European Commission

ESTEP
European Steel Technology Platform

STRATEGIC RESEARCH AGENDA 2026




FOREWORD & INTRODUCTION

As being the second largest steel producer in the world, the European steel industry has a vital role in contributing to the EU's low carbon energy transition, achieving the Energy Union ambitions and meeting the circular economy targets. At the same moment global overcapacity and unfair trade practices are creating additional challenges. Thus, the road ahead for the European steel sector clearly shows the need for a fast introduction of innovative technologies while ensuring the competitiveness of the sector.

In the context of circular economy and a low carbon economy, the EU steel industry is a world leader in CO_2 emission reductions and is today very close to the physical limits of conventional steelmaking technologies. Only disruptive innovations may deliver emission reductions in line with the expectations as described in the Paris Agreement. The long-term competitiveness of energy-intensive industries depends on their ability to develop breakthrough technologies in areas such as energy efficiency or carbon capture and utilisation. Public and private investments in innovation, research and new technologies will therefore be needed. The EU steel industry is since many years at the forefront of R&D into breakthrough technologies. Furthermore, positive incentives and continued investments in demonstration projects of those technologies are essential to remain a frontrunner.

The 2025 European Steel Events highlighted the urgent decarbonisation and digital transformation of steelmaking, strengthening circularity and raw-material security, ensuring competitiveness through supportive policies and skills, and reinforcing steel's strategic role in Europe's industrial resilience. As highlighted on ESTAD 2025, the focus is on driving the steel industry's twin transition—technological innovation across ironmaking, steelmaking, rolling and materials, combined with supply-chain shifts in raw materials/energy and digitalisation—to support both ecological and digital transformation of steel applications. Steel will be the solution for climate and societal challenges. Indeed, steel is infinitely recyclable, which means that it will be used even more in the future. The sustainability of steel should not only consider today's emissions but also the long-term possibility that steel can become a fully circular commodity. Moreover, as the world is continuously developing, there will be more materials and more waste products. Recycling of end-of-life waste for new material and displace the use of natural resources will become the "New Normal". This is particularly true for the carbon cycle and the use of energy: steelmakers also need to look for solutions to use (external) renewable power and re-use the waste carbon and hydrogen from the primary steelmaking processes instead of incinerating this waste for power production.

In order to face global competition, EU-wide innovative solutions are required. In this regard, the ESTEP's "Big Scale" innovation initiative on ultra-low carbon European steelmaking is very important. This project aims to develop technological alternatives and tailor-made solutions in order to accelerate the demonstration at industrial scale. This Big Scale initiative fits perfectly into the Strategic Research agenda that sets outs what must be done over the coming decades. It also perfectly illustrates ESTEP's mission statement:

> *"to engage in collaborative EU actions (projects) on technology & innovation, which are tackling EU challenges (renewable energy, climate change (low-carbon emission), circular economy) in order to create a sustainable EU steel industry".*

EXECUTIVE SUMMARY

This document is the 2026 version - with some parts updated in December 2024 - of the Strategic Research Agenda of the European Steel Technology Platform (ESTEP), which was officially launched in 2004. It offers a global vision on the innovation and R&D initiatives which will lead to the achievement of the objectives identified in the frame of a sustainable leadership of the EU steel sector in the coming decades.

The ambition of the EU steel industry is to maintain and reinforce a global leadership, which is both sustainable and competitive, given the strong development in other parts of the world, notably Asia.

Focus Groups (FG) involving now around 200 persons have developed several R&D themes and research areas gathered under large and complementary R&D industrial programs with large societal impacts:

- Sustainable steel production: Low carbon technologies, energy efficiency, and circular economy
- Appealing steel solutions for end users, focusing on three main areas (transports, Construction and Energy) and a transversal theme regarding the human resources aspects has been also developed
- Attracting and securing qualified people.
- Enabling the digitisation of the steel sector

Together the Focus Groups aim at playing a major role in boosting competitiveness, economic growth and the related impact on employment in the EU steel sector and beyond. The corresponding R&D themes and areas that have been identified in these programs bring a strong contribution to the sustainable development.

This 2026 update is based on the 2017 version. While back in 2017 all ESTEP Focus Groups were the main authors, the 2026 update was done by the ESTEP Secretariat in close collaboration with the Focus Groups. The main modifications are related to the change in the ESTEP governance, the rollout of Horizon Europe 2021-2027 and the Clean Steel Partnership.

In the framework of this Strategic Research Agenda, the collaborative development of low-carbon technologies is regarded as priority. Protecting the environment (greenhouse gas emissions and more particularly CO_2 emissions) and increasing resource efficiency (including energy) both constitute major transversal issues in the universe of the RTD programs that are proposed.

Security and safety represent another important objective to be addressed, not only in the relevant industries but also in customers' everyday lives as users of steel solutions (surface transport, buildings, energy production, etc.) by developing new intelligent and safer steel solutions.

A major transversal theme regarding human resources has also been taken into consideration (attracting and securing qualified people to help meet the steel sector's ambition). In this respect, a large European network of universities, involved in education, training, communication and dissemination activities has been identified among the stakeholders of the EU steel technology platform. This network should play a leading role in analysing how the education system could meet the future requirements for qualified people of the European steel industry, and in devising effective approaches to address its anticipated shortcomings.

Industry 4.0 and digitisation are since the 1990s very important for the ESTEP community and the Focus Group Smart Factory (SF) addresses this area. Envisioning smart process factories characterised by vertical, horizontal and transversal integration is the focus of these activities.

ESTEP already integrates the European RTD partnership built in the frame of the previous ECSC[1] Treaty (more than 8,000 researchers) and the Framework Programs. Indeed, it constitutes large eco-systems involving the whole European steel industry, its suppliers and customers (transport industry, construction sector and the energy sector), SMEs, private and public research, public authorities and representatives of trade unions. The Research Fund for Coal and Steel (RFCS) which has followed successfully the ECSC from 2002. Both within the RFCS and the Framework Program, the collaborative research within the European steel sector was fostered and reinforced over the past 10 years.

The implementation of this roadmap should take place from until 2030 especially supported by instruments of Horizon Europe and by RFCS. In particular, on an annual basis, the priorities of the Horizon Europe Clean Steel Partnership should be devoted to foster programs also of this SRA, leading to the implementation of sectoral consensus-based R&D activities.

[1] European Community for Coal and Steel (ECSC)

ESTEP AT A GLANCE[2]

EUROPEAN STEEL TECHNOLOGY PLATFORM

Driving Innovation for a Sustainable, Competitive and Climate-Neutral European Steel Industry

The European Steel Technology Platform (ESTEP) is the leading European platform that unites steel producers, technology providers, research organisations, universities, SMEs, and plant builders in a common effort to transform the EU steel industry. Founded in 2004 and legally incorporated as an international non-profit (AiSBL) in 2018, ESTEP supports collaborative research and innovation (R&I) to ensure the sector remains globally competitive, environmentally sustainable, and socially responsible.

MISSION & VISION

ESTEP acts as the communication and dissemination hub for EU-funded steel research. Its mission is to foster technological innovation that addresses Europe's major challenges—climate neutrality, the energy transition, and circular economy—through strategic partnerships and EU-supported projects.

KEY ACTIVITIES AND SERVICES

- **Co-programming the Clean Steel Partnership (CSP)** with the European Commission under Horizon Europe (2021–2027)
- **Supporting over €1.7 billion in public-private R&I investment**, including funding from Horizon Europe and the Research Fund for Coal and Steel (RFCS)
- **Developing roadmaps and Strategic Research and Innovation Agenda (SRIA)** to shape EU funding calls and industrial pathways
- **Providing a compliance** framework for collaboration within EU competition law
- **Organising events**, proposal brokerage events, and dissemination of project results

CLEAN STEEL PARTNERSHIP (CSP)

ESTEP coordinates the private side of CSP—a co-programmed partnership with the EU aiming to reduce CO_2 emissions from steelmaking by 50% by 2030. The CSP focuses on breakthrough technologies across three main decarbonisation pathways:

1. **Carbon Direct Avoidance (CDA)**
2. **Smart Carbon Usage (SCU), including CCUS**
3. **Circular Economy (CE)**

IMPACT AND REACH

With 73 members across Europe (2025), ESTEP delivers tangible contributions to:

- **Climate goals** (50% CO_2 reduction by 2030, climate neutrality by 2050)
- **European industrial leadership** in green and digital transformation
- **Job preservation** and upskilling within the steel value chain
- **Sustainable resource** use through increased recycling and circularity

[2] ESTEP Flyer - https://www.estep.eu/assets/Publications/ESTEP-Flyer.pdf

WHY ESTEP MATTERS

Steel is central to Europe's industrial base. ESTEP ensures the sector can meet the climate targets while remaining globally competitive, resilient, and socially inclusive. It provides a unique, open forum for collaboration, innovation, and shaping EU policy through shared expertise and commitment.

GOVERNANCE STRUCTURE

The governance structure of ESTEP is shown in Figure 1. Since 2018 ESTEP is a legal entity in the form of a non-profit association in Belgium (AISBL). The General Assembly provides the highest power within ESTEP. The Board of Directors is composed of 6 members in 2024 from the steel producers, EUROFER, plant builders, and Research Technology Organisation (RTO). Two groups are the core of ESTEP and bring together all its members: The Steering Group, which addresses the Technology Platform aspects and the Implementation Group, which deals with the Clean Steel Partnership related issues.

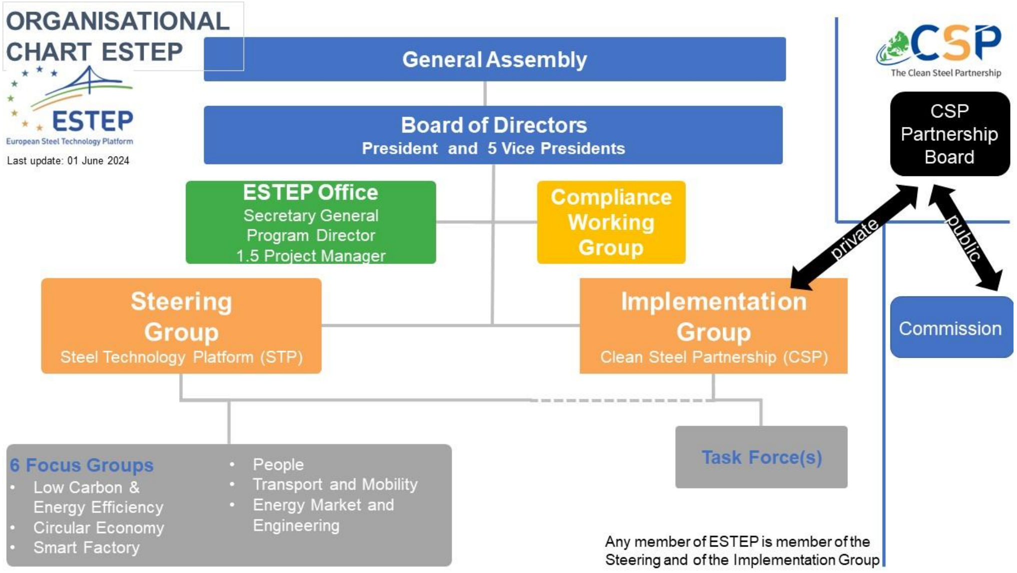

Figure 1: Organisational chart of ESTEP

The work is carried out by experts representing its members in the **Clean Steel Task Force** and the **Focus Groups (FG)**, also called the production unit, which convene to meet about 3 times a year. As being the core of the European Technology Platform (ETP), these FGs have been dealing with the implementation of the SRA in different domains **(figure 2).** Even if each FG has its own scope, today's challenges generate stronger cooperation between them. Indeed, as shown in figure1, even if each WG has its own industrial program, European projects within the EU framework such as [Industry 4.0](), circular economy, digitalisation, light weight solution and ultra-low carbon steel making project, foster a collaborative approach among the FGs.

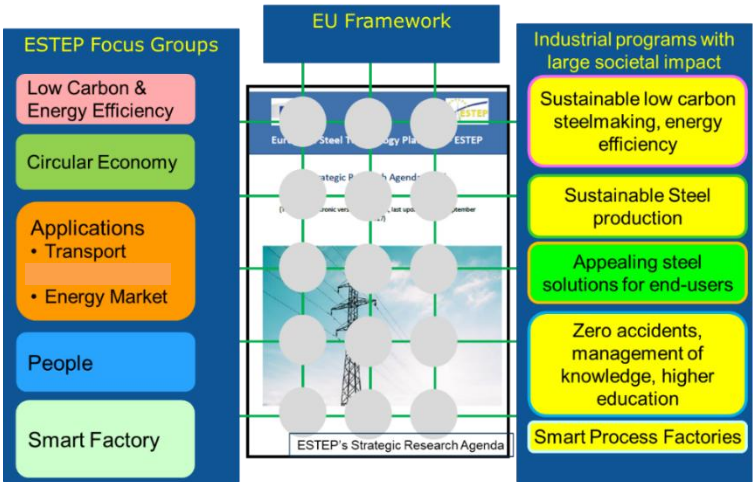

Figure 2: Structure of ESTEP's Focus Groups dealing key issues (for e.g., CE = Circular Economy, IS = Industrial symbiosis, BS = Big Scale low-carbon innovation initiative)

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PART 1. BACKGROUND

The Steel sector has long been essential to the economy and the competitiveness of Europe and it will remain important for a long time in the future. EU-28's steel industry has a total annual production of approximately 190 million tons over the past 10 years and generates more than € 190 bn in annual turnover. It provides direct employment to about 360,000 European Union citizens, and several times this number is employed indirectly in its processing, in the user and in the recycling industries. Steel is a worldwide commodity and world crude steel production is still growing. It exceeded 1 billion tons for the first time in 2004 and was at 1.6 billion tons. Steel production amounted to 1.8 billion tons in 2024 of which 140 million tons in EU27. Global steel demand is still expected to increase in the future, owing to the increased growth of emerging countries like China and India. Various scenarios (BAU and others) project a worldwide crude steel production between 2.0 and 2.5 billion tons in 2050.

The steel industry is the source of millions of other jobs, in many industrial activities, as steel is a key material for many of them (road, rail, sea and air transportation, construction, energy, chemical industry, household appliances, etc.). For example, the European steel construction industry and the automotive sector represent more than 2,000,000 jobs (EU-27). It is therefore vital for the future of Europe and of its citizens to maintain an active and competitive steel industry.

1.1. Ambition and long-term vision of the steel sector

The ambition of the European steel industry is to maintain and reinforce its global leadership in the world, and thus to remain sustainable and competitive in the face of the strong development of the steel sector elsewhere in the world, notably in Asia.

1.2. Main challenges for a sustainable global competitiveness

1.2.1. The impact of globalization and unfair trade

The globalization of steel customers has resulted in increased market power, stricter product requirements and standardization.

Collaboration with its traditional customers has been so deeply rooted in its culture that the European steel industry has taken the necessary steps to continue to satisfy their needs in terms of services, quality and economics wherever they are located. Thus, many of the European steel companies have established facilities in other regions of the world or developed strategic alliances overseas.

However, the steel industry remains less concentrated than its major supplier or client industries. Thus, it has been hard pressed to accelerate its concentration and rationalization on a global scale, to boost its ability to serve its customers, worldwide, with the same quality of products and services they already enjoy locally.

Moreover, the trend towards more international steel trade, and thus towards increased international competition, has become more and more obvious. The steel industry, faced with this growing impact of globalization and responding to pressure on its markets, needs that the rules of fair trade be enforced fairly, worldwide. On the European side, the industry is facing fierce dumping and unfair trading practices by third country competitors[3].

[3] https://www.eurofer.eu/assets/publications/reports-or-studies/annual-report-2024/EUROFER-Annual-Report-2024-.pdf p.19

1.2.2. Matching steel supply and demand

Past experience shows that crises in the steel industry have had their roots in imbalances caused by rapid fluctuations in demand combined with supply structures that are too rigid and with global overcapacity. Fluctuation in demand is related to business cycles but also to deeper structural changes. Economic cycles control steel demand, as steel is used to make both consumer and investment goods. Thus, when the financial crisis hit in 2008, it impacted European Steel with a drop in production from 200 Mt to 135 Mt in 2009 (crude steel). A significant but partial recovery occurred in 2010, 2011 and 2012 with production moving up to 170, 177 and 169 Mt respectively, but dropping to 140 Mt in 2024. In the future, the consolidation of demand in Europe will be strongly linked to the recovery of the global steel value chain.

The European Union's vision for 2030/2050 sets strategies and pathways to shift the European economy towards a sustainable and efficient global energy system, the renewal of transport fleets (air, water, land) coupled to the establishment of a smart transport management system, the refurbishment of all buildings and their integration in smart supply grids.

This vision is intensive in materials and thus the availability of advanced materials, like steel, at the proper level of quality, volume and price is a prerequisite to the successful implementation of that vision. In terms of steel quality, the industry is preparing the emergence of new, high added value steel products through research and development, which should result in an increased demand in highly developed countries (durable consumer products, capital goods). European steel production and exports ought to focus increasingly on these higher value-added products.

1.2.3. Fourth phase of the EU ETS

One of the most important pieces of EU legislation for the EU steel industry is the greenhouse gas Emissions Trading Scheme (ETS), which has been introduced in order to enforce commitments made by EU Member States in the context of the Kyoto Protocol. Across the whole EU economy, the costs for implementing these commitments are considerable. With the fourth phase of the EU ETS (period 2021-2030), the risk that European steel producers will see a further loss of business to non-EU competitors, which are not subjected to any CO_2 emissions limitations, is of major importance. This phenonium is called carbon-leakage and becomes the more relevant the higher the carbon price raises in the EU. The legislative framework of the EU carbon market is spelled out in the EU ETS Directive. Shaping the ETS Innovation Fund mechanism is an important objective.

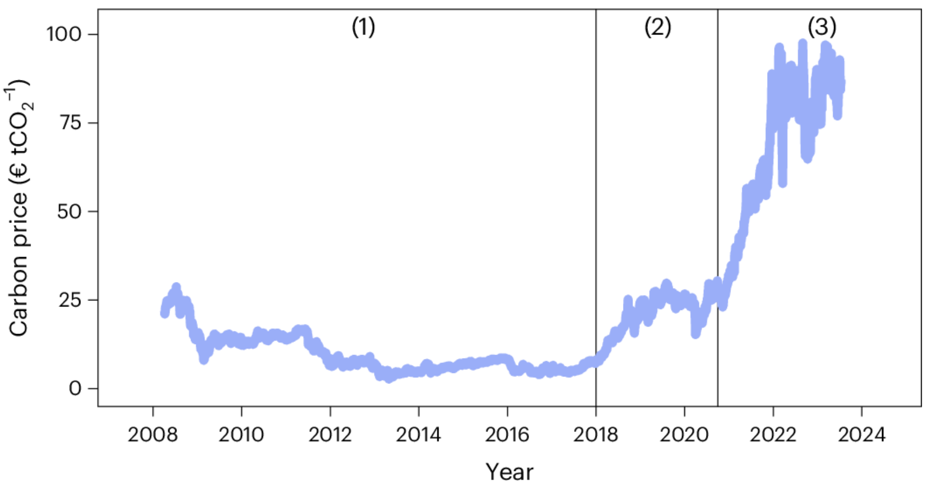


Figure 3 : Carbon price development
(source : Nature)

1.2.4. Compliance with other EU environmental regulations

Regarding environmental policy, various instruments are being introduced or under review at EU or national level. Initiatives with a potentially significant impact for the steel industry include:

- Integrated Pollution Prevention And Control (IPPC) permits,
- the Industrial Emissions Directives called (IED), which is the revision of this IPPC directive with the implementation of the BAT conclusions (Best Available Techniques) being the legal reference for permitting of installations,
- the new product and waste legislation (such as the Life Cycle Assessment approach and eco-design as well as PEF, the product environmental footprint),
- thematic strategies on natural resources, waste prevention and recycling,
- the EU legislation on chemicals ('REACH')
- the new Energy Efficiency Directive (EED)
- Europe's strict climate policies and the need to invest in costly new, green production processes create significant financial burdens compared to competitors in other regions with less stringent regulations.

The steel industry is energy-intensive, and high energy prices in Europe put EU producers at a competitive disadvantage, making their products more expensive to produce

1.2.5. Infrastructure

With a production of 140 million tons of steel in the EU28, nearly 230 million tons of iron ore, coal, scrap and other raw materials need to be transported to the steel plants, and 160 million tons of steel will be transported to the customers. However, most of the infrastructure in many parts of Europe was erected many decades before and suffers from the usage over all the years.

Not only roads and railways, but lock ship canals show as well wear out, malfunction and lack reliability. For industrialized economies such as the EU 27, the transportation infrastructure is the backbone and basis for the industrial value chain. However, in the years after the financial crisis, most countries have reduced their spending on the infrastructure.

For the upcoming years, the deficiencies of European infrastructure put the functioning of the steel industry as center piece of the European industrial supply chain at risk. Immediate measures to ensure the reliability of the European infrastructure are required in most countries of the EU.

1.3. Steel, an outstanding material

Steel is an important material in our societies and is bound to remain an important one in the future. Iron ore is abundant and energy required to produce the metal is relatively small, compared to other metals. Thus, steel has been developed into the most extensive alloy family in the engineering world over historical times, with a very broad range of applications.

Steel is rather inexpensive and offers a broad variety of functions and services, due to a unique combination of properties. First comes its tensile strength. Compared to other common materials like wood, concrete, stones or plastics, it exhibits high resistance under tension. This is the main reason for its huge success during the first industrial revolution. It can also be rather easily shaped using a wide variety of processes. This is the main reason why the ferrous sector, globally speaking, is contributing to several value chains, having thus a very large number of direct and indirect employees. Another interesting property is its high stiffness; this is very important for some applications. Its main drawbacks are its density (compared to lighter metals such as Aluminium, Titanium or Magnesium) and its corrosion resistance in air.

Steel is often pictured as a material of the past. Iron and Steel are indeed enduring materials based on cumulative technologies, invented in the Neolithic period. The metallurgical sophistication of ancient swords made of Damascus steel, in the Middle East or in Japan, is astounding! But steel is also a very modern material and a material of the future, because of its wide range of properties: iron-based alloys with some minor addition of other elements still offers many opportunities.

The present research agenda structures future prospects for new steels, according to their final application: transport, construction & buildings, energy production, storage & transport. This is the clearest way to identify what progress is required to reach the targets of our society for the years to come. However, a more transversal and abstract view may be useful as it can provide a guiding light for the analysis. The metallurgy of steel can progress significantly along the following lines:

- increase strength at more or less constant deformation ability,
- or, conversely, improve deformation ability at more or less constant strength.

Figure 4 gives an example of such an approach and of the trade-offs that this entails.

On the vertical axis, elongation is a measurement of the formability of steel. Tensile strength is on the horizontal axis. The range of strength is wide, an order of magnitude between the stronger and the milder steels. Most families of steels are grouped inside the "banana" curve. Labels show specific metallurgical structures. A second generation of steel categories is shown, such as Complex Phase (CP), Dual Phase (DP) and Transformation Induced Plasticity (TRIP) steels as well as a new third generation under development, the L-IP, TWIP steels and the new austenitic stainless steels, with large contents in alloying elements such as manganese, and, more classically also, chromium or nickel.

In order to extent the application of steel in particular in the automotive for protection of passengers during crash press-hardened steel were developed with tensile strength of 2000 MPa.

Beyond these new developments in metallurgy, a number of difficult technical questions have to be solved to properly answer market needs.

Beyond the conventional steel grades steel has one of the first smart materials so called electrical steel. Electrical steel is base material for supply chain of energy transformation, energy storage and energy transport. Due to its special and highly optimized electromagnetic properties it essentially contributes to the energy efficiency in electric systems. Furthermore, electrical steel has already an important role in the energy turnaround and will be increasingly significant for the electric mobility.

For example, steel needs quite often to be welded and the reliability of the welds under critical conditions has to be demonstrated. In case of carbon steel, it needs to be coated to withstand corrosion: the usual solution is zinc coating, but new steels that contain easily oxidized elements do not as a rule accept galvanizing; beyond zinc, new coating solutions based on other metals are under development. For higher temperature applications, a lot of new solutions are still under development. Last but not least, these new steels and new metallurgies have to be

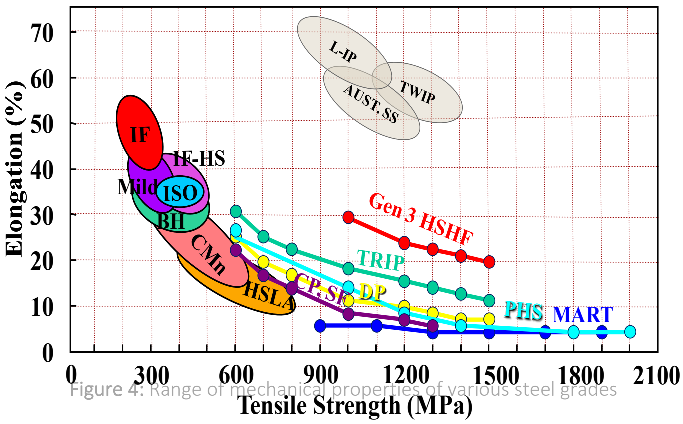


Figure 4: Range of mechanical properties of various steel grades

produced in large quantities with a very narrow control of process parameters in order to exhibit a specific range of properties.

Another very important iron-based material is stainless steel due to its application in e.g.,, household, medicine, food and chemical industry. Cutlery and pots are probably the most popular things in each household. In surgery: tools, implants and covering made out of stainless steel are essential due to hygiene requirements in combination with the need of strength or hardness. The refinement of pre-curser or final products under high pressure in a highly corrosive and hot environment demands the use of stainless steel in chemical reactors or pipe systems.

Steel is an important material for the fabrication of industrial installations, machinery and tools, necessary also in other materials value chain.

Optimal processing of these steel products of the future is a difficult challenge that can be addressed either by improving existing production technologies or by developing new processes or new technologies in combination with the new alloy design.

Based on its deep knowledge of the potential of its material, the European steel sector has been constantly addressing the challenge of meeting the demands of its customers to deliver a broad variety of ever more versatile high-performance materials. To achieve these goals, direct partnerships between steel producers and their direct customers are a necessary approach. This constitutes the core of the development and promotion of new products by the steel industry.

Beyond these developments in fairly classical directions, longer term efforts are addressing more challenging issues than the strength or formability of steels.

On the one hand, the density of steel is one area of development, as the present density of 7.8 is not a barrier and there are ways to reduce it by 10 to 15%, thanks to the addition of specific alloying elements, such as aluminium. This is a promising approach to reduce the weight of steel objects beyond the increase in strength (AHSS), which was presented previously.

Similarly, Young's modulus is not upward bound by the classical value of 210 GPa. Various paths are being explored, among which the design of a new steel grade that would be a metal matrix composite with ceramic compounds, such as TiB_2 precipitates. This would also help reduce weight, without being limited by the value of Young's modulus, when thickness becomes small.

Multilayer steels are also at the core of new development efforts: the point is to associate steel qualities with very different properties (strengths) by joining them into layers (5-7), a kind of revival of Damascus steel, beefed up by the concepts of modern metallurgy. Defining the process used to create this lamination is at the core of the investigation: co-rolling, co-casting, etc.

Finally, one might stress the point that nanostructures have been present in steels, since long before the name of nanomaterials was coined - perlite and precipitates like NbC have nanometric dimensions - and that further efforts are devoted to developing the concept (Nanosteel, USA).

The SRA is engaging or planning to engage stakeholders in the automotive, construction and energy sectors, as a priority.

1.4 Strategic objectives

The main challenges for the European steel industry's sustainable global competitiveness include high energy and decarbonization costs, intense global competition from subsidized, less regulated steel imports, significant investments required for green transition, geopolitical instability impacting supply chains, and low domestic demand. These can be summarized into four strategic objectives: decarbonizing production, ensuring fair global competition through border carbon adjustments and industrial policy, fostering innovation for green technologies and circularity, and securing access to affordable clean energy.

1. Decarbonize and innovate for sustainability

Invest in and deploy breakthrough technologies for green steel production, focusing on resource efficiency, waste management, and circular economy principles to lower environmental impact and operational costs.

2. Ensure fair global competition

Implement strong industrial and trade policies, including the prevention of carbon leakage through measures like the Carbon Border Adjustment Mechanism (CBAM), to level the playing field with subsidized imports.

3. Secure affordable and clean energy access

Prioritize ensuring access to abundant, affordable, and clean energy sources to reduce production costs and support the green transition for the European steel industry.

4. Strengthen industrial capacities and demand

Foster a robust domestic industrial ecosystem for steel and related technologies, while also promoting demand for sustainably produced steel through lead markets and public support to de-risk investments in green transformation projects.

The corresponding Focus Groups[4] of ESTEP are:

- Circular economy
- Low carbon & energy efficiency
- Transport and mobility
- Energy market & engineering
- People
- Smart factory (ICT)

1.5. R&D&I approach: three industrial programs with large societal impacts

To face such important challenges and to meet the objectives of the European Steel Technology Platform, it was decided in 2017 by the ESTEP Steering Committee to launch resolute and structured long-term R&D actions. Seven working groups corresponding to the 4 pillars of sustainable development of the Platform as well as Integrated Intelligent Manufacturing are working on 3 industrial programs with large societal impacts each of them encompassing several R&D themes and research areas. These themes and areas are continued of the last SRA. In March 2016, it was decided to update this SRA with this present third edition in electronic format before the next booklet that will be printed in 2018. The structure of the industrial programs remains the same, but the research areas have been totally reviewed and completed by the Working Groups. The present ESTEP organization is shown in figure 3. The approach and the structure of R&D themes and areas are shown in the figures 4 and 5.

The 3 industrial programs with large societal impacts are the following:

- Sustainable steel production
- safe, cost-effective and lower capital-intensive technologies

[4] As of August 2022 the area of construction is not followed by a dedicated Focus Group but via ad-hoc actions and a wider perspective of the other FG and their events (in particular workshops and mini-conferences).

- appealing steel solutions for end users

to which two transversal objectives regarding human resources and ICT have been added:

- attracting and securing qualified people to help meet the steel sector's ambition
- smart factory (Industry 4.0)

1.6. The DRAGHI-report

The Draghi report is a 2024 report addressing European competitiveness and the future of the European Union. Authored by former ECB president and former Prime Minister of Italy Mario Draghi, it was a widely anticipated report on EU reforms in 2024. Parts of the Draghi report's proposals have already been adopted by European Commission president Ursula von der Leyen for the work programme of her 2024–2029 Commission term. Draghi's report urges the EU to foster more investment to increase European productivity.[5]

1.6.1 The Draghi report outlines several strategies to increase the global competitiveness of the European steel industry

Reduce energy costs through long-term contracts and investments in clean energy

The steel industry's competitiveness is heavily impacted by high energy costs in the EU. To mitigate this, the report suggests establishing long-term power purchase agreements and investing in clean energy sources, storage, and grid infrastructure, which could reduce price volatility and lower operational costs.

Streamline permitting processes

Current EU permitting processes are lengthy, often taking three to five years, and create obstacles for investments in new facilities or upgrades for decarbonization. Simplifying these processes, particularly for green projects, could help reduce delays and foster quicker modernization of production facilities.

Improve access to decarbonization funding

The EU's funding landscape is fragmented, making it difficult for steel producers to secure necessary financing for green technologies like electric arc furnaces and hydrogen integration. The report emphasizes the need for cohesive funding strategies, including simplified access to multiple EU and national funds.

Encourage the formation of green industrial clusters

Regional clusters that integrate low-carbon supply chains, renewable energy, and carbon capture infrastructure could enhance resource efficiency and competitiveness. By promoting industrial symbiosis—such as sharing energy, raw materials, and waste products—European steelmakers could achieve economies of scale and reduce operational costs.

Enhance international trade defense and collaboration

Global steel overcapacity and subsidies from other countries pose significant challenges. The report suggests reinforcing trade defense mechanisms and collaborating with international partners to address excess capacity and trade distortions, which could protect EU steel producers from unfair competition.

Foster research, development, and innovation (RD&I)

Innovation is crucial for achieving competitive advantages, particularly in green technology. By enhancing RD&I in carbon capture, recycling, and green production methods, the EU can strengthen its position in high-quality, low-

[5] https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en

emission steel production. This would allow EU producers to remain competitive even with higher production costs.

1.6.2 Research, development, and innovation (RD&I) are critical for the steel industry, particularly as it faces decarbonization pressures and needs for technological advancements. Key points from the Draghi report underscore its importance

Enhancing competitiveness and product quality

The EU's steel industry, known for high-quality and specialized products, relies on innovation to differentiate itself and stay competitive. RD&I has allowed the industry to improve energy efficiency and promote recycling, helping offset higher production costs in the EU compared to other regions.

Decarbonization and green technology

RD&I in green technology is essential to meet climate objectives. Innovations in areas like energy savings, recycling, and carbon capture are vital for reducing emissions. The steel industry requires new technology, such as electric arc furnaces and carbon capture, to move toward sustainable production.

Investment in low-carbon solutions

The report highlights that EU steelmakers face high investment needs, particularly for RD&I in low-carbon processes. Significant funding and technological breakthroughs are necessary to make green steel viable and cost-competitive, given the expensive nature of clean energy and green hydrogen in Europe.

Global RD&I coordination and funding disparities

The report notes disparities in RD&I funding across regions, pointing out that countries like the US offer substantial subsidies for green innovation. The EU must bolster its RD&I support to keep pace, particularly with programs that streamline access to funds and encourage cross-border collaborations.

Research, development, and innovation are thus indispensable for the EU steel industry's transformation and resilience.

1.6.3. The Draghi report identifies several critical research topics for advancing the European steel industry.

Low-carbon steel production technologies

Development of low-carbon technologies such as electric arc furnaces (EAF), hydrogen-based direct reduction of iron (DRI), and carbon capture and storage (CCS) is essential for decarbonizing the steel industry. The transition from blast furnace-basic oxygen furnace (BF-BOF) to greener production methods is a major focus.

Energy efficiency and emission reduction

Research on energy-efficient processes, heat recovery, and the reduction of emissions is essential to make the steel industry more sustainable and cost-competitive. Improved efficiency directly impacts operational costs and helps in meeting stringent EU regulations.

Recycling and circular economy

Innovation in recycling processes to increase the use of secondary raw materials (scrap) and improve the quality of recycled steel is vital. This includes research on enhancing scrap quality and exploring ways to minimize scrap exports, which would help in retaining valuable materials within Europe.

Hydrogen production and infrastructure

Hydrogen plays a significant role in decarbonizing steel production, but requires advancements in production and distribution. Research is needed to improve electrolyser efficiency, lower the cost of renewable hydrogen, and build infrastructure for hydrogen transport and storage.

Digitalization and smart manufacturing

Adopting digital technologies, such as artificial intelligence and advanced sensors, in production processes can enhance monitoring, reduce waste, and improve overall efficiency. Research in digitalization supports predictive maintenance and quality control, optimizing production.

Carbon Capture and Storage (CCS) and Utilization (CCU)

Research into CCS and CCU is essential to mitigate emissions from existing BF-BOF production routes. CCS/CCU offers a way to manage unavoidable process emissions and is an area requiring significant technological advancements to reduce costs and increase effectiveness.

These research topics are crucial for maintaining competitiveness, achieving EU emissions targets, and reducing production costs in the European steel industry.

1.6.4. The Draghi report discusses several ways in which circular economy principles can be applied in the steel industry

Increased use of scrap metal

Recycling and using scrap metal in production help lower emissions and reduce reliance on primary raw materials. This shift supports both environmental goals and cost efficiency, as using recycled materials generally requires less energy than processing new raw materials.

Managing scrap exports

Monitoring and regulating the export of scrap metals ensures that high-quality recycled materials are retained within the EU. This would help maintain a steady supply of scrap metal for the European steel industry, supporting local recycling initiatives and lowering costs.

Incentivizing the use of recycled materials

Establishing policies that encourage the demand for secondary (recycled) materials can further circularity in the steel industry. Measures such as minimum recycled content requirements for products or the adoption of a Digital Product Passport could enhance the market for recycled steel.

Industrial symbiosis in green clusters

The report suggests forming green industrial clusters that can facilitate circular economy practices by sharing resources like energy, raw materials, and by-products. Such collaboration improves resource efficiency and reduces waste, making the steel industry more sustainable.

The application of circular economy practices in the steel industry offers multiple benefits, including reduced emissions, cost savings, and support for EU sustainability goals.

1.6.5. To improve energy efficiency in steel production processes, the Draghi report recommends several approaches

Investment in emission-abatement technologies

Using advanced technologies, such as electric arc furnaces (EAF), carbon capture and storage (CCS), and clean hydrogen, can significantly reduce emissions and improve energy efficiency. Transitioning to EAFs from traditional blast furnace-basic oxygen furnace (BF-BOF) routes reduces energy intensity, though the upfront costs are high.

Adoption of Power Purchase Agreements (PPAs)

Long-term PPAs for renewable energy can provide the steel industry with stable, lower-cost energy sources. This approach minimizes exposure to energy price volatility, especially important for energy-intensive sectors like steel.

Promoting industrial symbiosis in green clusters

Establishing industrial clusters allows sharing of resources like energy, raw materials, and waste products among nearby facilities, boosting resource efficiency and reducing waste. Industrial symbiosis facilitates a more circular economy within the steel sector.

Implementing energy efficiency measures

The report also encourages improvements in production processes to reduce energy use. This includes measures to optimize heat recovery, minimize waste, and employ smart technologies to track and reduce energy consumption at various production stages.

These methods not only improve energy efficiency but also enhance the competitiveness and sustainability of the European steel industry by aligning with decarbonization goals.

1.6.6. The Draghi report discusses the potential of hydrogen to decarbonize the steel industry, emphasizing the following approaches

Hydrogen as a reducing agent

In steel production, hydrogen can replace coal as a reducing agent in the direct reduction of iron (DRI) process. This method, known as hydrogen-based DRI, reduces iron ore without emitting CO_2, as hydrogen combines with oxygen to produce water instead of carbon dioxide. This is a significant shift from traditional processes that rely heavily on carbon, making hydrogen-based DRI a pivotal pathway to zero-emission steel.

Investment in infrastructure and production

For hydrogen to be economically viable, substantial investment in infrastructure is necessary. The development of large-scale electrolysers, which can generate hydrogen using renewable energy, and supportive infrastructure (such as pipelines and storage facilities) will help enable widespread hydrogen adoption in steelmaking. The European Hydrogen Bank (EHB) also supports hydrogen projects by providing financial stability to encourage investments in hydrogen production.

Cost and energy efficiency challenges

Currently, green hydrogen production is more costly than conventional fossil-based hydrogen. The high electricity demand of electrolysis, coupled with high electricity prices in Europe, makes hydrogen-based steel production costly compared to traditional methods. Continued advancements in electrolyser technology and access to low-cost renewable energy sources are critical for making hydrogen a competitive option in steel production.

Hydrogen offers a promising route to decarbonize the steel industry, but it requires coordinated policy support, infrastructure development, and technological advancements to achieve competitiveness and scalability on a large scale.

1.7 The Clean Industrial Deal

The Clean Industrial Deal offers a comprehensive framework to ensure that the European Steel Industry has the necessary resources, incentives, and regulatory environment to achieve its decarbonization goals while maintaining European steel competitiveness.

The Clean Industrial Deal can foster the Clean Steel Partnership by providing financial, regulatory, and market incentives to accelerate the decarbonization of the European steel industry.

Funding and investment support

The Industrial Decarbonisation Bank aims to mobilize €100 billion for clean manufacturing, including support for industrial decarbonization projects like clean steel.

Innovation Fund & InvestEU provide funding mechanisms that can be aligned with the needs of the Clean Steel Partnership.

The Hydrogen Bank and support for low-carbon hydrogen will help develop alternative energy sources crucial for green steel production.

Regulatory and policy framework

The Industrial Decarbonisation Accelerator Act will streamline permitting for industrial projects, including steel production.

Carbon Border Adjustment Mechanism (CBAM) protects the EU steel industry from carbon leakage by ensuring imported steel meets similar carbon pricing requirements.

The Circular Economy Act will promote scrap metal recycling, reducing reliance on raw materials and supporting cleaner steel production.

Market incentives and demand creation

The EU will introduce low-carbon product labels, starting with steel, to distinguish and incentivize cleaner products.

Public procurement policies will include sustainability criteria, ensuring that clean steel has a competitive advantage.

Support for lead markets will increase demand for low-carbon steel, making investment in cleaner technologies more attractive.

Affordable energy and hydrogen access

The Action Plan for Affordable Energy aims to lower energy costs, a critical factor for the energy-intensive steel industry.

Policies promoting renewable and low-carbon hydrogen will support the transition to hydrogen-based steelmaking.

Skills and workforce development

The Union of Skills initiative and Quality Jobs Roadmap will provide training and transition support for workers in the steel industry to adapt to new clean technologies.

1.8 The Steel and Metals Action Plan

1.8.1 Context for the EU Steel Industry

The European Steel and Metals Action Plan, published by the European Commission in March 2025, provides a foundational policy framework to guide industrial transformation in support of the EU's climate, competitiveness, and strategic autonomy goals. For the **steel sector**, the plan reinforces the critical role of research and innovation in enabling a **climate-neutral, resilient, and globally competitive industry**.

1.8.2 Key Policy Drivers

1. ***Decarbonisation and clean energy integration***
   - Direct electrification and hydrogen-based processes (e.g., DRI-H2) are prioritized.

- Research is essential for cost-effective Carbon Capture, Use and Storage (CCUS), waste heat recovery, and flexible grid integration.

2. *Carbon leakage prevention*

- Enhanced monitoring and extension of CBAM to downstream products highlight the need for robust carbon accounting methods.
- Research into lifecycle emissions methodologies and CBAM-compatible verification systems will be critical.

3. *Circularity and scrap optimization*

- Promoting high-quality steel scrap usage requires advanced sorting, design-for-recycling standards, and process integration.
- Innovation in secondary steel production and alloy separation will be a core research priority.

4. *Supply chain resilience and trade defense*

- The plan supports defensive trade tools and anticipates shifts in global flows due to foreign subsidies and tariffs.
- Research is needed on supply chain modelling, forecasting overcapacity impacts, and origin traceability technologies (e.g., "melted and poured" verification).

5. *Just transition and skills transformation*

- A strong focus on maintaining quality jobs and social cohesion underlines the need for interdisciplinary research on labour dynamics, reskilling strategies, and digital training frameworks.

6. *De-risking investment via innovation and market pull*

- The Action Plan calls for voluntary low-carbon product labelling and green public procurement to create lead markets.
- Strategic research should focus on cost-benefit models, certification systems, and public-private mechanisms to accelerate deployment of clean technologies.

PART 2. RESEARCH & INNOVATION APPROACH

This chapter presents the Research and Innovation areas that ought to be developed within the next 10 years. The industrial programs presented in the previous chapter and the transversal activities regarding human resources have been fleshed out by the ESTEP focus groups. The respective R&D&I themes and areas of the working groups are presented from chapter 2.1. to chapter 2.7.

2.1. Sustainable steel production (Planet)

2.1.1. Introduction: context, ambition & foresight

Steel is 100% recyclable and for endless times and **by-products** from steelmaking process has to be considered as a real alternative to traditional raw materials that can be valorised either within the steelmaking process or in other industrial sectors avoiding the depletion/ consumption of natural resources. Therefore, steel and steel by-products are essential materials for the circular economy.

At the same time more holistic, prospective and longer-term issues must be tackled to meet both economic and environmental regulation targets synergistically in the day-to-day business of the steel industry. In this contest, in which a strong synergy between ESTEP WGs is required, Planet covers the following area:

- Life cycle assessment (LCA) and life cycle thinking (LCT)
- Digital technologies for environmental impact assessment (see also WG I²M)
- Circular economy:
    - Resource issues due to energy and raw materials supply
    - Scrap vs. steel quality
    - Energy recovery and upgrading (see WG Profit)
    - Carbon-lean steelmaking (see WG Profit)
    - Transform by-products to new feedstock or (secondary) raw materials for Internal recycling or other industries
    - Re-use of residues and by-products of other industries in the steel plant
- Eco-design of processes and steel solutions as a method to integrate the above concepts and methodologies and turn them into operational tools
- Work synergistically with nature (biomass, biomimetics, etc.) and integrate steel's activity with ecosystem services (how to deal with biodiversity in the steel's business model)
- Other emerging global issues (acid rain and dust are becoming global issues) and future rules for setting long term targets for the environment, as well as toxicity and ecotoxicity issues

2.1.2. Exploring solutions: the R&D&I approach

a) Low-carbon steelmaking

In order to contribute to the Paris agreement, and thus to reduce GHG emissions, the steel industry's players are intensifying their efforts to accelerate the transformation of the European industry towards carbon limitation and neutrality. The **Big Scale initiative**, which is the large scale ultra-low carbon future steelmaking project, is heading towards this achievement.

The company-driven initiatives of the Big Scale are dealing towards the smart, low-carbon industry of the future based on two main pathways:

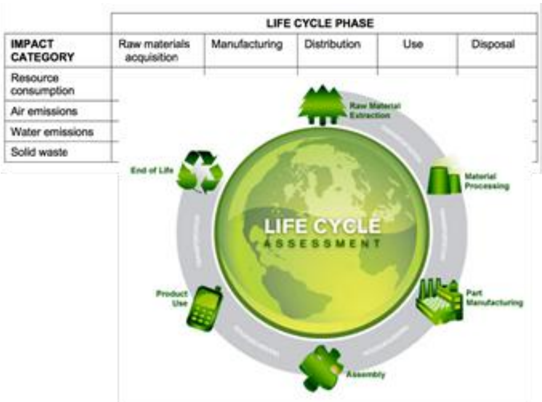
- Carbon direct avoidance (CDA), which substitutes carbon as the reducing element with hydrogen or via the use of electricity
- Low carbon without CO_2 emissions (LCWCE), which further optimises carbon-based metallurgy and applies carbon capture and utilisation or storage methods to mitigate greenhouse gas emissions.

The Big Scale is further explained in chapter 2.2. Process (section 2.2.2 e)).

b) Life Cycle Assessment (LCA) and Life Cycle Thinking (LCT)

Life Cycle Assessment (LCA) remains a cornerstone methodology for evaluating the environmental performance of steel and other industrial materials across their full life cycle—from raw material extraction to end-of-life. While attributional LCA (describing systems as they currently are) is nowadays consolidated, more advanced and forward-looking methodologies such as consequential LCA, social LCA (S-LCA) and dynamic LCA are gaining traction. These approaches better reflect systemic impacts, time-based dynamics, and socio-economic trade-offs. In particular, evolving policy tools like the Eco-design for Sustainable Products Regulation (ESPR) and the EU Product Environmental Footprint (PEF) are increasingly embedding LCA principles into regulatory and market instruments[6] (Figure 5)

Figure 5: Full Life Cycle Assessment



[6] European Commission. Eco-design for Sustainable Products Regulation (ESPR).

As LCA matures, Life Cycle Thinking (LCT) is being promoted across EU industry policy as a broader conceptual approach that encourages sustainable decision-making beyond product-level assessments. The steel industry actively supports this shift, recognizing its value in driving responsible production, product design, and material circularity.

However, standard LCA methodologies often remain limited in scope and granularity. Addressing strategic challenges—such as global supply chain complexity, recycling loop efficiency, or system-wide decarbonisation—requires complementary macro-scale approaches. These include Material Flow Analysis (MFA), Exergy Analysis, and Input-Output-based LCA, particularly relevant for sectors like steel where recycling, alloy traceability, and cross-sector integration are critical. (Figure 6).

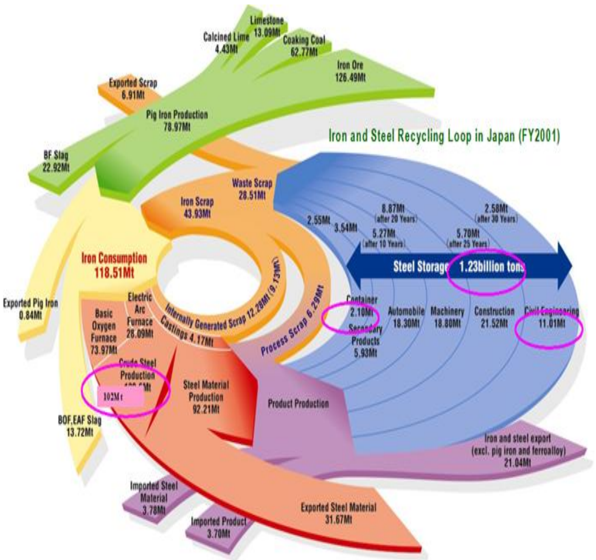


Figure 6: Iron and steel recycling loop

Moreover, the steel sector advocates for methodological innovation beyond traditional LCA, which explore the concept of "social value" as a pillar of holistic sustainability. This calls for enhanced collaboration between LCA practitioners, system modelers, sociologists, and ecological economists to integrate environmental, economic, and social metrics into strategic decision-making. For instance, Dynamic LCA can be profitably connected to digital simulation tools to assess the impact of changes in process chain and operating practices, select most promising paths to reduce C-footprint of steel production as well as in the context of multi-objective optimization frameworks.

Ongoing projects funded by the Research Fund for Coal and Steel (RFCS) and Horizon Europe aim to develop sector-specific sustainability toolkits, traceability frameworks, cross-sectoral impact models and decision support system relying on advanced also Artificial Intelligence (AI)-based digital solutions to enable daily implementation of C-lean practices and solution.

These contribute directly to the implementation of the European Steel Technology Platform (ESTEP) SRA and align with the EU's goal of climate-neutral industrial ecosystems.

c) Digital technologies for environmental impact assessment

Cyber-Physical Systems, Internet of Things (IoT), Big-Data Technologies and AI are nowadays pervasive for a twin transition (digital and green) and are intensively applied to improve process flexibility and reliability as well as total product quality control. However, such techniques can be successfully applied:

- to continuously monitor and assess the environmental impact of the production processes (e.g., through a network of sensors and tools for easy interpretation of the collected data);
- to improve control of both production and auxiliary processes (e.g., water and off-gases treatment plants) which have an impact on the environmental performance of the steel production;
- to improve characterization of raw materials (e.g., scrap) and by-products (e.g., slags);
- to provide key performance indicators for sustainable resource efficiency.

Such tools will be coupled with advanced modelling and simulation tools supporting both real-time control tasks and strategic scenario analyses aimed at evaluating the actual environmental benefits and the technical and economic feasibility of major process modifications and new operating practices as well as of the different possible transition pathways from conventional to novel C-lean steel production processes. Digital twins of steelmaking and auxiliary processes can quantify the expected environmental benefits, technical impacts, and economic feasibility of process modifications, new technologies, or alternative operating practices. Combined with predictive modelling, these systems help reduce risk and accelerate innovation cycles.

Furthermore, this kind of digital technologies can greatly support also the task of energy efficiency and decarbonisation, through the development of intelligent systems for low-carbon flexible energy management and smart interaction with energy grids and aligned with broader sustainability objectives and regulatory developments in the EU industrial ecosystem.

d) Circular economy

The Circular Economy is a contemporary and widely concept based on waste prevention and re-use, repair and recycling of products and superior products design for long life. It implies that resources are brought back into the supply chain after the end life of the product. In a circular economy:

- the products and materials are used for as long as possible;
- waste and resource use are minimised;
- and resources are kept within the cycle when a product has reached the end of its life, to be used over and over again.

To accelerate this transition, the European Commission adopted an ambitious Circular Economy Package which establishes a concrete and ambitious programme of action, with measures covering the whole cycle: from production and consumption to waste management and the market for new (secondary) raw materials.

In terms of primary raw materials for the iron and steel industry such as iron ore, carbon carriers (fossil, bio-based, waste fractions, such as plastics or automotive shredder residues) and natural gas, the access is not a short-term issue but may create large price fluctuations and force players in the field to adjust their strategy to accommodate this kind of business risk. A slightly different scenario should arise regarding alloying elements, where tension on prices may reflect some short-term scarcity. On the other hand, new (secondary) raw materials constitute a growing proportion of raw material feedstock, where quality is an important question for recycling.

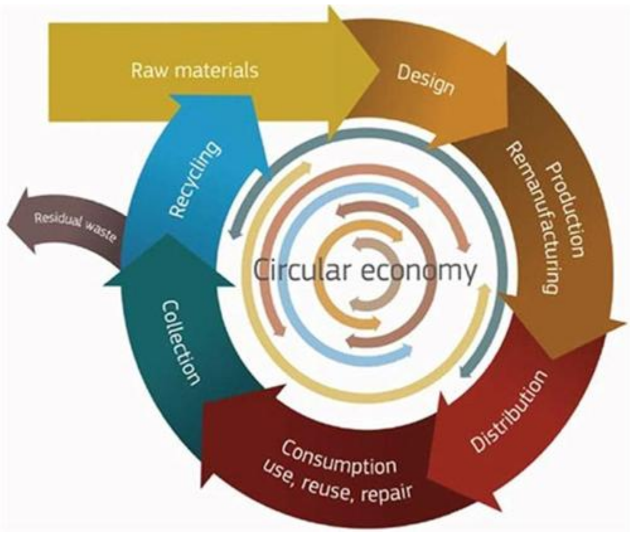


Figure 7: EU view on Circular Economy (Source: https://www.fcc-group.eu/

The most important (secondary) raw material is ferrous scrap (in addition to iron-rich by-products or fractions thereof). Continued recycling is essential to keeping scrap in a constant loop. In such a way, steel can be classified as a Permanent Material that once produced can be recycled or reused without the loss of quality, regardless of how often the material is recycled. However, in "the current situation" of insufficient supply of scrap with a certain quality required to produce high-quality steel grades, a circular system cannot be realised yet, while in "the future perspective" at some point in time a balance can be created (Figure 8)[7]. Precise scrap characterization and advanced sorting and purification solutions can support maximum valorisation, enhanced scrap usage and reduction of primary raw material exploitation (not only iron ore but also ferro-alloys).

Steelmaking also results in useful by-products, such as process gases dusts, sludges, scales and ferrous slags (from primary and secondary metallurgy), whereas mineral-rich fractions from slags can substitute natural resources in other sectors and contribute to resource efficiency. Process gases are used for electricity generation for industrial and domestic applications, replacing fossil fuels and natural gases. Mineral fractions from iron and steelmaking slags are used in a range of applications (e.g., civil engineering like road construction, fertilizer and cement production etc.), saving millions of tons of natural resources annually and putting into practice the concept of industrial symbiosis far before it gained the current popularity.

Therefore, the steel production has been working on circularity since its existence as yield improvement and energy savings: cascading use of resources, waste recycling, internal residues recovery and recycle are only some of the circular actions put into practice during the daily steel production. Steel sector is committed to progress further and to develop solutions for turning into an even leaner sector also, through innovation, reuse has and can be increased. More precise and punctual characterization of raw materials and byproducts enabled by advanced sensing technologies and AI can greatly support implementation of Circular Economy and Industrial Symbiosis solutions and practices leading to joint environmental and economic benefits.

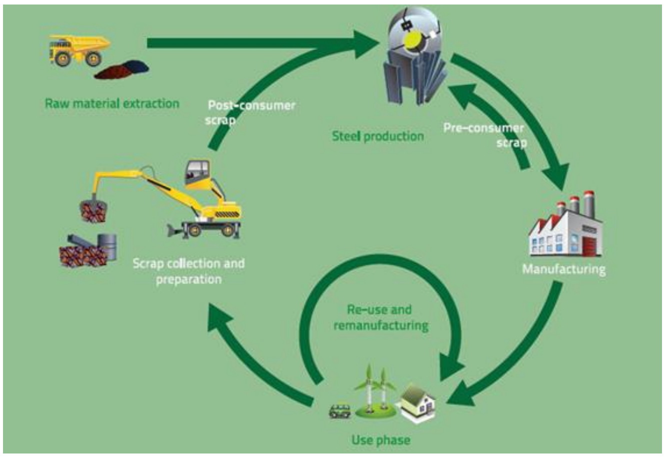


Figure 8: The recovery and steel recycling cycle

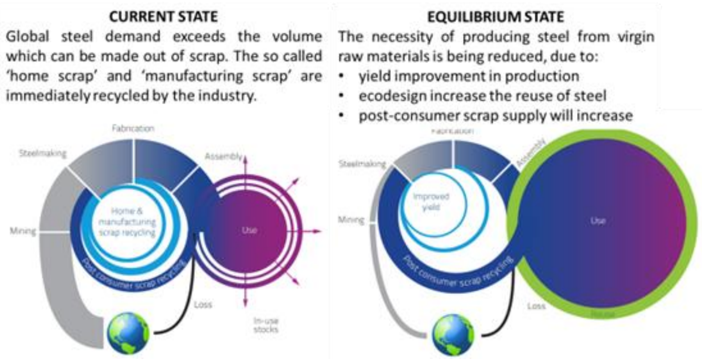


Figure 9: Scrap in the circular economy

Circular Economy consists of interconnected loops, each of them, with its own life cycle frequency while interconnecting different sectors through industrial symbiosis. Circular Economy is more than Waste Management

[7] Steel and Circular Economy, EUROFER

and Materials loops: it is an «economic plan» based on the sustainability framework and following an «integrated approach» that includes the target for materials industry to by-product as feedstock and reduces primary raw materials to produce "virgin" material. Re-use and remanufacturing of products are seen as integral part of a circular economy. Steel products and parts can be part of this, which has implications on steel production and possibly business models.

This requires addressing different aspects:

- Resource issues due to energy and raw materials supply
- Scrap vs. steel quality
- Interaction between scrap flows and steel quality requirements
- Opportunity for energy recovery and upgrading (see WG Profit)
- Pathway toward carbon-lean steelmaking (see WG Profit)
- Efficient use of by-product for Internal recycling or other industries
- Re-use of residues and by-products of other industries in the steel plant
- Development of value of technologies, value-chains and business models for re-manufacturing and re-use

Resources issues due to energy and raw materials supply

Europe has become attuned to the issues of resource scarcity in relation to rare earth elements and the international trade tensions that they generate. This is an interesting revival of a concept which stresses that resources come from a finite earth, both fossil resources and renewable ones, which are also bound by competition for land and environmental limits.

A more balanced view is thus being framed, acknowledging that many resources will remain abundant but that the growth of demand related to population growth and urbanization may have a faster dynamic than what the supply side of the economy can provide, thus creating a tension and a volatility on prices. The ideas of a lean economy and of resource preservation by increasing energy and material efficiency are ever stronger. This includes recycling of steel in as well as recycling and use of the all the large volume of industrial residues – waste and by-products - generated by the sector.

The steel sector has to imagine incremental solutions to a leaner steel sector, which is again part of the task of the working group on process innovation (Process), but ought to maintain a global picture to prioritize the more ambitious parts of the potential technological agenda for dealing with these matters. Transversal, through-process issues are key, as well as the quick integration of new technologies developed outside of the sector and cooperation with other economic actors (see further).

Scrap vs. steel quality[8]

The European Union is currently a net scrap exporter (world's largest exporter of ferrous scrap, shipping out about 20% of what it collects[9]). Despite the exportation, research shows that there is no shortage of steel scrap in the EU at the moment. However, Europe could greatly benefit from improved management of its domestic resources, hence reducing external dependencies. Not all scrap is equal. Currently, a significant portion of exported scrap is rather low-quality and mainly used in construction and building. A major part of long products can be manufactured from large portions of obsolete scrap without requiring a significant alteration of their processing parameters or compromising of their final product properties. The same accounts for many hot rolled commercial strip grades, although the level of tramp elements needs to be carefully controlled. One of the challenges with increasing amount of scrap is how to produce high-quality and high-performance products from scrap or recycled

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[8] Marique C.(coordinator), "Recycling of scrap for high quality products" (ECSC Steel RTD programme -7210-CB/205…1994-1997)
Marique C., Steel recycling: A key element of the circular economy- ESTEP-EUROFER Circular Economy Workshop – October 19, 2016

[9] Forging a more circular and sustainable EU steel industry, European Commission

feedstock: tramp elements can influence the quality of low and ultra-low carbon steels, and producing low nitrogen steel grades are difficult to produce via an electric steelmaking route remains particularly challenging.

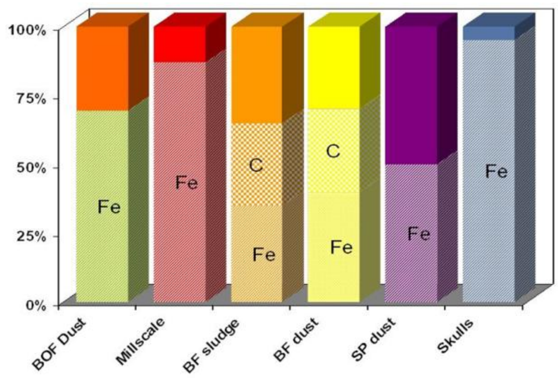
Although specific studies and investigations have been done several issues have also to be addressed such as:

- Develop industrial and economic feasible solutions for refining steel melts to remove non-volatile tramp elements like copper and tin;
- Improving scrap (pre-)processing to enhance scrap quality, including:
    - precise scrap characterization relying on novel characterization system and AI;
    - removal of metallic coatings of tin and/or zinc (limited economic viability solutions based on hydrometallurgy or thermal treatment are currently available);
    - separation of scrap into low and high residual fractions, which is partially feasible through the application of advanced physical separation techniques (sorting, shredding, size and density classification, …);
    - improvements on the whole value chain, which even might imply changes in the design of products to allow for easier separation of unwanted compounds in steel scrap.
- Enhancing traceability of critical alloys elements along the recycling value chain
- Enhancing traceability of critical alloys elements along the recycling value chain

By doing so, the EU could unlock an additional 20-40 million tons of high-quality scrap annually. Though it is poised to grow, this corresponds to a remarkable 52% of the EU's scrap consumption in 2024[10]. Enhancing scrap use in the EU would also mark a shift from blast furnaces (BF), coal-dependent and highly carbon-intensive and polluting, to electric arc furnaces (EAF), which generate roughly three times less emissions per ton of steel compared to BFs[11].

Use by-products for internal recycling or other industries

On average, the production of one tonne of steel results in 200 kg (in electric arc furnace steelmaking) and up to 400 kg in blast furnace steelmaking (BF) of residues. These include slags, dusts, sludges and other materials. All these residues – whether classified as waste or by-products - contain a relevant fraction of iron and metal oxides, making them potentially valuable secondary raw materials. (Figure 10)[10].



For this reason, iron & steelmaking residues must be revalorized either by reintegrating them into the steelmaking process or by using them as industrial by-product as raw materials source in other sectors via industrial symbiosis or as internal cascading use, for several reasons:

- the tightening environmental legislation which are increasingly making the landfill disposal of wastes more expensive;

[10] Malfa E. , *Environmental Impact and Climate Change*, EUROSTEELMASTER 2015, Terni, Italy, 13th May 2015.

Figure 10: Relevant fraction of iron and metal in residues

- the high content of iron and metal oxides which make the residue valuable raw material for BOF and EAF charge;
- the chemical and physical properties that allow the re-use of residues and by-products from the steel plant in other industries or contexts.

Developing new solutions often require technical development and new business models that reflect the needs of the business partners and allow for more circularity.

Slags

Concerning the slag generated in the liquid processing phase of iron and steelmaking, it has been already been classified at REACH[11].

Family no.	Common name		EINECS name	EINECS No. CAS No.
1	Granulated Blast furnace Slag	GBS	**Slag, ferrous metal, blast furnace** (granulated)	266-002-0 65996-69-2
	Air-cooled Blast furnace Slag	ABS	**Slag, ferrous metal, blast furnace** (air-cooled)	266-002-0 65996-69-2
2	Basic Oxygen furnace Slag (converter slag)	BOS	**Slag, steelmaking, converter**	294-409-3 91722-09-7
3a	Electric Arc Furnace slag (from Carbon steel production)	EAF C	**Slag, steelmaking, elec. furnace** (carbon steel production)	932-275-6 294-410-9[a] 91722-10-0[a]
3b	Electric Arc Furnace slag (from Stainless/ high alloy steel production)	EAF S	**Slag, steelmaking, elec. furnace** (stainless/high alloy steel production)	932-476-9 294-410-9[a] 91722-10-0[a]
4	Steelmaking slag	SMS	**Slag, steelmaking**	266-004-1 65996-71-6

Table 1: Slag families and corresponding CAS- and EINECS-numbers; [a] = "old" EINECS or CAS numbers

Figure 11: Slags families and corresponding CAS & EINECS No.

Examples of use of the GGBS (Ground Granulated Blast Furnace Slag vitrified, with hydraulic properties) as cement or concrete addition according to EN 197-1 and EN 15167-1, respectively, as well as the uses of the ABS, BOS and EAFs C slags as aggregates for concretes, asphalts, ceramics and road bases are already implemented in some countries. Less demanding applications include fillings, ballast and soil conditioning. SMS has a high potential of expansion and its use is mainly oriented to re-injection in EAF, soil stabilization, fertilizer. Additional research is necessary to evaluate its combination with other slags and its use in special concretes (SCC) as well as EAFs S slag need further research and long-term analysis to assess durability and environmental/health risk (Figure 12[12]).

The main driver is the economic viability: a new trend is to valorise, when possible, the recycled material in the local economy, to limit transport and logistics costs and to effectively create economic value in the region. However, the heterogeneous legislative framework across the EU together with future threats for by-products and wastes represent the strongest constraint to develop common approaches.

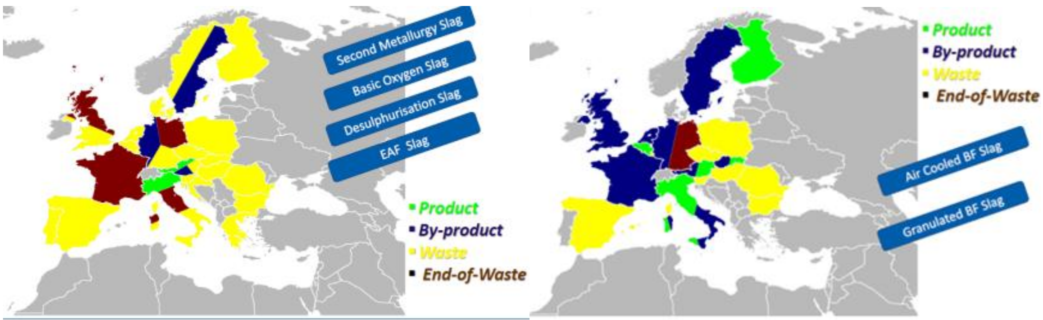


Figure 12: (Simplified) Legal situation of Slags

[11] European Union, Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC, Official Journal of the European Union, 30.12.2006, L 396/1.

[12] A. Braconi,Legislative constraints and future threats for by-products and waste, Circular Economy WorkshopBrussels, 10 November, 2016

The replacement of the BF by direct reduction technologies (DR) 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, i.e., slags 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 Electric Smelting Furnace (ESF) representing a link between the DR of low/medium grade ores (fines or pellets) and new or existing EAF/BOF plants. An ESF as an aggregate working under reducing conditions is also a suitable recycling aggregate for steel mill internal by-products with certain iron contents (e.g., slags, dusts, scales) or for post-consumer scrap. The properties of this ESF slag must assure a full recycling e.g., within the cement sector.

Dusts and sludge

Dusts and sludge are mostly coming from the pollution abatement equipment that used to clean the gases and wastewater discharges from the various iron and steelmaking processes. In the recent years, significant improvement has been realised reducing the level of materials sent to landfills. These residues are increasingly being reprocessed internally, at least at the integrated steelmaking route. The recycling of converter dusts and sludges via cold briquetting and returning to the BOF is well established technique. Recycling of BF dust has also been developed and implemented[13]. Technologies based on cold agglomeration were investigated to manufacture self-reducing briquettes out of iron oxides residue and to recycle them into EAF without negatively influencing on the performance and on the environment.

Another point to note is that while slag tends to be used ‘internally’ or 'externally' to site, dust and sludge utilisation is mainly on the whole recovered using 'internal' processes but still there is material sent to landfill or to external site for further treatments. This different approach to the two residues streams suggests that slag is viewed more as a material which can and should be marketed and managed accordingly – i.e., it is a by-product – , whereas for dusts and sludges, legislative and sustainability drivers lead more towards technical and innovative solutions.

The most widely used pyro-metallurgical processes process is the Waelz Kiln already dating from 1910. The process is specifically applied to treat EAF dust, and it retrieves only 60% of the zinc in the form of oxides while 40% remains in the slag that cannot be used anymore and has to be landfilled. Several new processes have been developed over the past years with the aim specifically to increase the recovery of zinc up to 94%.

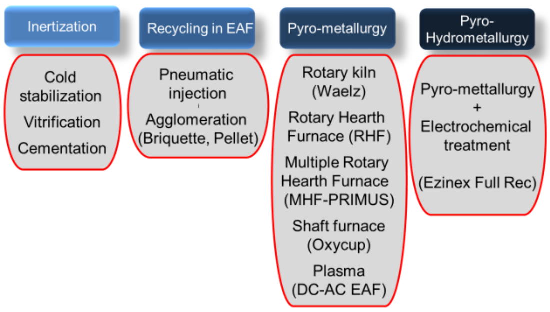


Figure 13: Dust treatment process

Re-use of residues and by-products of other industries in the steel plant

The steel industry is also looking at residues from other industrial sectors as alternative carbon materials (ACM) . as it is clear that carbon (non-fossil sources in the best case) is required even after the transformation to low-carbon steelmaking is finished (among others as energy carrier or slag foaming agent for the EAF or as reducing and carburization agent in an ESF)

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[13] RFCS project Flexinject, RFSR-CT-2008-00001, EUR 25909, 2013

Former examples are use of plastic residues as chemical feedstock for Coke oven where the coke quality allows the addition of 1-2% of plastics in the coal blend. Plastic residues can also be injected in the Blast Furnace (BF): in Japan this technology is applied since the mid-90s, while in Europe Voestalpine Stahl GmbH has been using plastics as a reducing agent on its Linz BF A since 2006. Heavy fuel oil and coke have been replaced by up to 100.000 tons of outdated synthetic materials annually.

Rubber from tires, plastics, Automotive Shredder Residue (ASR) and biomass residue have some application as slag foaming agent in the EAF. The former RFCS projects RIMFOAM and GREENEAF and the Horizon Europe project GreenHeatEAF involved a variety of steelmakers operating EAFs with different sizes and configuration (AC/DC) and contribute to producing general guidelines for European Electric Steelmakers.

A factor restricting the utilization of residue from other industries is the cost associated with their collection and treatment. A reliable supply of consistent quantity and quality and at a competitive cost is essential. For example, certain plastic qualities, used also in packaging and as containers, contain chlorine (e.g., from PVC waste) which is of great concern due to its corrosive effects. Consequently, the chlorine needs to be removed from the plastic residue prior to use. A step in the right direction has been the introduction of the recent UNI 10667-17, which regulates the blends of heterogeneous plastic from industrial residue and/or from postconsumer materials to be used as reducing agents in iron and tell industry.

Energy efficiency and new energy frontiers

Even when it becomes leaner and moves towards circular economy, the steel sector can "green" its energy sources. Factory roofs can be covered by solar panels or wind turbines can be installed on the extended piece of lands on which steel mills are placed. However, steel mills based exclusively on renewable energy alone will probably be unlikely, because of the large energy needs of making steel, due to basic thermodynamically needs. Nevertheless, if renewables are inter-mediated by an energy vector such as electricity today and maybe hydrogen tomorrow, then the transition can be as high as the renewable content of the grid. Some of these topics are more extensively detailed in the Process section (Chapter 2.2.)

It should also be stressed that the current energy system is built around steel. This has been true in the last century, remains true today and it will continue to be true in the future. The energy generation technologies based on renewables, due to the smaller scale with respect to traditional power plants, are several times more material intensive, with steel being one of the key required materials.

Hence, ESTEP supports the creation of the Industry Driven Initiative (IDI) of Energy Materials Industry Research Initiative (EMIRI) (www.emiri.eu).

As pointed out in the Energy section (Chapter 2.6.), steel is also the almost exclusive material for the extensive grids of pipe, which will transport natural gas, fracking gas, shale oil, hydrogen and CO_2 from production fields to urban-industrial consumption areas or to geological storage sites.

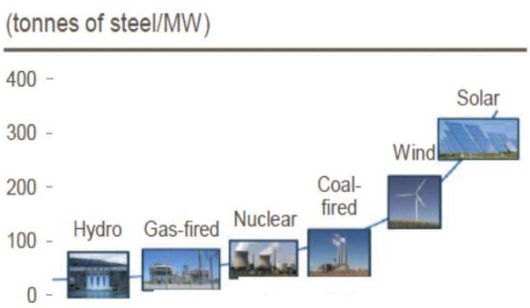

Figure 14: Renewables in steelmaking

e) Eco-design of steel solutions, steel grades and steel processes

The EU legislation on Eco-design and energy labelling is considered as an effective tool for improving the energy efficiency of products.

- The Eco-design Directive[14] sets minimum standards of performance requirements for products, which results in poorly performing products being removed from the market while driving innovation in the product design and manufacture of new products is encouraged to improve their performance.
- The Eco-labelling Directive[15] provides consumers with clear information on product performance to inform their buying decisions.

In circular economy terms, the longer the first life use of a product is the better as it reduces the need for manufacturing new products. In principle this is the best approach to closing resource loops since any form of refurbishment, remanufacture, reprocessing or recycling necessarily requires an injection of additional resources and potentially a degrading of the product functionality or material value.

However, the benefits of extended product durability cannot be assessed in isolation, as several factors must be considered, including:

- Practical limits on lifetimes from current manufacturing methods;
- Cost implications of changes to product materials, components and manufacturing to extend lifetime;
- Innovation rates that could make extended lifetime products obsolete and inefficient;
- Consumer buying habits and expectations of product performance for different types of product;
- Possible impacts of more durable products on their second life potential – e.g., any risk of reduced refurbishment potential;
- Availability and acceptance of appropriate standards, testing and compliance methods for enhanced durability.

These factors mean that there is more than just looking at the materials and environmental side of products: dedicated tools and processes for doing Eco-design need to be developed further, success stories have to be told and the deployment of that methodology organized, starting at the interface between steel production and steel market and progressively expanding throughout the entire steel value chain.

f) Steel and its synergies with nature

The term “Biodiversity” derives from a contraction of "biological diversity" and commonly refers to a measure of the variety of organisms, which are present in different ecosystems. In particular, it can refer to genetic variation, ecosystem variation, or species variation within an area, biome, or planet.

As the preservation biosphere integrity is widely recognized as a core objective for a sustainable development of the society, the meaning of the word “biodiversity” is no more exclusively associated to the preservation of endangered species, but mostly on the management of natural resources from a system’s perspective. In this context, the biosphere is considered as an open system (ecosystem) with a special property called resilience, defined as the skill to perpetrate itself under changing environmental conditions.

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14 Official Journal of the European Union, Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009, Framework for the setting of Eco-design requirements for energy-related products 31.10.2009, L 285/10-35.

15 Official Journal of the European Union, Directive 2010/30/EU of the European Parliament and of the Council of 19 May 2010, The indication by labelling and standard product information of the consumption of energy and other resources by energy-related product, 18.6.2010, L 153/1-12.

Within this context, the steel sector can contribute to the protection and enhancement of biodiversity, to secure available ecosystem services, such as water for example, and contribute to the stability/resilience of the system in which it operates[16]. On the other hand, biodiversity can represent for the steel industry not only a heritage to preserve, but also a strategic opportunity.

In fact, some steel companies have already collaborated with local communities in order to achieve a sustainable use of forests as a source of livelihood, or they have been committed to programs aiming the conversion of mines and quarries into habitats for local wildlife: relevant examples of such cooperation can be found in Liberia, Canada, Brazil and Sweden[17] [18].

The importance of steel as a valuable and fundamental material in order to develop measures and systems for protection of biodiversity can be enhanced and promoted. Steel can be an ideal structural material to build boundaries between the biosphere and the anthroposphere or to build infrastructures for maintaining or restoring biodiversity, such as biodiversity corridors, which allow animal species to safely move through different geographic areas.

At the same time, biodiversity offers an ecosystem´s perspective to industrial companies. The Millennium Ecosystem assessment[19] provided a methodological and compelling analysis of the Earth's ecosystems providing the humankind with essential and specific *Ecosystem services*. In the same document, in order to assess the natural capital represented by ecosystem services, an approach was proposed to monetize ecosystem services, i.e., to attribute a financial value to the benefits provided to people by the ecosystem services. In this light biodiversity can be considered an integral part of businesses, as it represents one of the boundary conditions within which the industry can operate. The connection to the economic sphere is realized through the exploitation of ecosystem services to integrate biodiversity issues into business practices and management strategies.

An exemplar but not exhaustive list of topics, applications of methods within steel operations that affect biodiversity can be as follows:

- Management of land surrounding the plant and landfills: use of functional (agro-) biodiversity in and around sites and landfills to the aim of performing phytoremediation[20], production of food and goods and overall biodiversity conservation. A positive impact is foreseen for such kind of actions also for the local community and the workers, as such measures positively affect air, soil and water quality as well as the aesthetic of the plant.
- Benefits of by-products for functional biodiversity: increased use of by-products coming from iron and steelmaking processes to replace natural raw materials in order not only to increase their recycling but also to reduce the environmental impact and loss of biodiversity in the exploited areas (e.g., ferrous slags replacing natural aggregates, P-rich fractions of steelmaking slag used as fertilizing or liming agent in agriculture, steel slag used as effective adsorbent for the heavy metals in filters, BF dusts exploited for heavy metals ions removal from aqueous solutions).
- Improvement of water effluents from plant through biodiversity management: application of botanical bioremediation[21] to decontaminate soils, water and air, as a cost effective and safe technology.

[16] Hanson C., Ranganathan J., Iceland C., and Finisdore J., The Corporate Ecosystem Services Review: version, 2012, 2, 1-48.

[17] Rio Tinto, URL: www. riotinto. com/documents/ReportsPublications/RTBidoversitystrategyfinal. pdf, 2008.

[18] Berg A., *Empowering the Steel Industry as a Stakeholder: Environmental Management and Communication through a Social-Ecological System Approach*, PhD thesis, 2013.

[19] Reid W.V., Mooney H., Cropper A., Capistrano D., Carpenter S., Chopra K., Dasgupta P., Dietz T., Duraiappah A., & Hassan R., *Millennium ecosystem assessment: ecosystems and human well-being: synthesis*, 2005.

[20] Batty L.C. & Dolan C., *Critical reviews in environmental science and technology*, 2013, 43(3), 217-259.

[21] Chaney R.L.,, Malik M., Li Y. M., Brown S. L., Brewer E. P., Angle J. S., and Baker A. J., Current opinion in Biotechnology, 1997, 8(3), 279-284.

Investigation should also cover the viability of plant combustion to obtain energy[22] and recovery of metal from the ashes[23] [24], while in the case of forest species, the wood could be industrialized.

- Reduction of water footprint of steel production through advanced digital solutions and water treatments which can reduce freshwater intake and can promote water efficiency, while also recovering valuable materials from wastewater.
- Aesthetics impact of the plant: adoption of measures such as green roofs and walls, special night lights to the aim of improving sound insulation, reducing energy costs, extending the life of the roof, create, recreational spaces where workers can get in touch with nature, improve the industrial landscape colour, attracting animals in the areas surrounding the plant.
- Management of old mining sites: application of phytoremediation but also recreation of agricultural land or natural habitats that can be colonized by species that have lost habitats elsewhere
- Climate change adaptation and preservation of biodiversity: examples of applications are: re-composition of fragmented environments, that can give the possibility to animals and vegetables to migrate in response to climate changes and to the ecosystem to restore own structures and functions or CO_2 capture through reconstitution of forests, humid areas and other ecosystems that work as sink of carbon absorption.
- Ecological remediation of industrial sites: transformation of old industrial sites into different types of green areas with varying degrees of bio-diversity and for different purposes. This transformation always results in an increase in biodiversity and can furthermore contribute to solve common environmental problems such as attenuation of noise levels, decreased effects of dust emissions, by also providing a valuable recreation site for the personnel of the company, improving work environment and decreasing levels of stress.

Finally, a participatory approach is important for the research in this field, in order to include also evaluation of social impact and economic effects, by also improving their level of social acceptability. Therefore, the involvement of internal and external stakeholders, such as local administrative and municipal authorities and local communities, should be encouraged.

g) Global threats and future environmental demands

In the past (roughly until the end of the nineties), the research was focused mostly on mitigation of the environmental risk at the specific site level and the environment has long been perceived as an externality in the economy. Current short term research activities are addressed toward the reduction of the environmental impact of the production cycle in both the surrounding areas and in general at a wider level. Global environmental issues are gaining strength, as they are becoming threats and grand challenges.

Figure 15 Foreseen dimension and time evolution of the SRA activities in the frame of sustainability

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[22] Dimitriou I. and Aronsson P., *UNASYLVA-FAO-*, 2005, **56**(2), 47.
[23] Pilon-Smits E., *Annu. Rev. Plant Biol.*, 2005, **56**, 15-39
[24] Yang X., Ye H., Long X., He B., He Z., Stoffella P., & Calvert D., *Journal of plant nutrition*, 2004

The ozone layer and climate change were the major global threats perceived until recently, but more issues are becoming global, like acidification, eutrophication of fresh and ocean waters and biodiversity (BES) issues. Projections of demands for the middle of the century show that the environment in general will be posting limits on various emissions, which will be as demanding as the ones for CO2 today (figure 16).

Substances	2000	2010	2020	2030	2040	2050
GHG	0%	10%	20%	30%	40%	50%
VOC	0%	24%	49%	60%	70%	81%
SO_x	0%	20%	75%	77%	80%	82%
NH_3	0%	0%	27%	44%	62%	79%
PM	0%	0%	50%	50%	50%	50%
NO_x	0%	26%	53%	64%	74%	85%
others	0%	10%	20%	30%	40%	50%

Figure 16: Targets for major environmental emissions from 2000 to 2050

From a practical standpoint, this will also mean for steel demands on dust emissions, NO_x and SO_x for example, which are way beyond what is achieved or even achievable today. Therefore, this calls on deep research and development work to arrive in time at technological solutions, which are not simply waiting on the shelf today.

By 2050, according to the *OECD*[25], global water demand is projected to increase by some 55%, due to growing demand from manufacturing (+400%), thermal electricity generation (+140%) and domestic use (+130%). The growth population, the uneven water distribution around the world and the droughts put in evidence the importance of a rational water usage that goes from the optimization of the current water systems, following to recycle and reuse strategies and to find alternative water resources.

Consequently, research efforts need to be devoted toward both technologies and novel practices supporting the improvement of the quality of water effluents, by limiting or even eliminating the consumptions of freshwater while improving internal recycling as well as recovery of energy and valuable raw materials from industrial wastewater. Being issues common to many industrial sectors, especially those belonging to the category of Energy Intensive Industries, a synergic approach with other sectors will be of utmost importance and will allow a real progress toward sustainability of production processes. This is especially valid for the regions characterised by water scarcity as well as for densely populated areas, where large urban settlements and a several economic activities jointly exploit land and water resources.

Water is essential for producing steel and consequently it could be considered as another raw material. Average water consumption and discharge per tonne of steel are close to each other, 28,4 and 25,4 m3/tonne respectively[26] In the steel industry, 75% of water is for cooling or heat transfer (Johnson, 2003). There are different water-cooling strategies that may lead to water savings. For example, the extensive recirculation cooling systems reduces the total water intake to 2.4% of the requirement of the once-through systems (Initiatives U. F. (2002).

Finding and implementing cost-effective technologies that meet legislative discharge requirements and/or allow the reuse of effluents is a technical challenge faced by the steel industry.

2.1.3. Partners, disciplines, level of the innovation step, bottlenecks and risks

Sustainability needs to address the environmental dimension but it is also needing to consider the wider social and economic impacts in a global context. In addition, the circular economy calls for new business models in the light of increased (when reasonable) prolonged lifetime, re-use and re-manufacturing.

[25] OECD, *Environmental Outlook to 2050: The Consequences of Inaction*, 2012
[26] Worldsteel Association, Water Management in the Steel Industry, 2011

Having this in mind such industrial program (WG Planet) calls on industries of the steel value chain, but also of the end-of-life and recycling community and of other industries and urban communities with which waste energy and residues can be traded and exchanged.

This means make include in the design cycle of the steel process disciplines like Life Cycle Assessment (LCA) and Material Flow Assessment (MFA), but also new methodologies like SAT and those being worked out in the SOVAMAT initiative, which are essential for future research and development areas assisting in the transition of the steel industry towards a complete circular economy:

- Material Input
    - High use of secondary materials
    - Retain functionality of alloying metals in ferrous scrap.
    - Investigate possibilities for alternatives to Critical Raw Materials (CRM) as alloying components.
    - Investigate the use of residue of other industries for industrial symbiosis
- Eco-design
    - Assist/work with customer to make products having a longer life (such as steel property improvement/adaptation, improvement of corrosion protection/resistance) and/or are designed for disassembly, reuse and remanufacture (such as new designed steel products facilitating this requirement).
- Production
    - Development of alternative steel products to current ones with environmentally hazardous substances in production (chromium-6, cobalt, lead).
    - Development of new business strategies with customers including circular concepts such as products/materials ownership, remanufacture and service-based offers.
    - Increase of yield of steel production (e.g., lower need for internal recycling) in the steel industry.
- Consumption
    - Development of advanced steel grades to ensure (extended) long life in products.
    - High rate of reuse of water within the steel plant and zero waste release
    - Develop with customers tools and build databases as basis for LCAs and Environmental Product Declarations (EPDs)
- Waste recycling
    - Improve processes to avoid waste generation such as maintaining process liquids or water streams
    - Transform residue to new feedstock or (secondary) raw materials for other industries.

The main bottlenecks can be identified in the legal burden and complexes permitting that if not clear and uniform between all the European countries can be a strong obstacle to economic viability of horizontal and vertical symbiosis in and between different industrial sectors and more in general to the circular economy development.

Moreover, the death rate (failure to secure capital investment) was enormous due to low return on investment and/or high operating costs of "environmental investment, thus:

- a system of subsidies would have had to be implemented, like it is done for renewable energy and many other examples;
    - the transversal, through-process approach pursued as well as the quick integration of new technologies developed outside of the sector and cooperation with other economic players such as illustrated in Figure 17.

2.1.4. Stakeholders

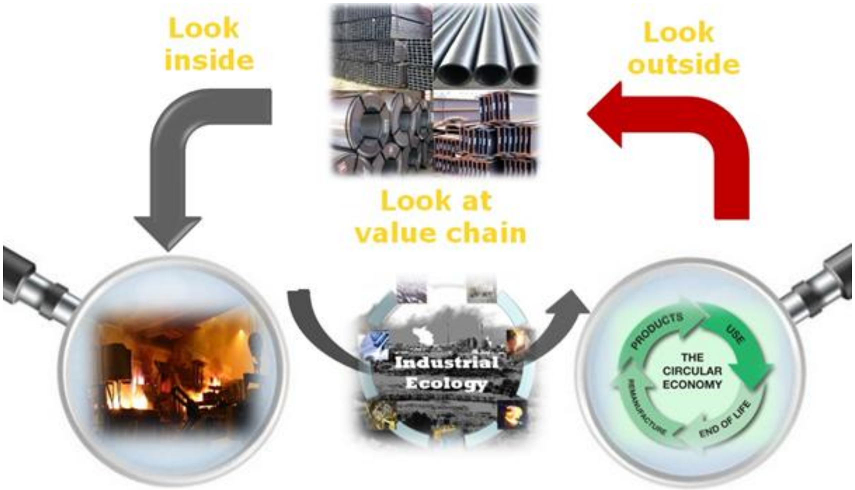

Figure 17: Cross-sectorial approach to foster by-products reuse

- Steel industry
- Steel research centres
- Suppliers of iron ores and coals
- Equipment suppliers
- World Steel Association
- Other energy intensive industries (cement, pulp & paper, glass, chemicals, etc.)
- Non-ferrous metals producers
- Electricity producers
- Public authorities
- Recycling industry
- Universities
- Modelling laboratories for eco-design and LCA studies

2.2. Profit through innovation in production processes (Process)

2.2.1. Introduction

In a global world economy evolving continuously towards fiercer competition, the European Steel sector must continue to meet essential challenges: safe conditions at the working place, high standards of quality, steady renewal of the offer while applying highly productive, safe, clean, sustainable and cost-effective processes.

More specifically, attention is paid to promote key-enabling technologies and to develop new approaches with low capital expenditure and higher resource and energy efficiency along the value chain and the life cycle.

After the significant progress achieved by the European steel industry over the past 45 years with a decrease in energy consumption of more than 50%, more reduction is targeted, particularly in fossil energy intensity, by combining further process integration, introducing novel energy-saving processing routes, using alternative and renewable energy sources and implementing intelligent automation solutions.

Another major objective is the reduction in the consumption of high-quality virgin or primary raw materials (including alloying elements) by improving global process yield and using more variable or diversified raw material including secondary (recycled) raw materials, by-products or land-filled waste.

Much investment has already been engaged in recent years by the steel industry to meet the objectives of the industrial program of this section. To go further, new R&D&I effort and technological development are needed.

2.2.2. Exploring solutions: The R&D&I approach

Further progress will require additional R&D&I efforts and continued technological development to sustain competitiveness while advancing toward long-term sustainability goals

The European steel sector's innovation approach is increasingly characterised by an integrated "system architecture" that couples technology development with demonstrator evidence, investment de-risking, and enabling conditions such as permitting readiness, standards and market pull (e.g., procurement and labelling). In this framing, R&D&I is not only a sequence of projects but a coordinated portfolio that must deliver industrial integration at scale while maintaining competitiveness, quality and safety under changing boundary conditions, including variable input materials and evolving energy systems.

In continuity with the previous version of the SRA, the solution space remains structured around safety, new steel products, continued improvement, leaner use of raw materials, and carbon-lean steelmaking. What changes post-2025 is the explicit emphasis on (i) robust operation under variability (scrap/DRI/HBI quality, impurities, fluctuating energy), (ii) late-stage pilot/demonstration execution and "industrialisation logic" (integration plans, preliminary economic viability, energy/material balance appraisals), and (iii) aligning technology readiness with standards, data governance and skills to accelerate adoption.

a) Safety at the workplace

The first priority of steel producers is the objective of "zero accident". It is tackled by promoting the use of safer practices on the plant floor. The related managerial and organizational aspects are developed in the section People (chapter 2.7). Process improvements regarding safety concentrate on withdrawing human beings from dangerous zones (liquid metal and slag, toxic or asphyxiant gases, flames, hot slabs, fast moving steel strips, etc). Three main directions have to be further explored:

- promoting new, intelligent and remote analysis and on-line contact-free measurement systems with no manual intervention
- using of long-range wireless systems allowing the control cabinets and the data harvesting equipment to be located far from dangerous zones and with no need to maintain the transmission hardware placed in harsh environments
- customizing industrial robots (hardware and software) for use in steel mills

The scope of these applications can be very wide, covering all processing steps on continuous or discontinuous lines.

Safety remains the non-negotiable foundation for any transformation of steel production routes and plant operation. As technology portfolios expand—introducing higher electrification, hydrogen handling, increased automation, and tighter coupling between cyber and physical systems—the safety agenda must evolve from isolated risk controls to an integrated "safety-by-design" approach across equipment, processes, digital systems and work organisation. The R&D&I approach therefore treats safety not as a separate work package but as an embedded requirement across demonstration, deployment and operational scaling. The related managerial and organizational aspects are developed in the section People (chapter 2.7).

A post-2025 safety agenda also implies that innovation programmes and calls increasingly expect project consortia to show credible plans for safe industrial integration. In late-stage pilot/demonstration settings, proposals are framed around industrial integration and exploitation strategies and—where relevant—explicit improvements to health, safety and ergonomics at steel facilities. This anchors safety within the same evidence chain as performance, emissions and economics, strengthening the case for rapid and responsible adoption.

R&D&I priorities for safety (capabilities and enablers) include:

- Systemic hazard identification and operational risk management for new process routes and retrofits, including how hazards propagate across tightly coupled unit operations and utilities (energy, gas, water, off-gas and by-product systems), particularly in pilot/demonstration operations.
- Human-centric design of automation and decision support, addressing the human-machine interface, safe operating envelopes, and operator roles in increasingly automated plants; and recognising socio-technical risks such as loss of situational awareness or "automation bias" when decision support becomes more autonomous.
- Cyber-physical safety integration, ensuring that digitalisation and connectivity do not introduce unacceptable operational risks, including the need for secure architectures and governance of critical control systems.
- Work organisation, competences and safe change management, reflecting the Industry 5.0 emphasis on worker well-being, resilience and sustainability alongside productivity. This includes competence development for safe operation of new routes and digital systems, and organisational learning in pilot/demonstration environments.

Safety-relevant innovation must be treated as a cross-cutting acceptance condition for all technology pathways described below. Demonstrators should therefore include safety evidence (procedures, training concepts, human-machine interactions, and cyber-physical safeguards) alongside performance and emissions evidence, to enable regulators, insurers, workforce representatives and downstream customers to recognise readiness for scaling.

b) New steel products: grades, coatings and manufacturing processes

Innovation in steel products remains a core lever for maintaining European competitiveness and enabling downstream decarbonisation and resource efficiency. The former version of the SRA emphasises product development addressing higher strength-to-weight ratios, fatigue performance, corrosion resistance, formability and weldability, and the capacity to deliver more demanding performance profiles for key customer sectors. These objectives remain valid; however, product innovation post-2025 is increasingly linked to (i) the constraints and opportunities of low-carbon production routes and high-variability inputs, and (ii) emerging requirements for traceability and product information exchange along value chains.

A central implication is that "new steel products" R&D cannot be isolated from process-route transformation. Material design, processing windows, and quality assurance strategies must be co-developed with the production routes expected to dominate future capacity (e.g., higher EAF share, hydrogen-enabled routes, direct electrification options). This co-development must explicitly address robustness to input variability and impurity management, since variability can propagate into product properties, surface quality and downstream performance.

At the same time, policy-coupled innovation introduces additional "readiness" dimensions for products, including credible measurement, reporting and verification (MRV) of product-related environmental attributes and practical approaches to sharing product information without undermining confidentiality. While the specific regulatory instruments continue to evolve, the direction described in the literature points to increasing importance of carbon-intensity labelling and procurement criteria, implying that product innovation strategies must anticipate how environmental and traceability information is generated, managed and exchanged.

R&D&I priorities for new steel products (capabilities and enablers) include:

- Tramp-element-tolerant steel alloy design: Research advances, with a focus on accommodating higher recycled content while maintaining performance. While some tramp elements can be managed through alloy and process design, others remain significant challenges. The integration of advanced modelling, process control, and circular economy principles is essential for future progress.

- Product-process co-design: co-optimising alloy concepts, processing windows and quality controls for production routes with higher electrification, higher recycled content, and increased variability, ensuring stable mechanical and surface performance within defined operating envelopes.
- Advanced quality assurance concepts that combine sensing, modelling and data-driven methods to maintain quality and yield while reducing lead time and rework—particularly in high-throughput operations (e.g., casting/rolling) where quality losses are costly.
- Lifecycle-oriented product definition, including structured product information and traceability approaches that can support downstream requirements while respecting confidentiality (e.g., layered data access and pre-competitive data sharing).
- Qualification and standardisation readiness for new products and grades, recognising that market uptake depends on acceptance criteria, testing methods, and alignment with downstream certification practices (framed qualitatively where evidence is non-quantitative).

In practical terms, the product innovation portfolio should be designed to deliver (i) superior performance and reliability for key applications, and (ii) credible and interoperable product information that supports emerging market pull mechanisms. Demonstrators should show not only “what the material can do” but “how it can be manufactured robustly and how can it be recycled at EoL” under future input variability and energy conditions, with quality and traceability maintained at industrial pace.

New alloys and steel grades

R&D on new grades should continue to focus on delivering improved and application-relevant combinations of properties, but with stronger emphasis on robust manufacturability under variable inputs (e.g., higher recycled content and impurity constraints). This implies closer coupling between alloy/grade development and process-route realities, including quality assurance concepts that maintain property stability across wider operational windows. On top of these considerations, new alloys and steel grades have to be developed to obtain extended life in products and/or improved properties in use. Among high performance materials, high strength steel grades (AHSS, UHSS) for transport and construction applications, high temperature carbon steels for supercritical boilers and demanding engine applications, or new alloys for energy-related applications in harsh environments (high/low temperatures, highly corrosive media) are examples of grades for which further advances are required by end-users. The concept of “smart steels” which integrate various functions in new steel grades to support new applications is also gaining interest, especially when considering internal properties such as magnetic, piezoelectric or conductivity properties. For light-weight applications (especially transport), the development of alloyed steel grades with lower density than carbon steels is also regarded as a complementary approach to the use of high strength grades.

New coating formulations and new surface treatments

New coating formulations and new surface treatments are required to obtain improved resistance or new functional properties of steel products, or to achieve significant reductions in cost or environmental impact. Developing alternative steel coatings to avoid environmentally hazardous substances as per the REACH directive, such as chromium-6, cobalt, lead or BPA (Bisphenol-A), is an on-going effort of the steel industry which has to be pushed further. Modified or innovative coating processes and technologies also have to be developed for advanced high strength steel grades, which exhibit reduced coating ability. Beyond that, new tailored surface treatments also have to be developed to improve specific functional properties of steel products such as wear resistance, IR reflectivity, cleanability or self-healing properties. One of the paths to do so is through the industrialisation of advanced vapour deposition processes which have been successfully developed on small scale. These processes would allow significant steps forward in surface treatments in terms of coating thinness and cost or development of new coating strategies. Another concept of interest is the development of “smart coatings” which can integrate additional functions such as marking, information, identification or traceability along all the product life cycle.

New manufacturing processes

New manufacturing processes can allow creating new steel structures with specific properties. The development of hybrid materials such as steel/refractory matrix or multi-laminar structures is one of the alternative ways to generate added value to steel. Developments in powder metallurgy are also of notable interest to create gradient or layered structures that can accommodate the harsh operating conditions of some niche applications or to obtain complex near-net shaped parts such as aeronautical components which currently would still involve a long process chain. Additive manufacturing is one of the most promising technologies that could spark these metal powder developments.

c) Continued improvement of existing production routes

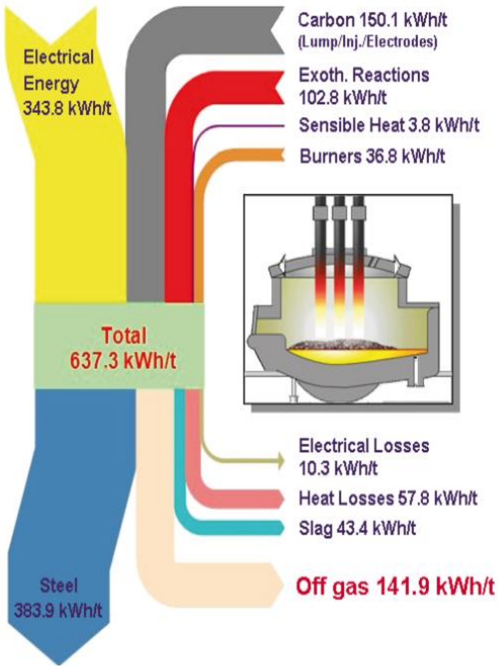

Figure 18: EAF Sankey diagram [A-P Hollands et al., METEC, Düsseldorf, 27 June – 1 July 2011]

Even as Europe accelerates the transition to low-carbon primary routes and deep electrification, continued improvement of existing and near-term production routes remains essential. This includes incremental measures that can be deployed within current asset bases, and that can also prepare plants for step-changes (e.g., new energy vectors, higher shares of scrap/DRI, tighter operating windows, and new monitoring and permitting requirements).

Incremental improvement remains a major source of competitiveness and near-term emissions reduction. The former version of the SRA highlights optimisation of industrial power consumption, waste heat recovery, energy management systems, and best available techniques to reduce environmental footprint. These themes remain essential, but post-2025 they are increasingly pursued through digitalisation-enabled, closed-loop optimisation that integrates sensing, modelling and advanced control.

A key shift is that “continued improvement” is less about isolated component optimisation and more about managing coupled systems under variability. This includes production stability with diverse input materials, grid-linked operation under renewable-dominant power systems, and minimising quality losses when operating flexibly. Literature emphasises that recent RDI increasingly treats robustness as a design objective—shifting from single-technology breakthroughs to system-level operational stability and flexibility.

- R&D&I priorities for continued improvement (capabilities and enablers) include:
- High-impact energy efficiency packages combining process optimisation, heat recovery and energy management with digital monitoring and optimisation, including the development of adaptive optimisation approaches that remain stable under changing production schedules and energy prices (qualitatively described where evidence is non-numerical).
- Advanced sensing and analytics for quality and yield, including hybrid modelling approaches where physics-based understanding is fused with data-driven learning to support reliable inference and control in complex processes.
- Predictive and prescriptive maintenance integrated with production planning, enabling reduced unplanned downtime and improved asset utilisation, while avoiding “pilot-only” solutions by designing for integration with legacy systems and plant operations.
- Process control and optimisation under variability, including soft sensors, model predictive control, and real-time optimisation approaches that can operate within safety and quality constraints. Evidence from

the literature highlights the presence of such approaches in recent research and demonstration contexts. However, they should be treated as enabling capabilities rather than prescribing single solutions.

Continued improvement therefore becomes a “bridge” theme: it delivers near-term operational gains while also building the digital, organisational and evidence foundations needed for deeper transformations. The focus is on solutions that are technically feasible, scalable, and compatible with industrial reliability constraints. Specifically, for the main steel production routes:

a) BF–BOF route (continued improvement while transition scales)

In the short-to-medium term, the BF remains a highly efficient reactor; therefore, systematic incremental abatement and efficiency measures remain relevant where BF–BOF assets continue to operate. Priorities include:

- Higher recycling rates in integrated plants, enabled by better scrap sorting/preparation and adapted steelmaking practices; where applicable, processing additional scrap in dedicated melting units.
- Use of pre-reduced materials (e.g., from direct reduction) to decrease carbon demand and reduce BF-related emissions intensity.
- Lower carbon load for heat and reductant functions through energy savings and partial substitution with leaner carbon sources, including biomass-derived alternatives where viable; note that analogous substitution concepts may also apply in parts of the EAF route.
- Improved internal use of energy-containing by-products, especially steel plant gases and waste-heat streams: higher internal valorisation for furnace heating and, where feasible, use of the reducing potential (CO/H_2) via internal recycling; this requires optimised preparation steps (cleaning, compression, preheating and/or reforming).
- CO_2 capture and use/storage readiness, recognising that integration concepts may include in-process/semi-integrated separation approaches and CO_2 valorisation routes; solutions should be developed with attention to integration constraints and cross-industrial cooperation needs.

b) EAF route (scrap- and DRI-based; continued improvement and operational robustness)

The EAF is positioned as a central unit of the future steel plant, whether processing scrap or DRI, and RDI emphasis is shifting from “melting” toward process stability, chemistry control, flexibility, and energy-system integration.

Key continued-improvement priorities include:

- Full electrification of heat inputs by substituting fossil-fuel burners with renewable-compatible alternatives (e.g., plasma-based or hydrogen-based heat input concepts) where supported by plant context and infrastructure.
- Adaptive process control and operational flexibility to accommodate variable renewable electricity availability and grid constraints (e.g., adaptive optimisation of power profiles), while protecting metallurgical quality and asset lifetime.
- Advanced sensing and control stacks (state estimation → inference → control), including soft sensors and model-predictive control concepts for refining, to improve repeatability, energy efficiency, and product quality under more variable inputs.

c) Potential role of ESF (electric smelting furnace)

Assess the potential of ESF-type electric smelting concepts, also called Smelter, Open Slag Bath Furnace or Submerged Arc Furnace, for utilisation of lower-grade iron-bearing feeds (e.g., lower-grade ore or DRI), including comparative positioning versus other direct-electrification pathways (e.g., plasma-based smelting reduction and related electrified concepts) and their implications for operability, refractory performance, and monitoring/control requirements.

d) Leaner use of raw materials

Resource efficiency is central to both competitiveness and decarbonisation. Core topics that are and will remain important are improving collection and sorting practices, developing standards for scrap quality, advancing scrap pre-treatment, and adapting processes to handle lower-quality ores and recycled materials. Post-2025, however, circularity constraints are more explicitly framed as strategic dependencies: the ability to expand EAF-based production and increase recycled content is conditioned by scrap availability, scrap quality, impurity management and the performance of sorting and upgrading technologies.

The literature highlights that circularity is not only a materials logistics problem but an RDI challenge requiring new process capabilities. One debated dimension concerns how policy might influence scrap retention and trade, with recognised tensions between keeping scrap available for EU production and maintaining incentives for collection and processing of lower-grade scrap. Rather than taking a position, the steel sector should recognise this as a boundary condition: innovation must enable profitable use of lower-grade and more heterogeneous scrap streams, reducing dependence on "prime" scrap while maintaining product quality.

A consistent implication is the strategic importance of **advanced sorting and scrap upgrading** as a decarbonisation enabler. This includes AI-enabled sorting, sensor-based grading, robotics, and process-integrated approaches to impurity detection and removal, framed as an industrial capability gap rather than a niche technology area. Where evidence is qualitative, the emphasis is on capability building and demonstrator validation rather than quantified performance claims.

Leaner use of raw materials also includes valorisation of by-products and residues (dusts, sludges, slags, mill scale, off-gases, but also **societal residues** such as plastics, used tyres, car fluff, etc.), both to reduce waste and to recover value and critical materials where feasible. Strategies should address these streams within a circular system approach that combines process-route design, residue treatment and value-chain integration, while remaining conservative in claims where sources provide qualitative rather than quantitative evidence.

R&D&I priorities for leaner use of raw materials (capabilities and enablers) include:

- Scrap quality management and upgrading, including sensor-based sorting and grading, AI-enabled classification, and robotics to increase recovery of usable scrap fractions from heterogeneous streams; and integration of these technologies with steelmaking and refining constraints (impurity tolerance, melt shop practice).
- Secondary metallurgy and impurity management, including process and metallurgy innovations to handle tramp elements and contaminants, enabling higher recycled content without unacceptable quality degradation (qualitatively stated).
- Standardised data and lifecycle inventories for recycling routes, recognising that fragmented data for emerging sorting and purification processes limits credible evaluation and comparison. Strategies should promote harmonised data structures and datasets to support consistent MRV and value-chain claims.
- By-product and residue valorisation, including technologies and system integration concepts that improve internal recycling, reduce landfill, and enable utilisation in other industries where feasible, while addressing environmental and operational constraints.
- Development of alloying strategies to limit the use of critical raw materials currently used for several steel grades, e.g.,, Niobium.

Leaner raw material use must be treated as a strategic enabler for both decarbonisation and resilience. The post-2025 RDI approach therefore prioritises technology packages that combine physical infrastructure (sorting and treatment), metallurgy (impurity management), and data governance (traceability and LCI), with demonstrators designed to validate performance at scale and under realistic variability.

Iron-ore is the base material for traditional BF/BOF route and new DR/EAF route. DR/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 content of 65 wt.% and above, which has lower levels of impurities. 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 (iron contents <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).

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. The 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). As mentioned in Section 2.1.2, the ESF will create a link between new and existing installations for crude steelmaking (BOF/EAF) in the medium- and long-term allowing the use of low/medium grade ores with Fe contents <65 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 ores, 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 DR process).

e) Carbon-lean steelmaking and GHG emissions of the BF-BOF route

The steel industry is willing to actively contribute to the greenhouse gas emission (GHG) reductions needed for keeping the global temperature rise this century well below 2 degrees Celsius as agreed at the COP21 in Paris.

Furthermore, carbon-lean steelmaking remains the central transformation challenge and the principal determinant of future competitiveness and strategic autonomy. The previous version of the SRA frames a progressive switch from carbon to electricity and “green” hydrogen, alongside carbon capture, utilisation and storage (CCUS), increased use of biomass as a carbon source, and improved recycling of process gases and other by-products. This framing remains relevant, however, European RDI is moving from conceptual route exploration to building and validating industrial-scale solutions, supported by late-stage pilots and demonstrators.

The emerging landscape is not characterised by a single “winning route” but by portfolio logic under uncertainty. Sources highlight debates and hedging strategies: hydrogen-based direct reduction is prominent in roadmaps, yet there are concerns about infrastructure timing and investment cycles; direct electrification options may be more energy-efficient in principle but are less mature and carry scale-up uncertainties. Rather than resolving these debates, RDI portfolios should be explicitly designed to reduce uncertainty through demonstrators, comparative assessment and robust integration evidence.

A further implication is the need for stronger **evidence chains** linking technology performance to economics and system constraints. Literature highlights extensive reliance on Techno-Economic Analysis (TEA) and LCA to validate feasibility, including increasing attention to dynamic energy pricing and renewable-dominant grids. At the same time, there are explicit cautions about scale uncertainty, particularly when extrapolating from pilot-scale performance to industrial scales with different thermal efficiencies, refractory life and stability constraints. This reinforces the need for larger demonstrators and transparent reporting of scale-relevant operational data.

In the European context, scaling is increasingly addressed through dedicated late-stage funding modalities and expectations such as the RFCS “Big Ticket” pilot/demonstration logic with explicit TRL targets and requirements for industrialisation strategies, economic viability assessment and energy/material balances. This reflects a post-2025 shift toward implementation readiness: carbon-lean routes must be demonstrated in configurations that are credible for industrial integration, not only in laboratory settings.

R&D&I priorities for carbon-lean steelmaking (capabilities and enablers) include:

- Hydrogen-enabled routes: technologies for hydrogen production interfaces, handling and integration in ironmaking/steelmaking routes, with emphasis on industrial operability and stable quality under variable feedstock and energy conditions (qualitative).
- Direct electrification options: exploration and demonstration of electrified process routes where maturity allows, with explicit focus on scale-up uncertainty reduction and industrial integration evidence.
- Smart carbon usage and CCUS/CCU: continued development of capture and utilisation concepts and integration with steelworks off-gases and energy systems, framed within credible industrial integration and policy/market conditions (qualitative).
- Downstream decarbonisation: targeted RDI for reheating, rolling and finishing where fossil fuels remain significant, including electrified reheating and alternative burners, with demonstration emphasis.
- Systems integration and flexibility: coupling of low-carbon routes with renewable-dominant energy systems, operational flexibility, and resilience to energy price and availability dynamics (qualitative).

In summary, carbon-lean steelmaking RDI must be organised as a staged portfolio that (i) advances multiple routes, (ii) reduces uncertainty through progressively larger and more integrated demonstrations, and (iii) anticipates the enabling conditions required for scaling (risk sharing, permitting, standards, market pull and skills).

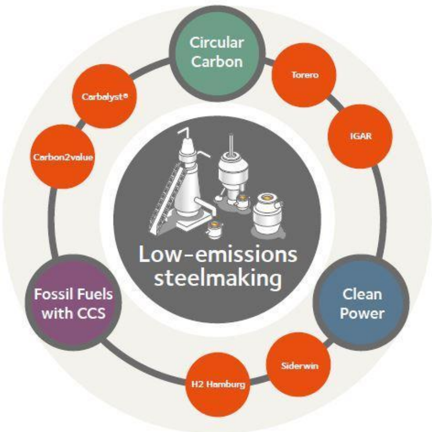

Figure 19: Pathways in low-carbon steelmaking

f) Additional R&D&I considerations

R&D&I approaches are increasingly defined by an explicit execution chain where technology progress alone is insufficient. Projects must anticipate how evidence is translated into investment decisions and market uptake, including the ability to demonstrate MRV-ready performance, industrial operability and integration feasibility. Further topics to consider are:

a) Demonstrators, testbeds and learning loops

Demonstrators are not only validation assets but learning platforms. Demonstrator programmes must generate operational evidence, integration experience, workforce learning, and data that can be reused across sites. They should therefore be designed with explicit learning loops—linking process modelling, digital twins, measurement plans, and operational decision support—rather than as "single-shot" installations.

Testbeds should be seen as structured environments for integration and qualification: enabling accelerated experimentation, interoperability testing, and safe validation of automation and cyber-physical functionality. This is especially relevant for smart factory enablers (data pipelines, edge/cloud architectures, and AI-supported control) that must integrate with legacy systems and satisfy safety and cybersecurity constraints.

b) Standards, permitting readiness and MRV

Permitting delays are described as a major barrier for new installations (e.g., hydrogen/electrolysers or capture units), and the policy landscape is presented as seeking to accelerate permitting and create lead markets through labelling and procurement criteria. Permitting readiness, MRV and standardisation should be treated as early design requirements: demonstrators should generate the evidence and documentation needed for subsequent replication and investment.

c) IP, data sharing and interoperability

A recurrent tension is that stronger traceability and data sharing expectations can conflict with confidentiality and vendor lock-in risks. Sources reference increasing strategic value of open interfaces and portable architectures and highlight that expanded value-chain information exchange needs defined access-control patterns and pre-competitive data layers. This calls for a pragmatic data governance stance for not slowing down the oriented to interoperability and data portability where it enables innovation and deployment, while protecting confidential operational knowledge through layered access and clear IPR/data-sharing agreements.

d) Skills and workforce as a deployment enabler

RDI approaches must acknowledge that deployment speed is constrained by skills availability and organisational readiness. Skills, training and organisational learning should be treated as part of the innovation system, particularly for pilot/demonstration execution, digitalisation adoption and safe operation of new routes.

2.3. Smart Factory (*Industry 4.0 and its successor Industry 5.0*)

2.3.1. Introduction

The journey toward realizing a fully autonomous and adaptive Smart Factory in the steel sector involves a complex evolution from legacy industrial production systems to next-generation digital ecosystems. This evolution builds on the foundational concepts of vertical, horizontal, and transversal integration. These pillars continue to be enabled and accelerated by an expanded set of disruptive digital technologies, now including Artificial Intelligence (AI), Internet of Things (IoT), Digital Twins, Smart Sensors, Machine Learning, Cloud and Edge Computing, Augmented and Virtual Reality (AR/VR), Big Data Analytics, and robust, modular system architectures.

ESTEP's term "Integrated Intelligent Manufacturing" (I^2M), introduced prior to the popularization of "Industry 4.0," remains highly relevant and now evolves into a broader and more connected paradigm driven by real-time data, autonomous decision making, and predictive intelligence.

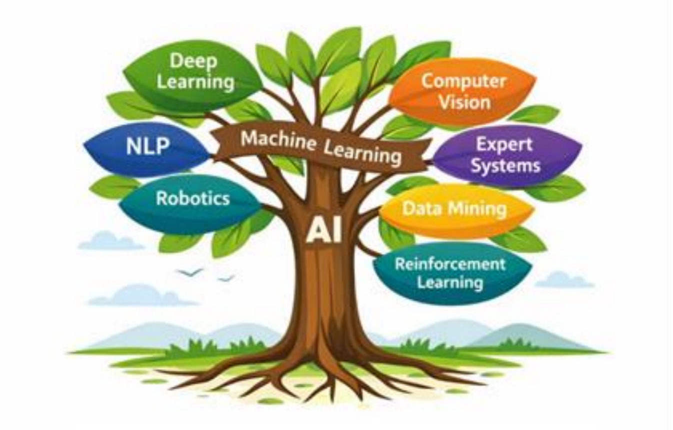

Figure 20: Schematic representation of AI as a tree.

Industry 4.0 focuses on the implementation of the integration of seamless data exchange among its two key directions of integration i.e., Horizontal and Vertical, and cyber-physical systems to increase efficiency, while Industry 5.0 builds upon this by integrating a human-centric, sustainable, and resilient approach. The key difference is that Industry 4.0 aims for optimized, automated production, whereas Industry 5.0 seeks to harmonize technology with human creativity and well-being, prioritizing sustainability and a human-robot collaboration over purely autonomous system. The integration of such factors in an AI and human cooperative scenario, might lead to the introduction of a new paradigm named Industry 6.0 that in practice, is an ecosystem of humans and cyber-physical systems which hold the full control of the manufacturing chain and the relevant components i.e., the nearest declination to the definition of Smart Factory as a holistic chain based on the generalized predictive capabilities, and the autonomous execution of plant operations as well as, managing event-driven scenarios where equipment are potential extensions, empowerment factors, and augmentation, of the natural human capabilities.

Figure 21: Economic evolution CAGR/GMS AI augmented process control

Figure 20a shows that the top AI manufacturing application area in terms of worldwide market size (GMS) is the "AI Augmented Process Control" sector (see the orange bars) around $2.183 Mn.

Furthermore, Fig. 2a also shows that the top AI market size (GMS) of the EAF Route[27] is lower than the sum of all the other topics that is around $4.444 Mn. Instead, the expectation of taking benefits remains high (values of CAGR higher than 15% are considered as a very high value) confirming that the expectations seem to be independent on the branch leaves di Figure 20 i.e. taking the risk of the buzzword" effects or "anything as long as AI". So, the obvious fact that investments on AI must be carefully analysed, leading to necessity of supporting R&D

[27] Data comes from the most reputed observatories of the industrial economic data and analysis of trends such as MarketsAndMarkets https://www.marketsandmarkets.com/Market-Reports/artificial-intelligence-manufacturing-market-72679105, Grand View Research https://www.grandviewresearch.com/industry-analysis/generative-ai-market-report and Fig 22 is authored by the SF FG.

also on the deployment phase i.e. not only on the R of the R&D&I acronym but also on the "I" for defending the leading position of the European Technology in the steel sector.

Moreover, the top position on the one side and the difference between the two values might be explained by the needs of accuracy velocity, and predictability of AI, that are needed by the steel sector (see for example, process setup, diagnosis of drifts, scenario evaluation etc.) In addition, the following considerations can be mentioned: 1) the Process Control topic include Monitoring, in-line, real time data analysis etc. where accuracy, fast reactivity and Continuous Learning are premium factors. 2) the others topics, where the previous factors are also important but other AI characteristics are premium factors for activities such as design where Generative AI may play an important role. Whatever, the supervision or the direct execution of activities needs Human Centricity approaches. The two very different values demonstrate that, pervasiveness of AI but also, its differentiation push R&D&AI activities with large spectra of applications, and as an enabler of Human Centricity rather than a risk.

2.3.2. Needs and challenges

European steel production is engaged to defend its worldwide technological leadership by embracing the challenges of competitiveness, sustainability, and agility. To achieve this, the Smart Factory vision must address the overarching needs of top resilience, sustainability, and quality. These must be pursued within a digitally enabled, customer/stakeholder-centric manufacturing system.

New and maturing technologies such as AI-driven control systems, real-time process simulations, predictive maintenance, and autonomous quality monitoring systems offer tools to optimize operations while enhancing flexibility, transparency, and resilience. However, implementation must be treated as a socio-technical transformation: organisational readiness, workforce skills, and human-centric design are required so that advanced automation supports people and system resilience rather than only increasing complexity.

The integration of vertical (plant-level) and horizontal (supply-chain) systems continues to be essential. However, these results must be achieved through real-time connectivity, machine learning-enabled predictive insights, and decision-making automation. These layers must also be underpinned by robust data governance, cybersecurity protocols, and open communication standards. In addition, decision-making automation must increasingly operate under uncertainty, integrating probabilistic forecasting, optimization and real-time diagnostics (fault/anomaly detection) to support safe, robust actions under disturbances, process variability and dynamic energy constraints. In this context, the principal needs and challenges include:

1. *Closed-loop digitalisation under harsh steel-plant conditions*
- Reliable state estimation where direct measurement is limited (soft sensors) to provide actionable inputs for control and optimization.
- Advanced control and optimisation (including model-based approaches) that improve stability, productivity and quality while handling disturbances and constraints in real operations.
- Interpretable/operationally acceptable AI for quality and defect prediction, embedding process knowledge where feasible to support trust, auditability and adoption.

2. *Digital Twins as operational companions, not only engineering models*
- Digital Twins increasingly act as continuously updated operational counterparts that integrate real-time data with models to simulate, predict and optimise production, maintenance and logistics.
- A key challenge is orchestration across process islands and time scales, potentially involving distributed or multi-agent coordination approaches as system complexity increases (e.g., in decarbonised routes and under dynamic energy constraints).

3. *Data governance, interoperability, and circularity-enabled traceability*
- Robust data governance and open communication standards remain prerequisites for vertical/horizontal/transversal integration.
- Data interoperability is increasingly framed as a barrier for circularity (insufficient lifecycle composition/traceability data for high-quality recycling and scrap upgrading). Interoperable

product/lifecycle data structures are therefore an emerging enabler for circularity and high-quality recycling loops.

- Data sharing must be designed together with IP and exploitation rules (pre-competitive vs competitive layers), so that collaboration is feasible without undermining competitiveness.

4. *Cybersecurity and resilient architectures*

- Cybersecurity protocols remain foundational, and the Smart Factory increasingly requires cybersecurity-by-design to protect intellectual property, process stability and operator safety.
- Resilient, modular system architectures are needed to ensure availability and safe fallback modes as autonomy and connectivity increase.

5. *Workforce transition and human-centric operations (Industry 5.0 and beyond)*

- Skill ecosystems and "AI-fluent" operational capabilities become more critical as plants deploy advanced analytics, Digital Twins and autonomous decision support; the human role shifts toward supervision, exception handling, and continuous improvement in collaboration with digital systems.
- Beyond Industry 5.0, sources increasingly discuss a post-5.0 trajectory (sometimes framed as "Industry 5.0+" or "Industry 6.0") characterised by higher autonomy, multi-agent optimisation, and tighter integration with broader industrial and energy systems—while maintaining human oversight and governance.

2.3.3. Relevant technologies

Key enabling technologies for the future of the European steel industry are increasingly digital-driven. Indeed, metallurgy and process knowledge remain essential, but they will be empowered and supported by digital technologies including many domains of Artificial Intelligence (AI), as they are capable of gathering and analysing huge volumes of heterogeneous data, extract information and further knowledge and make it rapidly available to end-users. This will support processes and materials development as well as establishment of resilient, human-centric and sustainable value chains. In particular, the key advanced digital technologies which can be considered as strategically critical for the steel sector include:

- Machine Learning (ML) in all its different forms (see the exemplar Figure 21) and Multimodal AI for advanced data analytics and modelling. This includes the possibility to merge physics-based and data-driven approaches (the so-called Hybrid-AI) to improve transparency, explainability and trustworthiness of ML-based models.
- Federated Learning (FL) and Continual Learning (CL) to improve transferability and resiliency of ML-based solutions.
- Agentic AI especially applied in optimization frameworks and to support daily operations and training of workforce.
- Generative AI to explore the possibilities offered by metallurgy, material science and engineering in products design and process optimization.
- Non-structured data spaces which are mostly suitable to support AI, quality monitoring and materials tracking solutions.
- Digital Twinning (DT) of processes and products to support anticipation of anomalies and early decision making
- Extended Reality (XR) technologies including Virtual Reality (VR) and Augmented Reality (AR) to enable human-centric, resilient, and knowledge-intensive manufacturing systems, particularly when integrated with DT and AI-based decision-support systems for real-time, context-aware interaction between operators and complex processes.
- Advanced materials characterization solutions (e.g., LIBS, OES, XRF, etc..) to be integrated with AI tools for rapid and punctual characterization of feedstocks, by-products and waste streams (solid, liquid and gaseous) to enable their purification, sorting, optimal valorisation, etc. in the context of process optimization and implementation of Circular Economy and Industrial Symbiosis solutions.

- Edge computing and AI on the edge devices for data collection and real-time integration/pre-processing, handling real-time inference and supporting FL in the context, e.g., of product quality management, process optimisation and predictive maintenance.

Figure 22 : Machine Learning Taxonomy

2.3.4. Relevant applications for the steel sector

In line with the transition toward Industry 5.0, a portfolio of advanced digital applications and key development themes can be identified as strategically critical for the steel sector.

- AI-Driven Materials Design: AI can be a strategic accelerator for materials and steel grade development. By combining ML with computational materials modelling, AI enables more efficient exploration of composition–process–microstructure–property relationships, significantly reducing development time and experimental effort.
- Advanced inspection, sensing, and property prediction technologies: Advanced inspection, characterisation, and AI-based property prediction technologies for steel and steel by-products rely on the integration of multi-modal in-line sensing (including spectroscopic, imaging, ultrasonic, and electromagnetic techniques) with machine learning and physics-informed models. Within this framework, DT approaches play a central role by coupling physics-based models with real-time operational data to create virtual representations of steelmaking processes, enabling predictive optimisation, scenario analysis, and enhanced decision support across the value chain. The effectiveness of these solutions is further amplified by IoT-based architectures and edge computing, which ensure scalable, secure, and continuous acquisition and integration of high-frequency sensor data from heterogeneous sources.
- AI-based process optimisation and control. AI-based technologies, including advanced ML, generative AI, agent-based systems, and multimodal AI, are essential for predictive and prescriptive decision-making in complex steelmaking systems. The integration of data-driven models with metallurgical domain knowledge and physics-based process models enables improvements in energy efficiency, operational stability, and product quality, while contributing to Industry 5.0 objectives through human-centric decision support and improved occupational safety.
- XR-based monitoring and maintenance. In operational contexts, AR-based solutions support real-time decision-making by overlaying contextualised data into the operator’s field of view. In parallel, VR and mixed-reality environments enable immersive simulation of steelmaking processes, plants, and critical operations, allowing safe testing of scenarios, validation of procedures, and optimisation of human–machine interaction.
- Digital (Material) Product Passport (DMPP). The DMPP is expected to become a central policy instrument enabling transparency, traceability, and comparability of steel products across their full life cycle. The DMPP development requires robust and standardised, machine-readable data architectures that are

capable of representing steel-specific information related to chemical composition, microstructure, processing routes, embedded carbon footprint, and end-of-life options. The integration of DMPPs with eco-design tools, life cycle assessment methodologies, and sustainable procurement frameworks enables the operationalisation of Life Cycle Thinking and supports compliance with evolving European regulatory requirements.

- Steel Data Spaces. The implementation of DMPPs and related digital services relies on the development of a Steel Data Space, interoperable with broader Industrial Data Space initiatives. Such data spaces provide a trusted environment for cross-company data sharing, ensuring data sovereignty, cybersecurity, and interoperability. They enable value-chain integration, evidence-based policy implementation, and coordinated action across industrial ecosystems, while safeguarding competitiveness and intellectual property.
- Digital platforms for industrial symbiosis and circular value chains. The transition towards a more circular and integrated industrial system will be further supported by cross-sector industrial symbiosis enabled by digital marketplaces. Digital platforms will facilitate the matching of steel by-products, residues, energy streams, and services with demand in other industrial sectors, improving resource efficiency and enabling new value chains. Their effectiveness depends on high levels of data transparency, interoperability, and integration with economic and logistics tools, making industrial symbiosis technically feasible and economically scalable.

2.3.5. Enhanced Integration Concepts

The digital transformation of the European steel industry increasingly depends on advanced integration concepts capable of linking physical processes, digital systems and value-chain actors. While many steel plants have already implemented elements of smart manufacturing and AI-based data analysis and modelling, the next phase requires coordinated R&I efforts to move from locally optimised solutions to system-level, scalable integration architectures as well as inherently transferable solutions supporting competitiveness, decarbonisation and resilience. This implies to cover both the vertical and the horizontal dimension of the integration (see Figure 23-24).

a) Vertical integration

Vertical integration now entails seamless data flow across all levels of the automation pyramid, from sensor networks and control systems to plant-level execution systems and enterprise-level optimization tools. Future research must enable reliable, low-latency data flows across this automation pyramid, supported by interoperable architectures, standardised interfaces and semantic data models tailored to steelmaking processes.

From an R&I perspective, priorities include the development of AI-enabled control and decision-support systems, coupling physics-based models with data-driven approaches to improve process stability and flexibility with respect to variability in feedstocks, production demands and energy provision while enhancing energy and resource efficiency, yield and product quality. A particular focus is required on integrating vertical digitalisation with legacy assets, enabling retrofit-friendly, modular solutions that facilitate gradual deployment across heterogeneous European steel plants.

b) Horizontal integration

Full horizontal integration demands a digital thread that connects production units, logistics systems, suppliers and customer interfaces. This dimension is gaining strategic relevance in the light of increasing requirements for traceability, transparency and lifecycle data, notably driven by evolving European regulatory frameworks and customer expectations.

Research efforts should focus on **secure and interoperable data-sharing mechanisms**, including industrial data spaces, digital twins extending beyond plant boundaries, and standardised data structures supporting product and material traceability. Horizontal integration must enable real-time synchronisation among production, order fulfilment and logistics, while safeguarding data sovereignty, cybersecurity and competitiveness. Achieving this level of integration is essential to support mass customisation, circular value chains and the deployment of Digital (Material) Product Passports within the European steel ecosystem.

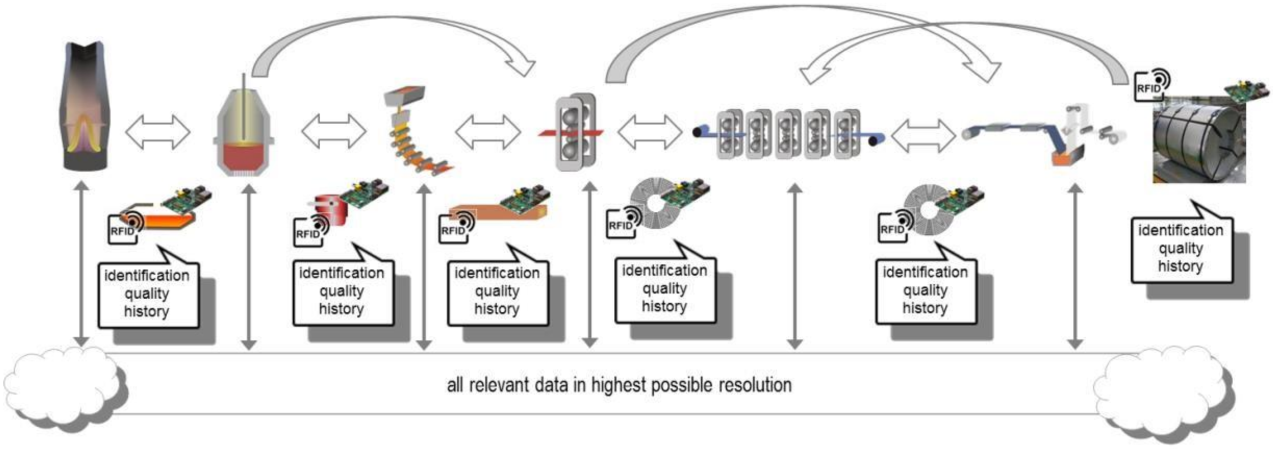

Figure 23: Horizontal integration

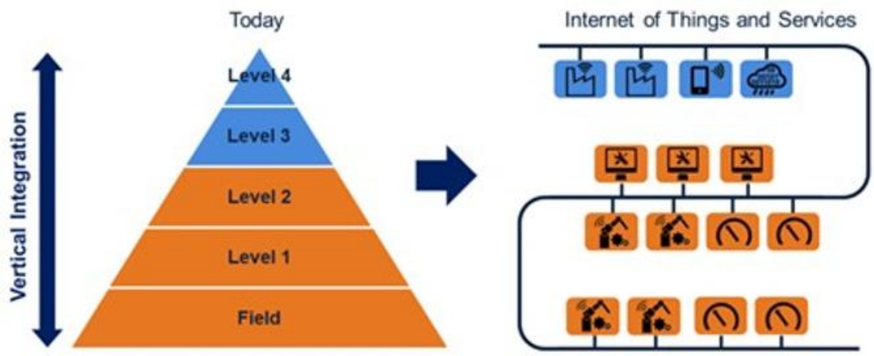

Figure 24: Vertical integration

2.4. Steel applications for transport

2.4.1. Introduction

The European steel sector constantly addresses the challenge of meeting customers' demands for a broad variety of ever more sophisticated high-performance materials. To meet these needs, direct partnerships between steel producers and their immediate customers are a strong requirement. Such collaborations, supported by academic research, are major features of new product development in the steel industry and an essential element in the promotion of steel use. In the framework of this Strategic Research Agenda, the transport, construction and energy sectors are regarded as priorities.

Optimal engineering and processing of advanced steel products is a challenge that must be addressed by improving computer-aided-engineering modelling and existing production technologies or by developing new processes or technologies in combination with adapted design.

2.4.2. Issues and challenges

Mobility is a basic requirement for people in modern industrial and knowledge-based societies. In the EU freedom of movement for both persons and goods is also a prerequisite of the European integration. Value creation and economic prosperity have only been made possible by the spatial mobility of people and goods.

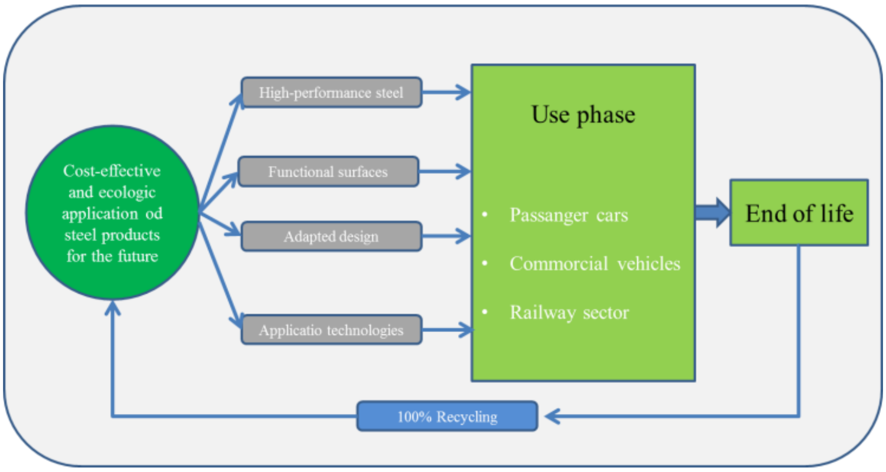

Figure 25: Appealing steel solutions for end users: cost-effective and ecologic application of steel products to meet society's needs.

Energy consumption in the traffic and transport sector is dominated by road (73%) and air transport (12%). Worldwide, the transport sector is responsible for about 20% of greenhouse gas (GHG) emissions. Energy efficiency of vehicles and alternative powertrains are at the heart of the Research and Innovation strategy of the transport sector. Light weighting of the vehicle structure can account for 8 to 10% of the CO2 emission reduction. In addition to new powertrain technologies in combination with hybrid- or electric engines, new affordable lightweight concepts for passenger and goods transportation systems, new transport concepts and construction methods are required in order to be able to reduce greenhouse gas emissions despite increasing traffic volumes.

The total 'Life Cycle Assessment' (LCA) of any product refers to the assessment of the environmental load during the complete lifetime of the product, from the raw material used for manufacturing, the emissions generated during the entire lifetime, and finally the disposal of the product. Steel is a very efficient material regarding GHG emissions while taking into account the whole life cycle, i.e., the production phase, the use phase and the end of life (the effective recycling).

Ancient practices took only into account the emissions arising from the fuel combusted by the engine, the so called 'tail-pipe emissions' or 'tank-to-wheel' emissions. In this case, the climate impact by the material production is not given any attention. However, as the drive-train gets more CO2-efficient by electrification or improved internal combustion engines, the significance of material production towards climate change will be higher. Therefore, to account for the environmental load of the complete life cycle, the following 3 phases should also be included: the fuel production phases (well-to-tank emissions), the material production phase for vehicle manufacturing and recycling.

Every year many thousands of people are killed in Europe in traffic accidents and more than 1.7 million people are injured. Road deaths are still the primary cause of mortality among the young. New strategies for maintaining mobility while mitigating the consequences of accidents will therefore be necessary in the future. In this context, the safety of passengers, drivers and pedestrians is increasingly becoming an important priority, as recommended by the EU Commission which targets a decrease by 60%. With its highest strength level, steel plays an important role in securing safety requirements of today and future trans-port systems.

2.4.3. Research and innovation areas of the transport sector

Work in close cooperation with the customers and all stakeholders of the supply chain is particularly important for the transport sector for proposing steel solutions meeting their requirements. The new solutions should use all technical progress: new metallurgy of steels, new functional coatings, new application technologies (forming, welding, joining, etc.) all included in an optimized design taking advantage of all these progresses. Mainly the automotive industry - as well as the whole transport industry in specific areas - is dedicated to respond to the mobility needs of individuals and those of society as a whole. The targets to be derived from these challenges are:

- Environmental sustainability related to
    - energy consumption reduction
    - CO_2 emissions reduction
    - resource efficiency
    - ease of dismantling
    - improve recycling behaviour
- Circular economy
- Safety
- Reliability
- Cost effectiveness
- Compatibility with new powertrains or self-driving vehicles

Those societal challenges will be addressed collectively by working in close co-operation with all relevant stakeholders.

The steel industry and the automotive industry in the EU have to maintain their leadership in the world market. Simultaneous engineering and concurrent engineering are tools to meet the challenges of the world market for the targeted manufacturing of vehicles. The steel industry, with its expertise in production processes and tailoring of material properties, and the automotive sector, with its vision for the future development of vehicles, are well prepared for an EU joint action to achieve a quantitative leap in the construction of the car of the future, which would not be attainable through the partnership of individual steel and automotive companies. The EU steel and automotive industry can also benefit from the support of a dense network of academic research groups in EU working in the frame of metallurgy and mechanics, and more particularly on steels and steel solutions.

The automotive industry stimulates lightweight construction innovations. It is essential for the steel industry to exploit its material expertise through material development and component design for use in mass production and, in cooperation with the transport and especially the automotive sector, to achieve further improvements or totally new solutions for vehicle concepts. Multi material mixed structures need to be discussed and comparable, affordable steel solutions have to be offered.

The targeted development of a production and manufacturing chain using new high-performance steels for lightweight constructions including new or modified forming and joining techniques and new coating processes

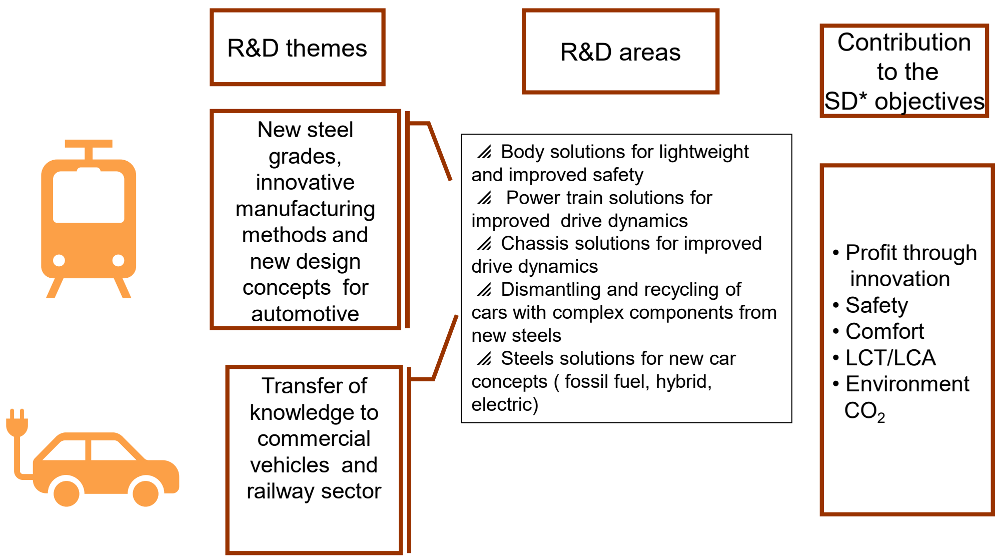

Figure 26: Appealing steel solutions for end users (transport sector): achieving the SD objectives through R&D

will be a very ambitious R&I aim. The new hot forming steel grades with advanced corrosion protection coatings and new process technology approaches like tailored properties leading to weight reduced steel cars are good examples of the capability of the steel industry - And the development is still going on with the third generation of Advanced High Strength Steels dedicated to cold stamping which will also contribute to address the future safety and weight reduction challenges. The significant advantages of the new generation of Advanced High Strength Steels can be efficiently exploited only by new design principles and simulation methods in advanced engineering.

The R&D&I themes to be derived from these challenges are:

- Development of complex components from new high strength steel grades using innovative manufacturing methods
- Development of new surfaces for optimized forming behaviour and corrosion protection
- Design of optimized steel solutions for the cars of the future
- Transfer of the knowledge to the whole transport sector especially to the truck and train industry
- Enabling technologies for new advanced high strength steels like spring back management or adapted joining techniques

2.4.4. Socio-economic aspects of the automotive sector

The importance of the transport and especially the automotive sector for the EU economy is characterized by the following figures:

- There are more than 14 million new car registration units per year in EU (15) and more than 17 million new vehicle registration units per year (including commercial vehicles, coaches and buses);13.8 PC +1.5 LC
- The passenger car share represents an estimated turnover of about € 300 bn/year in the EU (15);
- The European vehicle park reached nearly 220 million units in 2003 of which passenger cars account for about 87%;
- 23% of cars in use in the EU are diesel powered against 16 % in Japan and nil in the US;
- The number of directly employed persons in the production of motor vehicles is about
- 1 050 000 and the total number including indirect employment is about 1 900 000.
- Taxes associated with the purchase and use of motor vehicles contribute over € 350 bn/year to the revenues of the EU Member States Governments

Steel has an important transversal role to play in enabling the technologies necessary to achieve the challenges faced by the automotive industry. The automotive sector program would facilitate the integrated approach – design, materials and processes – needed for further innovation and value addition in the automotive industry. Several aspects are covered:

- Ecological aspects. In an ecological comparison of the products, taking life cycles and the recycling ability of steel (LCA) into account car bodies, made e.g., with cold and hot forming high strength steels, tailored blanks and tailored tubes (closed profiles) with more than 20% saving in weight, can be far less detrimental to the environment than today's conventional bodies regarding the resource efficiency indicator 'Life Cycle Assessment' (LCA) and the "global warming potential" (GWP). Improving the drive train efficiency would bring a strong contribution to decrease CO2 emissions, eg by using efficient electrical steels for electric or hybrid vehicles machines.
- The implementation of innovative technologies has in the past contributed to reducing the impact of motor vehicles on the environment. To give a few examples: 100 of today's cars produce the same amount of emissions as an average car built in the 1970s, the amount of local pollutants has been reduced 20-fold in the last 20 years, while vehicle noise levels have been reduced by 90% since 1970. Such progress should be pursued in the coming decades.
- Steel is a material easy to recycle (370 million tonnes per year)
- Societal aspect of increasing the integrated safety for all road users

2.4.5. Stakeholders

- Steel industry
- Steel research centres
- Transport sector
- Suppliers (surface treatments and chemical industry)
- Suppliers to the transport industry
- Universities & academic research centres

2.5. Construction and infrastructure sector

2.5.1. Introduction: context, ambition & foresight

The European construction industry supports the EU economy, by providing it with buildings and infra-structure that supports all other economic and social activities. It constitutes the largest single economic activity in Europe, contributing 8.8% of GDP, 28.7% of industrial employment and 6.5% of total employment (14.2 million people). Around 95% of the approximately 3 million construction companies are SMEs and in 2014 it was estimated that every €1 spent on construction output generates €2.84 in total economic activity. In use, buildings consume about 40% of global energy and are responsible for around one third of all greenhouse gas emissions. As such, a major goal in the EU is to promote green energy and encourage "smart infrastructure". Cities, and the buildings within them, are also subject to the pressures of increasing urbanisation, growing populations, climate change and, especially in the developed world, an ageing population. All these factors are driving change in the way that buildings are constructed and used and in the way that cities are developed and run.

Steel is one of the most important construction materials, competing with other materials but also opening up completely new possibilities. Figures from the World Steel Association indicate that construction continues to be the single largest market for steel, accounting for 52.2% or 838Mt globally. In Europe the mix is estimated at 40% or 42.5Mt. Many steel producers consider the construction sector to be among their largest single markets in terms of volume. To exploit the full potential of steel as a construction material, the development of new grades, building components and systems, composite structures, and construction technologies is needed. Safety and health are the main performance aspects of the built environment essential for the security and quality of life of occupants and other stakeholders.

The quality of built environment has a strong influence on the performance of individuals and organizations and on the well-being of society in general. However, the level of funding from European and national programs does neither properly reflect the significance of construction as an economic activity, nor the significance of the built environment as a fundamental contributor to the quality of life.

2.5.2. Issues and challenges

There is a wide range of pressures, expectations and drivers seeking to influence and shape the construction and infrastructure sectors. The most important issues and challenges are presented by market demands. There is a need for the industry to deliver increasingly innovative products at competitive prices within tight environmental regulatory targets.

The challenge for the industry is, simply, to find new ways or delivering new products with less resources and raw materials. Internally, the industry as a whole is not yet geared for a coherent response to these challenges. It remains highly fragmented and there is a need for much closer cooperation between leading suppliers and major construction companies. A key aspect of the steel industry strategic plan over the next 10 years is therefore to work more closely with customers seeking strategic alliances with research organizations and commercial companies. Strategic alliances with the EU construction sector would need to address the scientific, industrial and societal issues to meet the following global challenges:

- Impact of Climate Change
- Safety and health in manufacturing, construction and use of construction products
- Resource efficiency through improved recycling and reuse of construction material
- Life Cycle Thinking and Life Cycle Assessment for the construction sector
- Energy Efficient Buildings for new constructions and refurbishing of existing ones
- New EU directives and global challenges necessitating the tightening of regulations
- Resilience to and recovery from natural and accidental events like fire, earthquakes, flooding, and other accidental loadings
- Urbanization and other demographic changes

- Keeping pace, harnessing and facilitating information and communication technology integration with buildings and infrastructure and industry processes.
- Implementation of biomaterials and nanomaterials
- Integrating the supply chain and addressing the challenges of delivery
- Issues emerging from increasing partnership with customers.

Consideration of these factors leads to the definition of the following R&D areas grouped under three major R&D themes:

- High-performance
    - Clean and green
    - Resilience
    - Robustness
    - Adaptability
    - Integrity
    - Blast resistance
- Digital economy
    - Building information modelling
- Industrial/ Manufacturing 5.0
    - Energy-efficiency
    - Automation/Robotics
    - Modularisation
    - Additive manufacturing
    - Recycled materials
    - Design for reuse or flexible assembling
    - Digital solutions for materials tracking
- High added-value solutions and products for building and construction
    - Energy integration
    - Energy storage/harvesting
    - Multi-functional envelope
    - Renovation/refurbishment
    - Structure for disaster relief
    - Structures to resist man-made hazards
    - Intelligent/interactive buildings
    - Effective use of HSS
    - Hybrid steel/composite or laminate
    - Infrastructure solution
    - Structures for clean energy
    - Intelligent infrastructural components

2.5.3. Research and Innovation areas: exploring solutions and turning them into opportunities for both business and the planet

a) *High performance*

Blast resistance/ Structures to resist manmade hazards

Buildings are conventionally designed to resist loads that are applied over timescales much greater than their natural period of resonance, and the response to such loading events is governed by the peak load. When structures are subjected, accidentally or intentionally, to loads which are introduced over much shorter time periods the response is governed by a combination of the peak load and the impulse (i.e. the integral of force with respect to time). Under such conditions of dynamic or impulsive loading, where the loading event imparts significant momentum to the structure, the ultimate effect on the structure depends on the ability of the structure to sustain the forces associated with subsequently bringing its own mass to rest. The strategies appropriate to the effective management of such loading cases differ from those associated with the management of slowly-applied environmental or service loads.

In the contemporary urban environment, there may be concerns relating to the following sources of impulsive or dynamic loading:

- Accidental or deliberate collision of vehicles against the building
- Exposure of the building to airborne shock-waves arising from accidental explosions such as those that might arise from the ignition of leaking fuel gas
- Unintentional detonation in peacetime of military munitions that had remained undiscovered from earlier periods of conflict
- Deliberate malicious attack by terrorists or criminals armed with improvised explosive devices or with illicitly-obtained military munitions.

Various strategies are appropriate to the different scenarios. In the cases of vehicle collisions or criminal/terrorist attack, technical defences may take the form of deformable or rigid barriers around vulnerable parts of the building perimeter. In the case of accidental vehicle collisions such deformable barriers might be designed to not only protect the building but also to enhance the chances of survival of the vehicle occupants. In the case of defence against deliberate explosive attack an effective strategy might also involve a light-weight sacrificial barrier designed to trigger premature detonation of the warhead. Mitigation of the effects of accidental explosions would call for a more direct hardening of the building structure; the appropriate technical approach might then depend upon the relative probability of the different sources, as there are substantial qualitative differences between the airborne shock-waves arising from high explosives and from fuel gases.

Resilience / Robustness/ Adaptability/ Integrity/ Renovation/ Refurbishment

It is essential that buildings and items of infrastructure possess the ability to adequately resist reasonably foreseeable structural loads (including self-weight) without fracture, excessive deflection or instability (such as overturning, buckling or transformation into a mechanism) and so remain capable of performing their intended functions throughout the duration of their designed life. This characteristic, which may be defined either at the level of individual structural components or at system level, is denoted by the term "structural integrity"

It is important for buildings and items of infrastructure to be able to absorb damage without suffering complete failure (a characteristic denoted by the term "resilience") and to withstand severe events (such as fire, explosions or impact) without a loss of function that would be disproportionate to the cause (a characteristic denoted by the term "robustness").

It is desirable for buildings and items of infrastructure to be adaptable, throughout their anticipated lives, to reasonable changes both in the demands placed upon them and in the levels of performance expected of them.

It can be foreseen that technological and societal changes will lead to challenges in terms of adaptability, while the an anticipated increase in the frequency and severity of extreme weather events as a consequence of climate change may pose challenges in terms of structural integrity, robustness and resilience.

b) Digital economy

Building Information Modelling (BIM)

<Modern information technology is founded on the concept of the manipulation of data by algorithms. It is axiomatic that, for data to be manipulated by an algorithm, it must conform to some definite structure, i.e. a data model. Different data models can be created to represent the same information - to take a simple example, a position in 3-dimensional space could be represented in either a polar or a rectangular coordinate system. Where software has been designed to support the work of some particular engineering discipline, there is a natural tendency for the software authors to adopt a data model that corresponds closely to the perspective of that discipline. As different disciplines will thus tend to define different data models, this can lead to difficulties when these disciplines need to share data; quite apart from any superficial differences in data formatting (such as those commonly encountered when files are exchanged between different spreadsheet or word-processing packages), there is a more fundamental challenge in transferring the contents of one discipline's data model to the appropriate positions in another discipline's data model. This challenge may make it impractical to create a reliable automated system for the transfer of data between disciplines.

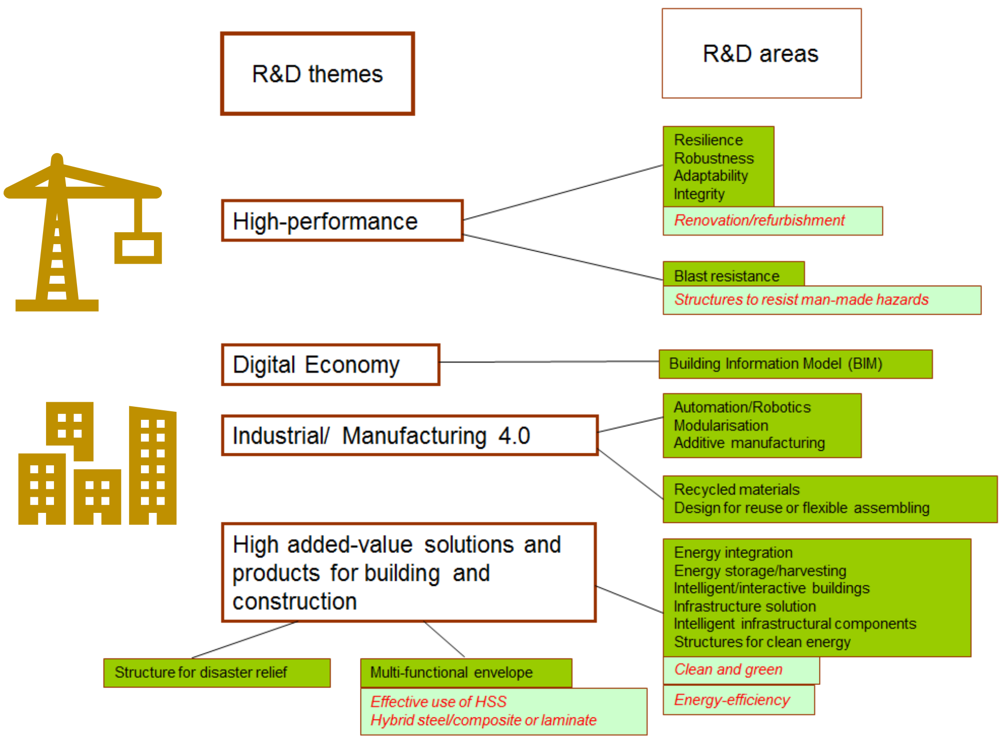

Figure 27: Appealing steel solutions for the construction and infrastructure sector

A number of problems can arise where human intervention or checking is required to ensure that data is correctly transferred from one data model to another:

- Data exchange is slow, expensive and liable to error.
- At any moment in time, different disciplines may be working with inconsistent data as data has either been incorrectly transferred or where correctly transferred has not yet been updated to incorporate subsequent design changes.
- The costs, delays, and potential-errors associated with data exchange lead to different disciplines working sequentially where they might otherwise have been able to work in parallel.
- The need to check and re-check the validity of data leads to an additional burden in verifying compliance with contractual and/or regulatory requirements

In response to the challenges in effectively sharing data a number of industrial sectors have devoted considerable effort since the 1980s in developing Product Data Modelling (PDM) standards. A family of mature multi-industry standards has been implemented across sectors such as automotive, aerospace, shipbuilding and electronic hardware. The widely recognised conservatism and fragmentation in the building sector has, however, led to a perceived need for progress to follow a slightly different path to that taken in these other industries.

Building Information Modelling (BIM) has been defined as the process of designing, constructing, or operating a building or infrastructure asset using electronic object-oriented information.

BIM is a lifecycle information delivery process that employs BIM authoring software to create and compile information including graphical (2D, 3D, 4D, etc.), non-graphical data (e.g., technical specifications) and documentation (e.g., installation instruction, warranty documents, environmental declaration documents, etc.).

There is now an industry standard for defining project organisation's competence and delivery from a BIM. The levels are defined as:

- Level 0: Unmanaged CAD probably 2D with paper (or electronic paper) as the most likely data exchange mechanism.
- Level 1: Managed CAD in 2D or 3D format using published standards with collaboration tool providing a common data environment, possibly some standard data structures and formats. This is the level at which most organisations currently operate.
- Level 2: Managed 3D environment held in separate discipline BIM tools with attached data using published standards with collaboration tool providing a common data environment. Integration on the basis of proprietary interfaces or bespoke middleware.
- Level 3: Integrated BIM or single shared project model based on fully open process and data integration enabled by web services managed by a collaborative model server.

Standardisation and interoperability should enable lossless information exchange between information technology systems. It can be achieved by implementing common or complementary interfaces for information sharing or platform neutral file format specification format that interested vendors can implement. The currently implemented standard file format can be exported from and imported to all BIM platforms but the exchange is far from lossless and considerable effort could be required in verifying the information exchanged. This has so far hampered its use.

The potential benefits to construction product manufacturers of implementing BIM are expected to include:

- Timely response to RFI/RFP
- Opportunity to sell more products through existing contacts.
- Opportunity for cross selling of product lines.
- Easier identification of product improvement and NPD opportunities.
- Lower overall cost of managing product information.
- Ability to participate in BIM-enabled collaborative business models.
- Access to product data as input for optimisation (energy, cost, performance) tools.

The following barriers to effective implementation of BIM have been identified:

- Learning curve and lack of skilled personnel
- High cost to implementation
- Reluctance of other stakeholders (e.g., architect, engineer, contractor)
- Lack of collaborative work processes and modelling standards
- Lack of interoperability between industry software tools.
- Lack of or ambiguous legal/contractual frameworks and agreements.

The availability of product information in BIM environment is pivotal to the success and actualisation of BIM benefits (beyond design authoring and visualisation) hence uptake by product suppliers is critical. The most cited barriers by manufacturers/suppliers to the adoption of BIM technologies are:

- Lack of demand by clients
- Poor internal understanding of BIM

c) Industrial/ Manufacturing 5.0

Automation/ Robotics/ Modularisation/ Additive manufacturing

The term "advanced manufacturing" is usually taken to refer to production processes that embody the results of recently-completed scientific and technical research. In this context, the qualifier "advanced" applies to the manufacturing process rather than to the manufactured product. While the term is often regarded as synonymous with "high-value manufacturing", some commentators maintain the distinction that "high-value manufacturing" is a concept embracing innovation in manufacturing systems, supply chains and business models, and so may be based as much upon new business ideas as upon new scientific or technical ideas. The concepts are nevertheless closely linked, as developments in production processes may facilitate the implementation of new business models.

Drivers for growth in advanced manufacturing include trends in global manufacturing and overseas freight costs (leading to some re-focusing of manufacturing activity from Asia back towards Europe) and increased resource scarcity (leading to an emphasis on production processes and business models that minimise use of resources and/or extend the effective product lifetime).

Advanced manufacturing technologies may capitalise on developments in materials (providing products with new or improved properties), in novel manufacturing techniques (such as additive manufacturing) or in the enhanced productivity of established manufacturing processes (for example through opportunities to refine automation).

Additive manufacturing processes (sometimes referred to as "3D printing") create physical objects by building them up directly from a digital model. They are thus clearly distinct from "subtractive processes", such as the removal of material by machining or cutting, and from other processes such as fabrication (an additive process involving the assembly of parts subtracted from bulk products) and casting or forging (in which an intermediate physical object, such as a die, pattern or mould must first be created from the digital model). Various techniques are available, typically involving powders or jets of liquid material, to build up the product by depositing successive thin layers of material.

Within the construction sector, additive manufacturing processes may be exploited by:

- Direct printing of metallic objects (e.g.,, by selective laser fusion of metal powder)
- Printing of non-metallic patterns for metal-casting processes such as sand casting or investment ("lost-wax") casting
- Printing of non-metallic parts (e.g.,, concrete) in steel-framed structures.

The direct production of metallic objects entails a number of challenges. While the additive process removes some design constraints associated with established manufacturing processes, it also places its own restrictions on material properties (for example, in order to obtain material properties in a printed part comparable to those of a casting or forging it may be necessary to add a post-printing production step such as heat-treatment or to use a more expensive alloy composition). Furthermore, there may be concerns related to the adequate assurance that specified mechanical properties have been achieved. These challenges would be avoided if 3D printing were to be used indirectly through the production of, for example, patterns for casting processes, as it would then be possible to employ well-established standards for alloy compositions and product approval. A further advantage of this approach would be that high production rates might be achieved more easily than through direct printing of metallic parts.

One major attribute of additive manufacturing processes is that they may enable a business model known as "distributed manufacturing", in which digital models are downloaded to distributed multi-purpose factories where manufacturing operations take place. The potential advantages of such a system have been identified as:

- Reduced financial and environmental costs associated with freight transport, as products are manufactured close to their final destination
- Increased responsiveness to market demands, as product design changes can be implemented without disrupting a production line or supply chain
- More scope for innovation, as rapid prototyping and limited production runs are readily supported
- Improved life-cycle support for complex products, as replacement parts can be produced on-demand.

Recycled materials/ Design for reuse or flexible assembling

Traditionally, product life cycles have been highly linear with a typical "make-use-dispose"-structure. More recently, there has been increased emphasis on the opportunity to extract value from resources at the end of the life-cycle; this has been particularly marked in the case of the capture of waste streams in sectors such as paper and glass. A "circular supply chain" is an advance upon this concept; it envisages that, as an integral part of the original product design, the material resources made available at the end of the product lifetime will be directed towards subsequent embodiment in some designated successor-product. This paradigm is enabled also by material tracking solutions enabled by digital technologies, which made full information of the end-of-life good available to the entities that should embody it in the successor product and support selection of the most viable and convenient valorisation pathway. By decoupling economic growth from resource consumption in this way, it is hoped that pressure on finite natural resources can be relieved; the significance of this can be judged from the European Commission's recent identification of twenty critical raw materials which have both high economic importance to the EU and high supply risk (including rare earth elements in modern technologies, less than 1% of which are currently recycled). It has been estimated by the World Economic Forum that by 2025 the circular economy could contribute as much as $1 trillion per annum to the global economy through reduced material use. The greatest potential benefits would be seen in economies such as Europe (through its reliance on imports) and industrial sectors such as construction (through its material-intensive attributes).

The EU Circular Economy Package published in December 2015 aims to enable the transition to a more circular economy through a range of measures aimed at increasing resource efficiency and minimising waste; in addition to EU Member States this package also applies to members of the European Economic Area.

Circular systems incorporate a range of activities that reduce the demand for material inputs, recover/reuse materials already in the system and extract the highest quality and value at each stage in the products' life cycle. For example, the useful life of a car can be extended through repair and maintenance; at the end of its useful life it can be disassembled, with serviceable components re-entering the supply chain as spare parts, before ultimate recovery of materials such as metals through scrapping.

A circular economy has implications for infrastructure to support product recovery, transport and reprocessing. These are particularly significant for the construction sector; while it has been estimated that over 86% of non-hazardous construction waste is currently recovered, much of the potential value is lost due to transport costs, challenges with multi-material product recovery and geographic mismatches between areas of supply and demand.

In construction sector, a great example of circular economy and industrial symbiosis between steel and cement is the use of blast furnace slag as a raw material for cement production. But this example of circular economy is facing the challenge of steel decarbonization, blast furnace production reduction, and, thus, the need to research other types of slags for the same circularity.

d) High added-value solutions and products for building and construction

Energy integration | Energy storage/harvesting | Intelligent/interactive buildings | Infrastructure solution | Intelligent infrastructural components | Structures for clean energy | Clean and green | Energy-efficiency

Safe and efficient infrastructure is the foundation on which a modern economy is built. All around the world infrastructure systems are increasingly coming under strain due to trends such as urbanisation, continued globalisation, and the effects of climate change. Furthermore, while developing countries struggle to build new infrastructure, developed countries face a need to replace ageing infrastructure. It has been estimated that between now and 2030; a minimum of $50 trillion in infrastructure investment will be required to fuel global development.

The present-day building stock accounts for some 40 percent of the energy consumed worldwide. In Europe, however, structures that were built prior to 1980 account for 95 percent of the energy used to provide buildings with heat, hot water, air conditioning, lighting, and ventilation.

The technological development of urban infrastructures has recently been classified into four well-defined stages.

"Infrastructure 0" is a basic brick-and-steel infrastructure characterised by simple road and rail tracks, lightly-serviced low-rise commercial buildings and "islands" of electrification (in which a supply is available only to small groups of users who generate their own electricity).

"Infrastructure 1.0" is characterised by semi-automated infrastructure in which railways have begun to be electrified (with some basic automation features), commercial buildings are constructed to modern standards (designed to incorporate services such as heating, lighting, air-conditioning, telecommunications, elevators, etc.) and where mono-directional power grids (in which generation is run in simple response to aggregate electrical demand) are ubiquitous.

"Infrastructure 2.0" features intelligent infrastructure, in which trains are largely driverless, buildings are fully automated and electrical power is provided via smart grids (in which continuous data exchange between generators and consumers facilitates active load management, energy storage and despatch of generating assets).

"Infrastructure 3.0" describes a fully-integrated intelligent infrastructure in which integrated real-time optimisation and incident management takes place across all infrastructure domains. In one vision of such a paradigm, smart buildings and a smart grid cooperate seamlessly to optimise energy consumption while user-friendly traffic systems integrate all transport modes so that travellers can optimally plan their journeys using real-time information.

Disparate challenges are faced in the implementation of intelligent urban infrastructure. While developed economies may possess the resources to support the construction of state-of-the-art systems, they will be constrained by the need to introduce these in ways compatible with the uninterrupted operation of the legacy infrastructure. Conversely, in emerging economies there may be greater opportunities to start from new, while access to finance may be a restricting factor.

A detailed understanding of the energy performance characteristics and energy flows in urban areas is of crucial importance for the design and planning of smart energy systems.

Smart cities will require smart energy grids which are able to communicate with each other to balance thermal and electrical loads depending on supply and demand. Energy-efficient buildings will need to employ energy conservation measures and on-site renewables to reduce their energy demand and to operate as interactive elements of the urban energy system.

In the development of smart urban energy networks, the large-scale integration of distributed renewable energy sources into existing energy grids presents some substantial challenges. In this context energy supply technologies such as heat pumps, solar thermal, photovoltaics, energy storage units, etc. will be significant. The development of smart integrated energy networks will require not only new components and systems, but also a better understanding of how to integrate distributed supply technologies into urban infrastructure in an efficient and cost-effective manner.

Electric steelmakers can be part of that grid as a big consumer. This is a challenge, but it can be an opportunity with enough flexibility from the steelmakers side.

Multi-functional envelope | Effective use of HSS | Hybrid steel/composite or laminate

A building envelope serves as a physical separator between the conditioned and unconditioned environments of a building. As such it is required to resist the transfer of air, water, heat, light and noise. It may also be required to resist and transfer structural loads and to satisfy other criteria such as internal or external aesthetic finish. The physical components of the envelope include the foundation, roof, walls, doors, windows and ceiling.

In many established forms of construction distinct elements and materials are intended to support each of the required functions.

In a multi-functional envelope, individual elements perform more than one control function. At one extreme this can take the form of a single element or material addressing all enclosure control functions. More typically, however, a multi-functional envelope may comprise a number of elements each of which performs one primary function while contributing to one or more other control functions.

Multi-functionality clearly has the potential to offer economical, and potentially synergistic, benefits which may enable novel design and construction concepts. However, the challenges should not be underestimated; for example, it is well known that several building systems introduced in the mid-twentieth century subsequently experienced severe shortcomings in respect of their envelope control functions, as a result of deficiencies either in design or in management of build quality.

Many forms of construction feature the use of steel as a structural material and polymers as barrier elements of the envelope. By appropriate materials selection and joining methods it is possible to achieve a hybrid element in which the polymeric components perform not only their barrier function but also contribute towards the load bearing function by communicating shearing forces. In this way it is possible to enhance overall flexural stiffness and to stabilise thin steel elements against buckling, both of which offer routes towards the more effective use of the higher strength steels that have long been available.

Structure for disaster relief

Major disruptions to civil society can arise from a number of sources. In addition to conflict-related issues (including the need to accommodate large civilian populations displaced by conflicts elsewhere), these sources include:

- Earthquake/tsunami
- Flooding
- Drought
- Famine
- Wildfire
- Hurricane/typhoon
- Major industrial accidents (e.g., widespread environmental contamination by chemical or radiological agents)

Fresh challenges are faced in the provision of relief efforts. In the case of weather-related catastrophes, the results of global climate change will be an important driver. In the case of seismic disasters, the physical threat may remain unchanged but its potential impact can be transformed as a region develops e.g., from a chiefly agricultural economy, with a large number of small population centres and unsophisticated infrastructure, to an industrialised economy with several major modern cities.

Facilities may be required to support affected populations over various timescales (e.g., overnight; several days; periods of weeks or months) which may determine the relevant priorities. Furthermore, these priorities may evolve over the duration of the relief effort (e.g., in the immediate aftermath of a disaster the main medical priority may be the treatment of traumatic injury, while within a matter of weeks an adequate level of maternity care and the effective provision of childhood vaccination may become increasingly significant health issues for the affected population).

Emergency structures and buildings may be needed to provide:

- Shelter (in a variety of formats including tents-and-blankets, dormitory-style cabins and family-unit household dwellings),
- Sanitation and water supply,
- Heating and lighting (e.g., distribution of portable propane gas appliances and arrangements for supply/re-charging of gas cylinders),
- Distribution, storage and preparation of food (e.g., field kitchens),
- Mortuaries and related facilities,
- Healthcare (including arrangements for the appropriate storage of medical supplies, e.g., refrigeration for vaccines and security stores for controlled drugs such as opiates),
- On-site maintenance and repair of basic mechanical equipment (including logistic management of spares),
- Childcare and education.

Modular construction techniques might offer particular advantages in disaster relief building systems. A common modular building envelope system might allow buildings to be deployed to sizes and ground-plans determined by on-site conditions while a compatible series of building services kits might allow completion of the buildings to suit different applications (e.g., one services kit might be used to complete the building as a clinic while another might allow it to be completed as an engineering workshop).

Different logistic management strategies may be appropriate to different scenarios. For instance, in seismic regions bespoke packages of equipment might be pre-positioned by the civil authorities in depots close to major centres of population, while relief of a major famine might entail the ad hoc coordination of multiple international supply streams across several modes of transport (e.g., marine freight, road haulage, commercial air cargo, military airlift) by a range of governmental and non-governmental organisations. Furthermore, individual packages might need to incorporate units with different storage characteristics: for example, a medical treatment package designed to be delivered to site as a single item might comprise a flat-pack building-and-equipment module with indefinitely long shelf-life, a stock of medical supplies (e.g., packs of sterilised surgical instruments and dressings) with a shelf-life of several years and a supply of pharmaceuticals with shelf-lives of possibly only a few months. Effective packaging (including suitable transit labels and compatible consignment-tracking technologies) and appropriate levels of modularisation are therefore important aspects of the specification of a disaster relief inventory.

2.5.4. Socio-Economic Aspects

Steel is one of the most important construction materials, competing with other materials but also opening up completely new possibilities. Almost half of the steel produced is used for construction purposes. New applications for steel can be found through the development of new grades, building components and systems, composite structures, and construction technologies.

Research themes are relevant in various fields including new buildings, renovation of old buildings, infrastructure, developing new materials, improving value chain, standardization, and dissemination of results.

Sustainable steel construction is based on competitive business that satisfies the needs of customers and societies. It captures economic and environmental goals along with social desirability. Steel-based construction with accurate and pre-fabricated components enable resource savings and waste reduction, and steel itself is an endless recyclable material.

Against this background, the usage of sustainable steel in construction is a perfect match for image and recruitment activities and attracting young talents for the steel production. Raising awareness and improving the image and the attractiveness of careers in the steel industry hand in hand with the construction sector will help to increase the positive perception of both, construction and steel.

As relevant skills are needed for both steel and construction collaboration is foreseen of ESTEP (and the steel related Skills Alliances, see chapter 2.7.5.) with the sectoral Construction Blueprint (https://constructionblueprint.eu/de/home-de/), especially on common topics like digitalisation, circular economy, and energy efficiency.

Steel and synergies with neighbouring communities

Steel is a key component of any construction activities. In fact, in terms of construction, some structures and forms would not be possible without steel. Therefore, steel is linked naturally to various other construction projects. This also extends to research and innovation. As a platform, ESTEP has synergies and collaborates with various platforms and initiatives such as ECTP, E2B, Building UP, reFINE, etc.

2.5.5. Stakeholders

- Steel industries
- Suppliers
- Architects, designers
- Construction sector
- Raw material producers
- Steel Research Centres
- Universities
- Public authorities and communities

2.6. Steel products and applications for the energy sectors

2.6.1. Introduction

This work is part of the effort to keep the SRA of ESTEP updated, to prepare HORIZON EUROPE and future research proposals on key strategic issues. More generally, it is meant to make sure that ESTEP is ready to face the challenges that lie ahead of it in a proactive and pioneering way. Energy sector is very important for the future of Europe as our society is willing to decrease GHG emissions resulting from power generation. This change will require huge efforts from many different actors and for very large investments. Materials used for the production, storage and transport of energy are very important elements to achieve the required performances at an affordable cost. In this general landscape, steel has a very important role to play. Working in collaboration with its customers, the European steel industry is ready to answer the challenge through innovative product and solutions.

2.6.2. Methodology

In order to better define the required steel applications to be developed, the energy industry has been subdivided in three main sectors:

- Energy Transportation (clean energy vectors like green hydrogen, green ammonia, other)
- Power generation/transmission, and CCS (e.g., transportation of captured CO_2)
- Renewables (wind energy, Photovoltaic, marine energy, others)

The time frame extends until 2035, as changing the energy system is a long-term endeavour. The approach of the working group has been to carry out a foresight analysis, trying to imagine how to bridge the present to the future.

In this context an ordered and rational set of research areas that could become populated by research proposals especially in the period up to 2020 has been proposed.

More specifically, the working group has proceeded as follows:

- picture the needs of Energy Industries up to 2035
- proceed, using a back casting method, to draw the roadmap that bridges the gap between that future and today
- translate the needs in terms of R&D&I areas
- prioritize the areas in terms of time and funding instruments (HORIZON 2021-2027, SET -Plan, RFCS, others).

2.6.3. Energy transportation and storage: hydrogen, other less standard fluids

a) Hydrogen

Future steel products for the transportation and storage of green hydrogen will play a critical enabling role in the scale-up of a hydrogen-based energy system. Hydrogen service imposes more demanding conditions than conventional natural gas because of hydrogen embrittlement risks, high diffusivity, and often higher operating pressures and cyclic loading. Next-generation steel solutions will therefore focus on advanced high-strength, low-alloy pipeline steels with carefully controlled microstructures, low impurity levels, and tailored thermo-mechanical processing to ensure resistance to hydrogen-induced cracking and fatigue. New steel grades will be required for high-pressure transmission pipelines, regional distribution grids, compressors, and offshore hydrogen transport infrastructure, combining strength with fracture toughness and weldability. Advanced coating systems and internal surface treatments will gain importance to reduce hydrogen permeation and corrosion interactions, while improved welding consumables and procedures will be needed to maintain joint integrity. For liquefied hydrogen transport, specialised cryogenic steels with stable toughness at very low temperatures will be essential. In parallel, research will address the compatibility and upgrading of existing gas pipeline steels for hydrogen blends and progressive network conversion. Digital monitoring, embedded sensors, and smart steel components will support integrity management and predictive maintenance across hydrogen networks.

Hydrogen storage adds a further layer of technical requirements and innovation needs for steel products. High-pressure gaseous hydrogen storage vessels — from stationary tanks to transport trailers — require ultra-high-strength steels with strict control of inclusions, residual stresses, and surface quality to prevent crack initiation. Underground storage in salt caverns and depleted reservoirs will depend on steel casings, tubing, and well components resistant to hydrogen attack and cyclic pressure variations. For liquid hydrogen storage, large double-wall cryogenic steel tanks must combine very high toughness at temperatures near −253 °C with excellent weld performance and low permeability. Steels for solid hydrogen carriers and hydrogen-derived fuels (such as ammonia or methanol) will also need enhanced corrosion resistance. Future developments will include multilayer steel structures, composite-steel hybrid vessels, and new inspection and certification methods tailored to hydrogen service. Together, advances in steel metallurgy, forming, joining, coating, and digital monitoring will underpin safe, durable, and scalable hydrogen storage infrastructure.

b) Transportation and storage of green hydrogen carriers and captured CO_2

The large-scale transportation of green hydrogen will increasingly rely on hydrogen carrier molecules such as ammonia, methanol, and other hydrogen-rich liquids, because they offer higher volumetric energy density, easier handling, and compatibility with existing logistics compared with pure hydrogen gas or liquid hydrogen. These carriers enable long-distance transport by ship, rail, barge, and pipeline, and therefore create important new requirements and opportunities for advanced steel products and systems. Ammonia is one of the leading hydrogen carriers due to its established global transport infrastructure and relatively high hydrogen content. However, ammonia is toxic and can be corrosive under certain conditions, so transport tanks, pipelines, and ship structures require steels with enhanced corrosion resistance, crack tolerance, and high weld integrity. Low-temperature performance is also important because ammonia is often stored and transported under refrigerated or pressurised conditions. Methanol and other synthetic hydrogen-derived liquids (such as e-fuels and liquid organic hydrogen carriers, LOHCs) are easier to handle than ammonia and can use parts of existing fuel infrastructure, but they introduce other material challenges linked to corrosion, permeation, and long-term exposure effects. Steel grades for tanks, pipelines, and process equipment must therefore be optimised with appropriate alloying, coatings, and linings to maintain durability and safety.

Future transport systems for hydrogen carriers will combine large marine vessels, port terminals, storage farms, and conversion plants where hydrogen is released from the carrier. This integrated chain requires a wide range of steel solutions: high-strength structural steels for ships and offshore terminals; pressure-resistant steels for tanks and reactors; and corrosion-protected pipeline steels for distribution networks. Research priorities include improved resistance to stress-corrosion cracking, better performance of welded joints in aggressive chemical environments, and multifunctional coatings that provide both chemical protection and inspection capability. Digital technologies will also play a growing role, with smart steel components incorporating sensors for leak detection, corrosion monitoring, and structural health assessment. In addition, circular-economy principles will influence material selection, favouring steel solutions that are recyclable and compatible with low-carbon production routes. Standardisation and certification frameworks for steels in ammonia, methanol, and LOHC service will need further development to accelerate deployment. Altogether, innovation in steel materials and engineering will be central to building safe, efficient, and scalable transport systems for green hydrogen carriers across global energy markets.

In parallel, the transportation of captured CO_2 will create a further major application field for advanced steel products. Large-scale carbon capture, utilisation and storage (CCUS) networks will depend on extensive pipeline systems, shipping infrastructure, and intermediate storage facilities operating with dense-phase or liquefied CO_2 under pressure and, in many cases, at low temperature. These service conditions introduce specific material challenges, including running-ductile-fracture control, resistance to corrosion in the presence of water and impurities, and good toughness under decompression and cyclic loading. Future steel pipeline grades for CO_2 transport will require optimised strength–toughness balance, strict control of inclusions, and qualified welding technologies. For ship transport of liquefied CO_2, cryogenic-capable structural and pressure-vessel steels will be needed for tanks and containment systems. Research will also focus on internal coatings and corrosion management strategies, impurity-tolerant materials, and real-time integrity monitoring using embedded sensors. As CO_2 transport networks expand across borders and offshore storage sites, harmonised standards and dedicated steel solutions will be essential to ensure safety, reliability, and cost efficiency.

c) Steel pipes & components for high productivity energy transportation

Hydrogen in connection with wind energy

Hydrogen in connection with wind energy is becoming an increasingly important topic as variable renewable power grows faster than grid-scale storage capacity. Wind generation is inherently intermittent, and large surpluses can occur during high-wind periods when electricity demand is low. Converting excess wind power into hydrogen through electrolysis offers a scalable storage pathway and supports sector coupling between electricity, gas, industry, and transport. One of the most practical near-term storage and distribution options is the injection of hydrogen into existing natural gas pipeline networks, typically up to about 5–10% by volume, depending on national regulations and infrastructure characteristics. This approach enables rapid use of existing assets while reducing curtailment of renewable electricity.

However, transporting hydrogen–natural gas mixtures introduces technical challenges that require dedicated research. Key issues include material compatibility of pipeline steels and welded joints, hydrogen embrittlement risks, fatigue under pressure cycling, leakage behaviour, and the influence of hydrogen on compressors, valves, and metering systems. Gas quality monitoring, sensor technologies, and digital control systems must also be upgraded to manage variable blends safely. Further research is needed on mixture thermodynamics, flow behaviour, safety limits, and long-term integrity of transmission and distribution networks. Advancing knowledge in gas mixture transport will be essential to enable large-scale renewable energy storage and to prepare infrastructure for a gradual transition toward higher hydrogen shares in future energy systems.

Onshore pipelines

Steels with a high amount of deformability have to be developed as well as plastic design criteria to understand pipe and pipeline behaviour. A key issue for pipeline safety is the avoidance of corrosion and external damage, especially in thin-walled structures. More than 80% of all pipe-line failures can be devoted to corrosive attack or external interference.

Modelling will gain prime importance in development of new steels, pipe production, pipeline design, pipe laying and pipeline operation. Development and improvement of welding technologies will be also a main task as well as the determination of appropriate material and pipe properties, full scale testing and field validation.

From the construction and operation point of view, developments and improvements are needed in cooperation between steel and pipe producers, laying contractors and operation companies like:

- Advanced girth welding processes such as dual tandem, laser and/or hybrid laser.
- Development of optimized and, if possible, automated pipeline construction techniques (e.g., in-creasing offshore laying speed, tie-in equipment, pipeline crossing techniques
- Advances in the inspection, measurement, interpretation and repair of pipeline construction and operational damage
- Improvement of the long-term behaviour of pipe coatings in accordance with pipeline operation and cathodic protection methods

Offshore trunk lines

Currently, 90% of the world’s offshore structures with their related transmission pipelines are in shallow waters, less than 75 meters deep. However, an increasing number of transmission lines in deep (>400 m) and ultra-deep (>1500 m) waters are to be expected. Key issues for offshore pipelines are the resistance against the extreme loading conditions (bending, tension, external pressure) during pipe laying and to allow a high speed of welding aiming at higher laying speeds, wall thicknesses and diameters, moreover their resistance to external damage can be a key point for shallow water pipelines. An excellent roundness of pipes is the basis for high-speed joining as well as for collapse resistance.

2.6.4. Power generation and CCS

Today’s electricity-generation mix is composed of fossil-fuel sources (coal + natural gas + oil) accounting for nearly 60% of global generation in 2024, nuclear power around 9%, hydropower about 14%, and other renewables (wind + solar + bioenergy + geothermal + waste) roughly 33%. In the next 20 years, fossil fuels are expected to remain a large share of generation globally, though their proportion is projected to decline in many scenarios rather than increase to 72%.[28]

[28] IEA – Global Energy Review / Electricity section - https://www.iea.org/reports/global-energy-review-2025/electricity

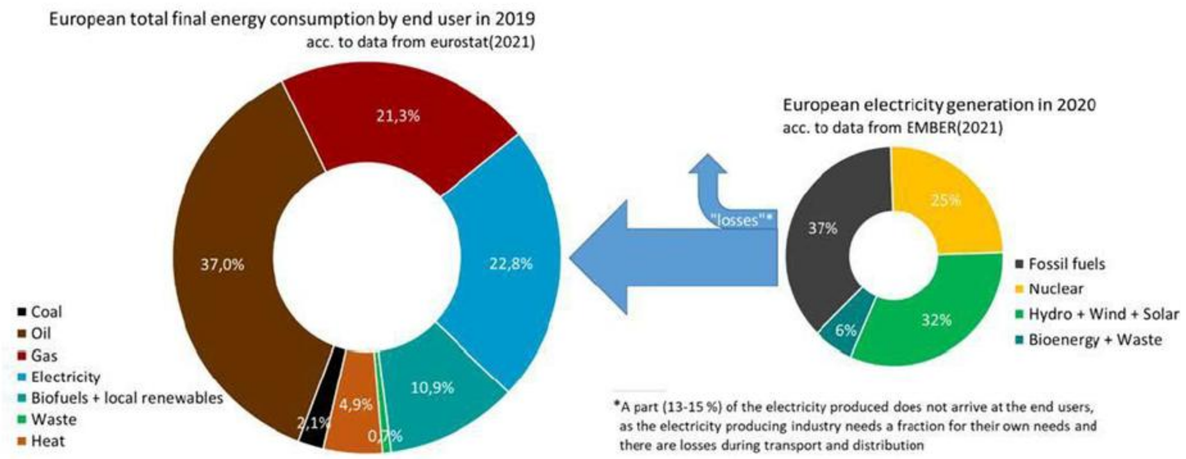

Figure 28: Electricity generation with its CO2 emission structure in quantitative relation to other CO2 sources, in terms of final energy consumption, European view (graphics based on Eurostat data)

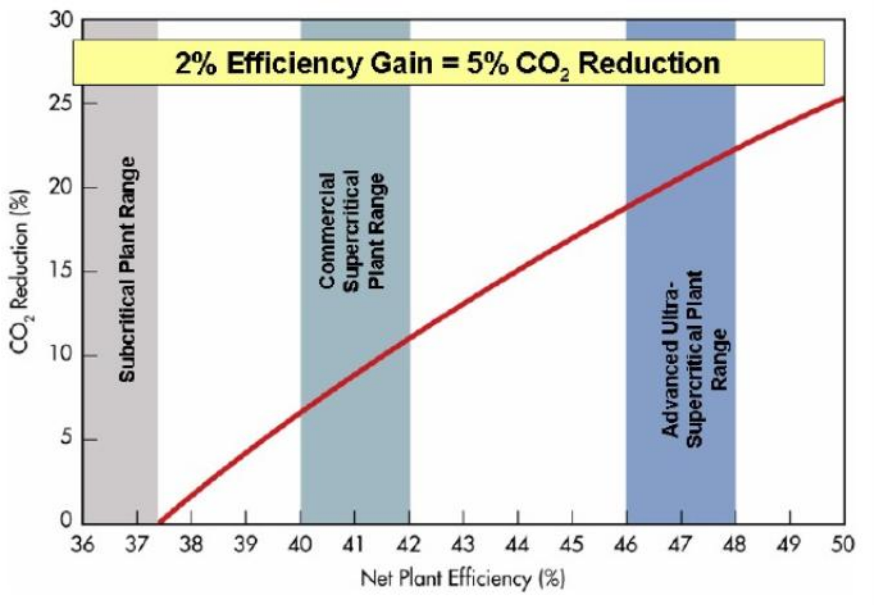

Figure 29: Efficiency improvement for advanced USC fossil power plant

A very large increase in electricity demand is expected in China, India and other emerging economies in the coming years. Consequently, hundreds of new large fossil-fuelled power plants are under construction or in planning. Although several new nuclear power plants are also being built, a major ramp-up of the next generation of nuclear technology remains some years away. According to data from the International Energy Agency (IEA) the world's biggest coal-fired power build-out remains centred on Asia — for example, in 2022 China alone added about 11 GW of new coal-fired generation capacity. [29] Meanwhile, in OECD countries coal power output fell: in 2020 coal-fired electricity generation across the OECD was approximately 1 983 TWh, down by around 15.5 % from the previous year.[30]

[29] IEA Coal Review - https://www.iea.org/energy-system/fossil-fuels/coal?utm_source=chatgpt.com

[30] IEA Key Electricity Trends - https://www.iea.org/articles/key-electricity-trends-2020

The development of the advanced USC fossil power plant with steam temperature up to > 700°C is urgently needed to reduce CO_2 emissions.

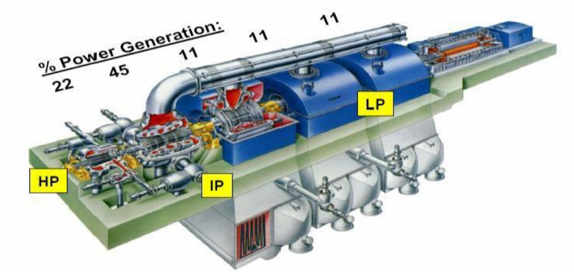

Figure 30: Steam turbine for power generation

2.6.5. Renewables (Wind, PV, CSP, H2, Marine energy, Nuclear, others)

Globally, the energy sector emits 26 billion tonnes of CO2 each year and electricity production alone accounts for 41% of emissions. The International Energy Agency expects CO2 emissions in 2030 to have increased by 55% to reach more than 40 billion tonnes of CO2. The share of emissions coming from electricity production will increase to 44% in 2030, reaching 18 billion tonnes of CO2. Europe is going to be importing a growing share of its energy at unpredictable but most likely higher prices, from unstable regions, in competition with the rest of the world and at staggering environmental cost.

a) Wind

At present, the largest turbines are designed for 6 MW and higher capacity (offshore) while much smaller units are locally applied in windy areas to generate the home supply electricity.

At present, the largest offshore wind turbines are rated at 20 MW and above (with prototypes as high as 26 MW), while much smaller units — typically in the 0.5 – 3 MW range — are still applied locally in windy areas for home-supply electricity.

The European Wind Energy Technology Platform has a vision in which wind energy covers 25% of electricity consumption, with 300 GW of installed capacity. Satisfying our energy needs over the coming decades will be a big challenge. The economic future of Europe can be planned on the basis of known and predictable energy costs, derived from an indigenous wind energy source free from all the security-related, political, economic and environmental disadvantages associated with the current energy supply structure. Europe can go a long way

FIG 4.1: **EWEA's three wind power scenarios (in GW)**

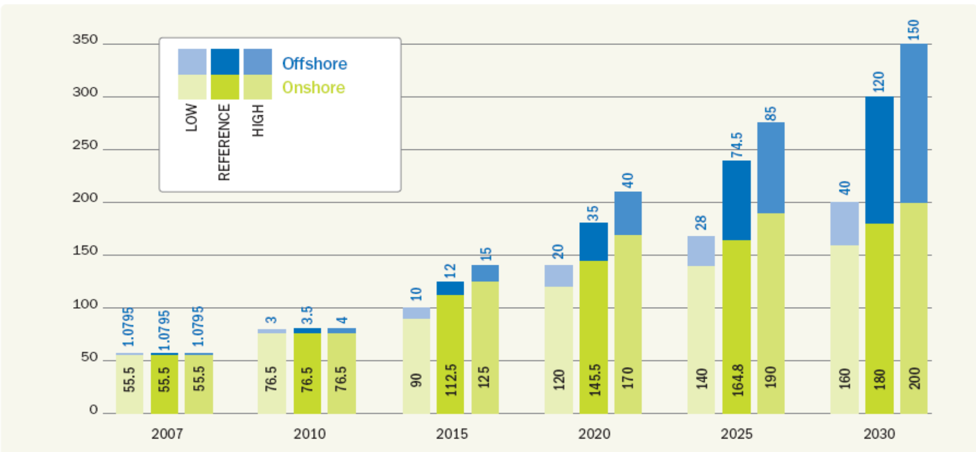

Figure 31: Offshore wind farms

towards an energy supply that is superior to the business-as-usual.[31,32] Steel is the cornerstone material in wind turbines and wind-farms: according to worldsteel, up to 80 % of the material in a wind turbine is steel. Most of the structural load-bearing elements — the tower, the foundation piles or monopiles, the nacelle frame, the rotor hub and low-speed shaft — are made of steel, often using high-strength grades tailored for large structural loads, fatigue resistance and long lifespan. The growth of wind energy both onshore and offshore is therefore a major driver for steel demand, but equally wind power is a partner for the steel industry's sustainability ambitions. For example, worldsteel highlights how steel plants are increasingly turning to wind power themselves, creating a "virtuous circle" in which low-carbon wind-powered steel is used to build more wind infrastructure. In terms of performance, modern wind turbines are becoming ever larger with heavier rotor blades and higher towers; this places increasing demands on steel quality (higher grades, larger plate thicknesses, better fatigue resistance) and also on logistics: transportation of large steel segments to offshore sites, fabrication of monopile piles up to 6 m in diameter and 150 mm wall thickness, and long service-life requirements in hostile offshore environments. Finally, from a sustainability perspective, steel's attributes align well with the lifecycle requirements of wind energy. Steel is highly recyclable (typical end-of-life recovery rates reported at around 90 %), and wind turbine systems have relatively short pay-back periods in terms of energy used to manufacture versus energy generated. worldsteel's life-cycle-assessment work shows the energy pay-back time for many turbines is in the order of six to nine months. [33]

b) Photovoltaic

The challenges of the photovoltaic sector is to further improve the competitiveness and ensure the sustainability of PV technology and to facilitate a self-sustaining large-scale penetration in both urban areas and free- field electricity production units, as well as its integration into the electricity grid. Materials are key enablers in all PV systems. There is a need to design and manufacture PV systems that are both efficient and low cost enough to meet specific grid parity targets within the next few years. The materials supply chain needs to be able to supply sufficient quantities of the required elements, and thus, cost effective recycling solutions should be developed along with standardized performance testing and reliability/ageing test protocols needs to be developed to provide confidence (and so bankability) for PV devices employing newly developed materials in a wide range of operating conditions (from Europe to Sunbelt environments).

To this end, the materials roadmap proposes a comprehensive research and development program on the optimization of materials usage through predictive modelling down to quantum devices at the nano-scale, the improvement of intrinsic performance and reduction in layer thickness of constituent materials for both inorganic and organic PV cells and modules.

The roadmap focuses also on materials for light management (anti-reflective, anti-soiling, anti-abrasion coatings, light trapping/guidance, spectral conversion and optical concentrators' materials); the development of high throughput, low-cost manufacturing processes for film/layer deposition/thin film (epitaxial) growth.

c) Concentrated solar

The aim is to support the competitiveness and readiness for mass deployment of advanced concentrated solar power (CSP) plants, through scaling-up of the most promising technologies to pre-commercial or commercial level. Achieving these objectives will require large-scale CSP plants with better technical and environmental performance and lower costs with increasing power availability. This necessitates materials with higher performance than those of today.

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[31] WindEurope – Wind Energy in Europe 2024: Statistics and the Outlook for 2025–2030

[32] European Commission / Clean Energy Technology Observatory (Wind)

[33] Worldsteel – Wind power & sustainable steel - https://worldsteel.org/media/steel-stories/infrastructure/wind-power-meeting-worlds-need-for-sustainable-steel/

Our materials roadmap proposes a comprehensive research and development program on low-cost, spectrally selective, high mechanically stable absorber materials suited also for higher temperatures; and the development of higher reflectance and/or specularity, cost competitive, sustainable reflector materials. The roadmap focuses as well on materials to allow for higher temperatures, better heat transfer; the development of more sustainable, reduced cost, corrosive-resistant structural materials such as steel and the development of storage materials (heat storage materials and materials for thermo-chemical storage) to increase the performance and extend the operating temperature up to 600°C. of heat exchangers also metal structures for central receivers as well as piping and tank structures are deeply needed.

d) Fuel cells and H_2

The aim is to support the development and test, of cost competitive, high energy efficient fuel cell systems and sustainable hydrogen infrastructure technologies under real market conditions for transport and stationary applications. Achieving this goal will necessitate dramatic improvements in the economics, performance and reliability of fuel cells and hydrogen technologies. The need for new materials is overarching.

We focus on developing novel steel and composite materials with enhanced performances to obtain low-cost functional components for hydrogen transport and storage, coal gasification and thermo-chemical cycles technologies (improved chemical and mechanical properties); the development of low cost, reliable and corrosion resistant structural steels and composite structures also for pressurized and cryogenic hydrogen storage.

e) Transportation of H_2 and H_2 mixtures

The transport of hydrogen is the major component of a clean sustainable energy system in the longer term. Although there are currently more than 2000 km of hydrogen transmission pipelines in service in Europe and in the U.S., several technological issues need to be resolved and significant cost reductions are required for effective hydrogen pipeline transmission and distribution. These issues include: a better fundamental understanding of hydrogen embrittlement and diffusion to enable the development of lower cost hydrogen resistant steels, or composites for hydrogen pipelines, improved welding or other joining techniques, improved coatings and seals. Grant applications are sought to develop advanced and novel approaches to significantly reduce the cost of new hydrogen pipelines (by as much as 50%) and/or technology to retrofit existing natural gas or petroleum pipelines for pure hydrogen transmission and distribution.

f) Marine energy

Of all the large natural resources available for generating electricity, ocean energy is one of the last investigated for its potential. Although there are other marine energy sources — the thermal energy resulting from the large temperature differences between deep and cold ocean waters and sun-warmed surface waters, the chemical energy in ocean salinity gradients, and marine biomass, wave and kinetic stream energy are the most well-known.

There are two forms of tidal energy: potential (i.e., harnessing the potential energy changes associated with the tidal rise and fall of sea level) and kinetic (i.e., harnessing the kinetic energy associated with the motion of the tidal stream). There are three types of kinetic energy from water: tidal, ocean current, and river streams.

But how much marine energy is available? What is the amount of electrical capacity available and ex-tractable from two forms of marine energy: wave and kinetic stream?

Estimates of the total renewable energy available from the marine environment can be made by summing together the individual components available from the principal subdivisions of this energy source (Wave, Bio - mass, Ocean Thermal, Tidal, Subsea Current and Salinity Gradient). Estimated availability varies widely with researchers such as Isaacs and Seymour[34] posting estimates of between 1,000 and 10,000 GW. All estimates identify a highly significant energy source, even if only a limited percentage of the available energy can be

[34] Isaacs & Seymour, "The Ocean as a Power Resource", *Int. J. of Environmental Studies*, vol. 4(3), p201-205

recovered, either due to the remoteness of the source, transformation inefficiencies, or impact on marine ecosystems.

The technology to convert these resources to electricity has been deployed in demonstration projects, but remains the main challenge to see a large development of the Marine Energy. Commercial projects are expected in the next five to ten years. Given proper care in design, deployment, operation, and maintenance, ocean wave and kinetic stream energy could be two of the most environmentally benign electricity generation technologies yet developed.

Interest in wave and tidal stream energy has picked up over the last few years. Currently, many different device concepts compete for support and investment, and while some are more advanced than others, all are at early stages compared to other renewable and conventional generation systems. Optimal designs have yet to be converged upon. A few large-scale prototypes have been built and tested in real sea conditions, but no commercial wave and tidal stream projects have been completed to date.

Marine renewable energy has the potential to become competitive with other generation forms in future. In present market conditions, it is likely to be more expensive than other renewable and conventional generation systems until at least hundreds of megawatts capacity are installed. By way of comparison, this capacity is equivalent to several offshore wind farms at the scale currently being constructed.

Fast learning or a step-change cost reduction is needed to make offshore wave energy converters cost competitive for reasonable amounts of investment.

Considerable emphasis needs to be placed on cost reduction to ensure commercial viability for wave and tidal stream technologies. We need to accelerate the progress of technology development, through concept and detailed engineering design to bring substantial reductions in cost.

g) Nuclear

Nuclear Energy contributes to the SET-Plan's objective to develop low carbon energy technology. In this framework, the SET-Plan aims to design and build over the next decade prototypes and demonstrators of fast neutron reactors, technologies for a more sustainable nuclear energy through better resources utilization and the reduction of potential impact of ultimate radioactive waste. On the other hand, the higher temperatures and irradiation levels as well as different coolants than Generation II/III reactors, foreseen for these systems, will require other materials to those used for Light Water Reactors. In response to these needs the materials roadmap for nuclear fission proposes a research and development program on commercially available material (steel and Ni-alloys) for the prototypes and demonstrators; and advanced materials for the industrial scale systems. The focus is put on cladding application (Oxide Dispersion Strengthened -ODS-steels for liquid metal fast reactor) with the aim to improve high fuel burn-up capabilities and high temperature resistance; on coating technologies to enhance corrosion and erosion/wear resistance in liquid metal fast reactor. Based on the research results, projects to validate manufacturing routes of 9Cr steel heat exchanger, of fuel cladding tubes with ODS are also needed.

Nuclear power is a reliable technology for electricity production without harmful emissions. Today's (2023) industrial nuclear power plants produce 26% of all electricity and 52% of energy from non-combustible sources in Europe. However, electricity represents only 24% of the European energy consumption, while heating and cooling for residential and industrial uses account for 50%. Almost 100% of derived heat originates from combustion and only 0.2% from nuclear reactors.[35]

Approx. 90% of process heat in most industrialized countries is characterized by high energy intensity at > 250°C (see figure below,). This, coupled with absolute dominance of fossil fuels in heat production, results in high emissions, not only of CO2, but also of fine dust, heavy metals, NOx, SO3 and others. Consequently, many issues concerning public health, environment, energy security, geopolitics, socio-economics etc. are at stake. As long as

[35] https://snetp.eu/wp-content/uploads/2020/10/NC2I-VISION-PAPER_Final-version_Web.pdf

no commercially viable alternative exists, fossil fuels remain the sole option for most high-temperature processes that power industry.

In Europe, about 50% of the process heat market is found in the temperature range up to 550°C, today mainly in the chemical and petrochemical industry, with perspectives for the production of hydrogen, steel, cement and other hard-to-abate applications.

To advance broader applications of nuclear cogeneration to industrial processes requiring heat at high temperature, international technology developments are focusing on nuclear reactor types designed to deliver this high temperature heat. Depending on the customer's needs, various reactor concepts can be considered, e.g., the well-known Generation IV International Forum concepts, including modular High Temperature Reactors (HTGR) and their long-term evolution towards very high temperatures (VHTR), Super-Critical Water Reactors (SCWR), Molten Salt Reactors (MSR) and different Fast Neutron reactor concepts cooled by either Sodium (SFR), Lead (LFR) or Gas (GFR).

However, for competitive nuclear solutions delivering process steam up to 550°C to be deployed as soon as possible to curb industrial CO2 emissions while maintaining energy-intensive industry in Europe despite the present energy crisis, the HTGR featuring the most mature technology for high temperatures, is currently the only option, ready for early deployment and covering the broadest range of temperature. The expected experience feedback from HTGR operation will later facilitate deployment of other advanced reactor types for nuclear cogeneration once these can deliver high temperatures, become mature enough and present certain advantages in comparison to HTGR.

Modular HTGR designs feature unique simplicity owing to their intrinsic passive safety concept and to the unique property of its fuel that can withstand temperatures above 1600°C without losing its integrity and releasing its radioactive content. The modular HTGR safety concept is therefore a clear advantage for siting in proximity to industrial end users. As it also makes expensive redundant and active engineered safety systems superfluous, it is an asset for competitiveness, a prerequisite for any industrial deployment.

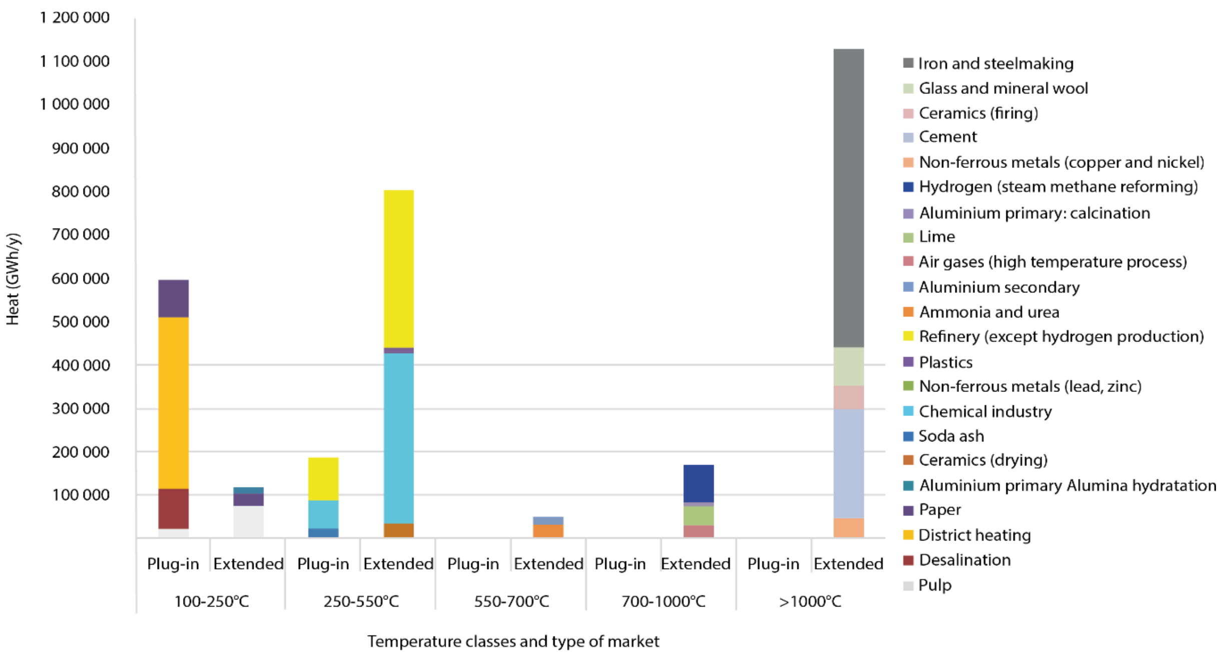

Figure 32: Distribution of the European heat market by temperature class and sector (Source: NC2I Vision Paper)

Emissions of CO_2 from industry are not only resulting from fossil fuel burning for process heat supply. Certain processes themselves generate a significant part of the CO_2 released by industry. Chemistry, steel industry, present hydrogen production from steam-methane reforming etc., use carbonated agents, which are responsible for significant CO_2 emissions. These could be avoided by substitution of carbonated agents by hydrogen stemming from water splitting processes. Any nuclear reactor can produce hydrogen through water electrolysis, but only HTGR can produce at the same time high temperature process heat and hydrogen required by industry.

In addition, the high temperature heat produced by HTGR allows the use of high temperature thermochemical processes or high-temperature steam electrolysis for large-scale hydrogen production. These processes achieve much higher efficiency than low-temperature alkaline electrolysis. Hydrogen or hydrogen derivatives such as synthetic hydrocarbons or ammonia could also be employed for energy storage or hard-to-abate transport purposes. Therefore, the use of HTGR could not only clean up many industrial processes, but also contribute to the decarbonization of road, air and maritime transport, as well as to energy storage. When including electricity generation, industrial process heat applications and hydrogen production for industry and transport, nuclear energy has the potential to cut about 75% of human CO_2 emissions.

Small Modular nuclear Reactors and the Future of Decarbonized Steel Production

The European steel industry's transition to electric arc furnaces (EAFs) and hydrogen-based direct reduced iron (DRI) requires an abundant, affordable, and reliable supply of clean energy. While renewable sources are essential, their intermittency presents challenges for large-scale industrial operations**. Small Modular nuclear Reactors (SMRs)** offer a complementary solution by providing both stable low-carbon electricity and high-temperature heat, which can enhance the efficiency of EAFs by preheating scrap and DRI. Integrating SMRs into the energy mix aligns with the European Commission's Steel and Metals Action Plan, ensuring long-term price stability, energy security, and industrial competitiveness. Policy support for SMR deployment—through targeted incentives, streamlined regulation, and integration into industrial decarbonization initiatives—will be crucial in enabling their adoption. By leveraging SMRs alongside renewables and hydrogen, the steel industry can achieve its decarbonization goals while maintaining global competitiveness.

The Energy Challenge in Steel Decarbonization

Decarbonizing the steel industry requires a reliable energy supply, as the shift away from coal-based blast furnaces significantly increases electricity demand. The European Steel and Metals Action Plan acknowledges high energy costs as a major challenge to competitiveness and sustainability. While renewables such as wind and solar provide low-emission energy, their intermittent nature poses limitations for continuous steel production. Hydrogen-based steelmaking, another key pillar of decarbonization, depends on large-scale electrolysis, which further amplifies electricity demand. Without a stable and affordable energy supply, the transition to low-carbon steel production could stall, leading to economic challenges for European steelmakers competing in a global market.

The Role of SMRs in Steel Decarbonization

SMRs present an innovative energy solution, offering **a stable, cost-effective source of clean electricity and process heat**. Their modular design allows for flexible deployment near industrial sites, reducing transmission losses and improving energy security. Unlike traditional nuclear reactors, SMRs have a smaller footprint, lower initial capital costs, and shorter construction timelines, making them well-suited for integration into industrial applications such as steel manufacturing.

One of the key advantages of SMRs is **their ability to provide high-temperature heat (500-800°C), which can be utilized to preheat scrap and hydrogen-based DRI.** This reduces the electricity demand of EAFs, improving overall efficiency and reducing operational costs. By incorporating SMRs into the steel industry's energy mix, companies can reduce dependency on volatile fossil fuel markets and fluctuating electricity prices, ensuring a stable and predictable cost structure.

Enhancing Industrial Competitiveness and Energy Security

The integration of SMRs into steel production aligns with broader European industrial policies aimed at reducing carbon emissions while maintaining global competitiveness. The European Steel and Metals Action Plan emphasizes the need for cost-effective solutions to lower energy prices, support industrial innovation, and prevent carbon leakage. SMRs can contribute to these objectives by offering a reliable and affordable energy source, mitigating the risks associated with energy price volatility and supply chain disruptions. In addition to enhancing competitiveness, SMRs support Europe's strategic energy independence. By reducing reliance on imported fossil fuels and mitigating the intermittency challenges of renewables, SMRs help stabilize energy supply, ensuring that steel manufacturers can operate at optimal capacity without energy-related interruptions.

2.6.6. Stakeholders

- Steel industry
- Steel research centers
- Contractors
- Energy Equipment suppliers
- Oil and gas companies
- Electricity producers
- Public authorities
- Universities

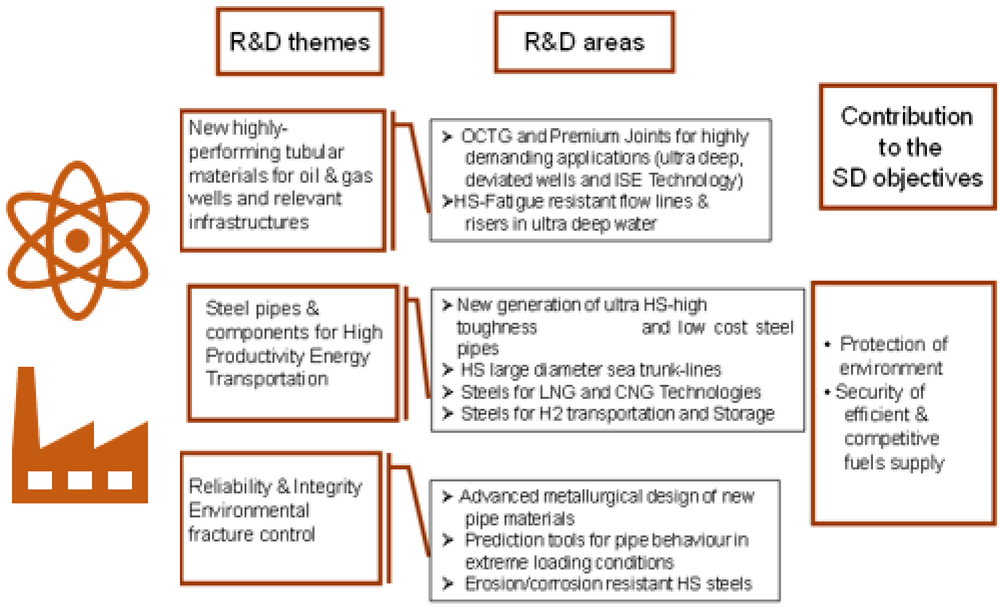

Figure 33-34: Steel applications for energy – R&D&I themes and areas

2.7. Attracting and securing qualified people to help meet the steel sector's ambition (People)

2.7.1. Introduction

From now until 2030, the world will undergo major changes, many of which will be brought about by the evolution of science and technology. The European steel industry will contribute its share with new processes and new products conceived to strengthen its competitiveness, answer evolving customer demands and to preserve the environment. Other changes will come from the increasing globalization of the world economy and the world steel market, which will induce continuing rationalization and concentration in the steel industry. Further changes will come from the evolution of society in a dynamic exchange with its own altered surroundings.

People, in the steel industry and in society in general, will be the drivers who make such changes happen, but they will also be those who will have to live through them, and may in some instances oppose them. This illustrates the key role of people in the success of the processes of change, as well as the need to prepare people to address constructively the changes ahead.

During this period the European steel industry will also be faced with an unprecedented and demanding situation. The population pyramid in most steel producing companies is such that more than 20% of its workforce will leave it during the next ten years, and close to 30% during the following ten years. Needless to say, this huge transformation will not only be quantitative, but will also have a crucial qualitative dimension. It represents, at the same time, a daunting challenge and a welcome opportunity.

The opportunity comes from the possibility to use this substantial transformation in the composition of the industry's workforce as an instrument of change.

The challenges lie in making sure that the education system will keep the capacity to supply the steel industry with the number of people and with the competencies it needs, while developing the steel industry's capacity to attract relatively scarce highly skilled people in a competitive labour market.

Requirements concerning labour organization and labour policy are increasing. The question about conditions of preservation and further development of innovation capacity at the level of organization of human work will become the central future issue of public innovation policy, where economic, technological and social innovations interact. One of the greatest current challenges of management is to organize effectively utilization of manpower dealing with core processes of interactive value creation and innovation. At the same time, in light of demographic change and apparent skilled worker shortage, the capacity of companies, to train, to recruit and to make qualified workers stay for a long period, is becoming a decisive success factor. In this context, it will become more important for companies to offer attractive workplaces. Issues of workplace quality will regain importance. The outcome of workplace innovation is to contribute to sustainable changes related to the economy, ecology and employability and to sustainable innovative capability of organizations and individuals.

The continuously improving record of the steel industry in the field of health and safety should also contribute to the attractiveness of the sector. The high priority given by the industry to its "zero accident" objective and the elimination of fatalities is a guarantee of further progress. Further, as reaching these objectives implies significant behavioural changes, improving health and safety at work also comes to be a potent agent of change management. In relation to health and safety and due to technological changes green and digital skills, expertise and awareness have to be developed continuously. All these trends converge on and represent different facets of Talent Management. During the last thirty years, Talent Management has become the nexus of steel companies' competitive strategies, securing the coherence of their implementation and, more generally, seeking the optimization of one of their key assets. In-deed, human resources are the holders of a company's core competencies, which are one of the main sources of its competitive advantages.

Thus, it comes as no surprise that most steel companies, in a way or another, have been pursuing new organizational configurations tending to transform enterprises into "knowledge organizations", dealing also with the management of knowledge.

Talent Management also plays a key role in change management. In this capacity, it is instrumental in developing an industrial relations system supportive of innovation, improvement of job quality, and competitiveness, thanks to a constructive social dialogue.

In the end, an effective Talent Management is essential to the successful implementation of the steel sector's long term vision regarding profit, partners, the planet, and people

2.7.2. Research theme and implementation of actions

The main objective of attracting and securing qualified people to help meeting the steel sectors ambition will be operationalized by four research and development themes:

- Health and safety
- Innovation management
- Attracting and retaining qualified people
- Talent management

Within the topic health and safety, attracting and retaining qualified people as well as talent management a lot of activities were already carried out within ESTEP's FG People from a perspective of best practice exchange and first research activities. These themes will be further developed within research activities and the acquisition of projects, integrating innovation management (as an integrated approach combining technological innovation with a social innovation perspective) and management of knowledge as new priorities. Needless to say that the existing and future cooperation with the Social Dialogue Committee will be fed by these themes and its results as well.

a) Health and safety: Zero accidents still being the ambition

The European steel industry has long been a pioneer in promoting and carrying out research to improve health and safety at work, mainly through the ECSC Social Affairs research programmes, which started in the early 1950s. The improvement of working conditions was in fact one of the most important objectives of the ECSC Treaty, and huge resources, amounting to approximately € 240 million, were dedicated to health and safety research until the programme lapsed in 1994. Subsequently, health and safety issues were only partly covered by ECSC Technical Research that ran to the end of the ECSC Treaty, and now, in the current Research Fund for Coal and Steel Research (RFCS) programme.

However, steel companies and organisations of the steel industry created specific methodologies and activities in the management of health and safety with the objective of reaching the "zero accident" target. All experts agree that in spite of the unquestionable progress that has been made, there are still too many accidents and health diseases occurring in the steel industry, even in the best cases. In order to foster breakthroughs, health and safety is and must be considered among the most important company objectives, with all hierarchical levels aware of its relevance and with adequate human and financial resources provided to achieve them. The most advanced steel companies in this field put health and safety at the top of the agenda of the periodic meetings of the board of directors, giving a clear signal to all the underlying layers down to the shop floor.

But working conditions are still changing rapidly, switching from physical to mental loading, and the consequences of new working conditions on workers should be investigated. The steel industry nowadays is characterised by a high internal risk potential due to the highly technology driven production process. The other way round, new technologies could take over harsh activities of the workers. Also, the increasing number of subcontracting accumulates the operation risks because of the lower standards of risk management in most of these enterprises (estimated up to five-time higher accident rates).

New safety concepts focus on technical and organisational, human and cultural factors. The acceptability and the achievement of these concepts could only be reached by a risk sensitive workforce. Therefore, awareness programmes and technologies have to be developed also than organisational models and risk decreasing tools and methods (simulation, monitoring, etc.), in line with the paradigm of social innovation combining different perspectives in an overall approach.

The long-term vision is the achievement of the zero accidents objective. This in turn calls for a multidisciplinary approach to prevent accidents and treat injuries, i.e., call for the integration of health and safety ergonomic, and even organizational aspects in research or research and development projects, as well as in designing new plants, production lines and products. FG People started with an exchange of good practice within the different companies engaged and went on to develop new research projects combining technological and behavioural development strategies supporting sustainable, fundamental and continuous improvement of performances towards zero-accident workplaces. This includes strengthening managers' understanding of their role and responsibility in health and safety and to provide managers with an overview of good practices and tools available within the company.

b) Innovation management: A comprehensive approach embedding technological innovation in a social innovation process

Requirements concerning labour organisation and labour policy are increasing. The question about conditions of preservation and further development of innovation capacity at the level of organisation of human work will become the central future issue of innovation policy, where economic, technological and social innovations interact. Again, this will be done in line with the EU 2020 Strategy: "Creativity and innovation in general and social innovation in particular are essential factors for fostering sustainable growth, securing jobs and increasing competitive abilities, especially in the midst of the economic and financial markets crisis."[36]

Innovation management from a people perspective is different from a pure technological perspective like it is nowadays mainly discussed within the recent digital developments named "internet of things", Industry 4.0 or the fourth industrial revolution. It's successor, Industry 5.0 seeks to harmonize technology with human creativity and well-being, prioritizing sustainability and a human-robot collaboration over purely autonomous systems. Every technological or economic innovation is also a social innovation because of the social adaption, implementation or refusal of these innovations. Therefore, innovation management has to be seen as new strategies, concepts, ideas and organisational models to meet social needs of the employees. Within joint initiatives between ESTEP, companies and universities research (even from other industry sectors than the Steel Industry) innovation management will be fostered or initiated by the development of innovation:

- to create, develop and implement innovation in different fields like organisational development, work practices, collective intelligence, knowledge and change management
- to foster the ability to change practices taking into account constraints and opportunities, to lead change, to take into account new expectations from personnel and society
- to advance working conditions and to enable work place innovation.

Taking this approach serious the integration of technological innovation within social innovation processes (every technological innovation is a social innovation as well) a more intensive co-operation between WG People and the other working groups is intended.

c) Attracting and retaining qualified people: the ground for a competitive steel industry

Due to the relevance of the steel industry for the industrial European added value and to ensure the ongoing competitiveness of a safer, cleaner and more technologically developed steel industry, a highly skilled workforce

[36] Barroso 2009, Rapid Press Release, IP-09-81

is required. In fact, highly skilled people are the vital resource for the industrial added value in Europe today and tomorrow.

For this very reason, it will be the sufficient supply of qualified and trained workforces which will decide the future success of businesses. Current and future social challenges like demographic change, an over aged workforce, skill shortages and others have to be proactively solved by the steel companies within competitiveness with other advanced manufacturing industries.

Therefore, the steel industry is developing its capacity to attract, recruit and retain highly skilled workers in a competitive labour market. It will be people, independent of organisational or technical innovations, which will create innovation and success in the end. The challenge is:

- How to raise awareness of young people at an early stage and broadly enough in the vast amount of possibilities technology can mean to them?
- How to communicate the leading technologies of the European steel industry in order to attract talented young people to study metallurgy/materials science and engineering?
- How to tempt talented people to find their way into steel industry, and to stay to further develop technology, products and solutions for customers and customers' customers?

Actions to be implemented by WG People are:

- surveys to evaluate the attitudes of school pupils and students towards the steel industry
- concepts and activities to promote the image of the steel industry
- supporting resources and teaching for technical education (mathematics, physics, chemistry, design, technology and engineering).

d) Talent management: crucial for current and future innovation and competitiveness

Talent management is one of the main current and approaching challenges for the competitiveness of the European steel industry in particular and the European economy in general. In line with the main European strategies[37], high qualification and competence of the workforce is seen as the prerequisite for the European industrial added value. In particular the steel industry of today, with its high-tech production processes, needs young talents to keep its European companies competitive by a continuous improvement of innovation in products and production (technologically, organisational, and environmental).

Of course, talent management is primarily a company's task and enormous activities and strategies already put in place by steel companies: events, fairs, target group specific and young potential programs, mentoring and management training programs, internship and trainee programs, systematic personnel development. Cooperation between steel companies and schools and universities seems quite normal nowadays. These activities are adjusted to short-term recruiting as well as to long-term retention and attractiveness.

The performance of talent management includes all phases of lifelong learning: it runs from informing and explaining pupils about technical professions in industry at (primary and secondary) schools over to students and graduates. The development of talents comprises systematic measures in personnel development and target group-oriented training seminars and coaching for all workforce members.

Collaboration between companies, regional and local education, training institutions, job centres, vocational schools, "steel related" universities, and also primary and secondary schools, management and training academies as well as faculties and universities have to be developed further in a more reliable way. New kind of co-operations like dual study, pathways between higher education and vocational education have to be established between companies and educational systems and in between the different educational systems.

[37] Particularly Europe 2020 strategy and its flagship initiative "An Agenda for New Skills and Jobs", Communication Paper on Integrated Industrial Policy putting competitiveness at centre stage

The results of the survey on Talent Management in the European Steel Industry conducted by WG People in 2015 is delivering the ground for further activities in the direction of targeted strategies to recruit, develop and retain talented people from every age. As well a comparative analysis of enterprise approaches as learning organisations will help to analyse the critical factors for success and constraints for future innovation and competitiveness.

2.7.3. Social responsibility and inclusive business

- Ensuring safe work conditions;
- Exchange of practices in view of the "zero accident" target;
- Close relationships with a network of top-level universities taking initiatives to attract the best students in the steel industry; disseminate a steel culture;
- Support and development of training at European level;
- Fostering the interrelation of technological with social innovation as co-creation processes, integrating all the relevant stakeholders and dealing with social and environmental impact

2.7.4. Stakeholders

- Steel sector
- European universities dealing with steel developments
- Steel research centres
- Unions organisations
- Stakeholders in the European Steel Technology Platform

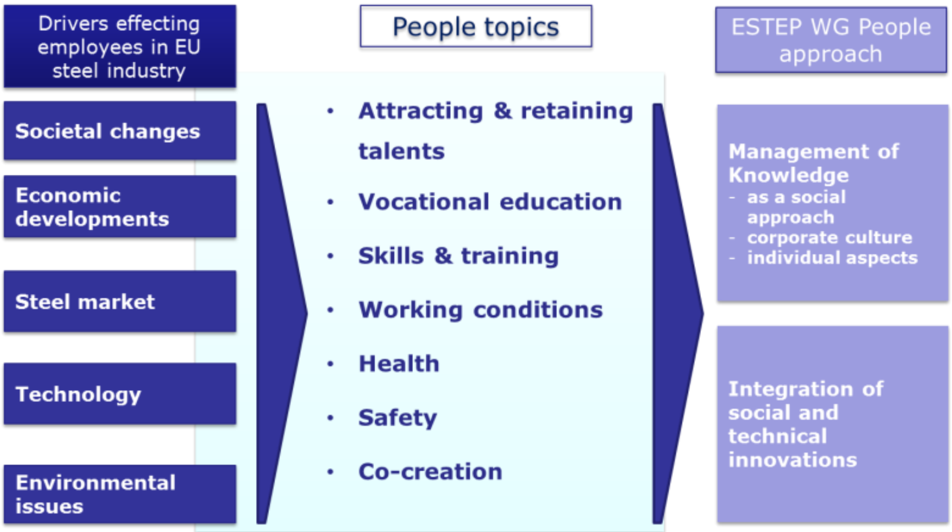

Figure 35: Attracting and securing qualified people to help meeting steel sector's ambition

2.7.5 The SPIRE Skills Alliance for Industrial Symbiosis (SAIS)

Background

In line with the European New Skills Agenda, the Pact for Skills and the series of Sectoral Blueprints the project developed a Blueprint "European Energy Intensive Industry Skills Agenda and Strategy (SPIRE-SAIS)" for an ongoing and short-termed implementation of new skills demands concerning cross-sectoral Industrial Symbiosis (IS) and Energy Efficiency. Against this backdrop, the implementation of the SPIRE-SAIS Blueprint strategy was performed already in its proposal phase as a Cross-Sector Skills Alliance on Energy Intensive Industries. It started as a (social) innovation process by involving a broad range of key stakeholders from the eight sectors of the public-private partnership A.SPIRE (Sustainable Process Industry through Resource and Energy Efficiency): Steel, Chemicals, Minerals, Non-ferrous Metals, Water, Engineering, Ceramics, and Cement - during the course of the project completed by two new SPIRE sectors: Refinery and Pulp & Paper.

Overview

The **Skills Alliance for Industrial Symbiosis (SPIRE-SAIS)** plays a critical role in embedding **technological innovation** within a **social innovation process**, fostering **talent attraction, retention, and management**, and advancing **social responsibility and inclusive business practices**. These efforts contribute to the **competitiveness and sustainability of energy-intensive industries**, including the steel sector.

SPIRE-SAIS is **pioneering a comprehensive, industry-driven strategy** that bridges **technological advancements, workforce development, and social innovation**. By aligning **innovation management, talent attraction, social responsibility, and health & safety**, it ensures that the steel and energy-intensive industries remain **competitive, inclusive, and future-ready.**

Innovation management and the integration of technological and social innovation

SPIRE-SAIS ensures that **technological advancements in Industrial Symbiosis (IS)** and **Energy Efficiency (EE)** align with **societal and economic needs** through:

- A social innovation process: Involving **companies, research institutions, training providers, and policymakers** from the outset ensures stakeholder-driven solutions.
- Iterative Development: The Blueprint evolves through **continuous feedback loops**, allowing it to adapt to new industry demands.
- Skills intelligence tools: The **Foresight Observatory** and **Skills4Planet platform** proactively monitor skill gaps and recommend adjustments.
- Industry 5.0 alignment: SPIRE-SAIS adopts a **human-centric approach**, ensuring that technology serves the worker rather than requiring workers to adapt to technology.

Attracting and retaining talent in the steel and process industries

To combat labor shortages and improve industry attractiveness, SPIRE-SAIS implements:

- Regional skills development: Tailored training programs align with local labor market demands, mitigating worker migration issues.
- Vocational Education and Training (VET) alignment: A focus on **lifelong learning** ensures that professionals continuously update their skills.
- Rebranding the industry: Modernizing the perception of steel and process industries through sustainability initiatives and **green job creation**.
- Cross-Sector Collaboration: The SPIRE-SAIS **training ecosystem** connects various industries, facilitating knowledge-sharing and job mobility.
- Digital and Green Skills Training: Addressing future workforce needs through **upskilling and reskilling initiatives**.

Talent management for innovation and competitiveness

Ensuring **workforce readiness for future challenges** involves:

- The SKILLS4Planet Online Training Platform: An open-access platform offering **training modules, self-assessment tools, and certification options.**
- Workforce Forecasting and Planning: The Blueprint leverages **data-driven insights** to anticipate skill shortages and training needs.
- Collaboration with Human Resources (HR) and management teams: Ensuring that businesses can efficiently **retain and develop their workforce.**

- Integration with European Policies: SPIRE-SAIS aligns with **the European Skills Agenda, Clean Steel Partnership, and the European Pact for Skills** to foster workforce resilience.

Advancing social responsibility and inclusive business practices

SPIRE-SAIS promotes a **diverse, sustainable, and responsible industrial workforce** through:

- Supporting underrepresented groups: Encouraging participation from **women, migrants, and disadvantaged communities.**
- Workplace modernization: Advocating for **flexible work models, improved working conditions, and lower hierarchical structures.**
- Industrial-urban symbiosis: Supporting **smart cities** by repurposing industrial byproducts (e.g.,, using excess heat for residential heating).
- Fostering public-private partnerships: Engaging **local authorities, industries, and educational institutions** in skill-building initiatives.

Commitment to health and safety: towards zero accidents

SPIRE-SAIS integrates **health and safety** as a core principle to achieve its **zero-accident ambition** by:

- Aligning with EU health & safety regulations: Ensuring compliance with European directives and integrating best practices for workplace safety.
- Promoting a risk prevention culture: Training programs emphasize **hazard recognition, emergency response, and risk mitigation strategies**.
- Leveraging Digital Safety Training: The **SKILLS4Planet platform** offers real-time learning solutions for evolving safety protocols.
- Enhancing Workforce Well-Being: Prioritizing **ergonomics, mental health, and inclusivity** to foster a safer and healthier work environment.
- Encouraging Cross-Sector Safety Collaboration: Industries share best practices to collectively improve workplace safety standards.

2.7.6. The SUPER project

Background

The steel industry faces a huge challenge to transform towards decarbonisation: new technologies, plants, energies and media create a lot of technical challenges but also substantial demand for new know-how. The industry also faces a transformation within its work force due to numerous retirements. Young talents are scarce and often have a rather critical perception of the steel industry relating it to emissions and low innovation. These two challenges have to be tackled at the same time, unfortunately under very high economical pressure. The next few years will decide about the survival of the steel industry and about achieving CO2 mitigation targets. While a lot of activities have been performed on technical R&D and on recruiting and skilling, the SUPER project follows a fresh approach which combines both topics with the focus on synergies supporting both challenges. Synergies are expected by linking R&D activities on local/national/EU level, along the maturity progress to industrial implementation but also with cross-industrial view. Interdisciplinary communication and cooperation are in the very centre of this activity, beyond technical and social disciplines. Digitalisation can provide synergies for both transformations, however also needs new skills and well-coordinated implementation. Thus, skilling is a key enabler and it has to go along with image building. It is imperative for the sector to show its high potential to mitigate emissions and to be innovative. SUPER performs talent training (RACE), desk research and stakeholder consultations and initiates interdisciplinary know-how dissemination and networking. Results and feedbacks are exploited into recommendations for future activities and policy initiatives to leverage the synergies. This comprehensive approach is enabled by the strong involvement of the project and the consortium partners into current activities and the ESTEP community.

Overview

The SUPER project strategically combines **technological, educational, and social innovation** to create a **sustainable, competitive, and inclusive steel industry**. By focusing on training, recruitment, and industry image transformation, it ensures that the steel sector remains resilient and attractive for future generations.

- Health and safety: zero accidents ambition

The SUPER project integrates health and safety within training programs such as **Steelmaster** and **Eurosteelmaster**, emphasizing the industry's shift towards digitalization, decarbonization, and sustainability. The project promotes **Industry 5.0**, which prioritizes a **human-centric approach** ensuring safer working environments and reduced accidents through improved processes and technology.

- Innovation management: embedding technological innovation in a social innovation process

SUPER aligns with **Industry 5.0**, advocating for technological advancements that are co-designed with workers and stakeholders. The project emphasizes **human empowerment**, ensuring that new technologies (like digital tools and AI-driven process management) are effectively integrated into the workforce. By supporting interdisciplinary collaboration between technical and social experts, SUPER fosters an environment where innovation leads to practical workplace improvements.

- Attracting and retaining qualified people: a competitive steel industry

One of the biggest challenges in the steel industry is the **aging workforce and difficulties in attracting young talent**. SUPER tackles this by integrating recruitment and training initiatives, such as **RACE (Raw & Circular Economy Expedition)**, which provides young professionals with firsthand experience in the steel sector. The project also promotes **a new industry image**, moving away from outdated perceptions of steel production as a traditional, polluting industry and positioning it as a **high-tech, green sector**.

- Talent management: crucial for current and future innovation and competitiveness

SUPER works to **build a future-ready workforce** by bridging gaps in digital and green skills. It incorporates training modules within platforms like **SKILLS4Planet, steelHub, and Skills4EII**, ensuring ongoing upskilling and reskilling. The project also facilitates cooperation between **industry, universities, and policymakers** to develop career pathways that attract diverse talent.

- Social responsibility and inclusive business

SUPER emphasizes **social sustainability**, supporting inclusive hiring practices by integrating **marginalized groups (women, migrants, vocationally trained workers)** into the steel industry. It also advocates for **work-life balance improvements**, such as flexible working conditions. Furthermore, the project supports **regional outreach**, strengthening relationships between steel companies, schools, and local communities to foster long-term employment opportunities.

2.7.7 The European Steel Skills Alliance (ESSA)

Proactive skills adjustment within a social innovation process is 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[38] 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

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

- 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, integration 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 36 shows an overview.

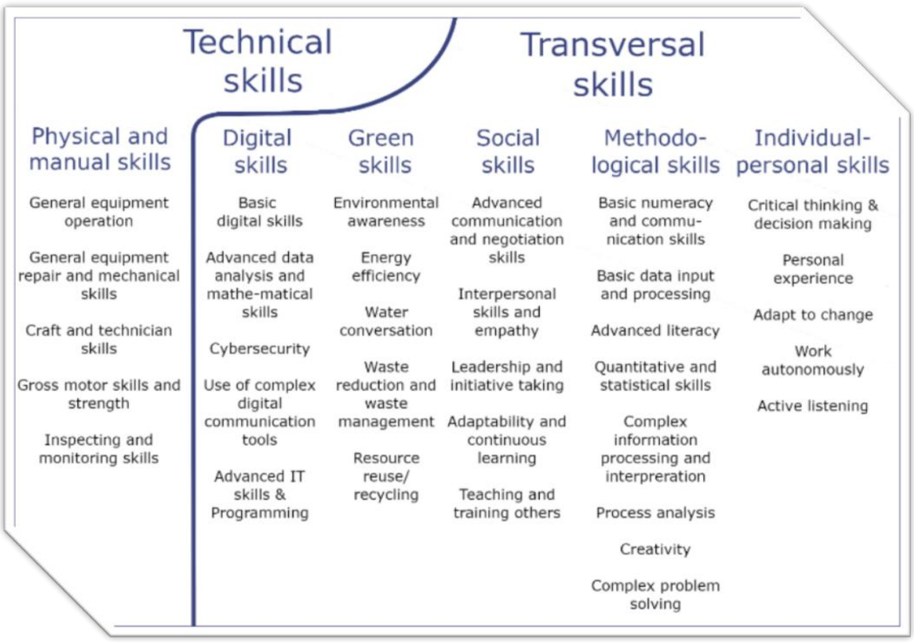

Figure 36: Overview of technical and transversal (soft) skills

PART 3. OVERALL VIEW OF ESTEP'S SRA AND CONSISTENCY WITH HORIZON EUROPE AND THE RESEARCH FUND FOR COAL AND STEEL

This 2026 updated SRA offers a global vision of the innovation and R&D&I efforts that should help the steel sector and its value chain reach the objectives highlighted by ESTEP to retain a sustainable world leadership of the sector in the coming decade.

The steel sector belongs to the strategic important sectors of the EU. A couple of high-level policy documents explain the importance of steel and its production for and in the EU. The European Green Deal addresses the twin transition of the EU towards climate neutrality and digitisation. Both elements are fully considered by ESTEP. The legal framework of the Research Fund for Coal and Steel was accordingly modernised in 2021.

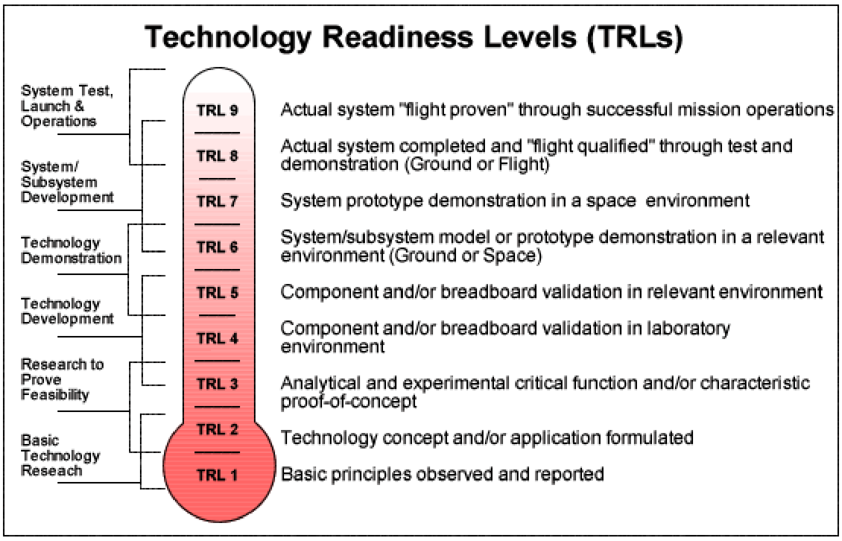

Figure 37: TRLs describing the whole chain of innovation

Priorities have been identified for the themes and R&D&I areas of the three industrial programs of ESTEP and of the 7 domains described in the previous chapters:

- Sustainable steel production: low carbon steelmaking ultimately leading to climate neural steelmaking
- Safe, cost-effective and lower capital-intensive technologies
- Steel solutions for transports
- Steel solutions for construction and infrastructures
- Steel solution for energy
- Attracting and securing qualified people for the steel sector.
- Enabling the digitisation of the steel sector

Another important aspect of this program is to cover the whole chain of innovation, addressing basic and applied research, pre-industrialization and deployment. The activities of the research & innovation cycle can be represented by the Technology Readiness Levels (TRLs). This methodology has become recognized internationally and is being at industry level: the 9 TRL steps, from basic principles to market commercialization are shown in Figure18.

In the **next part (4-Implementation)**, a deployment scheme will be proposed for the different R&D&I themes over the next decade, using TRL methodology.

Private funding from stakeholders as well as public funding from the EU, National and, possibly, regional institutions will be necessary to implement the 3 industrial programs and a transversal one.

3.1 Research Fund for Coal and Steel

The European Green Deal Communication of the European Commission is the European growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use.

The Communication also states that all Union actions and policies should pull together to help the Union achieve a successful and just transition towards a sustainable future.

The Monitoring and Assessment of the RFCS Research Programme 2011-2017 report highlights the major challenges for the European coal and steel industry: (i) to cut greenhouse gas emissions, (ii) to make sustainable use of energy and resources, and (iii) to develop new competitive, high-performance products and processes.

The RFCS Modernisation Package adopted on 19 July 2021 is in line with the Von der Leyen Commission's objectives and therefore enables the fund to tackle the sectors' climate and environmental challenges. This means in particular assisting the EU's coal and steel industries to reduce their emissions, thus contributing to the European Green Deal's goals and achieving a Just Transition towards a climate neutral economy.

The Research Fund for Coal and Steel is embedded in the political, scientific, and technological objectives of the Union, and complements the activities carried out in the Member States and within the existing Union Framework Programme for research, technological development and demonstration activities.

RFCS Research Objectives

The RFCS Research Programme (RFCS Decision 2021/1094) has the following research objectives for Steel sector:[39]

- New, sustainable and low-carbon steelmaking and finishing processes (Art. 8).
- Advanced steel grades and applications (Art. 9).
- Conservation of resources, protection of the environment and circular economy (Art. 10).
- Management of work force and working conditions (Art. 10a).

3.2. Horizon Europe 2021-2027

The new Research & Innovation roadmap proposed by the European Commission[40] has been carefully analysed by the ESTEP Focus Groups, and this revised agenda already includes the topics which are relevant to the steel sector.

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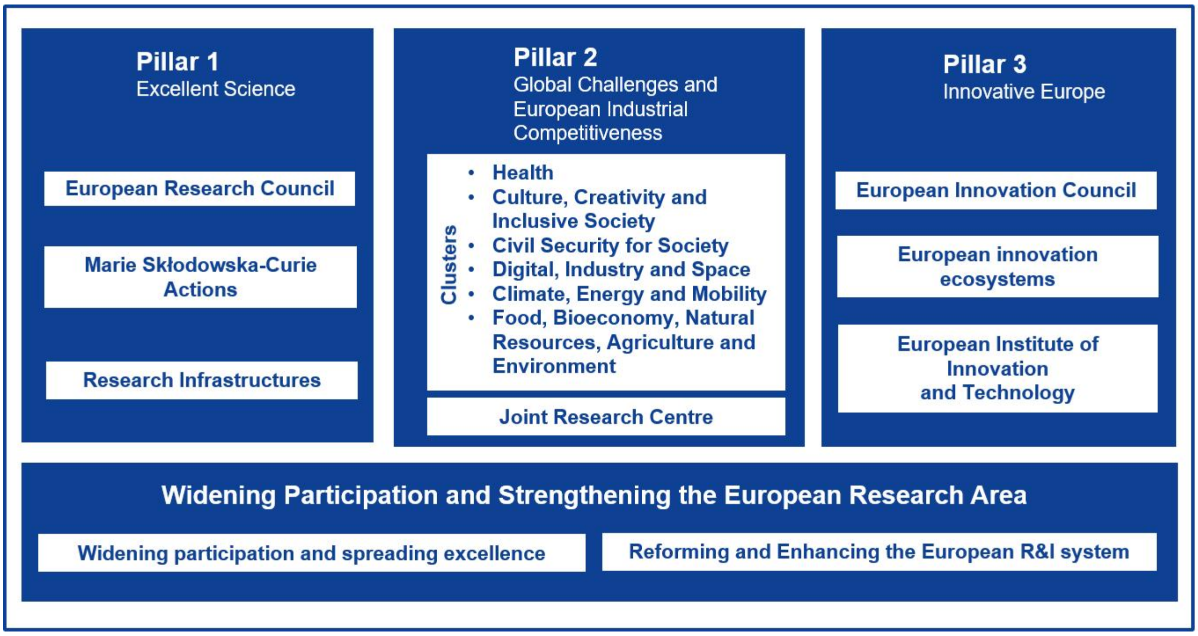
[39] Council Decision of 29 April 2008 2008/376/EC amended by the Council Decision (EU) 2017/955 of 29 May 2017 and Council Decision (EU) 2021/1094 of 28 June 2021 (OJ L 130, 20.5.2008, p. 7).

[40] https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en

Horizon Europe is a evolution of Horizon 2020 and continues to follow 3 key priorities for impactful implementation of R&I:

- Excellent science
- Industrial leadership
- Societal challenges



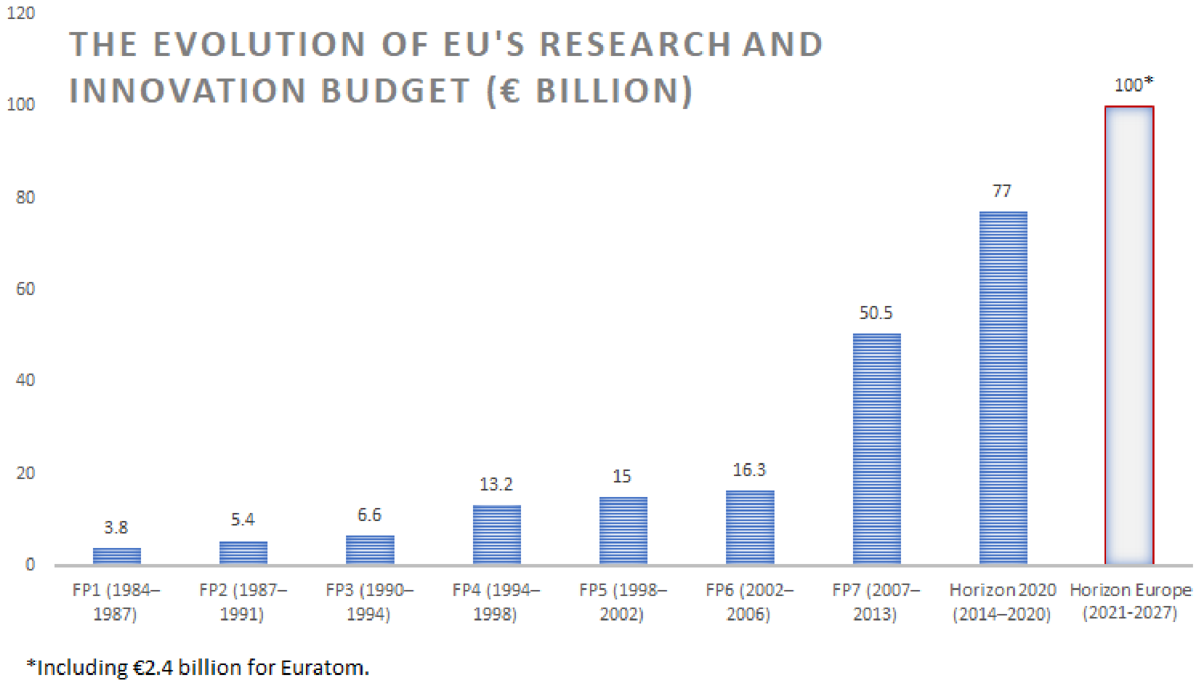


Figure 38-39: European Research Area - Evolution of EU's research & innovation budget

3.3. Types of European Partnerships with the European Commission

The **European Commission** establishes different types of partnerships under the **Horizon Europe** framework to drive research, innovation, and industrial transformation. These partnerships involve collaboration between the public and private sectors to achieve EU policy objectives, including sustainability, digitalization, and competitiveness.

1. **Co-programmed partnerships**
   - Based on a **Memorandum of Understanding** between the EC and private/public partners.
   - Partners commit to investing in R&D&I alongside EC funding.
   - Example: **Clean Steel Partnership (CSP)** with ESTEP.
2. **Co-funded partnerships**
   - Funded through **Horizon Europe grants**, with additional financial contributions from national and regional authorities.
   - Supports coordination between national R&D programs.
   - Example: **European Partnership for Clean Energy Transition** (drives green energy solutions).
3. **Institutionalised partnerships**
   - Created through **EU legislation**, requiring long-term commitment.
   - Managed by **joint undertakings (JUs)** or **Article 187/185 TFEU initiatives.**
   - Higher financial and administrative complexity, often with dedicated legal entities.
   - Example: **Clean Hydrogen Joint Undertaking (JU)** (supports hydrogen-based energy systems).

These partnerships allow industry, research organizations, and governments to **align efforts and pool resources** to achieve strategic European goals.

3.4. Other initiatives

a) The SET-Plan, Strategic Energy Technology Plan, adopted by the European Union in 2007, aims at establishing an energy technology policy for Europe over the next 20 years. The implementation of the SET-Plan started with the establishment of the European industrial Initiatives (EIIs), aiming at the rapid development of key energy technologies at European level for the production of renewable and conventional energy. ESTEP participated actively to the preparation of the materials roadmap of the SET-Plan, proposing innovative material solution for energy production and energy efficient buildings[41] . The Chapter 2 of ESTEP's SRA is well in line with this material roadmap.

The SET-Plan includes also initiatives for the "energy intensive industries" like chemicals, cement, metal, which have since been renamed process industries. In 2016, the implementation started by a public consultation. Action 6 (energy efficiency for industry) and action 9 (carbon capture storage/use) are of high relevance for the steel sector. ESTEP/EUROFER are contributing to these working groups of the SET-Plan. In action 6 two sectors are given a priority: steel and chemistry.

The SET-Plan roadmap

2007 – SET Plan established

2015 – Communication on the integrated SET Plan introduced 10 key actions

2016 – Declaration of Intents adopted

2017 – 14 implementation plans (IPs) adopted, defining the R&I priorities and investment agendas

2017 – First implementation working groups (IWGs) established

2018 – Agenda 2018-2023

2020 – First SET Plan Progress Monitoring Report published

2020 – IWGs on energy consumers and energy systems merged

2020 – Second SET Plan progress monitoring report published, linked with the European Green Deal2021 - Establishment of the HVDC working group

2021 - Third SET Plan monitoring progress report published

2023 – Revision of the of the SET Plan

[41] SEC (2011) 1609 Final- Materials Roadmap Low Carbon Energy Technology.

2024 – Developments under revised SET Plan

Under the revised SET Plan, the Net-Zero Industry Act (NZIA) came into force on 29 June 2024 with the aim to boost the EU's domestic manufacturing of clean energy technologies. As such, the SET Plan Steering Group is formally established as a high-level expert group to the European institutions. Composed of Member States and Commission representatives, and with EEA observers, it will oversee alignment of energy R&I programmes and advise on strategic actions.

In line with the SET Plan revision and the 2023 SET Plan Communication, five SET Plan task forces (TFs) were officially established in 2024. They will support the work of the SET Plan Implementation Working Groups and ETIPs, addressing cross-cutting challenges in clean energy R&I at the European level.

The new Temporary Working Group on hydrogen focuses on two main activities: transitioning new hydrogen technologies from R&I to market uptake and incorporating hydrogen into the energy mix to boost clean energy efficiency. Additionally, the new hydrogen working group addresses legislative issues such as the temporal and geographical correlation in the revision of the Renewable Energy Directive.

Figure 40: European Strategic Technology Plan (SET)

b) The Strategic Transport Technology Plan (STTP), together with subsequent EU R&I frameworks, underlines the central role of innovative, sustainable materials in the transformation of European transport. These initiatives provide the European steel industry with clear opportunities to contribute to EU priorities — particularly by delivering climate-neutral, circular, and high-performance steel solutions for future mobility.

By actively engaging in these EU initiatives, the steel sector strengthens its position as a strategic partner in building a greener, smarter, and more resilient European transport system.

Overview of the STTP

The Strategic Transport Technology Plan (STTP), adopted by the European Commission in 2011, established a long-term vision for a competitive and sustainable transport system in Europe. It laid out strategic goals to reduce dependency on imported fossil fuels, lower greenhouse gas emissions, enhance transport safety, and support a modal shift toward cleaner, more efficient transport modes. The STTP's objectives are now fully aligned with key EU policy frameworks, including the European Green Deal, the Sustainable and Smart Mobility Strategy (2020), and the Fit for 55 legislative package under the European Climate Law.

To guide implementation, a dedicated Research and Innovation (R&I) framework was launched in 2012, structured around three priority areas:

- Clean, efficient, safe, and smart transport means
- Infrastructure and intelligent transport systems
- Passenger and freight transport services and operations

These pillars have since been embedded in EU R&I programmes such as Horizon 2020 and Horizon Europe (2021–2027), which are directly shaping innovation across transport modes. This has clear and growing relevance for the European steel sector.

Implications for the steel industry

The transformation of Europe's transport system requires new vehicle and infrastructure concepts that combine decarbonisation, digitalisation, safety, and circularity — all areas where steel is a strategic enabling material.

Key initiatives supported by the European Commission include:

- 2Zero Partnership (Towards Zero Emission Road Transport), which builds on the former Green Vehicles PPP and supports the development of zero-emission and energy-efficient vehicles. These rely on lightweight, high-strength, and recyclable steel solutions to meet safety and environmental standards.
- Europe's Rail Joint Undertaking, the successor to Shift2Rail, which focuses on digitalised, electrified, and interoperable rail systems. Steel remains essential for rolling stock, railway infrastructure, and noise and vibration control technologies.
- Zero Emission Waterborne Transport (ZEWT) partnership, which promotes innovative solutions for low-carbon shipping and inland navigation. Advanced steel grades are critical for shipbuilding applications requiring corrosion resistance, weight reduction, and durability.
- Connecting Europe Facility (CEF) and TEN-T (Trans-European Transport Network) policy, which enable investment in future-proof transport infrastructure across the EU. These initiatives create strong demand for durable, sustainable steel components in bridges, tunnels, railways, ports, and logistics hubs.
- Digital Europe Programme and CEF Digital, supporting the digital transformation of transport systems and logistics. Here, steel also contributes through modular infrastructure designs and smart, integrated systems.

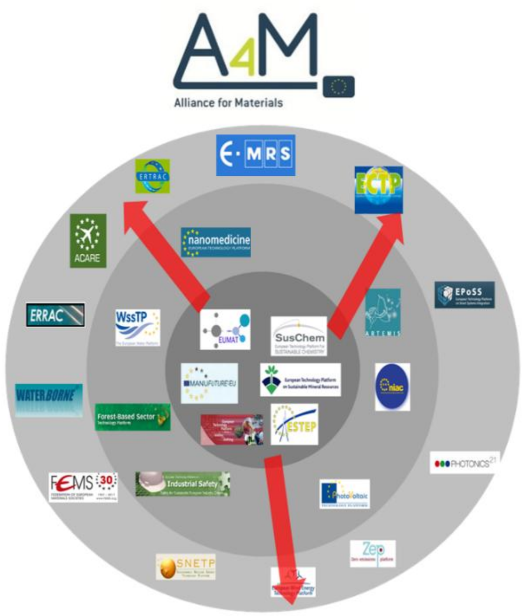
Strategic Alignment with ESTEP and the Steel Sector

The European Steel Technology Platform (ESTEP) and its members are actively contributing to these initiatives by driving forward innovation in advanced steel products, green manufacturing processes, and multi-sector collaboration. The transport sector presents a major opportunity for the steel industry to support EU climate and digital goals while advancing its own decarbonisation pathway.

Steel's contribution is not limited to materials supply: it also includes research excellence, industrial symbiosis, and participation in Joint Undertakings and Public-Private Partnerships supported by the European Commission.

c) The Alliance for Materials (A4M)

The Alliance for Materials (A4M) plays a strategic role in ensuring cross-sectoral coordination of materials research and innovation (R&I) in Europe — with clear benefits for the European steel industry. As materials science remains a key enabling field across value chains, **A4M** strengthens the integration of steel into wider industrial innovation strategies. ESTEP's active participation ensures that steel-related priorities are represented in broader EU-funded research frameworks, including Horizon 2020, Horizon Europe 2021-2027, and future programmes. This coordination is critical for accelerating the development and deployment of high-performance, sustainable steel solutions aligned with EU industrial and climate objectives.



Overview of A4M

The **Alliance for Materials (A4M)** was launched in 2011 under the initiative of EuMaT, the European Technology Platform for Advanced Engineering Materials and Technologies. Its primary objective is to promote value-chain collaboration in the field of materials R&D, ensuring more efficient and coherent implementation of innovations within European R&I programmes.

Materials R&D is by nature a cross-cutting and enabling technology area, with applications across virtually all industrial sectors. Recognising this, A4M brings together six European Technology Platforms (ETPs) with strong materials-related agendas:

- **EuMaT** – Advanced materials and technologies
- **SusChem** – Sustainable chemistry
- **Manufuture** – Advanced manufacturing
- **FTC** – Future textiles and clothing
- **ESTEP** – Steel technologies

- **SMR** – Sustainable mineral resources

By promoting multi-sectoral alignment and joint strategic thinking, A4M helps bridge gaps between sectors, avoid duplication of efforts, and strengthen Europe's position in key industrial value chains.

Relevance to the steel industry and ESTEP's role

For the European steel sector, represented by ESTEP, A4M provides an essential platform to:

- Ensure that steel innovation needs are considered in broader EU materials strategies and roadmaps;
- Promote collaborative research across sectors such as chemicals, manufacturing, mining, and advanced materials;
- Coordinate input into EU Framework Programmes (e.g., Horizon Europe, future FP10) and European Partnerships;
- Support circularity, decarbonisation, and advanced design approaches where materials integration is crucial.

Through **A4M**, ESTEP reinforces the importance of materials-system thinking — where advanced steels are developed and deployed with full consideration of performance, sustainability, life-cycle cost, and value-chain integration.

In this context, the strategic alignment between platforms ensures a united voice in European policy dialogue and a stronger impact on shaping the R&I landscape in favour of sustainable industry.

d) The flagship initiative "An agenda for new skills and jobs"

Addressing skills needs and labour market transformation remains a top priority for the European Commission, particularly in the context of the twin green and digital transitions. Initiatives originally launched under the **"Agenda for New Skills and Jobs"** have evolved into a broader EU strategy encompassing the Pact for Skills, the European Year of Skills (2023–2024), and multiple actions under the European Skills Agenda. These policies are of strategic importance for the steel sector, which is undergoing rapid transformation driven by decarbonisation, automation, and digitalisation. The ESTEP transversal group on attracting and securing qualified people plays a key role in aligning the steel industry with EU efforts, particularly through education, training, and social dialogue. Strong cooperation with universities, vocational institutions, and social partners is essential to secure the future workforce of the European steel industry.

Background: From Flagship Initiative to Skills Agenda

Launched as part of the Europe 2020 strategy, the European Commission's flagship initiative "An Agenda for New Skills and Jobs" (2010) aimed to modernise labour markets, improve employment opportunities, and equip the European workforce with the skills needed for a rapidly changing economy.

Since then, the EU's focus on skills has intensified, culminating in the European Skills Agenda (2020), the Pact for Skills (2020), and the designation of 2023–2024 as the European Year of Skills. These initiatives are designed to:

- Upskill and reskill workers across sectors
- Support sectoral transitions in line with the Green Deal and Digital Europe
- Boost cooperation between industry, education providers, and public authorities
- Ensure inclusion and mobility in the labour market

Relevance to the Steel Industry and ESTEP's Role

The steel sector faces profound changes due to the push toward climate neutrality, smart manufacturing, and circular business models. These transformations require a new generation of workers with expertise in:

- Green and digital technologies
- Advanced process engineering
- Materials science

- Data analysis, AI, and automation
- Energy and environmental systems

To address these needs, the ESTEP transversal group on attracting and securing qualified people engages in:

- Strategic cooperation with universities and technical institutes
- Support for lifelong learning and vocational education
- Dialogue with social partners to anticipate and manage workforce transitions
- Participation in EU-level initiatives and calls related to skills, talent retention, and industrial change

These efforts ensure that the steel industry contributes to — and benefits from — the broader European skills ecosystem.

Moving Forward

- Continued engagement with EU skills initiatives will help the steel industry:
- Remain competitive in the evolving industrial landscape
- Support a just transition for workers and regions affected by transformation
- Attract young talent and diversify the sector's workforce
- Embed skills foresight and adaptability into future innovation agendas

The ongoing activities of ESTEP and its members will be instrumental in ensuring that the steel industry's skills agenda evolves in parallel with Europe's strategic industrial priorities.

PART 4. IMPLEMENTATION

Clean Steel Partnership (CSP) 2021-2027

In 2021, the co-programmed Clean Steel Partnership became a mature organisation. The Memorandum of Understanding was finalised and signed; and the Strategic Research & Innovation Agenda (SRIA, available on the ESTEP web-site) became an official document. The organisation became fully operational and its main decision body is the Partnership Board.

Memorandum of Understanding (MoU)

In August 2021, the Memorandum of Understanding (MoU, available on the ESTEP web-site) for the Co-programmed partnership was signed by the public and the private side. The MoU presents the objectives and underlying key performance indicators (KPIs) of the Clean Steel Partnership. The private contribution has been increased up to 1 billon EUR, while the public side provides a funding envelope of 700 million EUR.

Horizon Europe (HEU) and Research Fund for Coal and Steel (RFCS)

The call topics of the Clean Steel Partnership are launched by Horizon Europe and the Research Fund for Coal and Steel (RFCS), respectively. The call topics cover all six areas of intervention, as stated in the SRIA. The private side provides input to the call generation via ESTEP. HEU and RFCS form two legs of the CSP. HEU provides EUR 50 million per year and RFCS EUR 54 million per year.Both pathways are accompanied by the principle of achieving higher levels of circularity (Circular Economy, CE).

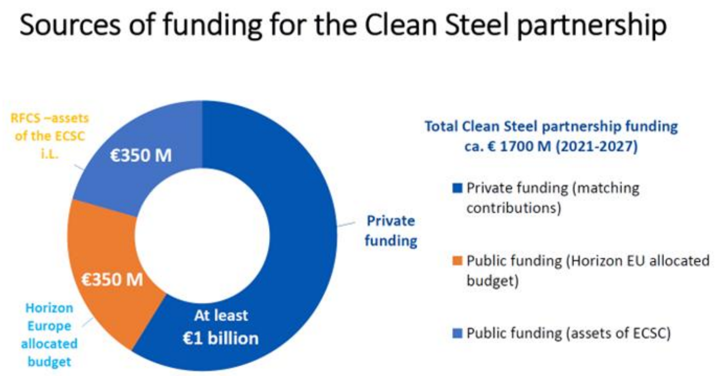


Figure 41 – Clean Steel Partnership Funding Sources

The Strategic Research and Innovation Agenda

The Strategic Research and Innovation Agenda (SRIA) of the Clean Steel Partnership (CSP) is the strategic blueprint guiding the EU steel industry's transformation toward climate neutrality by 2050. Developed jointly by the European Commission and the European Steel Technology Platform (ESTEP), the SRIA lays out the research, development, and innovation (R&D&I) roadmap for drastically reducing CO_2 emissions from steel production while maintaining industrial competitiveness.

Contextually, the SRIA aligns with key European policy goals such as the European Green Deal, the Paris Agreement, and the UN Sustainable Development Goals (SDGs). It responds to growing environmental and geopolitical challenges, as well as to the economic imperative of sustaining a globally competitive EU steel industry. The SRIA also supports the EU's broader ambitions for clean technologies, strategic autonomy, and green industrial growth.

The SRIA proposes a staged R&D&I framework:

1. Short-term: Immediate emissions reductions using near-deployable technologies.
2. Medium-term: Scaling up breakthrough technologies in industrial settings.
3. Long-term: Radical innovation to revolutionize steelmaking.

Three technology pathways are embedded in Clean Steel: Carbon Direct Avoidance (CDA), Smart Carbon Usage (SCU), and Circular Economy (CE). CDA comprises the activities using non-carbon energy and reductants to produce steel, namely hydron and/or electricity.

When using carbon, it will be done smart, which means without emitting the process gases into the atmosphere. So, the activities consist of further improvements of the processes (process integration, PI) and capturing the process gases. These gases are used to generate other products like fuels or chemical building blocks for example (CCU). Another pathway relies on storing the process gases permanently (CCS).

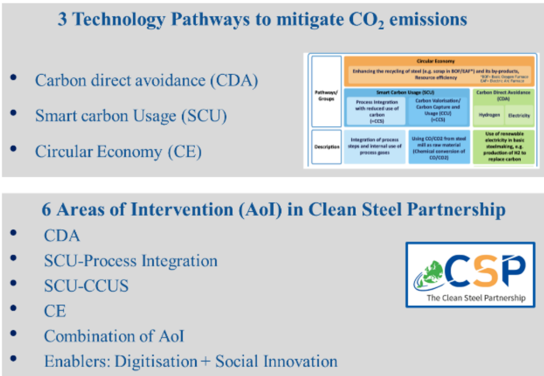


Figure 42: CSP Technology Pathways

For **stakeholders in the steel industry**, the SRIA provides a unified, EU-endorsed strategy to:

- Pool risk and investment in high-cost, long-cycle innovations.
- Leverage up to €1.7 billion in coordinated public-private funding.
- Align R&D priorities with EU climate and industrial policy.
- Access demonstrator-scale support for breakthrough projects.

In essence, the SRIA empowers the European steel ecosystem—including producers, technology suppliers, researchers, and policymakers—to collaboratively drive innovation, meet regulatory goals, and remain globally competitive in a decarbonised future.

Large demonstrator projects

The main result of Clean Steel will be large size, high TRL demonstrators. At least, two demonstrators will show the emission reduction potential of at least 50%, while two additional demonstrators will prove the emission reduction potential of at least 80%. These demonstrators may combine several technologies into a technological pathway and organise field campaigns on physical demonstrators, leading to pre-engineering of full-scale projects.

CSP Timeline

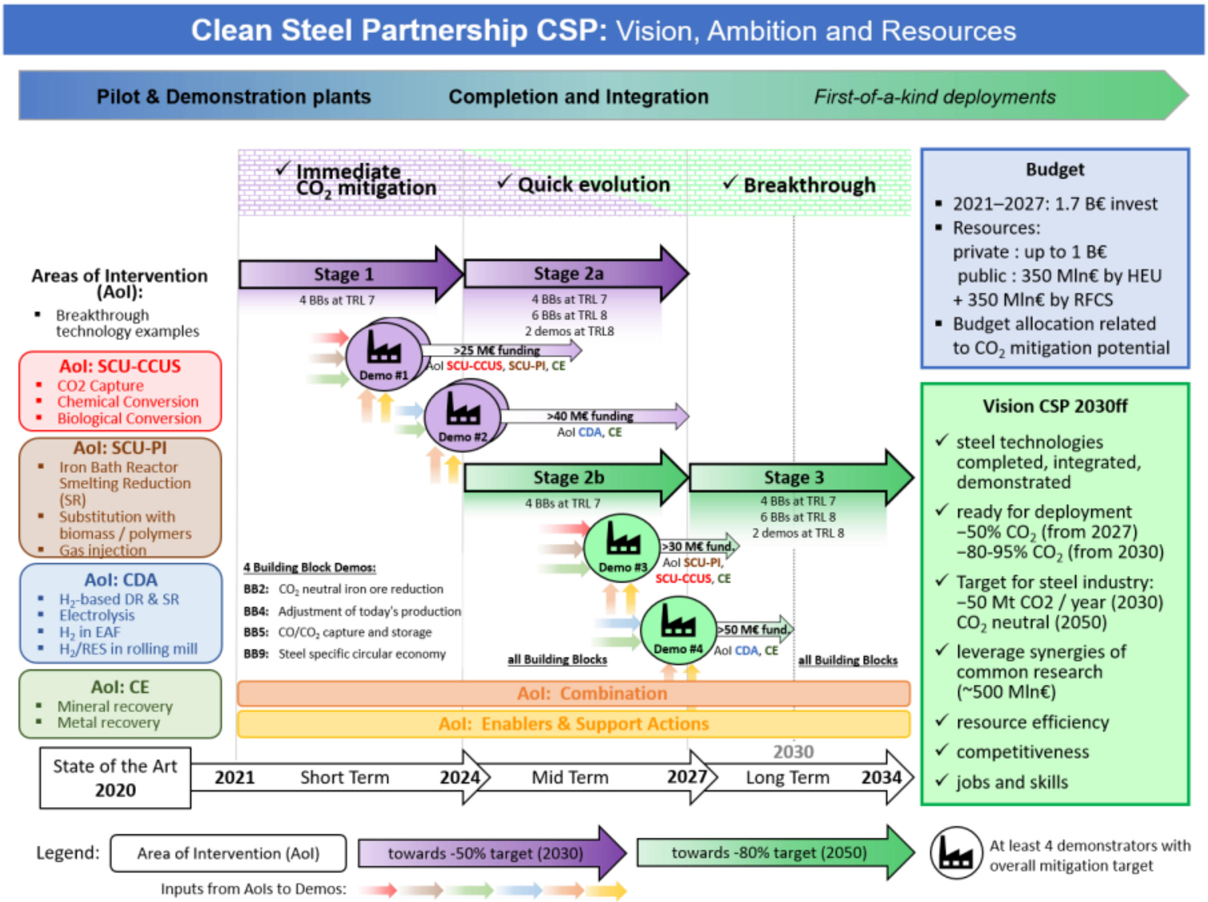


Figure 43 – CSP Timeline

PART 5 – STRATEGIC WAY FORWARD FOR ESTEP

5.1 Introduction

The European Steel Technology Platform (ESTEP) and its members enter the next decade at a decisive moment. The European steel industry remains vital for the EU's industrial base, yet it is among the most energy-intensive and CO_2-emitting sectors. Achieving climate neutrality by 2050 while maintaining competitiveness requires pragmatic, stepwise innovation. The *Steel and Metals Action Plan* (2025) and the planned *Steel and Metals Partnership* under the next framework programme provide the guiding framework: accelerate decarbonisation, strengthen circularity, and safeguard competitiveness.

The European steel industry is currently facing one of the most challenging environments in its history. Soaring energy prices, volatile raw material markets, and insufficient availability of green electricity and hydrogen undermine the sector's capacity to plan and invest. At the same time, global competition has intensified, with subsidised imports, structural overcapacity in other regions, and the growing impact of import tariffs affecting trade flows and market access. Demand growth within the EU remains modest, while high inflation and stricter environmental requirements further increase operational costs. These factors combined put profitability under strain and reduce the financial headroom required for investment. Yet such investments are indispensable—not only to advance decarbonisation, but also to secure long-term competitiveness, modernise production facilities, and maintain Europe's position as a global technology leader in high-quality steelmaking.

However, the pace of green electricity and green hydrogen deployment remains insufficient. Therefore, ESTEP's research strategy must combine immediate transition pathways with long-term innovation, focusing on integration and upscaling of solutions already developed under the Clean Steel Partnership (CSP) and earlier programmes.

5.2 Mission and vision

Vision

ESTEP aspires to be the recognised platform where the European steel community jointly shapes the technological transformation of the sector. By fostering cooperation among industrial players, research organisations, policymakers, and civil society, ESTEP will enable the creation of innovative, sustainable, and competitive steel solutions for Europe's future. The platform will serve as the reference point for research, development, and innovation, ensuring that Europe remains at the forefront of green and digital steelmaking.

Mission

To achieve this vision, ESTEP will further develop a strong R&D&I community model for the steel industry, providing a collaborative framework that supports both long-term strategy and short-term responsiveness. Its work will be structured along a triangle of cooperation between the European Commission, ESTEP members, and other stakeholders, ensuring that the expectations of all three are met in a balanced and transparent way. ESTEP will continue to act with agility, adaptability, and flexibility, providing strategic guidance while remaining responsive to rapidly evolving challenges such as decarbonisation, digitalisation, circularity, and competitiveness.

Core Objectives

- **Innovation Leadership**: Guide and accelerate the development of breakthrough technologies that enable climate neutrality and digital transformation.
- **Policy Support**: Provide evidence-based input to European policy processes and align R&D&I priorities with the EU Green Deal, Industrial Strategy, and the forthcoming Steel and Metals Partnership.
- **Stakeholder Integration**: Strengthen the role of ESTEP as the bridge between industry, academia, policymakers, and society, ensuring broad acceptance and impact.
- **Industrial Competitiveness**: Secure Europe's position as a global leader in high-quality, sustainable steel, while preserving jobs, skills, and regional development.

5.3 Research priorities for the next decade

The European steel sector is ready and willing to lead the green transition, but this requires a policy and funding framework that creates a viable business case for low-carbon steelmaking. Industrial-scale demonstration projects can only succeed if they are supported by large, highly flexible funding schemes, simple administrative procedures, and shared pilot infrastructures, all aligned with the pace and needs of industry investment cycles. EU funding instruments must therefore become more impactful. The Research Fund for Coal and Steel (RFCS) Annual Call remains the backbone of EU steel research, and the current TRL structure is appropriate. Its effectiveness, however, could be significantly enhanced through higher funding rates, CAPEX coverage, and streamlined administrative structures.

Competitiveness in the long term requires R&D across all areas, going beyond decarbonisation to include product quality, advanced materials, process and resource efficiency. A good balance must be struck between decarbonisation-related research and these broader R&D needs. Optimisation of plants through new technologies and improved process integration will be of key importance. At the same time, technology innovation alone will not deliver the transformation: success also depends on stable energy pricing, predictable regulatory frameworks, market incentives such as green lead markets, and a coherent approach to EU and national funding that ensures coordination and impact. These priorities define the framework for the research themes outlined in the following sections.

5.3.1 Decarbonisation Pathways

Decarbonisation remains the most urgent R&D challenge. Work must continue on Carbon Direct Avoidance (CDA) technologies, in particular NG-based DRI with the option to switch to hydrogen once sufficient volumes of renewable energy are available. Research should also focus on hybrid electrification routes, including electric melting units, while taking into account the limitations of the current grid mix. Smart Carbon Usage (SCU) will play a more limited role, with priority given to synergies with the energy sector and efficient carbon capture from suitable point sources. Upscaling, integration, and system optimisation of these technologies will be key to bring them from pilot to industrial scale.

5.3.2 Circular Economy and Resource Efficiency

Circularity and efficient use of resources are central to competitiveness. Research should address the removal of tramp elements such as Cu, Sn, and Zn from scrap to increase recycling rates and enable higher-quality secondary steel. By-product valorisation, closed-loop recycling, and innovative waste treatment solutions should be pursued. Advanced process control and digitalisation will allow optimisation of resource flows within and across plants. This will ensure not only reduced emissions but also improved cost efficiency, supporting the long-term viability of the industry.

5.3.3 Advanced Materials and Product Quality

Beyond decarbonisation, competitiveness also depends on the ability to deliver new and improved steel grades for demanding applications. Research is required into advanced high-strength steels, corrosion-resistant alloys, and steels for energy, mobility, construction, and defense. Dual-use materials, serving both civilian and defense markets, will be increasingly important under the evolving European industrial and security policy. Product innovation must go hand-in-hand with sustainable production, ensuring that Europe maintains its reputation for premium steel quality.

5.3.4 Process Integration and Plant Optimisation

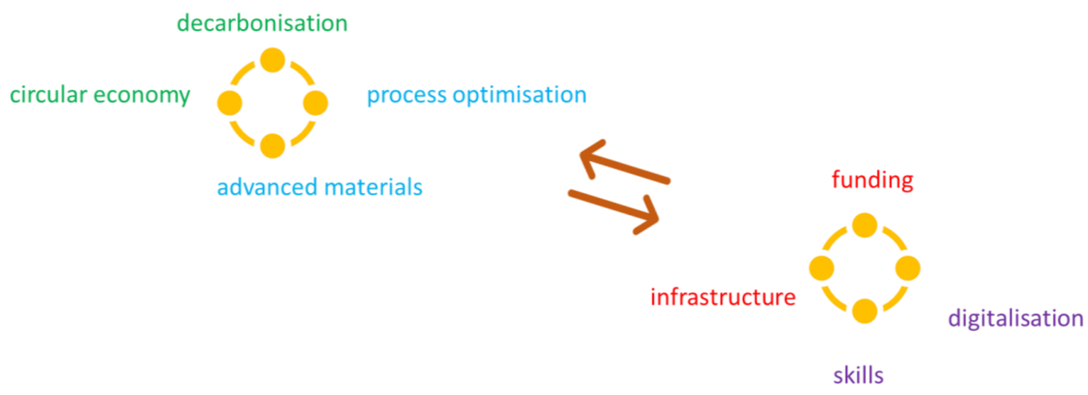
Optimisation of existing and future steel plants is critical for reducing costs and emissions while improving efficiency. Research should focus on integrating new low-carbon processes with legacy assets, improving flexibility, and ensuring compatibility with fluctuating energy inputs. Digital twins, AI-driven process control, and smart sensors will support predictive maintenance, quality assurance, and energy efficiency. Plant-wide integration, covering both primary and secondary routes, will be essential to maximise resource use and competitiveness during the transition period.

5.3.5 Cross-cutting Enablers

Achieving the transformation of the European steel sector requires more than technological innovation. Supporting enablers must be developed in parallel. These include:

- Funding models that combine EU, national, and private resources in a coordinated manner, covering both CAPEX and OPEX.
- Infrastructure for hydrogen, electricity, and CO_2 transport and storage, developed in sync with industry needs.
- Skills and workforce development to ensure that employees can adapt to new technologies and processes.
- Digitalisation and data management as accelerators for efficiency, integration, and decision-making across the entire value chain.

These cross-cutting enablers are essential to ensure that research and innovation translate into industrial deployment and long-term competitiveness.



Together, these research priorities and cross-cutting enablers form a coherent agenda that supports both the decarbonisation of steelmaking and the long-term competitiveness of the sector. They provide the foundation for the forthcoming Steel and Metals Partnership, which will bring together multiple industrial value chains and strengthen synergies across Europe's metals industries. ESTEP will ensure that the specific needs of the steel sector are fully reflected in this new framework, while contributing to broader objectives of circularity, digitalisation, and resilience. In this way, European steel will remain a driving force for sustainable industrial transformation and strategic autonomy.

5.4 Implementation pathways

Delivering on the research priorities set out in Section 5.2 requires a clear and coordinated implementation strategy. The transformation of the steel sector is unprecedented in scale and speed, demanding a combination of technological, financial, and regulatory instruments that reinforce one another. ESTEP will act as the coordination platform to ensure that innovation moves smoothly from concept to pilot, demonstration, and full industrial deployment.

The phasing-out of the Clean Steel Partnership in 2027 and the preparation of the new Steel and Metals Partnership will be decisive milestones. In this transition, ESTEP will work to align the priorities of the steel community with those of other metals sectors, ensuring that the specific technological pathways of steelmaking are safeguarded while benefitting from cross-sectoral synergies, particularly in energy and infrastructure.

Implementation must follow a stepwise, yet flexible, approach:

- **Pilots and demonstrations**: ensuring that technologies such as NG-DRI, hydrogen-based steelmaking, advanced scrap sorting, and digital plant integration are tested at scales relevant to industry.
- **Upscaling and replication**: creating shared pilot infrastructures and reference plants that can be replicated across Europe.
- **Market creation**: working with policymakers to establish lead markets for green steel, supported by incentives, carbon border measures, and public procurement.
- **Integration with policy and funding**: coordinating EU and national funding streams, simplifying administrative procedures, and ensuring that industry investment cycles are matched with predictable support.

The success of these implementation pathways will depend on close cooperation within the triangle of the European Commission, ESTEP members, and other stakeholders. By maintaining its agile, adaptive, and flexible steering role, ESTEP will guide the European steel industry through the transition, ensuring that research results are translated into industrial competitiveness and societal value.

5.5 Roadmap

The transformation of the European steel sector will require a structured and phased approach over the next decade. The roadmap combines decarbonisation, circular economy, competitiveness, and enabling conditions into a coherent timeline, closely linked with EU and national policy developments.

2025–2027 – Transition Phase

- Phasing-out of the Clean Steel Partnership and preparation of the Steel and Metals Partnership.
- Launch of new pilot projects for NG-DRI with hydrogen-readiness, hybrid electrification routes, and advanced scrap sorting (Cu, Sn, Zn removal).
- First deployment of digital twins and smart process integration tools in industrial environments.
- Strengthening of RFCS annual calls, with simplified procedures and higher impact.
- Initial development of green lead markets through procurement initiatives.

2028–2030 – Demonstration Phase

- Start of the Steel and Metals Partnership, establishing cross-sectoral synergies with other metals industries.
- Large-scale industrial demonstrations of NG-DRI with partial hydrogen use, electrified melting units, and advanced circularity solutions.
- Integration of plant optimisation and digital technologies for resource and energy efficiency.
- First demonstrations of advanced materials and dual-use steels for energy, mobility, and defense.
- Development of shared pilot infrastructures and coordinated funding mechanisms combining EU, national, and private resources.

2030–2032 – Upscaling Phase

- Industrial-scale demonstrations of full hydrogen-DRI combined with electric furnaces where renewable power is available.
- Widespread use of advanced scrap recycling technologies and by-product valorisation systems.
- Expansion of AI-driven plant optimisation and predictive maintenance solutions across sites.
- Broader deployment of innovative steel grades responding to new mobility, construction, and defense needs.
- Consolidation of EU–national funding alignment and scaling up of green lead markets.

2033–2035 – Deployment Phase

- Rollout of integrated H_2-DRI/EAF steelmaking chains, supported by developed infrastructure for hydrogen and electricity.
- Operation of fully circular steel plants with high scrap shares and closed-loop material systems.
- Large-scale market uptake of green and advanced steels, supported by stable regulation and demand incentives.
- Embedding of cross-cutting enablers: skills, digitalisation, and coordinated policy frameworks ensuring resilience and competitiveness.
- European steel sector recognised as a global leader in low-carbon, high-quality, and technologically advanced steel production.

5.6 Cross-sectoral aspects

The transition of the steel sector cannot be achieved in isolation. Strong cross-sectoral collaboration is required, particularly with the energy sector, which will be decisive for the timely availability of renewable electricity, green hydrogen, and infrastructure for CO2 transport and storage. Close cooperation with energy suppliers, grid operators, and infrastructure providers will be essential to match the scale and timing of industrial investments with the provision of resources.

Beyond energy, synergies may also emerge selectively with other metals industries in the framework of a Steel and Metals Partnership in the future framework Horizon Europe 2028-2034.

ESTEP, European Aluminium, and European stand united fully committed to establish a dedicated Public–Private Partnership for Metals, building on the European Steel and Metals Action Plan, the successful Clean Steel Partnership, and the sector's vital role in Europe's strategic resilience, decarbonisation, and competitiveness. The partnership is designed to bring together public and private research and innovation efforts to develop practical technological solutions to fill existing and newly emerging technology gaps, support fast development via pilot- to demonstrator-stage ready for subsequent industrial use, and lay the foundations for a clean, competitive, and strategically autonomous European metals industry.

Metals are among the most energy- and capital-intensive sectors, facing high investment barriers, volatile costs, and weak market incentives to deploy clean technologies. Pillar 6 of the European Steel and Metals Action Plan highlights the need to de-risk decarbonisation projects through lead markets and targeted public support. A dedicated Public–Private Partnership for Metals would turn this pillar into action: pooling resources, aligning research priorities, and giving investors the confidence to advance industrial transformation in Europe towards processes with low environmental impact. Metals share close technological and industrial interconnections, with comparable energy needs, transformation steps, and material flows. They face common challenges and solutions developed in one metal stream often have direct spill-over effects in others, from heating systems to digital twins and carbon capture. Grouping metals with other process industries such as plastics, glass, or ceramics would blur this focus and slow progress; metals require targeted approaches rooted in their specific production routes and circular value chains. A single, coordinated partnership would harness these synergies, speed up knowledge transfer, and build the foundation for a competitive, low-carbon, and circular European metals ecosystem.

The Steel and Metals Partnership would focus joint research and innovation efforts on:

- Alternatives to fossil carbon sources developing hydrogen, renewable gases, non-fossil carbon fuels and reducing agents, as well as electrification technologies for high-temperature processes, ensuring flexibility and high energy efficiency.
- Recycling and circular economy – advancing sorting, purification, and alloy design technologies to maximise recovery and reuse of metals and industrial residues within Europe, advance use of by-products and waste from one metal stream as valuable raw material for other metals.
- Carbon capture, utilisation and storage (CCU/CCS) – creating tailored capture systems, purification methods, and reuse pathways suited to metallurgical gas streams.
- Circular advanced metals for a clean and sovereign Europe – high performing metals under extreme conditions, multifunctional properties, extended lifetime, along the value cycle and across the material classes optimised systems and products, fully considering repair-, remanufacturing- and reuse concepts.
- Digitalisation, sensors and modelling – developing and integrating advanced sensors, digital twins, AI-driven optimisation, and interoperable data spaces to enable real-time control, traceability, and efficiency
- Human dimension – equipping the workforce with the skills needed for the green and digital transition, ensuring safety, inclusion, and social acceptance of new technologies.

The partnership would be built on a simple, transparent governance model with joint task forces and implementation groups driving each research area. To deliver impact at scale, the metals community foresees a total investment of €2.5 billion, combining EU funding for research and innovation with at least matching commitment from industry going beyond direct co-funding, in-kind contributions, research projects, pilots and demonstrators.

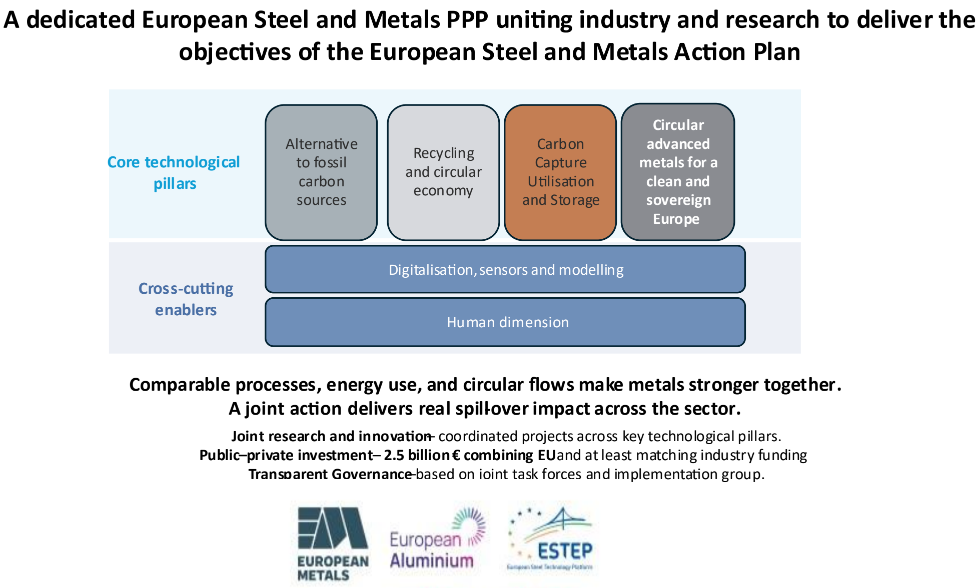


Figure 44 – Steel and Metals Partnership

5.7 Governance

The governance of ESTEP and its Strategic Research Agenda must ensure transparency, inclusiveness, and alignment with both industrial and policy needs. ESTEP will continue to work along the triangle of cooperation – the European Commission, ESTEP members, and other stakeholders – to ensure that research priorities address the expectations of all three sides.

To succeed, governance must remain agile, adaptive, and flexible, enabling rapid responses to changing technological and economic conditions. The integration of the steel sector into the broader Steel and Metals Partnership will require balanced representation and coordination mechanisms to safeguard steel-specific pathways while benefitting from synergies with other sectors.

Effective governance will also depend on continuous dialogue with EU and national authorities to align funding programmes, simplify administrative procedures, and create the right market framework. By maintaining its strong community model and its role as the recognised voice of European steel R&D, ESTEP will ensure that the implementation of the Strategic Research Agenda delivers both technological breakthroughs and industrial competitiveness.

5.8 Conclusion

The coming decade will be decisive for the European steel industry. The sector is determined to lead the green transition, but success will depend on a framework that combines technological innovation with stable and supportive boundary conditions. The research priorities strike a balance between decarbonisation, circular economy, advanced materials, and process optimisation, supported by cross-cutting enablers such as funding, infrastructure, skills, and digitalisation.

Through ESTEP, the steel community will maintain its role as the trusted platform for aligning industrial ambition, stakeholder needs, and European policy objectives. By ensuring strong governance, effective funding mechanisms, and close cooperation with the energy sector and other metals industries, Europe can secure both climate neutrality and long-term competitiveness. The roadmap towards 2035 shows a clear path: from pilots and demonstrations to industrial deployment and global leadership in sustainable, high-quality steelmaking.

GLOSSARY

A4M	Alliance for Materials
ABS	Air-Cooled Blast Furnace Slag
ACM	Alternative Carbon Materials
AHSS	Advanced High Strength Steel
ASR	Automotive Shredder Residue
AUST SS	High strength Austenitic Stainless Steels
BAU	Business As Usual
BF	Blast Furnace
BH	Bake Hardening steel
BOF	Basic Oxygen Furnace
BOS	Basic Oxygen Slag
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CCS	Carbon Capture and Storage
CDA	Carbon Direct Avoidance
CE	Circular Economy
CIP Programme	Competitiveness and Innovation
CCU	Carbon Capture and Utilisation
CMn	Carbon Manages Steel
CNG	Compressed Natural Gas
CP	Complex Phase steel
CSP	Concentrate Solar Power plant
CSR	Corporate Social Responsibility
DP	Dual Phase steel
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
E2B	Energy Efficient Building
EC	European Commission
ECTP	European Construction Technology Platform
EED	Energy Efficiency Directive
EGVI	European Green Vehicle Initiative
EII	European Industrial Initiative
EIP	European Innovation Partnership
EIT	European Institute of Technology
EMIRI	Energy Materials Industrial Research Initiative
EMS	Energy Management System
EPD	Environmental Product Declaration
ESTEP	European Steel Technology Platform
ETP	European Technology Platform
ETS	Emissions Trading Scheme
EuMaT	European technology platform for advanced engineering Materials and Technologies
EWEA	European Wind Energy Association
FoF	Factories of the Future
FP6 (2000-2006)	6th Framework Programme
FP7 (2007-2013)	7th Framework Programme
GDP	Gross Domestic Product
Gen 3 HSHF	Third Generation High Strength, High Formability Steel
GHG	Green House Gases
GMS	Global Market Size
HEU	Horizon Europe
HSLA	High Strength Low Alloy steel
HSS	High Strength Steel
I2M	Integrated Intelligent Manufacturing
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
IDI	Industry Driven Initiative

IED Industrial Emissions Directive

IF Interstitial free steel

JRC Joint Research Centre

JTI Joint Technology Initiative

IF-HS Interstitial Free High Strength

IPPC Integrated Pollution Prevention and Control

KPIs Key Performance Indicators

KET Key Enabling Technology

LCA Life Cycle Assessment

LCC Life Cycle Costing

LCWCE Low Carbon Without CO_2 Emissions

L-IP Light Induced Plasticity steels

LCT Life Cycle Thinking

LNG Liquefied Natural Gas

Manufuture European technology platform for Manufacturing

MART Martensitic Steel

MFA Material Flow Analysis

Mild Mild steel

MoU Memorandum of Understanding

NER-300 New Entrant Reserve of CO2 emissions rights (300 million tons allowances)

OCTG Oil Country Tubular Goods

OECD Organization for Economic Co-operation and Development

OES Optical Emission Spectroscopy

ORC Organic Rankin Cycle

PHS Press Hardened Steel (hot stamping)

PI Process Integration

PPP Public Private Partnership

REACH Registration, Evaluation, Authorization, and restriction of Chemical substances

reFINE research for Future Infrastructure Networks in Europe

R&D&I Research & Development & Innovation

RFCS Research Fund for Coal and Steel

RTD Research Technology Development

SCC Self-Compacting Concrete

SCU Smart Carbon Usage

SET-Plan Strategic Energy Technology Plan

SF Stretch Flangeable steel

SMR Sustainable Minerals Resources ETP

SMS Steelmaking Slag

SPIRE Sustainable Process Industry through Resource and Energy efficiency

SRA Strategic Research Agenda

SRIA Strategic Research and Innovation Agenda

SSC Sulfur Stress Corrosion

STTP Strategic Transport Technology Plan

Suschem European technology platform for chemicals

TEA Techno-Economic Analysis

TGR Top Gas Recycling

TRIP Transformation Induced Plasticity steel

TRL Technology Readiness Level

TWIP Twinning Induced Plasticity steel

ULCOS Ultra Low CO2 Steel making

USC Ultra Super Critic power plant

VD Vacuum Degassing

VOD Vacuum Oxygen Decarburization

WG Working Group

XRF X-Ray Fluorescence

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