, BB9, BB10, BB11: • Raw material preparation issues are cross-sectional to most of BBS as they are pertinent to energy management, resource-saving, reuse (CE), Process Transformation and should be based on robust enablers

Enablers & Support Actions - Major contribution	• R&D&I in the field envisages:
	  ○ experimentation of expeditious analytical methods for the identification of the impurities present in scrap and effective methods for their removal before loading into the furnaces
	  ○ scrap yard management including scrap identification, mapping of yard, evaluation of scrap charge in the basket to relate steel grade with scrap
	  ○ AI algorithms for scrap/steel grade correlation
	• Improvement of the technique of assessing in real-time tramp elements content in the scrap
	• Improvement and/or development of ways to mitigate the impact of higher tramp element content on steel properties (casting conditions, etc.)

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.7. Building block 7: Heat generation for clean steel processes

This building block focuses on **energy efficiency, energy recovery and energy carriers without fossil carbon**. Technologies for in-process usage of different energy carriers and out-process usage of waste heat and residues will be considered. Different energy carriers should be used simultaneously, whereas hybrid heating, a combination of two different types of energy carriers (e.g., electric and H2 heating) plays a crucial role.

Regardless of the technology choice for iron and steelmaking, the processes will be energy-intensive, as metal processing requires high temperatures. This will lead to **off-gases with useful energy content**, which should be utilised to maximise energy performance. In addition to this, many processes exist with their own heat energy input needs, which can be approached within the framework of PI for both **waste heat usage, heat recovery and residual gas recovery**.

Heat energy recovery and generation are associated with **pre-heating of non-fossil energy feeds** to primary and secondary processes (e.g. through green hydrogen, biomass[51], green electricity and heat exchangers); **pre-heating of raw materials** to primary and secondary production processes (e.g. through waste heat recovery, process off-gas combustion and green electricity); **preheating of non-fuel feeds** (e.g. of air, enriched air or oxygen); **recovery of heat from hot processes and other waste** (e.g. from slag and the solidifying metal, cooling water); and usage within other related fields (e.g. reheating furnaces, dryers/pre-heater for raw material, energy recovery units).

To facilitate these requirements in future clean steelmaking, it is key to enable the **efficient transfer of heat from unconventional sources**, which will require new materials and processes. Examples include new burners for fossil-free energy carriers: solids (e.g., biocoke), liquids (e.g. bioethanol, bio-methanol) and gaseous feeds (e.g. green hydrogen, ammonia and top gases), heating concepts for electric heating (e.g., inductive, resistive or rotodynamic heating) or hybrid heating approaches. In addition, these new sources require that heat exchange materials are suitable for this new environment, and that the systems can be used flexibly depending on the availability of renewable resources (e.g., integration of hydrogen systems with green electricity).

Table 9 summarises the contribution of heat generation to the areas of intervention covered by the Clean Steel Partnership.

Table 9 Contribution of Building Block 7 to the six areas of intervention

CDA - Major contribution	• Hydrogen gases (from upstream processes) for heat input in downstream processes. Utilisation of residual heat from the "new" steelmaking process • Usage of electricity as a sole energy carrier for heating processes • Hybrid heating concepts for up- and downstream operations to allow flexible usage of renewable electricity, hydrogen and/or process gases

[51] Here "biomass" means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin as defined in the Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (EU, 2018).

SCU-CCUS - Minor contribution	• Recovery of chemical and thermal energy for utilisation in other processes
SCU-PI - Major contribution	• Recovery of chemical and thermal energy from process gases for utilisation in heating/preheating of process streams
CE - Minor contribution	• Preheating of recycled material before charging to metallurgical processes.
Combination – Major contribution	• In particular combinations including PI, CDA and SCU-CCUS, as explained above.
Enablers & Support Actions - Minor contribution	• The technologies provide important know-how and concrete actions (e.g. measurement and control technologies) which can partly be rated as enablers for future hydrogen-based ironmaking

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.8. Building block 8: Energy management / Energy vector storage (H_2, electricity, intermediate materials, …) for clean steel production (LC&EE)

Despite the increasing fluctuations in the provided energy mix, a reliable energy supply is essential for consistent and effective steel production. The **storage and distribution of energy** are important means to compensate for increasing fluctuations and availability related to seasonal effects and renewable sources. All energy vectors including their links as well as the links to production planning will be considered here. Allowing more use of renewable electricity and developing concepts enabling 100% of renewable energy sources is key. The research on storage technologies coping with potential fluctuations in the energy supply, the needs-based distribution and their integration into the steel production chains is not limited to the **energy sources** but will also include **energy-rich intermediate materials**.

This building block will consider chemical (H_2, intermediate materials), electricity and heat storage (e.g., for waste heat recovery from slag) and transportation. Moreover, emphasis will be placed on reusing existing facilities (gasholders out of service, grids…) as energy storage, as well as buffer solutions for grid balancing. In this sense, there is also open field for mixing and using fluctuating energy sources in thermo-processing plants. Novel process-gas storage processes are also relevant to technology improvement, as well as technologies that involve molten salts technology for high-temperature energy storage.

Table 10 summarises the contribution of energy management and energy vector storage to the areas of intervention covered by the Clean Steel Partnership.

Table 10 Contribution of Building Block 8 to the six areas of intervention

CDA – Major contribution	• Allowing more use of renewable electricity; develop concepts enabling 100% utilization of RES (e.g., electrified processes, concentrated solar etc.)), dealing with potential fluctuations in the energy supply ensuring 24/7 availability • Allowing advanced smelting processes using electricity and H_2 • Coupling of the steel production process with high-temperature H_2 electrolyser through steam production by waste gases.

	• Dealing with fluctuating energy supply and supporting energy system transformation, through storage solutions and accumulation systems in the steelmaking plants • Enhancing the storage of heat in the energy vector. Introduction of heat transfer media (e.g. diathermic oil, molten salt, liquid metals) not yet considered state-of-the-art in the steelmaking process, but that could improve the thermal exchange process and ultimately reduce CO2 emissions • Demonstrating smart energy use through the integrated energy management also considering storage strategy and relevant devices • Buffer solutions in steel production processes aimed also at electric power balancing through harmonisation of demand and supply response • Integration into an existing and optimised steelwork and gradual transformation towards a low CO_2 production site • DRI as a solution for iron powder for energy purposes • CDA has one of the greatest influences of all industrial sectors to the energy management system. Strong influence of a 24/7 operation of CDA technologies to the production, transport, and storage of renewable energy (electricity, H_2, artificial NG)
SCU-CCUS - Minor contribution	• Allowing smart energy management as a result of the reduction of carbon usage
SCU-PI - Major contribution	• Allowing higher efficiency and cost-effectiveness for heat recovery at high temperature (>600°C), e.g., from off-gas (EAF, LF, VD) and slags maintaining the potential for residual valorisation • Integration in the steel production of new technologies for heat recovery at low temperature for gas (<300°C) and water (<100°C)) e.g., power generation at low temperature by Peltier cells, heat pumps, stirling cycles, rankine cycles,…);, • New materials and processes to efficiently transfer heat to semi-finished product from unconventional energy sources; this includes new combustion system in hot rolling mill furnaces, such as reheating and heat-treatment of cast and rolled products with a smart integration of fossil-free energy carriers, such as liquids (e.g. bioethanol, bio-methanol), electricity and gaseous feeds (e.g. green hydrogen and gaseous fuels resulting from iron and steelmaking process); these new energy sources require that furnace refractories and heat exchange materials are suitable for this new environment, and that the systems can be flexibly used and controlled depending on the availability of renewable resources (e.g. integration of hydrogen systems with green electricity); • Plan for the introduction of on-site advanced and renewable energy solutions and/or for flexibility of energy demand with reduction during peak hours, to support the power system to adjust to demand and generation variability. • Integration of novel pre-melting scrap (or other raw materials) technologies using available heat sources (waste heat, renewable energy, or excess steel plant gases, etc.); • Develop new technologies to reduce steelworks energy consumption by implementing improvements in the materials and energy flows whilst reducing fossil carbon related emissions
CE - Major contribution	• Increased onsite heat recovery and recycling onsite and/or for external applications. • Management/ storage finalised to reusing existing facilities (gasholders out of service, grids…) as well as buffer solutions for grid balancing.

Combination – Minor contribution	With BB1, BB3, BB8, BB9, BB12: • Energy management/storage is linked to technologies related to energy generation and reuse at any production level (e.g., even involving scrap preheating, downstream processes)
Enablers & Support Actions - Minor/Major contribution	• Development of smart tools functional to efficient energy management • Development of sensoring functional to special energy storage management and actions, e.g., heat recovery at low temperature for gas (<300°C) and water (<100°C) • In synergy with CDA, smart tools/digitalisation support to buffer solutions in steel production processes (e.g., electric power balancing through harmonisation of demand and supply response)

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.9. Building block 9: Steel specific circular economy solutions

CE approaches ensure competitiveness of steel sector through increased resource efficiency and sustainability and consist of different issues: enhanced steel recycling (scrap use), valorisation of metal and mineral part of steelmaking residues (dusts, slags, sludge, scale) for internal recycling in the steelmaking process and external use in other sectors, use of secondary carbon carriers from non-steel sectors as a reducing agent and energy and water source in the steelmaking process chain

The recyclability, durability, and versatility make steel a **material "permanently" available to future generations**. Therefore, the steel production works through a profound synergy between the primary route, using mostly virgin raw materials and a limited amount of scrap (in BF-BOF), and the secondary route, using essentially ferrous scrap (in EAF). New process configurations, in which the two production routes will continue to work in a synergic approach is mandatory to reach the CO_2 reduction target of 2030 and 2050.

These opportunities will have also impact on by products: how they will change during to the steel sector modernisation and how this will influence the present circular economy and industrial symbiosis business model both in economic and environmental terms.

The first topic to address in the context of this building block is "**2050 scrap blending wall**". In fact, although ferrous scrap will be part of the future strategies for reducing GHG emissions and achieving a truly circular economy, there are still limitations linked to the availability of scrap with the right quality. The presence of tramp elements such as non-ferrous metals might limit the use of ferrous scrap to produce certain steel grades and scrap characterisation, treatments, processing and cleaning (as addressed in BB3) will be necessary. All these steps are linked to the recovery of certain non-ferrous fractions, such as tin, copper and zinc but there is also a corresponding increase in the amount of waste produced from scrap sorting (e.g., automotive shredder residue and sweepings). If the preparation of scrap is enhanced, the slag quantity and the electricity used would be highly reduced offering relatively fast access to reduce CO_2 emissions. Innovative technologies will be required for upcycling these waste streams and exploiting also in combination with other industrial sectors, in an Industrial Symbiosis perspective. Research efforts on this topic are one of the key elements for fostering a green transition of the steel production as a whole, increasing the value of lower quality scrap and maintain the sustainability of the steel value chain.

The second one is the "**materials recirculation with high recycling rate**". There is still a huge room for improving the yield of the iron and steel making route by r**ecovering of metal contents from metal oxides** both directly in the existing production process (e.g., agglomeration of residues rich in metal-oxides to recharge in the melting process or re-charge of fines residues within DRI plant) and in a dedicated unit (e.g. pyro-metallurgic unit recovering the metals and Zn oxide by EAF/BOF residue).

The third topic covered by this building block is the "**residue valorisation**". Residue from steel industry is already successfully used inside the steel production itself or by other sectors but new EU legislations or more stringent national laws might endanger good practices and then the level of circularity reached by the steel sector. To reach the **full circularity of the steel sector**, every material stream (residue) generated together with steel has to find its proper fate, to be reused, recycled, or recovered. Research efforts are, therefore, treatment for primary steelmaking slags to recover the metal and mineral phase, conditioning the properties of minor residues (i.e., dry fast cooling process for the secondary metallurgical LF, VD and AOD slag) and for developing new processes to **lower the demand for primary resources** (i.e. bio-char and syngas production integrated with steel plant using waste heat) and **reduce landfill volume** (i.e. use of slag as heat accumulator for heat recovery). At the same time, additional applications and final user for residuals streams must be identified for mitigating the risks of over-demanding legislations in **full respect of environmental safety and human health**.

Research efforts are necessary for consolidate and generate new ecosystem for steelmaking slags to valorise the metal and mineral phase (i.e., dry fast cooling process for the secondary metallurgical LF, VD and AOD slag) and reduce landfill volume. The replacement of the BF by DR technologies for ironmaking also implies that the BF slag being an essential secondary raw material for the cement sector will disappear in the long-term future. New slag systems will be generated during iron and steelmaking, such as EAF/BOF slags with different composition depending on the feed mix including lower quality secondary resources. Another relevant "new" primary slag will come from the ESF representing a link between the direct reduction of low/medium grade ores (fines or pellets) and new or existing EAF/BOF plants. The properties of this ESF slag must be investigated thoroughly to assure a full recycling e.g., within the cement sector.

Moreover, development of new processes to lower the demand for primary resources (i.e., bio-char and syngas production integrated with steel plant using waste heat). Use of secondary raw materials as substitutes coal as slag foaming agent are functional to achieve low CO2-emission raw material for steel production especially for EAF and ESF.

The current climate emergency has led to increasing water scarcity; therefore, water circularity has become a critical issue and focus has to put also on recovering and recirculating water. Some examples are:

- recovery and reuse of process water through closed-loop systems and membrane technologies.
- water regeneration.
- digital monitoring and management tools, new technologies implementing water-efficient design in new facilities, such as utilizing low-flow fixtures.
- nano-filtration, reverse osmosis, or electrodialysis to recover valuable materials from water.

- urban-industrial symbiosis focusing on water.

In this building block, the definition of **common life cycle impact assessment tools** is mandatory to monitor the effect of the steel specific circular economy solutions on the environment and in particular on GHG reduction in both direct (e.g., slag as a substrate material for CO_2 sequestration) and indirect ways (e.g. slag as a substitute of lime) or by avoiding transportation (e.g. raw materials to plant or residues from plant to landfills).

Table 11 summarises the contribution of steel specific circular economy solutions to the areas of intervention covered by the Clean Steel Partnership.

Table 11 Contribution of Building Block 9 to the six areas of intervention

CDA - Minor contribution	• Widening of application ranges for slags from direct reduction route • Reuse of residues and increase the use of scrap within direct reduction route
CCUS - Minor contribution	• Use of slag as a substrate material for CO_2 sequestration • Use of CO2 separated from process gases for a conversion into valuable products, such as but not limited to methane and higher hydrocarbons to be used internally as substitute for fossil natural gas or in other industries as raw material (chemical feedstock) enabling sector coupling (industrial symbiosis)
SCU-PI - Major contribution (in combination with BB2, BB4, BB6, BB7, BB8, BB9)	• Improving the yield of the iron and steel making route by recovering of metal contents from metal oxides both directly in existing production process either in a dedicated unit • Residue as an energy source for direct substitute of solid fuel • Auxiliary reducing agent and slag foaming material (i.e., polymers from waste plastics, rubber form tyres, bio-char from agricultural and food residues) • Use of slag heat accumulator for heat recovery • Development and integration in steel plants of carbonisation, pyrolysis and gasification processes designed for using C-rich waste streams as coal and/or gas substitute in existing steel processes (coke plant, sinter plant, BF, BOF, EAF • Reduction of carbon footprint by incrementally adapting to the use of low-CO2 hydrogen to heat up steel for rolling, shaping, and heat treatment, considering also a coupling between hydrogen and/or electrical heating and fuel-flexibility concepts;

CE - Major contribution	• Residue valorisation:
	  o Treatment of steelmaking slags from new and existing processes (ESF, BOF, EAF) to recover the metal and mineral phase
	  o Conditioning the properties of the minor slag phases (i.e. dry fast cooling process for the secondary metallurgical slag LF, VD, AOD)
	  o High materials recirculation rate such as but not limited to cold-bonded, cement-free, and self-reducing agglomerates for BF iron containing by-products and secondary resources for the EAF, ESF or DRP
	  o Recovery of iron and steel alloying elements from slag and other residues by pyro- and/or hydrometallurgical reduction technologies using renewable energies
	• Reduce landfill volume
	• Mitigating water scarcity through water efficiency and recirculation

Combination – Major contribution	With BB3, BB4, BB5, BB6, BB7, BB11: • The steel industry is a leader in the circular economy thanks to the use of scrap in liquid steel production. This leadership has been enhanced in the last decade due

	to the focus on residue valorisation saving primary raw materials and reducing environmental footprint related to landfilling. • Enhanced processes for smart use of resources integrated into the steel processes requiring sector-specific activities which further enable the contribution of the sector to EU circular economy strategy, EU energy transition and its effect on overall industry climate neutrality. • Include and intertwine machine learning, basics thermodynamics, kinetics, metallurgy, product design, EAF design for sorting, and removing of tramp elements
Enablers & Support Actions - Major contribution	• Definition of a common life cycle Inventory for residues • Design & development of a tool for continuous monitoring of the effects of circular approach/solutions on CO_2 emissions • Standardisation activities to certify residue from new and/or adapted processes as secondary products (end-of-waste status)

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.10. Building block 10: Drivers and Enablers (10a: digitalisation, 10b: skills) for clean steel development

The transition of steel production to low carbon technologies corresponds to a revolution for most major technical and organisational processes. There is a strong need for drivers and enablers to plan and handle such revolution and to **make the sustainable steel production** possible under the terms of the new technical and organisational boundary conditions along and around the steel production chains. This building block tackles Art. 10a of the RFCS Decision 2021/1094, indicating that proposals are expected to demonstrate digitalization technologies and approaches and support developing and disseminating competencies to keep pace with new near-zero-carbon steel production processes and to reflect the principle of lifelong learning ensuring that the workforce has the right skills to foster, implement and use new solutions at the workplace.

2.1.2.10.a Digitalisation

Digital and Twin Transitions

Digitalisation represents a major driver and a mandatory step for Sustainable Manufacturing for both societal and industrial point of view with its high potential of decarbonisation forecasted to be in the range of 20%.

Being an energy-intensive sector, it is at the same time an automation-intensive sector. There is a general agreement on foreseeing the continuation of such growing trend in the future because the effective and efficient transition needs monitoring, controlling and optimally managing manufacturing processes to ensuring the balanced environmental footprint and sustainability in general. This can be achieved only thanks to the development of digital technologies and the associated deployment of digital infrastructures founded on the Industry 4.0 paradigm to better exploit the enabling impact on Sustainability.

Indeed, sustainability needs seamless data circulation to fuel new digital applications and systems aimed at supporting through-process monitoring and optimal control of the steel manufacturing routes based on green technologies and their integration along the supply and manufacturing chains.

Due to the complexity of the digitalisation process, the R&D&I directions must be addressed and supported to maintain and even increase actual trend and, looking to the defined entities such companies and factory, make a forecast of R&D&I directions and relevant investments.

This question needs an integrated response considering both business, technical, scientific and social decision to be taken for maintaining the technological leading position of the European steel industry.

Current and forecasted investments and R&D&I directions for digitalisation

To rank the most important R&D&I direction, the relevant investments and answering to the above question, an in-depth business analysis based on literature data can help to define the economic scenario of the global Digitalisation Megatrend, considering the aggregated manufacturing sectors such as Aerospace, Transportations, Metals, Ores, Mechanics, Chemical, Electronics, Defence etc.

Aimed at discriminating the prevailing and characterising digital technologies of the current and forecasted Digital Megatrend, fifteen significant ICTs have been considered for the timespan between 2020, 2021 or 2022, depending on data availability, up to 2030. Forecasts are based on global historical data gathered since almost five or six years before the beginning of the timespan up to the starting year of observation and supported by technical and business processing.

Performances are measured by applying two economic performance indicators extracted by the specialised literature and a third one developed in the analysis.

Based on these considerations and on the chosen KPIs, the three most important emerging ICTs withing the Digital Megatrend are Artificial Intelligence & Machine Learning, Cloud Computing or better, Cloud Services and Internet of Things. Immediately after, there are Virtual & Augmented Reality, Big Data & Business Analytics and Cybersecurity.

Looking to the Megatrend up to 2030 in terms of the Global Market Size Indicator (see Fig. 18a), the resulted four leading digital technologies are respectively the Internet of Things, the Cloud Computing, the Big Data & Business Analytics and the Industrial Automation. Such technologies mostly define the infrastructure for implementing the others for monitoring and control manufacturing processes, enabled by the seamless flow of data realised along the Supply and Manufacturing Chain.

Furthermore, in the fifth position of the industrial perspectives is occupied by AI & ML, that is the largest disruptive set of technologies within the Global Digital Megatrend for turning factories from reactive into predictive systems. It has to be noticed that in the Global Market industrial context AI & ML is the first set of technology in the past three years because of the contribution to the other sectors. Moreover, AI & ML occupies is the first for investment attractivity and expectations.

Services and Internet of Things (IoT) becomes evident as well as the distance gap of expenditures between the other ICTs and the prevailing three (IoT, Cloud Computing and Big Data & Analytics).

Regarding the “ranking of digital technologies”, it is important to highlight that the ESSA[52] project and the relevant poll based on the feeling of apical positions in the technical and management role of companies

[52] Prof. Dr. Antonius Schörder, Prof. Dr. Michael Köhlgruber The European Steel Skills Agenda and Strategy (ESSA) and its Sectoral Blueprint discussed in the Final ESSA Conference held in Duisburg, May 11th, 2023.

is in line with the finding confirming the validity of Business and Technical considerations based on the analysis.

Figure 18a technological scenario of 2030.

Artificial Intelligence (AI), Machine Learning (ML) and Workplaces

The disruption of AI & ML stands not only on the technical aspects but also on the emergence of related social needs represented by the required new conditions of the workplaces:

1. Transformation of Workplaces and upskilling of workforce to be trained for operating into extended digital environment.

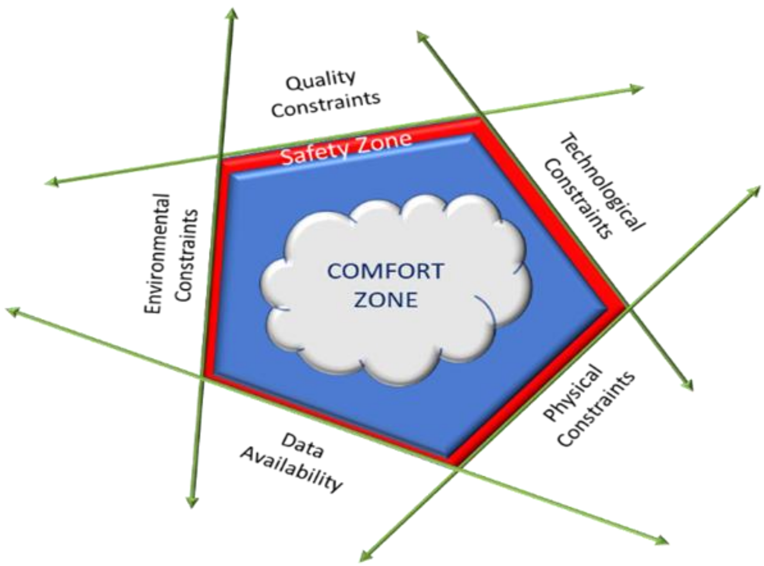
2. The implementation of a unique and efficient infrastructure along the Supply and Manufacturing Chains ensuring data gathering and seamless flow representing the key for the integrating assets and processes leading to their optimal management.

3. The extensive interconnection of "things" such as sensors, equipment, cyber-physical-systems and software tools is the key for transforming factories into data-driven systems through IoT/IIoT networks

4. Implementation of Data Science application and, in particular, Advanced Data Analytics for real time applications and Business Intelligence in the wider sense

As a consequence, although AI and Smart Factory are technology-driven, needs and constraints coming from employees' involvement and active participation must be considered to achieve the aim of acceptance and co-creation inside the cooperative ecosystem between workers, employees and machines to fully take benefit of such bigger disruption between the last and the next decade in both social and industrial contexts.

Figure 18b Comfort, Safety and Limit zones (source: Petuum, Next Generation AI)



Robust, Reliable and Flexible Infrastructure, Architectures and Frameworks.

Data availability is summarised by the way of saying *What, Where, When*, generally extendable to data exchange issues and used to highlight one of the main scopes of the digital Infrastructure for delivering right data where is needed and when it is required.

This needs to highlight the importance of Digital Infrastructure (also said ICT or Digital Landscape).

The key factors of such digital “landscape of the future” are:

- The achievement of the Smart Steel Factory aim is characterised by pairing humans and machines in presence of autonomous and Intelligent Systems/Cyber-Physical Systems. In this context, AI is the most attractive investments to realise
- The integration of the Manufacturing and Supply Chains into a seamless data-driven System of Systems as confirmed by the total amount of efforts forecasted for infrastructures, architectures and frameworks. For this aim robust, reliable and resilient infrastructure realised to host integrated architecture models and frameworks.
- Cybersecurity, that is a part of the ICT infrastructure, and the relevant attention will be more and more evident in the future

2.1.2.10.b Skills and social innovation

Proactive skills adjustment within a social innovation process is already coordinated by the European Steel Skills Alliance (ESSA). Against the technological innovations this alliance will guarantee a dedicated input and co-design of the human-centricity to ensure the new Industry 5.0[53] concept of the European Commission. ESSA works with different processes and actors who are implementing training ecosystems based on the specific company requirements and regional and national demands with different priorities and different activities:

- A European Foresight Observatory and its Steel Technology and Skills Foresight Radar and Panel in collaboration with ESTEP's Focus Group People and Smart Factories
- An online Ecosystem "steelHub" in collaboration with Worldsteel
- Regional Training Eco-Systems in collaboration with ESTEP's Focus Group People and national and regional associations, coordinated by a European Community of Practice (ECoP Steel).

Against this backdrop, the Clean Steel Partnership's mission is a steel industry driven proactive adjustment of the future skills based on demands developed by the industry and for the industry. The main objectives are:

- Proactive skills adjustments.
- New training and curricula requirements.
- Political support measures.
- Successful sectoral upskilling schemes.
- Efficient management of knowledge.
- Improve recruitment and retention.
- Design of a digitalisation plan for supporting effectiveness and quality of training and learning ever more based on the integration between IT and OT empowered of simulation and immersive tools for operational OT and decision making.

A large span of skills categories is involved following the T-shape approach of combining technical with transversal or soft skills. Figure 18 shows an overview.

[53] https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en

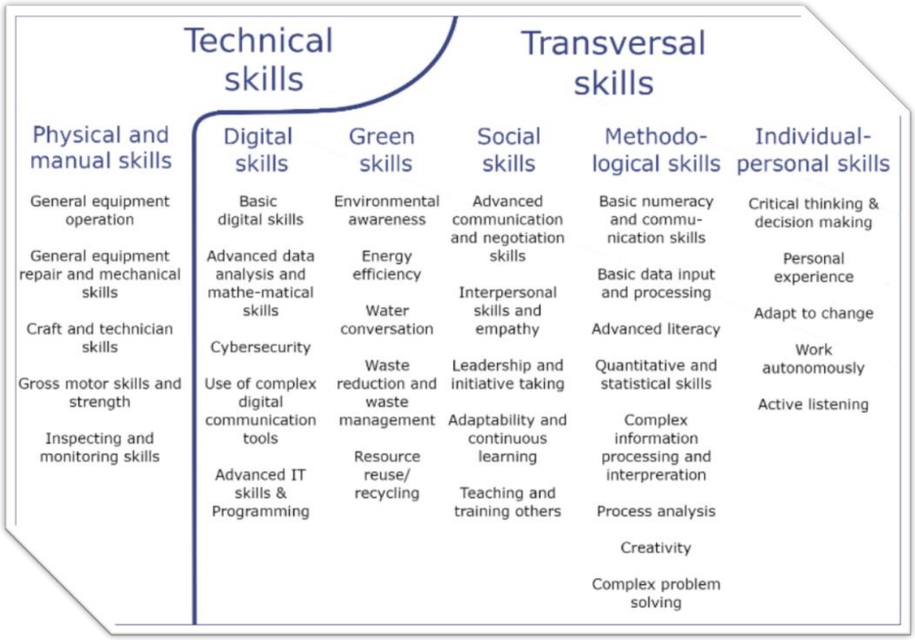


Figure 18 Technical and Transversal skills

Table 12 summarises the contribution of enablers for clean steel developments to the areas of intervention covered by the Clean Steel Partnership.

Table 12 Contribution of Building Block 10a and 10b to the six areas of intervention

CDA - Major contribution	• The new CDA techniques need new measurement technologies and digital tools e.g., to handle new safety issues (e.g., handling of hydrogen, specialists for hydrogen protection and security) and upskill/support of staff regarding the new processes with intelligent scheduling of resources and AI-enabled event management. • Optimization of energy (resource) usage by developing and further implementing digital twins of plant eventually including auxiliary devices and services. • Setting up of improved environmental and working conditions for a more favourable sentiment against carbon-neutral steel production and its impact.
SCU-CCUS - Minor contribution	• Integration of SCU-CCUS in the process systems needs new measuring technologies and digital tools (e.g., for control of gas circuits)
SCU-PI - Major contribution	• The realisation of SCU-PI technologies needs new measuring technologies and digital tools, this applies in particular for the intermediate transition states (e.g. to handle the influences on gas circuits) • PI in its general definition includes also the optimised combination resp. coordination of processes inside the process chain, thus, this area of intervention also considers techniques which are needed across the whole process chain for optimum process integration inside the future carbon-free steel production chains (closely linked to the area of intervention “Combination of technological pathways”). • Use of smart and soft sensors to be integrated into the network of the manufacturing chain for improving monitoring, control and management of

	stable processing in carbon-neutral steel production. Data coming from sensors, process monitoring and control are aimed at raising the digitalisation potential of new steel production technologies through the improvement of data quality using innovative approaches such as hybrid methods. • Introduction of embedded sensors, also via direct deposition (e.g. 3D printing) on parts of heat-generating and heat-exchanging technologies to better control the processes and their energy efficiency. Evaluate performance, quality, and reliability; validate the working conditions when sensors are custom designed for direct printing or deposition directly on working parts or exposed to harsh environments. • New and adapted digital methodologies and tools development, application and demonstration to plan, schedule, monitor, control, and analyse, etc. new material and residues, as well as processes in the steel manufacturing industry. • The PI integration is achievable by compacting and accelerating manufacturing processes through integrated multi-functional assets and the realisation of a seamless flow of data coming from process, assets and business through the full connection of the supply and manufacturing chains enabled by the digital architectures natively compliant with the Industry 4.0/5.0 paradigms. Such seamless connection is enabled by the deployment of novel digital infrastructures needing a multi-dimensional dataflow among the IT business systems, OT and the Human Factor supported by intelligent systems aimed at pairing humans and machines in a cooperative environment.
CE – Major contribution	• New digital tools are needed to plan, schedule, monitor and control the new material cycles • New tools to support life cycle impact assessment are needed • Further development of standardised sets of data for the evaluation of environmental footprint as a whole, together with methods and use of tools applied to measure and demonstrate the improvement of energy efficiency and greenhouse gases (GHG) emissions reductions, including Life Cycle Assessment and Life Cycle Cost Analysis (LCA/LCCA). • Digital solutions (such as but not limited to sensor systems, model algorithms…) to support life cycle impact assessment for continuously monitoring the effects of circular approaches / solutions on the societal/ environmental impact (with special focus on CO_2 emissions). • Integration between raw and secondary material suppliers, vendors and customers ensuring the timely access to market through matchmaking digital systems.
Combination – Major contribution	• The decarbonisation often includes combinations of techniques which will create several needs for the enablers considered in this building block, e.g. regarding planning, scheduling and automation tools with the extended application of process Digital Twins for in-line and off-line analyses (scenario evaluation, risk assessment etc.) • Use of smart and soft sensors to be integrated into the network of the manufacturing chain for improving monitoring, control and management of stable processing in carbon-neutral steel production. Data coming from sensors, process monitoring and control are aimed at raising the digitalisation potential of new steel production technologies through the improvement of data quality using innovative approaches such as hybrid methods.
Enablers & Support	• There are strong links due to the similar focus of building block and area of intervention

Actions - Major contribution	• Demonstrate the value of an integrated strategy relying on skills monitoring and assessment, with consequent adequate training for new technological solution (including workplace impact concerning e.g., digitalisation, safety, etc.) and shared infrastructures (e.g. H2 production and piping) in a cross-sectorial industry frame and/or in a circular economy scenario. • Integrating the experiences, competences of the workers at the concerned workplaces; co-creation processes with the workers affecting to come to more efficient and effective solutions for the technological implementation; by this empowering the workers to use the new technologies and fostering their acceptance right from the beginning of the innovation process. • Adopting and guaranteeing the human-centricity of technological innovations for a Steel Industry 5.0 being human-centric, sustainable and resilient via the empowerment of the workers by skills and competencies.

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.11. Building block 11: Low CO_2 emissions downstream processes

Today, downstream steel processing (rolling, heat treatment and finishing) accounts for a significant portion of direct specific CO_2 emissions, especially in case of the EAF/scrap route (more than 50%). **Reducing GHG emissions of downstream processes** is therefore a highly significant topic in case of the EAF route. However, it is also an important step for all the steel routes to support the decarbonisation process of the downstream production looking at 2030 target and a mandatory one for reaching the lower target of 2050. Several techniques are already available for reducing CO_2 emissions from the downstream processes that respond, besides the economic concerns related to the investment costs, also to the criteria of environmental sustainability. However further developments are needed for a more consistent reduction targeting to "zero CO_2 emissions" through a progressive path.

This building block starts from the consideration that the new scenarios based on CDA and SCU pathways consider new feedstock (syngas from CCU, H_2 or NH_3 from renewable electricity, biogas or biomass, etc.) hat will be available in a big quantity at the steel plant. The **feedstock can be used as low carbon fuels** to replace, in part or totally natural gas or process gases occurring from traditional steel mill plants (cookery, partly BOF, BF), contributing to the CO_2 emission reduction in the downstream steel processing furnaces and combustion systems. Therefore, **energy carrier flexibility** is one of the pillars of this building block, leading to the development of **high efficiency, low emission multi-fuel burners technologies, full electric reheating and hybrid heating approaches combining combustion and electric heating.** These allow the downstream steel processing to remain aligned and take advantage from the gradual decarbonisation of liquid steel production. The **combustion of hydrogen-enriched hydrocarbons or finally of 100% green hydrogen** seems to be the most promising development, however, the extension of the fuel flexibility concept towards an effective zero CO_2 emissions target can also require the adoption of **new carbon-free energy carriers** such as bio-fuel, ammonia or methanol.

The **furnace efficiency** is the second pillar. Today, heat recovery, by recirculating back to the furnace a part of the heat content in the flue gases preheating combustion air (up to 550°C), is the most common technique to reduce the energy consumption. Among the technologies already successfully applied, "Regenerative Combustion Systems", thanks to the integration between the burner and ceramic heat exchange, allows a further consistent reduction (15-20%) of the specific consumption of a reheating furnace thanks to a higher combustion air preheating (100-150 °C less than the process temperature).

Introducing innovations in the **technology of the metallic-bundled heat recuperators** and/or in using additive manufacturing can open new opportunity for improving efficiency. Moreover, the heat content of the flue gases, which cannot be recovered to the combustion chamber of the furnaces, is lost in normal conditions. R&D&I will address the potential reuse of such heat loss for thermal processes operated at a lower temperature. In addition, the energy input into the furnaces and material treatment could be electrified. **Oxyfuel combustion in combination with low carbon fuels** is another pillar to enhance furnace efficiency, which might require a significant change in the overall furnace concept for green hydrogen as fuel due to the highwater vapour content (~98 %) of the off-gas.

Nitrogen oxides (NOx) emissions occurring from higher peak combustion temperatures (higher thermal NO-formation) from the integration of new flexible combustion systems with more efficient heat exchangers, is the further challenge to effectively take advantage of new technologies and reach substantial CO_2 and GHG reduction. The increase of NOx emission, in fact, is well known in case of hydrogen rich fuels (such as today for the coke oven gas). Extension of flameless concept and oxyfuel combustion is a research topic to lead to energy saving and accordingly **less CO_2 emissions and, at the same time, less NOx emissions**. Potential benefits in term of operating expenses can come also come from the availability of oxygen as residues of green hydrogen produced by electrolysis.

Finally, **hot charging** is to be considered, allowing the reduction of the chemical energy input to the process by typically 10%. The development must be related to the handling that today limit the number of applications of this technology and to the production flexibility which is somehow reduced. Hot charging technology might be made more effective and more robust in giving positive outcomes using adaptive dynamic techniques for controlling the process while artificial intelligence can have a positive contribution and may open new research paths to be explored.

Table 13 summarises the contribution of low CO_2 emissions downstream processes to the areas of intervention covered by the Clean Steel Partnership.

Table 13 Contribution of Building Block 11 to the six areas of intervention

CDA - Major contribution	• Innovations in the technology of the heat recuperators and/or in using additive manufacturing can open new opportunity for improving the efficiency of re-heating and treatment furnaces. This must be combined with an extension of flameless concept and oxyfuel combustion to limit the NOx emissions. • Concepts for efficient use of waste heat in downstream processes • Full electric heating concepts for reheating and annealing processes • Energy carrier flexibility for the downstream processes, e.g., hybrid heating approaches combining electric heating and combustion of one or several fuels. • In addition, and in case of in-situ electrolysis for H_2 production, the by-produced O_2 can be directly used in the combustion process • Oxygen as residue from electrolysis has a great potential to replace air for combustion. Therefore, the connection of CDA technologies with a CO2 reduction of the downstream process is of high importance.
SCU-CCUS - Major contribution	• This building block starts from the consideration that the new scenarios based on CDA and SCU pathways consider new feedstock (syngas from CCU, H_2 from renewable, biogas for biomass, etc.) that will be available in a big quantity at the steel plant. The feedstock can be used as low carbon fuels to replace, in part or

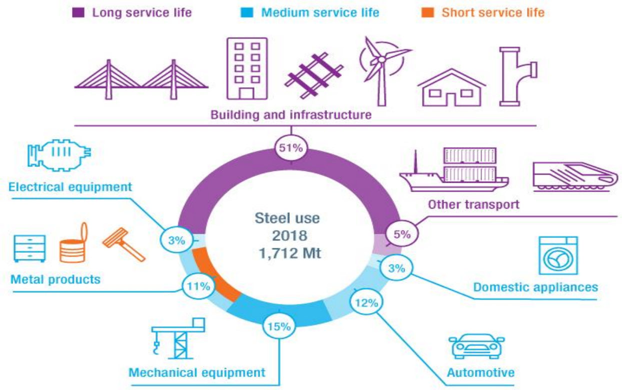
	totally the natural gas, contributing at the CO_2 emission reduction in the downstream steel processing furnaces and combustion systems. • Therefore, fuel flexibility concept is one of the pillars of this building block, leading to the development of high efficiency, low emission multi-fuel burners technologies that allow the downstream steel processing to remain aligned and take advantage from the gradual decarburisation of liquid steel production. • In addition, and in case of in-situ electrolysis for H_2 production, the by-produced O_2 can be directly used in the combustion process
SCU-PI - Major contribution	• Innovations in the technology of the metallic-bundled heat recuperators and/or in using additive manufacturing can open new opportunity for improving the efficiency re-heating and treatment furnaces. This must be combined with an extension of flameless concept and oxyfuel combustion to limit the NOx emissions. • Moreover, the heat content of the flue gases that cannot be recovered to the combustion chamber of the furnaces and in normal conditions is lost, can be reused for thermal processes operated at a lower temperature. This is the case of the steam production that can be realised by installing a boiler at the base of the stack of the furnace.
CE - Minor contribution	• Scale residues contain high % of ferrous oxide (> 90%) that can be recovered as scrap substitute flexible H2 production compensating fluctuations in energy demand when operating an EAF in the EAF route
Combination – Major contribution	With BB4, BB5, BB6, BB8, BB9, BB10, BB11: • Today, downstream steel processing (rolling, heat treatment and finishing) accounts for a significant portion of direct specific CO_2 emissions, especially in case of the EAF/scrap route (more than 50%). To address how to reduce the GHG emissions of downstream processes is therefore mandatory in case of the EAF route. However, it is also an important step for all the steel routes to support the decarbonisation process of the liquid steel production looking at 2030 target and mandatory for reaching the lower target of 2050.
Enablers & Support Actions - Major contribution	• Hot charging technology might be made more effective, flexible and robust in giving optimised indications (set up) using adaptive dynamical process control techniques based on machine learning and artificial intelligence can speed up the optimised sequence scheduling continuously adapting the execution to process evolution. In general, such expected contribution might open new research paths to be explored

Source: Author's elaboration on consultation with ESTEP members.

2.1.2.12. Building block 12: Innovative steel applications for low CO_2 emissions

Steel is a base material for economic activities accounting for about 1700 Mt/year globally, roughly 10% of steel (ca. 170 Mt/year) is consumed/produced within the EU. **Steel is applied for building and infrastructure, mobility and transport, energy and engineering and other metal products** (see Figure 16 below). Through components requiring higher strength and higher other resistance (for instance towards hot gases), technologies needed for clean steelmaking can be developed and deployed. **Infrastructure allowing operation at flexible energy supply** (for instance pressure vessels for intermediate storage e-gas) rely strongly on specific steel grades and design.

Figure 16 Steel markets



Source: Worldsteel, for further details please see: worldsteel.org/steel-by-topic/steel-markets.html

Solutions **generating renewable energy** rely strongly on steel: e.g., towers, engines, transmissions in wind power, support systems for solar power, vessels and tubing in solar heat, and many other applications. In renewable energy generation steel provides the characteristics needed and is available in huge quantities to enable the rapid deployment of various solutions contributing to the increase of renewable energy supply of the future. The CO_2 emission reduction of the production of renewable energy (compared to gas/coal-based generation) overrules the CO_2 intensity of the steel-based equipment within less than one year, further optimisation potential is put in place. Steel alloys addressing special applications generally exhibit the special characteristics of being highly resistant to harsh environments (high corrosion, high temperature, high pressure), being exceptionally durable and showing high hardness and high strength. Of primary interest under this objective are those applications that are contributing to the value chain of the technologies listed and named in the Net Zero Industry Act (NZIA), for example, but not limited to, steel alloys for towers of wind turbines and for nuclear applications.

In the field of **mobility**, the design and deployment of lightweight components and advanced high strength steel solutions enables the transport of goods and people with low specific energy need. In this case, steel is the best compromise between safety, economics, life cycle aspects and manufacturing technologies.

The development of modern high-strength grades in combination with advanced technologies for assembling allows the further optimisation of steel used in **buildings and infrastructure** – similar characteristics can be realised with a reduced amount of steel, thus lower CO_2 impact on the overall structure. Clean steel products may also be developed to extend the lifetime of steel, thus reducing demand for new steel in the future.

Table 14 summarises the contribution of innovative steel applications for low CO_2 emissions to the areas of intervention covered by the Clean Steel Partnership.

Table 14 Contribution of Building Block 12 to the six areas of intervention

CDA - **Major contribution**	• The design of new reactor concepts and process routes requires adapted steel grades compared with the BF-BOF route and other raw materials • Advanced reactor technologies using steel solutions based on high-performance steel grades (towards very high temperatures, aggressive gases);

	• Manufacture steels with improved life cycle contributions to CO2 emissions reduction; this is the case for, but not limited to, the transport sector, which includes improved possibilities for re-use and re-manufacture; this includes also innovative manufacturing technologies for steel grades supporting decarbonisation like, but not limited to, electric strip; • Advanced grades of steel for use in efficient high temperature processes including, for instance, thermal reactors for waste recovery; • Advanced grades of steel for use in the railway's systems of high-speed trains to assure high quality, good weldability, and very high mechanical properties, including high yield strength, metal-to-metal wear resistance, and high rolling contact fatigue resistance; • High-performance structural steels (e.g., high-strength, high-pressure resistant, creep resistant, oxidation resistant, etc.) not containing critical strategic elements (such as, V, Nb, Ti, etc.) and/or characterized by increased tolerance to the content of contaminants in the scrap, such as for instance Cu; • Demonstration at industrial scale (downstream processing and manufacturing processes) the manufacture of advanced and special steel grades with improved life cycle contributions to CO2 emission reduction and providing a quantitative analysis of the energy and materials system balance. Defining new test approaches and needs for standardization of 'clean steel' production and 'clean steel' products. • Develop and validate predictive simulations to define product characteristics and physical and/or mechanical properties, based on specific process variables in CO2 neutral steel routes. • Solutions should be looked for to move towards steel grades with a longer lifetime e.g., stainless steel and duplex steel; better understanding of reliability, quality and life time expectation of products
CCUS - Minor contribution	• Continuous improvement of existing processes
SCU-PI - Minor contribution	• Continuous improvement of existing processes • Temporary energy storage solutions (e.g., large volume higher pressure vessels) will mediate between energy (gas, electricity) supply and energy use in different processes • Evaluation of the effects of process variables changes when moving towards a carbon neutral steel production route and demonstration of the related development of special steel grades/alloys with specific mechanical and physical properties for the green economy (for example, but not limited to, steel with low corrosion level for offshore wind applications, H2 embrittlement, etc) and harsh environment applications (for example, high-temp high-pressure applications and nuclear): develop and validate the necessary process tuning to allow production of special steels. •
CE - Minor contribution	• Continuous improvement of existing processes • Steel grades with increased use of low-quality input materials (e.g., scrap, secondary raw materials, ores / dust, etc.) by new knowledge of the influences on the application properties of manufactured steel products tested under realistic operating conditions, taking into account the entire manufacturing process to identify the acceptance of buyers / users (incl. economic / ecological benefits, questionnaires, market research).

Enablers & Support Actions - Major contribution	• Continuous improvement of existing processes • Clean steel grades with improved in-use properties obtained by controlling the application properties (e.g., yield strength and/or high ductility steels, fatigue, embrittlement, internal and external corrosion and other properties relevant to service life in the application) supported by known or new techniques (e.g., machine learning (ML), metallurgical / thermodynamic simulations, multi-scale models, defect vs. structure vs. properties correlations, finite element methods (FEM), realistic and applied testing methods) to realise the desired steel grade characteristics; • Innovative simulation methods and tools (e.g., Calculation of PHAse Diagrams (CALPHAD), crystal plasticity, artificial intelligence (AI), machine learning (ML), realistic and application-oriented testing methods, multi-scale modelling, and microstructure, defects and properties prediction tools, digital twins etc.) to accelerate the development processes of the mentioned clean steel grades and their manufacturing processes; • Introducing and demonstrating new ad-hoc sensorics coupled with innovative digital monitoring systems at significant stages of the low carbon/carbon neutral steel production route that would allow collecting relevant data to monitor the manufacturing process and reconstruct the history of a product to improve quality control and detection of faults and defects. Confirm problematic parts via specific tests.

Source: Author's elaboration on consultation with ESTEP members.

2.2. Timeline and budget distribution

2.2.1. Timeline - the multistage approach

High capital intensity, long payback periods and investment cycles between 20 and 30 years are major obstacles to accelerate carbon mitigation in the steel industry. Therefore, the Clean Steel Partnership proposes a three-stage approach to address these challenges by dividing the investments into different phases and allow for a smooth transition towards clean steelmaking in the EU. **Stage 1** (short- to medium-term impact measures) targets projects that generate 'immediate' CO_2 reduction opportunities. **Stage 2** (medium-term impact measures) focuses on those projects that may not be implemented 'immediately' in the installed base, but allow for a quick migration (evolution) towards improved processes. Finally, **Stage 3** (medium- to long-term impact measures) looks at those projects that can 'revolutionise' the steel industry through breakthrough development, and require significant capital investment in new processes. The division of the Roadmap's timeline into three stages and the allocation of different BBs into these stages ensure proper balance between the short-, medium- and long-term impacts of the technologies developed under the Partnership. This **multi-stage approach** of the Clean Steel Partnership provides the rationale behind the budget split over time and areas of intervention, as further discussed in what follows.

As shown in Figure 17 the budget is expected to finance at least **16 projects resulting in building blocks at TRL7** (up to 30 million euros each), at least **12 projects resulting in building blocks at TRL 8** (up to 60 million euros each) and at least **4 demonstration projects** (up to 100 million euros[54] each).[55] Demonstration projects [56] cover the construction and/or operation of (significant parts of) an industrial-scale installation, in order to bring together all the technical and economic data in order to proceed with the industrial and/or commercial exploitation of the technology at minimum risk.

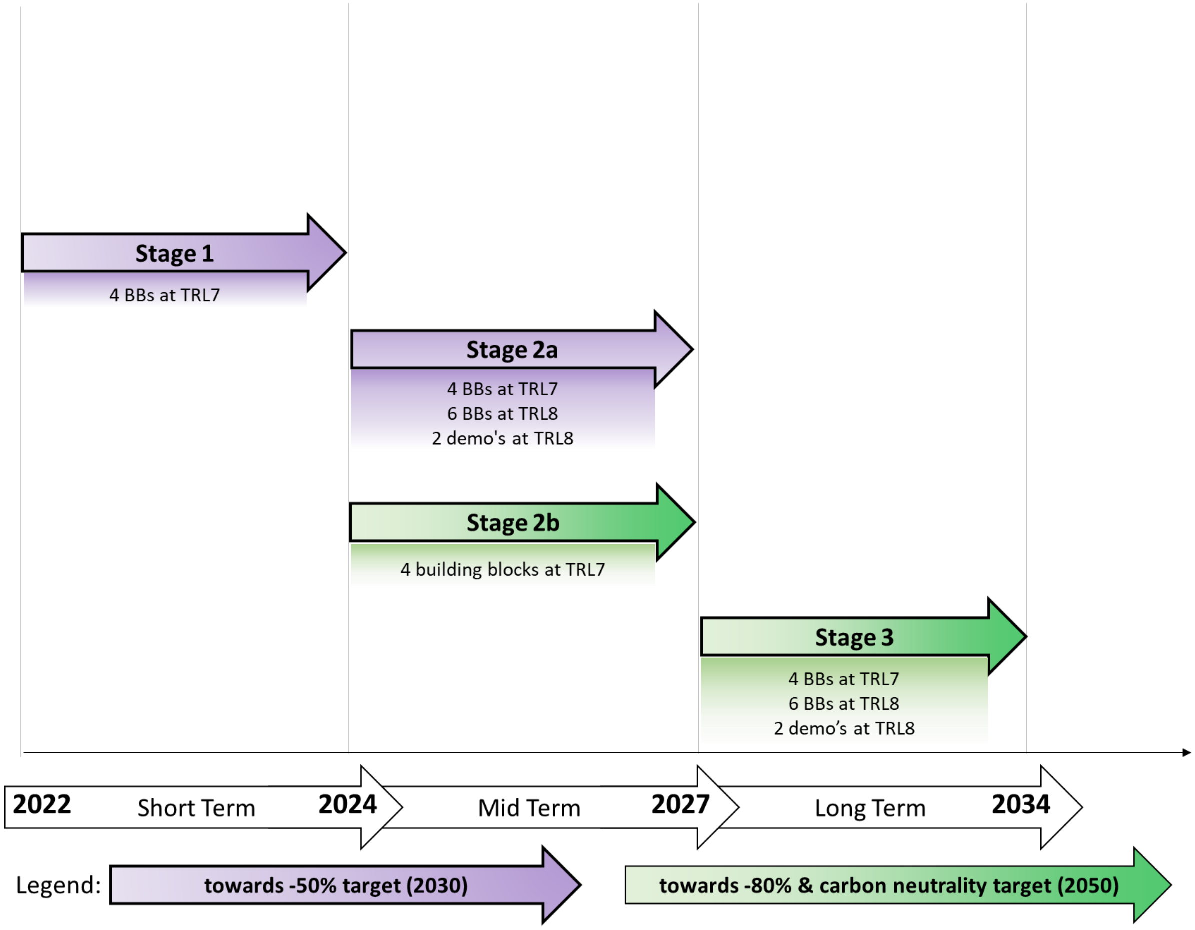
These 4 demonstrations, which will combine different building blocks, will be launched in 2023, 2024, 2026 and 2027. Two of them target technologies that have up to 50% CO_2 mitigation potential by 2027, and the other two support technologies with up to 80% of CO_2 reduction by 2030.

[54] These four demonstration projects should be large scale demonstration, more specifically installation with more than 10% of typical industrial production capacity or regarding a significant part of a full industrial-scale installation to ensure an adequate level of efficiency in the steelmaking process operation but neither mass production nor commercial activities.

[55] The budget of projects will depend on the total budget of the Clean Steel Partnership, which in turn depends on the Multiannual Financial Framework decision. The budget figures illustrate the total need for the foreseen R&D effort and can be achieved in a single project as well as by a cluster or combination of projects.

[56] Definition in https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/rfcs/wp-call/2023/call-fiche_rfcs-2023-jt_en.pdf

Figure 17 Multi-stage approach and related targets



Source: Author's elaboration on consultation with ESTEP members.

Table 15 shows the building blocks that are expected to achieve the TRL targets presented in Figure 17 in each stage, and the pathways affected by such building blocks. It is worth emphasising that in Stage 1 R&D&I activities will start in more than four building blocks, and in stage 2 R&D&I activities are expected to start in all building blocks. The proposed multi-stage approach will be updated, if needed, as a result of the review of the Roadmap performed by the Implementation Group of the Clean Steel Partnership (see Section 4.1)

Table 15 Multi-stage approach and building blocks achieving the targets presented in Figure 17

Stage	BBs	Activity	Associated pathway
Stage 1	BB2	CO_2 neutral iron-ore reduction	CDA
	BB4	Adjustment of today's production to prepare for the transition	Combined (CDA, SCU-PI & SCU-CCUS)
	BB5	CO/CO_2 capture and storage	SCU-PI
	BB9	Steel specific circular economy solutions	CE

Stage 2	BB1	Gas injection technologies	SCU-PI
	BB2	CO_2 neutral iron-ore reduction	CDA
	BB3	Melting of pre-reduced and reduced ore, scrap	SCU-PI
	BB4	Adjustment of today's production to prepare for the transition	Combined (CDA, SCU-PI & SCU-CCUS)
	BB5	CO/CO_2 utilisation	SCU-CCUS
	BB6	Raw material preparation	Combined (CDA, SCU-PI & SCU-CCUS, CE)
	BB7	Heat generation for processes	Combined (CDA, SCU-PI & SCU-CCUS)
	BB8	Energy management/energy vector storage	CDA
	BB9	Steel specific circular economy solutions	CE
	BB10	Enablers (skills, digitalisation)	Combined (CDA, SCU-PI & SCU-CCUS, CE)
	BB11	Low CO_2 emissions downstream processes	Combined (CDA, SCU-PI & SCU-CCUS, CE)
	BB12	Innovative steel applications	Combined (CDA, SCU-PI & SCU-CCUS)
Stage 3	BB1	Gas injection technologies	SCU-PI
	BB2	CO_2 neutral iron-ore reduction	CDA
	BB3	Melting of pre-reduced and reduced ore, scrap	SCU-PI
	BB4	Adjustment of today's production to prepare for the transition	Combined (CDA, SCU-PI & SCU-CCUS)
	BB5	CO/CO_2 utilisation	SCU-CCUS
	BB6	Raw material preparation	Combined (CDA, SCU-PI & SCU-CCUS, CE)
	BB7	Heat generation for processes	Combined (CDA, SCU-PI & SCU-CCUS)
	BB8	Energy management/energy vector storage	CDA
	BB9	Steel specific circular economy solutions	CE
	BB10	Enablers (skills, digitalisation)	Combined (CDA, SCU-PI & SCU-CCUS, CE)
	BB11	Low CO_2 emissions downstream processes	Combined (CDA, SCU-PI & SCU-CCUS, CE)
	BB12	Innovative steel applications	Combined (CDA, SCU-PI & SCU-CCUS)

Source: Author's elaboration on consultation with ESTEP members.

A way forward would be the launch of several **multi-partner projects** (targeting at least three beneficiaries and engaging at least three EU Member States) to achieve the objectives of the Clean Steel Partnership. Within the multi-partner projects, the partners would further develop individual or combination of technologies at industrial pilot scale towards TRL7 and/or TRL8. An industrial pilot installation can be established at one location with the contribution of all partners or modules of the industrial pilot installation can be established at several locations with the contribution of all partners. Results from multi-partner projects (intermediate and/or final reporting) would enable the creation of synergies within a maturing building block and between maturing building blocks in one or different pathways.

2.2.2. Budget distribution

The achievement of the objectives of the Partnership (i.e., piloting and demonstrating breakthrough technologies that can substantially reduce CO_2 emissions from the steel industry while at the same time preserving its competitiveness), and the realisation of the opportunities for the EU steel industry of becoming a global leader in clean steel technologies require both a number of **external conditions** and the **strong effort of the sectoral players**.

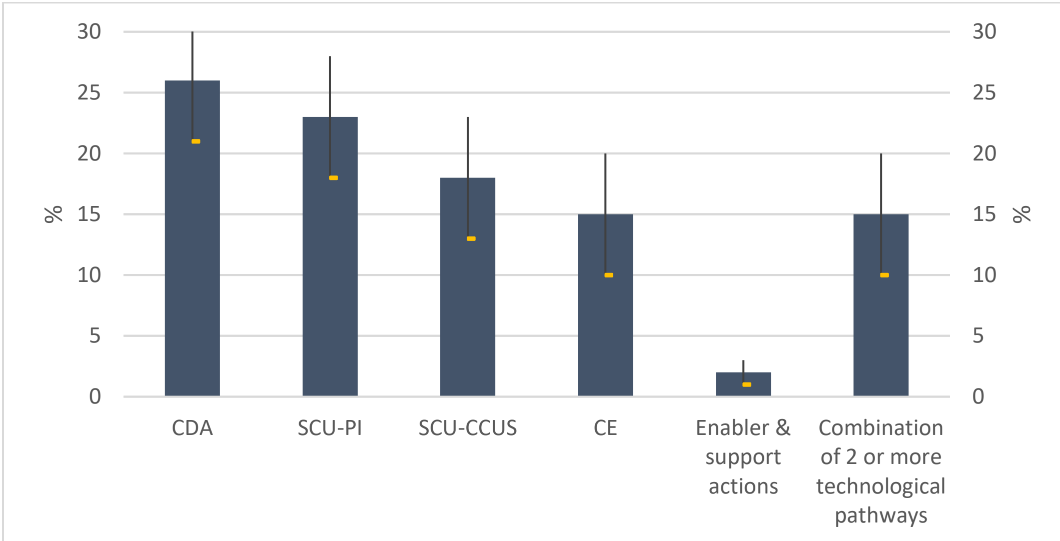
Based on the estimated industrial efforts from the steel sector in R&D&I projects falling within the scope of this Roadmap, **the total resource requirement is estimated at around EUR 3 billion during 2021-2030.**[57] This R&D&I investment will have then to be followed up by a multiple of these resources, to ensure that the technologies are deployed and rolled out. Due to the collaboration among steel producers, reasonable synergies are expected compared to the company-by-company approach, thus reducing **the investment need to approximately EUR 2.55 billion**. The **'wider boundary'** of the Partnership, i.e., the collective investments needed from the public and private side for the **period 2021-27, is estimated at EUR 2 billion.** The remaining **EUR 0.55 billion** will be allocated to the period 2028-30, during which projects will still be completed. The expected investments to be managed within the **scope** of the Clean Steel Partnership are worth **around EUR 1.4 billion** during 2021-27[58]. Major private funding would match public funding from the Union, such as Horizon Europe and the Research Fund for Coal and Steel. Furthermore, the Partnership's activities will mobilise **further resources from other EU funded programmes and the Member States**, as several countries have expressed their expectation to orientate their national R&D&I programmes to ensure complementarity with the Partnership and to further increase leverage. Besides financial support, the members of the Partnership will also provide resources to ensure proper staffing of the Secretariat of the Partnership, as well as the various bodies of the governance structure as indicated in Chapter 4 of the Roadmap (contributions in kind or cash).

The European Commission, the Member States and the European steel industry are also expected to invest massively in the market deployment of low carbon steelmaking technologies, going beyond R&D&I projects. Instruments outside the Clean Steel Partnership like the EU-ETS-Innovation Fund, Important Projects of Common European Interest (IPCEIs)and national decarbonisation funds are needed to support the roll-out of breakthrough technologies in the steel industry in the coming years.

Based on the analyses of the investment needs in R&D&I by the steel stakeholders, the **budget will be split over the different areas of intervention** as shown in Figure 18 and **across years** as shown in Figure 19. Further details on the scale of resources needed to implement the Roadmap and contribution from the private side are presented in Chapter 3, together with the rationale for the split across the various areas and years.

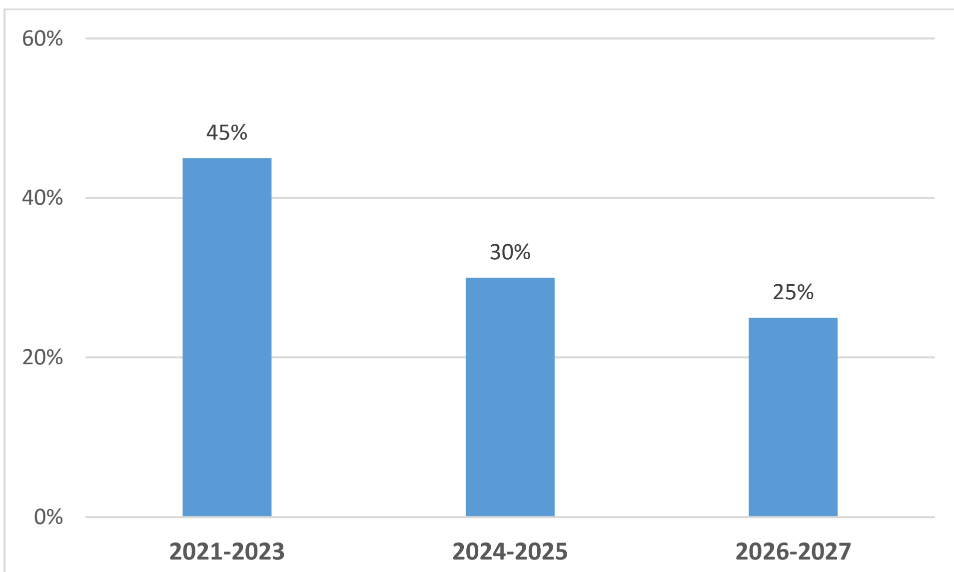
[57] Data collected by ESTEP and EUROFER.
[58] The total budget of the Clean Steel Partnership still depends on the Multiannual Financial Framework decision.

Figure 18 Budget spit over areas of intervention (average values, range min to max)



Source: Author's elaboration on consultation with ESTEP members.

Figure 19 Budget split over groups of years (percentage)



Source: Author's elaboration on consultation with ESTEP members.

Chapter 3: Expected Impacts

Summary

Scale of resources to implement the SRIA and potential for additional investment

- The resources needed to implement the SRIA have been split across three phases (2021-23, 2024-25, and 2026-27), with the highest emphasis being placed on the beginning of the Partnership, reflecting the need for immediate intervention.
- A range of contributions from both private and public side are required. From the private side, resources mainly consist in in-kind contributions and investments in projects funded by the Union and other activities foreseen by the SRIA. Private contributions concern both the implementation of the SRIA by setting up calls for the Partnership and mobilising resources beyond the Union programme, as well as other activities such as workshops, discussion, and the provision of information on EU R&D&I programmes.
- The Partnership will generate both direct and indirect leverage effects for additional investments.
- The investment needed to deploy the developed technologies at an industrial scale is envisaged to be at least three times the R&D&I resources provided by the Partnership.

Impacts on industry and society

- The objectives and impacts of the Partnership are in line with the pathways of Horizon Europe.
- The Partnership will also contribute to the Sustainable Development Goals 3, 8, 9, 12 and 13 under the United Nation's 2030 Agenda.
- Actions in the various areas of intervention will generate several impacts in various areas, such as:
    - CO_2 reduction: new technologies deployed that could reduce emissions from EU steel production by 50% by 2030, compared to 1990 levels;
    - Industry and EU competitiveness: The support for the deployment of the decarbonisation technologies will allow the EU to remain a global leader in the steel industry and to reinforce its knowledge-based competitive advantage;
    - Resource efficiency: the partnership enables the coordination of technological progress in the use of steel scrap and by-products, leading to an enhanced, larger use of those resources;
    - Jobs and skills: the Partnership will support the preservation of high-quality jobs in the steel making value chain.
    - Ensuring human-centricity will lead to a more resilient and sustainable Steel Industry 5.0

EU added value and additionality of the Partnership

- The EU added value of the Partnership is obtained through a coordinated approach across stakeholders, technologies, production routes, and Member States; leverage of private investments; timely and well-planned intervention and clear exit strategy to phase out from public support for R&D&I.
- The Partnership can generate other forms of additionality by cross-fertilising both suppliers and customers and collaborating with other Partnerships and research programmes under Horizon Europe.

- The Partnership will contribute to R&D&I Missions of Horizon Europe on climate-neutral and smart cities; soil health and food; and on adaptation to climate change including social transformation.
- Spill-overs in other value chains and industries will be generated via clean steel as input and by trickling know-how down the value chain.

Monitoring and assessing progress

- A range of Key Performance Indicators (KPIs) has been developed to monitor and assess the progress of the Partnership's specific and operational objectives. Each KPIs is accompanied by a target to be achieved by 2030.
- Within each KPIs, deployment and TRL of the technology is the most important indicator to measure whether the introduced innovations generate their expected impacts.

3.1 Scale of resources to implement the SRIA and potential for additional investment

3.1.1 Scale of resources

Addressing the R&D&I challenges that the Clean Steel Partnership is to tackle will require significant resources from both the public and private side. As mentioned in Chapter 2, the total resource requirements between 2021 and 2030 were estimated at EUR 3 billion, but due to expected synergies stemming from the collaboration of steel producers, the investment needs can be calculated at **EUR 2.55 billion** for the next decade. For the Partnership period of 2021 to 2027, collective investments needed from the public and private side are estimated at **EUR 2 billion ('wider boundary'),** and the remaining funding (estimated to be EUR 0.55 billion) will be allocated to the period immediately after the Clean Steel Partnership, **2028-30**, where some projects will still be completed. The European Commission envisages to dedicate up to EUR 700 million to actions within the scope of the Co-programmed European Partnership. Based on the assumption that within the **scope** of the Clean Steel Partnership it manages **EUR 1.4 billion,** major private funding would match public funding and is to be accomplished with in-kind contributions by industry. The financial resources will be continuously allocated during the seven-year period to high TRL projects and TRL8 demonstrators.

Table 16 presents the allocation shares for the budget of the Partnership by areas of intervention, and the sources of contribution and how they are split over the period covered by the Partnership. The expenditures have been divided for **three phases** (2021-23, 2024-25, and 2026-27), with the highest emphasis being placed on the beginning of the Partnership, reflecting the need for immediate interventions and for a big push to make existing technologies deployable with the shortest delay. A large initial investment is considered appropriate, since the technologies brought to TRL 8 by the CSP will need some time to produce their effects in terms of carbon reduction. Therefore, it is important that these technologies are deployed as soon as possible if carbon reduction targets are to be met in line with the timing proposed by EU climate policies.

As detailed in Chapters 1 and 2, there are two main technological pathways – **CDA and SCU** – to decarbonise the steel production, and these, together with the **CE approach**, are the primary focus of the R&D&I efforts proposed. The need for resources for CDA and SCU is larger compared to the CE, since these technological pathways are the prime target for R&D&I support, while CE represents an overarching approach of the whole Partnership, also considering that the circularity of steel production is to be enhanced by projects across all areas of intervention. As for the area "combination of pathways", it covers the resources needed by actions that, relying on the solutions developed under the other areas, attempt at bringing together and coordinating different solutions and technologies, enhancing the achievable impacts. The attribution by areas of intervention reported in Table 16 reflects these priorities. Importantly, the attribution is not cast in stone, and may be revised and adjusted reflecting the evolving technological needs and developments.

Table 16 Allocation of the budget by areas of intervention of the Clean Steel Partnership

Areas of intervention	**2021-2023**	**2024-2025**	**2026-2027**	**2021-2027**
	Total *(%)*	***Total*** *(%)*	***Total*** *(%)*	***Total*** *(%)*
Carbon Direct Avoidance	11.7%	7.8%	6.5%	26.0%
Smart carbon usage via CCUS (specific to steel)	8.1%	5.4%	4.5%	18.0%
Smart carbon usage via process integration	10.4%	6.9%	5.8%	23.0%
Circular economy	6.8%	4.5%	3.8%	15.0%
Combination of pathways	6.8%	4.5%	3.8%	15.0%
Enablers & support actions	1.4%	0.9%	0.8%	3.0%
TOTAL	**45.0%**	**30.0%**	**25.0%**	**100.0%**

Source: Author's elaboration on consultation with ESTEP members.

3.1.2 Public and private contributions

The ambitious objectives of the Partnership will require significant efforts from both the private and the public side, via a variety of different contributions**. Resources contributed by the private side** will consist of:

- **In-kind contributions** to the projects funded by the Union (on the basis of non-reimbursed eligible costs, non-eligible costs and infrastructure costs)[59], with lower funding rates for high TRL[60];
- **In-kind contributions** for additional activities foreseen in the SRIA[61] not covered by Union funding, such as:
    - Private company research funding linked to the Partnership on Clean Steel R&D&I framework;
    - Costs incurred by companies associated to the financing of demonstrators or pilot lines;

[59] The private side committed to finance up to EUR 1 billion by matching public contributions (see letter from CEOs of major EU steel companies to President Juncker, available at: https://www.estep.eu/assets/CSP-letters/20180925-Letter-to-Pres.-Juncker-and-College-of-Commissioners-on-Low-Carbon-Steel.pdf)

[60] In principle the normal funding rates should apply. In special cases, a lower funding rate for high TRL is acceptable, but must be more as 50%.

[61] Information on additional activities can only be shared if it is not bound by confidentiality and it is compliant with national and EU competition law.

- **Investments in operational activities**[62] that are spent beyond the work that is foreseen in the Roadmap, such as additional investments by companies whose trigger will stem from technology improvements generated by projects within the Partnership for Clean Steel;

The main contribution expected from the public side is to provide the support and means needed **for the steel sector to reach its ambitions** on climate neutrality, circular economy and zero-pollution for a toxic free environment, while at the same time improving its competitiveness. An open and transparent dialogue between the public and the private sides are fundamental. As the promoters of the European Green Deal, the Circular Economy Package, the Industrial EU policy, the Skills Agenda and other relevant policies, the public side is in a unique position to provide the private side with relevant information in a timely manner so to achieve the objectives of the partnership.

As far as the **implementation of the Roadmap** is specifically concerned, the public side commitment consists in:

- **Setting up calls** for the Partnership on Clean Steel in the Union programmes based on the building blocks identified in the Roadmap of the Partnership on Clean Steel.
- **Facilitate the mobilisation of resources beyond the Union programmes,** through an optimal combination of funding and financing schemes, from Member States and regions to de-risk the innovations up to TRL9 so that developments also can be implemented.
- Provide inputs to **enable a regulatory framework** for the expected impacts of the partnership to be delivered based on the sustainability principles.

In addition, the public side will facilitate an **open and structured discussion** to ensure the appropriate financing to de-risk investments up to TRL 9 and ensure **internal coordination** with complementary EU R&D&I programmes.

3.1.3 Leverage effect

A partnership like the Clean Steel partnership is expected to generate both **direct and indirect leverage effects** for additional investments. At the core of these leverages are the EU contributions to the partnership. Direct leverage effects will be manifested in the following:

- The private side matching the core EU contributions, for example from Horizon Europe and the Research Fund for Coal and Steel;
- Investments from Member States directly mobilised through the initial investments of the Partnership, which again will be matched from the private side to reach the required overall funding.

In addition to the resources directly related to the Clean Steel Partnership, indirect leverage effects are to be expected. There are several reasons and past experiences from other frameworks allowing such leverage effects to manifest, such as:

- The Partnership provides an important financial backing for R&D&I efforts to mature and take steps in its lifecycle up to the crucial demonstration phase, which **decreases the risk of**

[62] Information on operational activities can only be shared if it is not bound by confidentiality and it is compliant with national and EU competition law.

investment for other stakeholders and thereby gives them an incentive to undertake additional investments.

- **Private actors** have already indicated and shown their commitment to invest, but the willingness to take those is generally higher when the technology is more mature and near to deployment, as investments in earlier stages carry a significantly higher risk; the Partnership will indeed allow bringing several technologies to the deployment stage and leverage investments to exploit and up-scale technologies.
- The Partnership's activities will steer individual **Member States** to support a key industry with further resources and orientate their national R&D&I programmes to ensure complementarity with the Partnership, hence further increasing leverage.
- The **experience from other private-public frameworks** suggests that R&D&I investments built upon such frameworks are financially beneficial to stakeholders. Under the **RFCS** for example, EUR 1 spent by a stakeholder in R&D&I supported by the RFCS programme generated about EUR 5 of benefits.[63]
- The EU steel industry is diversified across numerous Member States and different production processes, leading to market players constantly aiming to optimise processes in order to comply with high environmental standards and **be innovative and competitive** within a global market.

A strong effort will be required by sectoral players even beyond the Clean Steel Partnership to realise its potential of drastically reducing CO_2 emissions while ensuring that the EU steel industry remains a global leader in clean technologies. The **investment needed to deploy the developed technologies at industrial scale is envisaged to be at least three times the R&D&I resources**, most likely even more. An **investment of at least three times the envisaged R&D&I resources is needed to deploy the technologies developed at an industrial scale**. The resources deployed via the Clean Steel Partnership and the subsequent investments will **ensure the delivery of demonstrators** combining several building blocks in the various areas of intervention. The subsequent steps, i.e. the **upscaling to full industrial roll-out**, may be outlined as a follow-up activity of projects under the Clean Steel Partnership, but will not be realised within the scope of the Partnership. However, the plant builders, with their capability to participate in the engineering and technology commissioning phase of the proposed solutions, are expected to take up the most promising technologies and bring these up to the market stage. These final steps, driven by the plant builders in collaboration with the steel producers and other stakeholders, will be decided on a case by case basis. Depending on the potential of the solutions, the engineering for **industrial upscaling would normally require a budget of about 25 to 35% of the demonstration budget**. The upscaling can be jointly supported by in-kind participation, rolling-up expenses, or remuneration from selling fees and intellectual property rights.

Testing the breakthrough technologies at high TRL requires significant effort from the steel producers. For instance, processing high volumes of hydrogen requires a modification of the gas infrastructure. The change might negatively impact the productivity of these steel sites. The Clean Steel Partnership and Roadmap would, therefore, need to take into consideration this type of efforts borne by the steel producers, i.e. additional operating costs, as an in-kind contribution from their side.

[63] European Commission (2020), RFCS – Monitoring & Assessment Report (2011-2017), DG for Research and Innovation, p. 110.

3.2. Impacts on industry and society

Implementing the Clean Steel Roadmap will lead to environmental, economic, and social impacts through what the European Commission calls 'this generation's defining task'[64] by **tackling climate change and fostering sustainable growth**. In this respect, the Clean Steel Partnership is intended to support EU policy priorities, in particular by increasing the uptake of new green technologies, and in doing so generating economic growth and more and better jobs. Achieving those objectives will ensure that the Clean Steel Partnership and this Roadmap deliver many impacts, which are beneficial for both the steel industry and the EU society as a whole.

The objectives and impacts of the Clean Steel Partnership are in line with the pathways of its overarching framework, Horizon Europe. More in detail, the Partnership's objectives in relation to **Horizon Europe** programme can be summarised as follows:

- Promoting the decarbonisation of the EU steel industry facilitates the attainment of Programme's **objective on fostering innovation and technological development**;
- Strengthening the global competitiveness of the EU steel industry contributes to the Programme's **objective to foster the Union's competitiveness in all Member States and industries**;
- Upskilling the steel workforce is linked to the Programme's **objective on creating and diffusing high-quality knowledge and skills**;
- Fostering R&D&I collaboration between EU companies operating in clean steel value chains helps achieve the Programme's **objective on facilitating collaborative links in European R&D&I.**

With specific respect to the **UN's 2030 Agenda and SDGs**, the Partnership will contribute to the following goals:

- **Goal 3 on Good Health and Well-being.** By decarbonising the steel industry, the Partnership will contribute to reducing the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.
- **Goal 8 on Decent Work and Economic Growth.** Additional circularity of materials and improved productivity and efficiency in steelmaking contribute to sustainable growth and better working conditions;
- **Goal 9 on Industry, Innovation, and Infrastructure**. Technical developments in the steel sector bring huge potentials for less resource-intensive infrastructure solutions and contribute to the transformative innovation in other industrial sectors, leading to growth, high-value technology, innovation, and resource efficiency;
- **Goal 12 on Responsible Consumption and Production**. The enhancement of circularity in the steel industry contributes to the promotion of responsible consumption and production patterns;
- **Goal 13 on Climate Action**. The Partnership will facilitate research, development and demonstration of technologies that eliminate CO_2 emissions in the steel sector.

[64] European Green Deal, p. 2.

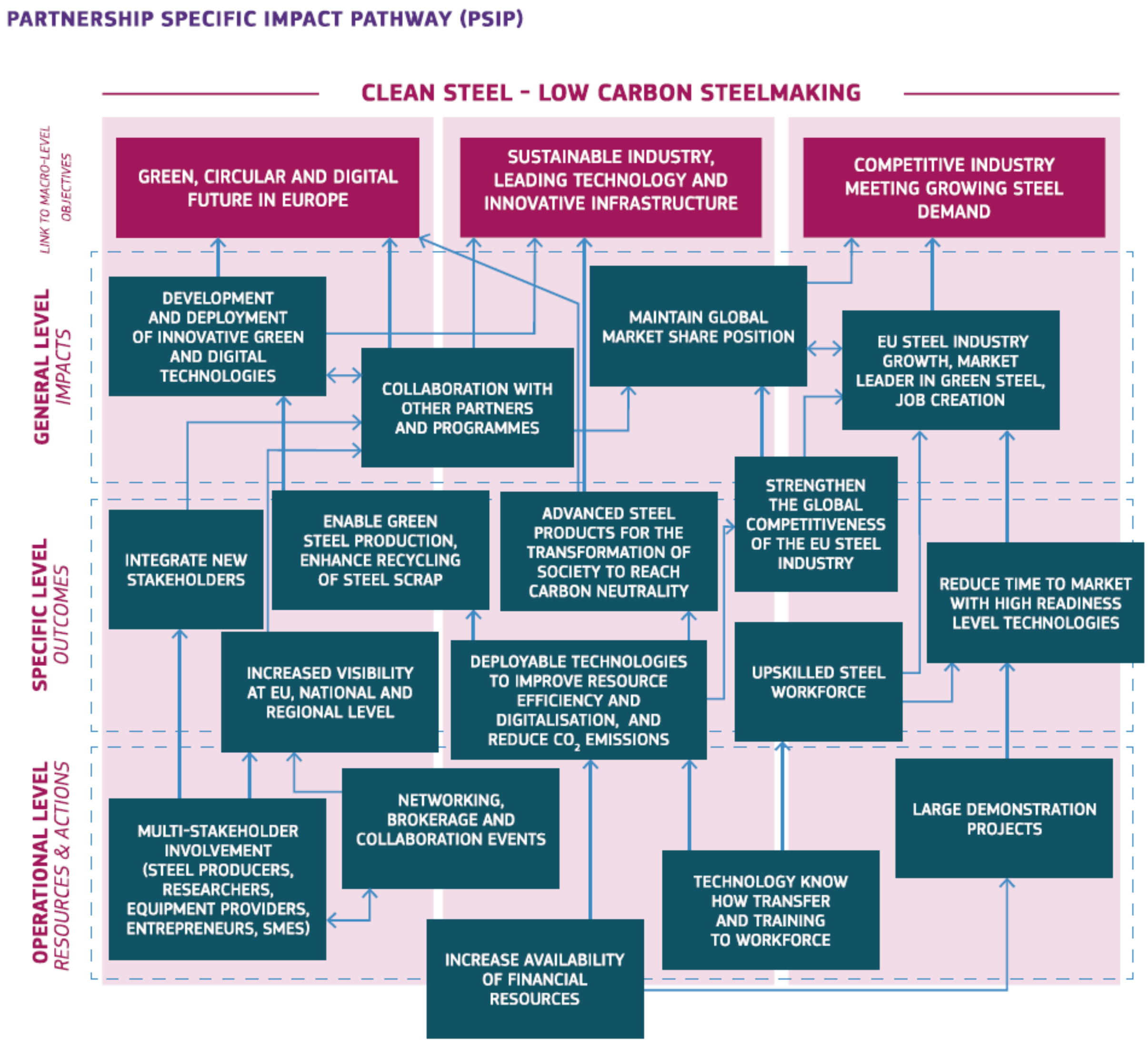
Actions in the various areas of intervention will generate a number of impacts in different spheres, namely:

1. **CO_2 reduction.** With the appropriate conditions in place, notably the right infrastructure and a supportive regulatory framework, the European steel industry will be empowered and fully committed to the EU's climate objectives and sustainable growth targets. The sector would be able to develop, upscale and roll out **new technologies that could reduce CO_2 emissions from EU steel production by 50% by 2030 and by 80 to 95% by 2050** (compared to 1990 levels), thus proceeding towards climate neutrality, while also contributing to greenhouse gas mitigation across all sectors. The most promising breakthrough technologies, which are to be tested and implemented between 2020 to 2030, and beyond include CDA, SCU-PI and SCU-CCUS.
2. **Industry and EU competitiveness.** The support for the deployment of the decarbonisation technologies will allow the EU to remain a global leader in the steel industry and to reinforce its knowledge-based competitive advantage. The generation of a new market for clean steel and related technologies, along with a global level playing field with regard to CO_2 costs, has the potential to increase the competitiveness of the EU steel industry, as a first mover and technology leader (combined with the strong position of EU plant builders). However, decarbonisation technologies lead to an increase in operating costs of 30% to 100%, which thus justify a joint public-private approach to avoid that these costs put EU players out of the market. Furthermore, to be cost-effective, the transition should take place in steps, taking into account that during the transition period a significant amount of CO_2 emissions will be already mitigated.
3. **Resource efficiency.** The steel industry is in a prime position to foster resource efficiency through the Circular Economy concept. Steel is endlessly recyclable, though the quality of recycled still is lower, which in turn calls for more R&D&I efforts in this area. Furthermore, the residues of steelmaking, such as slag, can be a valuable resource for other industrial uses. In addition, the process gases from steel plants have the potential to be reused within the production process or also be passed on as a resource. The right R&D&I framework enables not only the coordination of technological progress in the utilisation of steel scrap, process gases, and waste heat, but also the enhanced cooperation along the value chain to increase the use of recycled resources. Thereby, the necessary input of raw materials is significantly reduced, and less CO_2 emitted.
4. **Jobs and skills.** The steel sector is characterised by high-quality jobs, with relatively high salary and secure contractual conditions. During the transition towards climate-neutral steelmaking, ensuring the viability and competitiveness of the steel industry will determine the number of jobs that can be preserved. While productivity gains may lead to a reduction in the number of jobs, ensuring that the EU becomes a leader in clean steel will increase market opportunities. At the same time, jobs will become more challenging, as workers will have to familiarise with and manage new advanced technologies. The Clean Steel Partnership will consider this perspective, by looking at the support of dedicated instruments which focus on skill and job programmes.

As shown in Section 2.1 above, each area of intervention corresponds to one of the specific objectives described in Section 1.4. In what follows, the expected impact of achieving each of the specific objectives is thoroughly analysed.

The Partnership's intervention logic (also known as the Partnership Specific Impact Pathway, or PSIP) shows the directionality of the progress of the Partnership towards the objectives at the general, specific and operational levels as shown in figure 18a.

Figure 18a – Clean Steel Partnership Specific Impact Pathway



Source : European Partnerships First Biennial Monitoring Report 2022

3.2.1. <u>Specific Objective 1. Enabling steel production through carbon direct avoidance (CDA) technologies at a demonstration scale</u>

CDA, as the name already suggests, is the technological pathway striving for new processes of steelmaking from virgin iron ores and suitable scrap while abating CO_2 emissions. The key is to replace current fossil fuels via one of the two main technologies under CDA, namely hydrogen-based metallurgy and electricity-based metallurgy.

This objective of steel production through CDA technologies will be achieved by using renewable energy to replace fossil fuel, developing hydrogen-based reduction, and melting processes, and performing direct reduction with electrolysis. Due to the direct avoidance of carbon, this objective has a very high impact factor on **CO_2 reduction**. Additionally, it utilises renewable energy inputs and achieves new applications for residues, such as slag from the EAF-route, and thereby impacts the **resource efficiency**. The following are examples of concrete technology that will allow these impacts to manifest:

- Utilising **H_2** for different technologies, for example, as a reduction agent to remove impurities, mainly oxygen in various forms, via **direct reduction** of iron ores. Removing impurities before melting allows a more efficient use of resources and reduces CO_2 emissions. The hydrogen-based direct reduction has a short- to mid-term mitigation potential of up to 95% for the respective EAF production route it is used in, using only zero-carbon electricity. Another example using H_2 is to directly perform a **transformation from iron oxides to liquid steel with hydrogen plasma**. This technology will only be able to manifest in the long-term and has a mitigation potential of up to 95% for steelmaking using the CDA technology.[65]
- **Fuel flexibility concepts**, which consider new feedstock, such as H_2 from renewables or biogas from biomass, leading to the development of high efficiency, low emission multi-fuel burners technologies. This will allow the downstream steel processing to take advantage of the gradual decarbonisation of liquid steel production. Industrial development of the **alkaline electrolysis for iron oxides**, which will cover a range of different technological developments, such as the grinding and leaching of ores and the valorisation of non-conventional feedstock.

3.2.2. <u>Specific Objective 2. Fostering smart carbon usage (SCU – Carbon capture) technologies in steelmaking routes at a demonstration scale, thus cutting CO_2 emissions from burning fossil fuels (e.g. coal) in the existing steel production routes</u>

The SCU pathway entails two groups of technologies and business processes:

- CCUS, which is dealt with under this first specific objective.
- PI with reduced use of carbon, which is more closely related to the Specific Objective 3.

Fostering SCU technologies will decrease the use of fossil carbon in steelmaking and optimise capturing and utilising the CO_2 and CO that is generated in the production process. The two main impacts of achieving this objective will be a significant contribution to the **CO_2 reduction** targets and more **resource efficiency**. Concerning Specific Objective 3, the main target is to integrate these CCUS technologies into the specific steelmaking processes. This should lead to CO_2 becoming more and more a resource rather than a cost.[66] These impacts will be achieved through fostering a range of different technologies with distinct mitigation and resource efficiency potential, such as:

- **CO_2 capture processes**, which can be done at different sub-process stages. For instance, pre-combustion capture is mostly done via physical absorption, while post-combustion capture via

[65] Gerald Stubbe, VDEh-Betriebsforschungsinstitut GmbH (2020), LowCarbonFuture Final Webinar 24.03.2020: Results – Pathway “Carbon Direct Avoidance”.
[66] Institute for European Studies (IES) (2018), Industrial Value Chain: A Bridge Towards a Carbon Neutral Europe, p. 10.

chemical absorption. The mitigation potential of CO_2 capture processes in the short- to mid-term is up to 90% for the respective sub-processes.[67]

- **Biological and chemical processes** can be utilised to precondition the process gases from integrated steel plants for the production of fuels like ethanol or methanol or base chemicals such as formic acid. A concrete example is the Steelanol project, that is expected to produce around 80 million litres of bio-ethanol per year from steel plant process gases. The impact of biological and chemical processes on CO_2 reduction can reach up to 63% reduced emissions from process gases in the short- to mid-term.[68]
- Utilising **non-fossil carbon** in the steelmaking process. This is building upon the full internal valorisation of steel plant gases and other residues as new feedstock, including biomass[69], for the production process.

At least in the short run carbon remains structurally important as a reducing agent in steelmaking, but the capturing and reintroducing will increase resource efficiency and reduce the carbon footprint in the short-term before technological breakthroughs are deployed at industrial level.

3.2.3. Specific Objective 3. Developing deployable technologies to improve energy and resource efficiency (SCU - Process Integration)

Steelmaking is still a fossil fuel-based production process in many cases and the complete non-usage of coal does not appear as a realistic option for the time being. However, PI will modify current production routes to make intelligent use of fossil fuels and process gases, thereby contributing to the steel industry becoming at least climate neutral. This pathway entails a range of different possible modifications to existing processes, but largely centred around reducing energy needs, switching to cleaner energy sources, and avoiding the release of CO_2.[70]

Achieving the objective of optimised process integration will positively impact **resource efficiency** and has many links to CE,[71] as it focuses on the recycling or further processing of internally produced gases and other steel residues. Additionally, process integration leads to a **reduction of CO_2** in itself and, with synergetic reduction effects when used jointly with SCU-CCUS. Two exemplary projects are the following:

- Enhance resource efficiency by optimised processes relying on the **increased use of pre-reduced iron carrier**. This entails improved cleaning actions to provide cleaner scrap for the production process and the integration of DRI, for example thanks to H_2, as outlined under specific objective 2 above.

---

[67] Gerald Stubbe, VDEh-Betriebsforschungsinstitut GmbH (2020), LowCarbonFuture Final Webinar 24.03.2020: Results – Pathway "Carbon capture and usage (CCU)".
[68] Ibid.
[69] Here "biomass" means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin as defined in the Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (EU, 2018).
[70] Borlee, Jean & Pierret, Jean-Christophe (2020), LowCarbonFuture Final Webinar 24.03.2020: Results – Pathway "Process Integration (PI)" (CRM).
[71] Ibid.

- **TGR-BF** is a project combining some of these options by optimising the BF usage by utilising top gas recycling. The project in itself has a CO_2 mitigation potential of 20-25% for the producing plant.[72]

3.2.4. Specific Objective 4. Increasing the recycling of steel scrap and residues, thus improving smart resources usage and further supporting a circular economy model in the EU

To achieve the EU climate targets, CE is a key concept to be exploited. The EU has acknowledged its important role by launching a 'Circular Economy Action Plan' within the framework of the European Green Deal.[73] The main target is to extract less raw materials, recycle and recover more existing materials, thereby contributing to the reduction of CO_2 emissions. The Clean Steel Partnership will have a significant impact on **resource efficiency** if it achieves a higher level of CE. Due to its characteristics (i.e., permanent material, reusable and endlessly recyclable, residues as a valuable resource), steel is highly suitable to contribute to those objectives.

The impacts will manifest through enhanced recycling of steel and by further utilising its production residues. By doing so, less natural resources, raw materials, and energy input will be required, creating up to **50% CO_2 savings** in the steelmaking process.[74] There are a few illustrative examples to show the impacts of achieving the objective.

- Enhanced **utilisation of scrap**, through improved scrap sorting and removal of scrap pollution, thanks to new detecting technologies; this requires ensuring the availability of high-quality iron and steel scrap in the EU.[75]
- **Adjustment and processing of residuals** (e.g., EAF and BOF slag, scale, electric-arc furnace dust, etc.) to make it usable in steel products (e.g., internal reuse substituting lime with Ladle Furnace slag) and to be suitable for construction and other resource-saving applications, and to provide for heat recovery.
- Usage of waste heat to support CE. For example, **EAF gas or surplus BOF gas** could be used as fuel in the scrap preheating process, with an overall impact of (average) reduction of 0.1 tonne CO_2/tonne of final steel product. Another example would be heat recovery from slag.

3.2.5. Specific Objective 5. Demonstrating clean steel breakthrough technologies contributing to climate-neutral steelmaking

The outlined impacts of the first four specific objectives demonstrate that the technological pathways and CE approach have a significant impact potential to reach the reduction of emissions and resource efficiency. Nonetheless, a large enough impact to achieve the ambitious **CO_2 reduction** targets will only be manageable by combining two or more technologies and areas of intervention. Demonstrating synergies of the different technologies will achieve the general objective of developing technologies at TRL8 to reduce CO_2 emissions by up to 95% by 2050 compared to 1990. Attaining this target will be done

[72] Ibid.
[73] European Commission (2020), Circular Economy Action Plan: For a cleaner and more competitive Europe.
[74] https://www.stahl-online.de//wp-content/uploads/2013/09/20120621_Bericht_Multi-Recycling-Ansatz_Stahl-final.pdf
[75] Reusing iron and steel scrap, by ensuring that a larger quantity of scrap is available to EU steelmakers, can contribute to the CE and reduce CO_2 emissions from the steel industry. In addition, steel scrap should be of sufficient quality, ensuring that impurities and contamination are reduced to manageable levels. Cirilli, Filippo (2020), Exploitation of projects for Low-Carbon future steel (LowCarbonFuture). RFCS Accompanying Measure: CO_2 mitigation and circular economy.

step by step. First, by demonstrating clean steel breakthrough technologies by 2030 that enable at least a 50% reduction in GHG emission compared to 1990 levels for similar plants; and then by achieving TRL 8 by 2030 in most of the technology building blocks funded by the Clean Steel Partnership.

One example of a combination of technological pathways is integrating water electrolysis in steel plants to produce H_2 and O_2. Green H_2 and O_2 supplies are necessary for all technological pathways: process integration for H_2 injection into BFs; CCUS as H_2 is needed for most CO_2 valorisation processes; and CDA because H_2 can be for example used as reduction agent; O_2 is necessary for BOF and EAF steelmaking.

3.2.6. Specific Objective 6. Strengthening the global competitiveness of the EU steel industry in line with the EU industrial strategy for steel

The Clean Steel Partnership can significantly improve the **competitiveness** of the EU steel sector, in line with the EU industrial strategy for steel, by exploiting arising business opportunities and making the steel industry more profitable. This impact will manifest because the Partnership enables sustainable growth in the steel sector and puts the industry in a position to become a global leader in low-carbon steelmaking. The following are two examples of how achieving this objective will impact the steel sector's competitiveness:

- **New or enhanced markets and value chains** will arise. First and foremost, the Partnership, together with a number of supportive regulatory and market mechanisms, will spur the emergence of a market for clean steel. This will increase the demand for low-carbon steel products that can be produced via the technologies developed under the Partnership, especially from sectors which are set to grow in the future (e.g., for renewable energy technologies). Furthermore, other markets are likely to emerge from the technological solutions deployed, such as the market for carbon feedstocks, which can be supplied from steel makers to the chemical industry.
- There will be increasing demand for **know-how and innovative concepts**. The EU steel industry is already a world leader in the highly technologically specialised product segment.[76] Further developing R&D&I in clean steelmaking will secure their competitive advantage. This would benefit more technologically advanced EU plant builders, which could see their global market share increase.

Strengthening the competitiveness of the steel industry will also entail considerable impacts on **jobs and skills**. The development and operation of new technologies will require dedicated training of the workforce to acquire new skills. For instance, the injection of H_2, hot gas in the blast furnace and plasma technology involves new safety issues that will require the right skills to ensure a safe production process and the automatised integration of those gases into the BF control systems. Overall, the transformation of the steel industry will demand a highly skilled workforce, but in return, the sector will also provide employment opportunities for well-trained and well-paid workforce. The need for low-carbon steel and the related skills in other areas of industrial value chains will ensure that the steel sector will continue to support a high level of quality employment directly and indirectly. Furthermore, the increased use and

[76] European Commission (2017), Steel: Preserving sustainable jobs and growth in Europe' (COM(2016)155, Available at: eesc.europa.eu/en/our-work/opinions-information-reports/opinions/steel-preserving-sustainable-jobs-and-growth-europe

recycling of residues of the steelmaking process is expected to create further jobs linked to the CE approach.

Finally, the partnership will impact the **R&D&I collaboration** between EU companies, as the projects shall bring all EU steel producers together in a collaborative manner to carry out the relevant aspects of the technological pathways. The projects will facilitate information exchange and the development of sustainable solutions. Concretely, the collaboration will manifest for example in the formation of multi-partner consortia for large scale demonstration at TRL 8, which will build upon results on finished and on-going multi-partner projects at TRL 7 and 8. This collaboration will result in the launch of projects leading to the deployment of the concerned technologies in an industrial installation or a serious of modules comprising an industrial installation (at one or more locations). The investment of such larger-scale industrial demonstrators should be aligned with public support.

3.3. EU added value and additionality of the Partnership

Following the analysis of the expected impacts carried out above, in this section, three related aspects are assessed. First, the **EU added value**, i.e., the additional impacts which can be generated since this action is taken co-ordinately at EU level. Then, other forms of additionality are explored, i.e., that originating from **synergies with other Partnerships** and research programmes, and the **spill-overs** in other value chains and industries.

3.3.1. <u>EU added value</u>

There is significant EU added value in the Clean Steel Partnership as a new coordinated framework for the path towards a modern and sustainable steel industry. In this context, the Clean Steel Partnership will ensure a strong commitment from all actors of the steel value chain – steelmakers, plaint builders, Member States – towards decarbonisation, thus leading to a **higher degree of additionality** compared to research activities funded by the Horizon Europe Programme. The reasons for such EU added value can be described as follows:

i. The Partnership is a **coordinated approach** across stakeholders, technologies, production routes, and Member States, ensuring effective **removal of systemic bottlenecks** preventing breakthrough technologies from being realised. The steel production in the EU is spread across numerous Member States and production technologies can vary from plant to plant. Therefore, there is no 'one-size-fits-all' solution and a variety of new technologies (and a combination thereof) need to be simultaneously deployed in different EU production sites. EU added value is thus generated by such the holistic approach of the Partnership, which can (i) maximise synergies and avoid duplications of efforts, (ii) cover different technological solutions while stimulating healthy competition among them, (iii) share risks among public and private actors, and (iv) ensure a critical investment mass to decarbonise the steel industry in a timely fashion.

ii. As described more in details in Section 3.1 above, the Clean Steel Partnership fosters the steps necessary to go from piloting to commercial deployment of new technologies and thus **leverages major private investments**, thereby helping to **remove R&D&I bottlenecks**. Due to the high costs of developing and testing technologies in a competitive global steel market, there is a danger of low-cost steel being favoured and of 'carbon leakage' occurring. Hence, the EU added value is realised through reducing risks and catalysing further investment to decarbonise the steel sector, while creating market opportunities and standards for clean steel.

iii. The Partnership is accompanied by the present Roadmap, thus securing **a timely and well-planned intervention** to decarbonise the steel industry. This will allow additional early achievements in terms of CO_2 reduction.

iv. The clear planning ahead also promotes a clear **commitment from partners to progressively phase out** from public support for R&D&I, ensuring that the Clean Steel Partnership results in additional, market-based, deployment of the technologies developed with its support.

3.3.2. <u>Further additionality and collaboration with other partnerships</u>

Further additionality of the Clean Steel Partnership is envisaged to be realised through high **openness and transparency**, seeking to attract **all relevant stakeholders** to participate in the wider framework. This shall be done via different measures, such as yearly workshops, a dedicated online presence, and thematic and networking events. Thereby, the Partnership will achieve visibility within the steel sector and beyond and advertise the activities that are being carried out, to ensure broad and representative participation of players of the EU steel value chain and those connected to it.

The Partnership's openness and transparency can thus generate additionality **by cross-fertilising both suppliers and customers**. The positive spill-overs on suppliers will consist in them having more incentives to further develop research in green energy, efficient production systems, and hydrogen technologies. For customers, the steel R&D&I investment will lead to the production of a cleaner high-quality steel, which in turn will stimulate further research on products with lower lifecycle impacts. Moreover, the Clean Steel Partnership will not only create synergies among technology domains, but also collaboration across Member States and Associated Countries to develop breakthrough technologies.

For the Partnership to foster such additionality, it will **collaborate with other Partnerships and programmes**, for example:

- The proposed Partnership "**Processes4Planet"**, aiming to transform European process industries to (i) make them climate neutral by 2050, (ii) turn them into circular industries together with material and recycling industries, and (iii) enhance their technological leadership at the global level and international competitiveness. The Clean Steel Partnership and Processes4Planet have been working closely to align R&D objectives and plans.
- The proposed partnership "**Clean Hydrogen**", setting the objectives to accelerate the market entry of nearly-zero GHG-emission hydrogen-based technologies across energy, transport, and industrial end-users. There is a strong link between Clean Hydrogen and Clean Steel, as H_2 is one of the most effective solutions to substitute carbon-based energy resources in steelmaking, particularly if the hydrogen is produced from renewable energy sources.[77]
- The proposed partnership "**Built Environment and Construction**", focusing on technological and socio-economic breakthroughs for an improved built environment to support the achievement of EU 2050 decarbonisation goals and the transition to clean energy and CE, while improving social wellbeing, mobility and competitiveness. As construction is the biggest steel-using industries, increased demand for high-quality and low-carbon building materials will provide additional incentives for the R&D&I efforts of the steel industry in these respects.
- The proposed Partnership "**Made in Europe**" which sets objectives to achieve a competitive discrete manufacturing industry with a world-leading reduction of the environmental footprint whilst guaranteeing the highest level of well-being for workers, consumers, and society. The achievements of CO_2 reduction and circularity in the steel industry will have a multiplier effect down the manufacturing chain. Therefore, dialogue and collaboration with the "Made in Europe" partnership can maximise the value creation for society and respond to the customers demand for customised products with a lower impact on the environment.
- The Clean Steel Partnership will be able to contribute to the following R&D&I **Missions of the Horizon Europe** programme:
  - Mission on climate-neutral and smart cities;
  - Mission on soil health and food;
  - Mission on adaptation to climate change including social transformation.

[77]For further details see:
fch.europa.eu/sites/default/files/FCH%202%20JE%20Annual%20Work%20Plan%20and%20Budget%202019%20%28ID%205167414%29.pdf, p.36

- On a more general note, the Clean Steel Partnership falls under the **Pillar II "Global Challenges and European Industrial Competitiveness"** of the Horizon Europe Programme. It is particularly linked to the following Clusters:
    - **Cluster 4 - Digital, Industry and Space**. The Cluster aims to achieve three main objectives, which are (i) ensuring the competitive edge and autonomy of EU industry, (ii) fostering climate-neutral, circular, and clean industry, and (iii) bringing a major contribution to inclusiveness. R&I, as well as technology demonstration under the Clean Steel Partnership will contribute largely to these objectives.
    - **Cluster 5 - Climate, Energy and Mobility**. The main objectives of this cluster are to fight climate change, improve the competitiveness of the energy and transport industry as well as the quality of the services that these sectors bring to society. Reduction of GHG in the steelmaking process, including through energy efficiency and the use of renewable energy, is remarkably connected to the objectives of this Cluster. In addition, the energy-intensive industrial facilities of the steel industry can play an important role in balancing the over/underproduction of renewable energy: therefore, the steel industry can be an important interlocutor for balancing and stabilising the electrical grid in Europe.

3.3.3. Spill-overs in the value chain and other industries

As discussed in Chapter 1 above, steel is a key material in many other industries by being used in the value chain of sectors like construction, automotive, mechanical engineering, energy generation and networks, mobility, or defence. Thereby, producing clean steel will enable **spill-overs within these value chains**, both via clean steel as an input and by trickling know-how down the value chain. In addition, the Partnership will allow the steel industry to become a first mover in the development and deployment of new technologies **among energy-intensive sectors** in the EU. Table 17 demonstrates how the underlying technologies of energy-intensive industries have reasonable commonalities. This would allow for breakthrough technologies to spill over to other industries.

Table 17 Decarbonisation potential – Cross-sectoral comparison of energy-intensive industries

	Electrification (heat and mechanical)	Electrification (processes: electrolysis/ Electrochemistry excl. H2)	Hydrogen (heat and/or process)	CCU	Biomass (heat and feedstock)/ biofuels	CCS	Other (including process integration)
Steel	**xxx**	xx	xxx	xxx	x	xxx	Avoidance of intermediate process steps and recycling of process gases: xxx Recycling high quality steel: xxx
Chemicals fertilizers	xxx	xxx	xxx	xxx	xxx	xxx(*)	Use of waste streams (chemical recycling): xxx
Cement Lime	xx (cement) x (lime)	o (cement) o (lime)	x (cement) x (lime)	xxx (cement and lime)	**xxx** (cement) x (lime)	xxx (cement and lime)	Alternative binders (cement): xxx Efficient use of cement in concrete by improving concrete mix design: xxx Use of waste streams (cement): **xxx**
Refining	xx	o	xxx	xxx	xxx	xxx	Efficiency: **xxx**
Ceramics	xxx	o	xx	x	x	o	Efficiency: **xxx**
Paper	xx	o	o	o	**xxx**	o	Efficiency: **xxx**
Glass	xxx	o	x	o	xxx	o	Higher glass recycling: xx
Non-ferrous metals/alloys	**xxx**	**xxx**	x	x	xxx	x	Efficiency: **xxx** Recycling high quality non-ferrous: xxx Inert anodes: xxx

o: Limited or no significant application foreseen
x: Possible application but not main route or wide scale application
xx: medium potential
xxx: high potential
***xxx**: Sector already applies technology on large scale (can be expanded in some cases)*
(*) in particular for ammonia and ethylene oxide[116]

Source: VUB study, Sep 2018.

3.4. Monitoring and assessing progress

The specific and operational objectives of the Clean Steel partnership have been set (see Chapter 1) in line with the general objective to develop technologies to reduce CO_2 emissions by the steel industry. To monitor and assess the progress that will be achieved, a range of **Key Performance Indicators** (KPIs) has been developed and included in the MoU of the CSP. Each KPI is linked to an operational objective, and each operational objective can be monitored by one or more KPI. The activities of the Co-programmed European Partnership will be subject to continuous monitoring and periodic reporting. The outcomes of monitoring and reporting will feed into the evaluations of the Co-Programmed European Partnerships as part of Horizon Europe evaluations. It will feed into the biennial monitoring of the European partnerships in the context of the Strategic Coordinating Process.

To allow a quantitative evaluation, each KPIs is accompanied by a target to be achieved by 2030 (project completion). While the Horizon Europe programme runs from 2021 to 2027, the assessment of the extent to which the Partnership met is objective should be done at least 3 years thereafter, to account for the completion of the projects launched and financed in the last years of the programme.

Table 18 displays the KPIs and targets assigned to the respective operational and specific objectives.

The KPIs measure progress in terms of the concrete changes to the production processes and inputs that the Partnership is expected to trigger. Therefore, to assess whether the individual objectives are on path to being realised, the deployment and the TRL of the developed technology is the most important indicator, which in turn can be used to measure whether the innovations introduced produced their impacts in terms of e.g., reduced resource usage or improvement in emission efficiency. From the perspective of monitoring and evaluating the Partnership, this is considered the soundest methodology as it will allow measuring whether the Partnership is effective in delivering on their direct outputs and outcomes. Importantly, once those outputs and outcomes in terms of TRLs and input and process efficiency are achieved, steel companies and the whole industry will be in a position to generate the impacts described in the Section above, thus achieving the general objective of the Partnership in terms of reduced CO_2 emissions.

Technologies deployed to decarbonise the steel industry will contribute to protecting the health of EU citizens and ecosystems in line with the European Green Deal, both directly (by reducing CO_2 emissions) and indirectly (by reducing other types of industrial emissions to air, soil and water). In this context, ad hoc indicators will be used to monitor and reduce the impact of projects funded by the Clean Steel Partnership on industrial emissions other than CO_2. These will be integrated into a semi-quantitative indicator expressing the potential contribution of the project towards the zero-pollution ambition for a toxic-free environment, as expressed in the European Green Deal communication.

Table 18 KPIs and Targets by 2030 for the respective operational and specific objective

General Objectives	Specific Objectives	Operational objectives		KPIs	Targets by 2030
CLIMATE					
GO1.- Develop climate neutral solutions for the steel production. The transformation of the EU steel industry towards climate neutrality requires the development and deployment of technologies at high technology-readiness-level. The implementation of these technologies enables the steel producers to reduce their CO2 emissions by 80-95% compared to 1990 levels by 2050, ultimately leading to climate neutrality.	SO1. - Enabling steel production through carbon direct avoidance (CDA) Technologies	OO1.-Replacing carbon by renewable energy	KPI1	Decrease of scope I and II CO_2 emissions proven at a demonstration scale	TRL8 > 70 % CO_2 reduction compared with reference operation
		OO2.-Development of H_2-based reduction and/or melting processes	KPI2	a.-Reduction degree of iron oxide	a.-TRL8: > 90 % reduction degree of iron oxides
				b.-Replacement rate of fossil carbon by hydrogen injection	b.-TRL8: > 10 % replacement rate of fossil carbon at the injection point
				c.-Replacement rate of natural gas by H_2 in the feed of the direct reduction plant	c.-TRL8: > 50 volume-%
		OO3.-Electrolytic reduction	KPI3	Electric efficiency of the electrolytic cell	TRL8: > 85% electric efficiency
	SO2.- Fostering SCU technologies in steelmaking routes	OO4.-Improving process integration with reduced use of carbon (e.g. gas injection in BF) upstream + downstream	KPI4	Decrease of process-related CO_2 emissions proven	TRL8: > 25 % reduction compared with reference operation
		OO5.-Increasing the use of non-fossil carbon	KPI5	Share of non-fossil carbon proven in reducing and/or melting process	TRL8: > 20 % of non-fossil fuels/ reducing agent
		OO6.-Capturing CO_2 for CCU and/or CCS	KPI6	CO_2 capture rate from process/off-gases	TRL8: > 95 % from dedicated gas stream
		OO7.-Conditioning of metallurgical gases (containing CO2, CO, CH4, etc.) to meet specifications to finally produce chemical feedstock/alternative fuels/materials (the "use" part supported by the P4P partnership)	KPI7	Share of the carbon content of the process gas (CO_2/CO) provided to be transformed into products	TRL 8: more than 65 % of C
	SO3.- Developing deployable technologies to improve energy and resource efficiency (SCU Process Integration)	OO8.-Increasing the use of pre-reduced iron carriers	KPI8	Share of pre-reduced iron carriers out of total Fe carriers	TRL8: > 20 % pre-reduced Fe carriers in iron and steelmaking process
		OO9.-Developing technologies to reduce the energy required to produce steel or recuperation of waste energy from steel production route to replace fossil C for on- and partially off-site energy requirements as SCU	KPI9	a.- Decrease the use of energy per tonne of steel for clean steel making b.- Decrease CO_2-emission by replacing fossil C-based energy by recuperation of waste energy	a.-TRL8: > 10 % specific energy consumption reduction for a dedicated process b.-TRL8: <90% CO_2 emission by use of waste energy compared to previous replaced process

General Objectives	Specific Objectives	Operational objectives		KPIs	Targets by 2030
CIRCULAR					
GO2.-Developing and deploying technologies aiming at closing the feedstock and energy loops	SO4.-Increasing the recycling of steel scrap and residues to increase smart resources usage and further support a circular economy model in the EU	OO10.-Enhancing the recycling and re-use of industrial residues of the steel production process	KPI10	Re-use and recycling of solid residues co-generated during the steel production process	TRL8: internal and external recycling and re-use rate > 85 % (in total)
		OO11.-Enhancing the recycling of steel scrap	KPI11	Scrap pre-treatment and cleaning technologies and scrap yard management procedures and techniques for progressively increasing the uptake of low-quality scrap grades (post-consumer) into higher-quality steel-grades production process Progressively replace the use of solid pig iron with post-consumer scrap grades and/or with Fe-bearing material recoverd by iron and steelmaking residue rich in iron metal oxide (such as scale, sludge, dust and slag)	TRL8: Share of low-quality scrap and/or Fe bearing material rcovered by residue ~~share~~ input over the total scrap input increased by at least 50% or more compared to the usual practice for a specific steel quality
COMPETITIVENESS					
GO.3-Preserve the competitiveness and viability of the EU steel industry – both for BF-BOF and EAF routes and including the wider steel value chain – and making sure that EU production will be able to meet the growing EU demand for steel products.	SO5.-Demonstrating clean steel	OO12.-Achieving high maturity by 2030 in projects funded by the	KPI12	Percentage of projects that reach high	Share of projects with TRL6-7 in CSP :
		OO13.- Fully implementing several demonstrators	KPI13	Number of demonstration projects	TRL8: Implementing at least 5 demonstrators leading to 50% CO2 emission reduction compared to 1990 levels. Implementing at least 2 demonstrators with > 80% CO2 reduction
	SO6.- Strengthening the global competitiveness of the EU steel industry in line with the New Industrial Strategy for a globally competitive, green and digital Europe	OO14.-Creating a new market for 'clean steel' products that would benefit from a labelling/certification schemefor clean steel based on a life-cycle assessment approach	KPI14	Start of the roll-out of clean steel and its products	% of clean steel out of total EU steel demand
		OO15.-Contributing to the EU's efforts towards ensuring growth and jobs with long-term stability	KPI15	GVA generated by the steel industry and key steel-supplied value chains	Increase GVA by 2% compared to 2020
		OO16.-Establishing the EU steel industry as a leader in low-carbon steel and ensuring standardisation and global market uptake of successful technologies developed in the EU	KPI16	Global market share of EU technology providers	+10% in global market share of EU technology providers
		OO17.- Fostering R&D collaboration between EU companies and science in the clean steel value chains	KPI 17	a.-Number of visiting periods of external researchers working on projects funded by the Partnership b.-Number of calls in collaboration with other Partnerships	a.- > 10 visiting periods (CDA, SCU, CE) b.- > =5 linked or joined calls
		OO18.-a.Upskilling steel workforce -Training of the steel plants workforce on the new technologies for low CO2 steelmaking and high level automation b.Deployment of the optimal mix of predictive and programmed maintenance of critical assets c.Establishing the total awareness, prediction and optimal management of the environmental footprint in case of events through the integration of dedicated tools in the Process Automation landscape. d."No Man on the Floor" through automatic operations made by autonomous ore remotely supervised Cyber-Physical Systems and extensive sensorisation of harsh environments	KPI18	a.Number of supporting dedicated programmes (EU, national), with which the Partnership operates in synergy b.Reduction of emissions due to the increase of process continuity c.Decrease Scope I and II emissions due to unpredictable events d.Proliferation of upskilled workplace versus workers exposed to harsh environments	a.>= 3 dedicated supporting programmes b.=<25% of failures c.=< 5% emissions in the manufacturing areas armed with new systems d.=<10% of the initial situation regarding the selected environments

Chapter 4: Governance

Summary

Governance model

- The Clean Steel Partnership has been established between the European Commission and the European Steel Technology Platform (ESTEP).
- The Partnership is open to the entire EU steel value chain community and Horizon Europe Associated Countries.
- The 'Partnership Board' (including representatives from both the public and private side) discusses and approves the periodic Work Programmes and ensure compliance with the vision, ambition, objectives, and research programme laid down in the multiannual SRIA.
- The 'Implementation Group' is the general assembly of the Partnership. It discusses the technical needs and research progress, identify the R&D&I needs, discusses and proposes the Work Programmes to the 'Partnership Board', coordinates revisions to the SRIA, and shares conclusions with Task Forces.
- The 'Task Forces' define future short- to mid-term R&D&I needs related to the different technological pathways and propose the content of the periodic Work Programmes to the Implementation Group.
- The 'Programme Office' supports coordination and communication activities, measures and reports on KPIs, organises events and promotes the Partnership.
- The 'Implementation Group' is supported by two external bodies:
    - The 'Monitoring Group' advises on improvements on the current research development, monitors towards meeting the CSP objectives and the European Commission policy objectives.
    - The 'Stakeholder Forum' provides feedback on potential revisions to the multiannual SRIA and on the social and environmental impacts of activities under the Partnership.

Openness and transparency

- The decarbonisation of the steel industry requires a coordinated approach across all countries, technologies, and steel plants. Therefore, the impact of the Partnership will be maximised by involving all relevant stakeholders and remaining open to new partners.
- ESTEP and the Clean Steel Partnership are open to the entire European steel value chain community, i.e., to all EU based steel stakeholders comprising steel producers, steel processors, customers, suppliers, plant builders, research and academia, and civil society representatives.
- The Clean Steel Partnership provides a dedicated website where the multiannual SRIA and periodic Work Programmes, as well as non-confidential information about ongoing and finished projects, are published.
- Rules and information on how to join the Clean Steel Partnership are published on the dedicated website and circulated through the Partnership mailing list. Ad hoc membership campaign may be implemented, based on needs for specific project partners emerging from

any update to this multiannual SRIA. To maximise participation from entities other than steelmakers and technology providers, a special ‘partnership fee’ is applied to specific categories of participants such as governmental and non-governmental organisations and research institutes

4.1. Governance model

The Clean Steel Partnership has been established between the **European Commission** (public side) and the **European Steel Technology Platform (ESTEP)** on behalf of the entire European steel value chain community (private side). ESTEP is a membership-based organisation, established as an international non-profit association under Belgian law (AiSBL), with the role of representing its members concerning R&I strategies defined within its statutes.[78]

ESTEP and the Clean Steel Partnership are **open to the entire European steel value chain community**, i.e. to all EU based steel stakeholders comprising steel producers, steel processors, customers, suppliers, plant builders, research and academia, and civil society representatives. The Clean Steel Partnership is also open to actors from Horizon Europe Associated Countries.[79] Any relevant stakeholder may participate in the Partnership by submitting an application form and paying a ‘partnership fee’, collected by ESTEP. Upon approval of the Implementation Group (see below for further details), certain categories of stakeholders, such as representatives of national and regional authorities in the States Representatives Group, civil society and reputable professionals may also participate in the Partnership as **observers**.[80]

The Clean Steel Partnership benefits from **synergies of funds from two European research programmes**: Horizon Europe and the Research Fund for Coal and Steel.[81] Both programmes coordinate efforts to achieve greater impact and efficiency. The research activities are aligned with Horizon Europe Work Programme activities and with the objectives of the Research Fund for Coal and Steel.

- The Partnership has established a governance structure to manage the implementation of the research activities under Horizon Europe and the Research Fund of Coal and Steel under differentiated and complementary calls.
- Each research programme (Horizon Europe and the Research Fund of Coal and Steel) is bound by the obligation to inform the respective Programme Committee (Horizon Europe Programme Committee and COSCO, respectively) of the overall progress of the implementation of the actions of the specific programme.
- The Governance structure takes into consideration the legal basis for the implementation of the respective programmes, in particular as regards countries participating in the programmes, timing for alignment in calls for proposals and information to the European

[78] For further details see: estep.eu

[79] Their participation in Calls for Proposals funded via the Research Fund for Coal and Steel programme may be, however, limited by the relevant eligibility criteria.

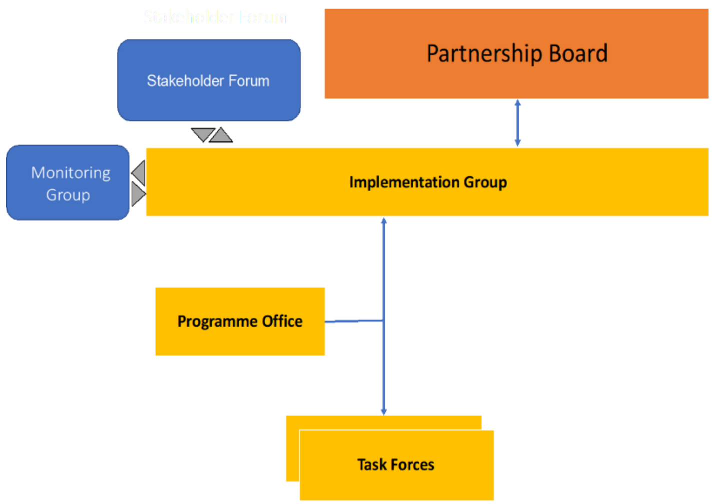
[80] Observers will be invited to selected meetings of the Partnership only and will have the opportunity to review and provide comments on the draft multiannual SRIA upon decision in the Implementation Group.

[81] Subject to the approval of the ongoing proposal for modification of RFCS Legal basis, establishing the rules of the research activities, part of the Research Programme may be implemented through co-programmed European Partnerships established in accordance with the rules set out in [Article 8 and Annex III to the Horizon Europe Regulation].

Commission and the respective Committees. The structure will aim at simplifying the procedures as much as possible.

The structure of the Governance is summarised in Figure 20.

Figure 20 Governance structure of the Clean Steel Partnership



Source: Authors' own elaboration.

4.1.1 Partnership Board

As mentioned in the Memorandum of Understanding of the co-programmed Clean Steel Partnership, the governance will be centred around the so-called '**Partnership Board**' (or 'the Board'). The Partnership Board is the main forum for dialogue and steering to reach the objectives set out in this Memorandum of Understanding. It, among others, discusses and approves the periodic Work Programmes and ensures compliance with the vision, ambition, objectives and research programme laid down in the multiannual SRIA, which guides the work and decisions of the Board. The Board consists of a public component, i.e. representatives of the European Commission services, and a private component, i.e. representatives of the Partnership members.

- On the **public side**, DG R&I, DG ENER, DG GROW, DG CLIMA, DG ENV and the Research Fund for Coal and Steel are involved, thus fostering coherence and synergies with the EU R&I landscape relevant to the Partnership. The Commission decides, however, on the final composition of the public side of the Board.
- On the **private side**, Board members are proposed by ESTEP and appointed by the European Commission. Board members are selected among the members of the so-called 'Implementation Group' (see below) in order to ensure **balanced representation of the different EU steel production routes and adequate experience of the relevant decarbonisation challenges** affecting the EU steel industry. The private component of the Partnership Board presents and discusses with the public component of the Board: (i) the decisions made by the Implementation Group with public members of the Board, such as the technical needs for the Partnership (which

may evolve over time) and proposals for the Work Programme; (ii) the research progress of the Partnership demonstrating the progress of R&I activities and their alignment with mid- and long-term objectives of Clean Steel Partnership. The private side of the Board collects and reports to the Implementation Group all feedback and suggestions put forward by the public side of the Board. Ideally, decisions in the Partnership Board, including those on the periodic Work Programmes, should be **based on consensus**.

- The Partnership Board laid down its Rules of Procedure, based on a harmonised proposal provided by the European Commission, covering inter alia rules on confidentiality, transparency and avoidance of conflicts of interests.

4.1.2 Implementation Group

The **Implementation Group** is the General Assembly of the Clean Steel Partnership, including all paying members. The voting rights of members follow the membership fee, by taking into account *inter alia* possible discounts on the partnership fee for specific categories of members, based on inputs from the Task Forces (see below) and after consulting the Stakeholder Forum and (where needed) the Monitoring Group (see below), the Implementation Group will:

- Discuss the technical needs and research progress of the Partnership by periodically analysing progress in R&D&I activities and their alignment with mid- and long-term objectives;[82]
- Share conclusions with the Task Force;
- Identify on yearly basis the overall R&D&I needs of the evolving Clean Steel Partnership to be shared with the public side of the Partnership Board;
- Discuss on Work Programme proposals coming from the Task Forces in order to balance the interest of the different Partnership members;
- Decide on how the private side of the Partnership Board will propose the content of the periodic Work Programme to the public side of the Board; and
- Discuss and coordinate any revisions needed to the multiannual SRIA.

Decisions made by the Implementation Group need to be discussed with the public side of the Partnership and finally approved by the Partnership Board. In case consensus is not reached within the Partnership Board (see above), the Implementation Group **takes into account the feedback and suggestions of the public components of the Board to reconsider its decisions** and contribute to achieve consensus.

4.1.3 Other components of the governance

The work of the Implementation Group relies, among others, on the inputs of a'**Task Force**'. Based on the periodical assessment of research progress and the multiannual SRIA, the Task Force **defines future short-to mid-term R&D&I needs** related to the different pathways. In addition, in order to meet the detected needs, the Task Force **proposes the content of the periodic Work Programmes**, which will be further discussed and decided upon by the Implementation Group. The Task Force includes technology experts from organisations that are members of the Partnership as well as external experts, upon approval of the Implementation Group.

To ensure the smooth functioning of the Clean Steel Partnership, a **Programme Office** is organised by ESTEP. The Programme Office assists the Partnership when it comes to internal coordination, internal and external communications, support to the bodies of the Partnership, measuring and reporting on KPIs, organisation of events and promotion of the Partnership.

The work of the Implementation Group is supported by **two external bodies**, thus ensuring openness as well as the opportunity to rely on expert opinions and views to take key decisions.

- **Monitoring Group**. This body is composed of members from the public side: DG RTD, DG GROW, HaDEA, REA; of members from the private side: ESTEP members, and of technical experts of

[82] All monitoring activities will be summarised in *ad hoc* 'monitoring reports', which will be reviewed and discussed at fixed intervals by both the Board of ESTEP as well as the Partnership Board.

steelmaking and related technologies, including, among others, academics and leading researchers not affiliated to organisations which are members of the Partnership. Under a strict confidentiality agreement, the Implementation Group provides information on the current research development and the Monitoring Group will advise the Implementation Group on improvements on the current research development. Cluster Portfolio Management is done by the technical experts, with an overview of technology based on information from CSP related HEU & RFCS funded projects, possibly also IF and other HEU domain. Information is collected through dedicated yearly meetings with project co-ordinators. The Monitoring Group will assess the fulfilment of the MoU, through achieving the common objectives and feed the selected KPIs. The output is shared with European Commission, and feeds the HEU monitoring requirements for the CSP.

- The **States Representatives Group** advises and actively supports the achievement of objectives of the Co-programmed European Partnership and ensure complementarity with national policies, priorities and programmes. They may review information and provide opinions on the progress of the Co-programmed European Partnership towards its scientific, economic and/or societal impacts. The States' Representative Group supports exchange of information, in view of the exploitation of synergies between relevant EU, national and regional funding, and avoiding gaps and overlaps.

Stakeholder Forum. This body includes all relevant stakeholders that are not members of the Partnership and may contribute to the successful implementation of the Partnership. The Forum is open, among others, to stakeholders representing the civil society as well Member States and regional authorities in order to ensure coherence and synergies with national and regional R&I efforts. Non-technical experts from reputable research institutes may also be included. The Implementation Group interacts with the Stakeholder Forum in order to make sure that the Clean Steel Partnership generates social and environmental impacts going beyond the steel industry and benefitting the EU as a whole. The Stakeholder Forum plays a central role to provide feedback on potential revisions to the multiannual SRIA. In fact, to ensure an open and transparent approach, the preparation of the SRIA (as further discussed in Section 2.2) as well as any major revisions of the document undergo a public consultation process. The first consultation has been organised by ESTEP between 20 July and 27 September 2020, via an online survey. The results of the consultation are presented in Annex I of this document. A second Stakeholder Forum event took place on 20 October 2022.

- Finally, it is important that the governance structure of the Partnership take into account the **synergies between Horizon Europe and the Research Fund for Coal and Steel**. In this respect, while it is not possible to transfer funds between the two programmes for the time being, the Research Fund for Coal and Steel financing scheme is moving closer to Horizon Europe through legal modification. The Partnership closely follows the European Commission's guidance on harmonisation of these two programmes through e.g., establishing a number of evaluation criteria, technical project meetings and reports, and modifying Memoranda of Understanding with stakeholders to blend funds from different sources, different governance, calls and committees.

4.2. Openness and transparency

The decarbonisation of the steel industry requires a coordinated approach **across all countries, technologies, and steel plants.** In fact, one of the operational objectives of the Clean Steel Partnership is about fostering R&D cooperation between all key actors of the steel value chain. Clean Steel will ensure openness by attracting new partners and players in this ecosystem, in particular **SMEs**, **innovative companies, research institutes, and universities.** The impact of the Partnership will be certainly maximised by **involving all relevant stakeholders** and **remaining constantly open to new partners**.

The Partnership is designed as a cooperative tool, in which any relevant stakeholder may participate by submitting an application form (the form will be made publicly available on the Partnership website) and paying a ‘partnership fee’. This includes, *inter alia*, stakeholders outside the remit of the industry or the typical group of participants to this kind of Partnership (e.g., civil society organisations, public administrations). The full list of members is published on the website of the Partnership. Membership will be rejected only for exceptional reasons, such as lack of European added value or applications from countries outside the perimeter of the Horizon Europe (or RFCS, depending on the applicable participation rules).

The Partnership will be established between the European Commission (public side of the Partnership) and ESTEP[83] on behalf of the entire European steel value chain community (private side of the Partnership). For further details on participation and governance see Sections 4.1. Most of ESTEP members are the initial members of the Clean Steel Partnership. ESTEP and the Clean Steel Partnership are open to the entire European steel value chain community, e.g., to all EU based steel stakeholders, comprising steel producers, steel processing companies, customers, suppliers, plant builders, research and academia, and societal representatives.

All members of the Clean Steel Partnership may have **equal access to documents and information produced in the context of the Partnership**. Openness is the rule, and restriction due to confidentiality should be the exception, depending on the content of the documents and information. However, to comply with EU and national competition law, company data and information necessary to be supplied by organisations that are members of the Partnership for reporting purposes will be handled securely and confidentially and only used for creating and presenting aggregated data and information.

Information on key activities and projects are also available to the general public, via a dedicated website and other communication and dissemination tools (see below for further details).

Participation in Call for Proposals will be open, by definition, to both members and non-members of the Clean Steel Partnership, as long as they are eligible under the general conditions laid down in the Horizon Europe Regulation, specific conditions laid down in the Work Programmes and Calls for Proposals, and the RFCS legal framework if applicable.[84] Brokerage Events are organised by the Clean Steel Partnership, aiming at bringing together members and providing the opportunity to collaborate on project proposals in view of upcoming funding Horizon Europe and RFCS calls.

[83] For further details, see: estep.eu

[84] The different requirements between Horizon Europe and other funding schemes are foreseen and should be made clear to candidates when they submit their project proposals.

The Clean Steel Partnership has launched a **dedicated website** where this multiannual SRIA and periodic Work Programmes, as well as non-confidential information about ongoing and finished projects, are published. Access to results of specific projects will be granted in line with the general provisions of the Horizon Europe Regulation, the RFCS legal framework (if applicable) and specific provisions set out in the Grant Agreements. The website has a 'private' section, accessible only to members of the Clean Steel Partnership, where any relevant working document is available. Confidentiality needs of Partnership members are being met.

In addition to the website, the Partnership creates dedicated **social media accounts** and a public **mailing list**, where any update published on the public part of the website as well as key consultation activities are advertised. Any interested stakeholder is able to follow the social media accounts as well as to register to the mailing list via the dedicated website, free of charge.

Finally, on a yearly basis, the Clean Steel Partnership arranges **dissemination events to present the main activities carried out and seek new partners**. The workshop is arranged in Brussels or other suitable location. Participation is open to the public, free of charge, upon registration. Interactive participation from remote is allowed to overcome barriers linked to travel costs and maximise participation from stakeholders based in other Member States or outside the EU. The Clean Steel Partnership may also decide to arrange additional **thematic and networking events**, where participants will be requested to pay a cost price fee.

ESTEP and the European Steel Association (EUROFER)[85] invite all their members to join the Clean Steel Partnership. This ensures **broad and representative participation of all the players of the EU steel value chain**, from technology providers to steelmakers and research organisations. EUROFER and ESTEP ensure adequate information flow on the Partnership across their members, which also include companies operating on a global scale. In addition, to ensure outreach beyond the EU border and participation from Horizon Europe Associated Countries, EUROFER establishes a **formal mechanism of coordination with the Worldsteel Association.** The mechanism allows sharing basic information regarding the Partnership and relevant projects and outcomes with Worldsteel members (which represent about 85% of the global steel production), while ensuring full protection of confidentiality needs and intellectual property rights of Partnership members and grant beneficiaries.

When it comes to **recruiting new members**, rules and information on how to join the Clean Steel Partnership are be published on the dedicated website and circulated through the Partnership mailing list. *Ad hoc* **membership campaigns** may be implemented, based on needs for specific project partners emerging from any update to this SRIA. New members are accepted on an ongoing basis. **To maximise participation from entities other than steelmakers and technology providers**, **a special 'partnership fee' is applied to specific categories of participants** such as governmental and non-governmental organisations and research institutes. These categories of participants may also decide to join the Clean Steel Partnership, **free of charge, as observers**, upon approval of the Implementation Group.[86]

[85] For further details, see: eurofer.be
[86] Observers will be invited to selected meetings of the Partnership and will have the opportunity to review and provide comments on the draft multiannual SRIA.

The Clean Steel Partnership ensures openness by attracting new partners and players in its ecosystem, in particular SMEs, innovative companies, research institutes and universities. Digitalisation is a typical aera of collaboration with specialised SMEs and innovative ventures. Bottom-up and top-down integration of engineering, applied sciences and basic sciences is a key success factor in R&D&I activities. Spill-over of innovative technologies developed for Clean Steel can be beneficial for related iron and steel industries, like the casting and stainless-steel sectors. Collaboration between universities and SMEs in related sectors can be useful for small scale testing e.g., on small scale EAFs when testing on full scale plants is not affordable.