Improve the EAF scrap route for a sustainable value chain in the EU Circular Economy scenario

ROADMAP

An evolution document for a strategic look to the future of European EAF steelmaking

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By ESTEP
The Circular Economy Focus Group

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Executive summary

The main purpose of the present roadmap is to highlight the relevant topics and directions in which research and development efforts will be concentrated to implement the EAF-based steelmaking route of the future.

The timeline considered in the roadmap covers a time horizon of 10 years, i.e. up to 2030, which is the first milestone set up by the EU Commission in the path of achieving the Carbon Neutrality.

The focus is on Crude Steel production, from scrap to semi-finished product (Ingots, Billets, Blooms and Slabs), therefore the steel rolling mills for further production of finished products like hot rolled sections, flats, plates and sheets are not included in this analysis.

The priorities were selected during discussions and analyses, carried out in the framework of the European Steel Technology Platform (ESTEP) under the leadership of the Circular Economy Focus Group. Considering the whole value chain of the electric steelmaking route, the following macro-topics were identified:

- primary raw material of the EAF-based route, i.e. the scrap: pre-treatments to improve scrap quality and reduce tramp elements, on-line quality analysis and characterization, yard management and use of HBI/DRI;
- reduction of CO_2 emissions:
  - rational utilization of the energy in EAF-based route, i.e. energy recovery and utilization;
  - alternative and environmental-friendly energy sources, i.e. use of renewable energy sources and alternative non-fossil fuels: renewable electricity and direct use of renewable or green H_2;
  - replacement of lump and pulverized coals as reducing or foaming agent with alternative C-bearing materials and reduced consumption of graphite electrodes;
- resource efficiency improvement and cost reduction by valorisation of wastes, residues and by-products for internal and external use;
- enable digitalization technologies for achievement of the above stated objectives, such as the extended sensorization through existing and new sensors to monitoring the supply chain as well as the EAF process, supported by the parallel implementation of integrated digital systems; i.e. new tools and sensors for process improvements.

All topics has been recognized to be linked; therefore, a holistic approach is required.

For each identified macro-topic, the main aspects are discussed in deep details and expected impacts are analyzed and quantified, in order to translate the vision into a series of measurable targets toward which the developed actions will be assessed. A synthetic technical and economic analysis is pursued, which includes also a risk probability estimation, a quantification for the impact of each risk as well as identification of possible mitigation measures. A chronological order for each relevant aspect of the pursued investigation is envisaged to achieve the aimed targets in the selected time horizon as well as to maximize the synergies across the different research topics. Finally, a preliminary assessment of the budget that is required for the full implementation of the identified research and development activities in the considered time horizon is provided. Thus, a strategy is identified to stepwise reach the aimed objectives.

1. Vision

Within the energy transition stage being required to reach the Carbon Neutrality in 2050[1], the electric steelmaking route is foreseen to increase the ratio over the integrated route, due to its link with the concepts of Circular Economy and Industrial Symbiosis. Therefore, further efforts are necessary to improve the EAF-based production cycle and to integrate it in the future carbon neutral EU steel production scenario. Research and Development must provide the tools and means which are necessary for ensuring the EU steel sector's capacity of delivering high-quality steel grades using different raw materials and contributing to the sustainable value chain for steel in the European scenario.

Only an active collaboration among all the involved actors (e.g. companies, research institutions and academia, policy makers, stakeholders) can allow reaching the objectives required by the EU and improving the competitiveness of European electric steelworks.

The EAF-based steelmaking route of the future is a sustainable seamless production chain, integrated in the society in terms of optimal use of raw materials and resources, including energy and its flow, contributing to welfare and progress of the surrounding communities and of the society as a whole.

Emission of Greenhouse Gases (GHG) will be reduced both by maximizing energy efficiency through waste heat recovery and by the utilization of technologies and techniques in the landscape of renewable energy sources and green fuels. For further reducing the environmental impact and contributing to lowering CO_2 emissions, fossil coal will be replaced with alternative carbon-bearing materials.

Resource efficiency will also play a central role by implementing maximum valorization of residues for both internal and external usage as well as by optimizing utilization of scrap through suitable pretreatment and characterization techniques. This will also lead to optimization of product quality and enlargement of the range of products produced through the EAF-based route. To this aim, alternative iron sources like DRI/HBI or pig iron / hot metal will be used to compensate the increased content of impurities like tramp elements, which are especially introduced the increased use of by post-consumer and obsolete scrap.

The requirement of alternative iron sources (e.g. recovered by iron-oxide reach residual) is also linked to the long lifetime of steel products that could lead to a not enough amount of available scrap.

With the aim of achieving the above-mentioned ambitious objectives, the production process will need to be constantly monitored and deeply controlled in all its aspects by exploiting suitable sensing tools and advanced information processing techniques also based on Artificial Intelligence (AI), Machine Learning (ML) or on hybrid solutions that couples these advanced techniques with physic-based modelling. Fast and accurate materials characterization in the different stages, on-line monitoring of energy consumptions and emissions, product quality monitoring and control across the whole process chain are needed to practically implement the future EAF-based route and to allow optimization of resources consumption and efficiency of the process in terms of material and energy.

The implementation of advanced AI and ML-based techniques is foreseen to empower human operators by preserving and enforcing their role in decision-making, as decisions will be taken based on a complete and updated overview of the process conditions, relieving workers from cumbersome and repetitive operations.

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[1] This objective is at the heart of the European Green Deal (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en) and in line with the EU's commitment to global climate action under the Paris Agreement

2. Context

Steel is a fundamental material for the evolution of our society and the transition towards the model of Green and Sustainable Society. This is related to the intrinsic features of steel material that are summarized by three words (**Figure 1**): *durability*, *versatility* and *recyclability*.

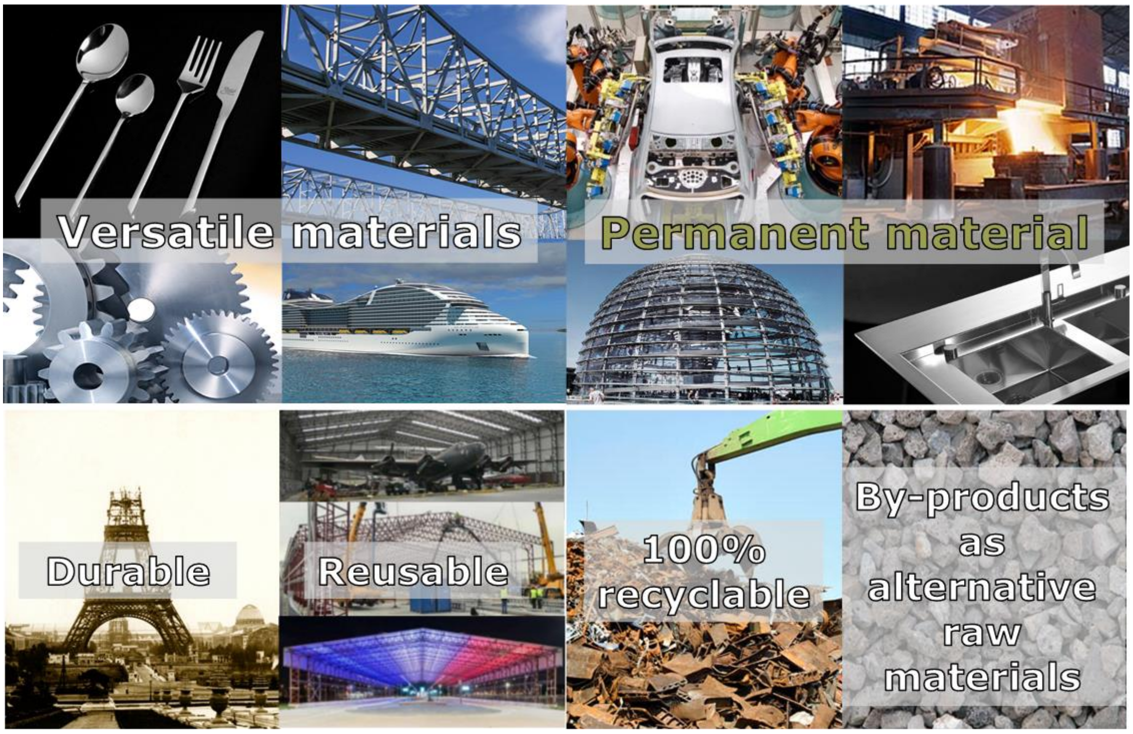


Figure 1. *Steel, the backbone of sustainability [1]*

Once produced, steel can be considered as a *permanent material*. However, considering the fundamental role of steel, it is of utmost importance to keep on improving the sustainability of the production processes in terms of energy and resource efficiencies, carbon footprint and emissions, by following the evolution of today's society.

The crude steel production in Europe represents about 16% of the Worldwide production (**Figure 2**) and the sector plays a fundamental role for sustainable growth and high-quality employment in the EU.

The coronavirus pandemic slowed down the estimated growth of worldwide steel production. In Europe, the negative economic impact of COVID-19 was softened by strong social security schemes and fiscal stimuli, but the deep contraction of major steel end-using sectors contributed to production reduction in 2020. However, the post lockdown recovery in the steel demand in the EU is turning out to be stronger than expected [2], and the improvement of steel production processes shows a relevant potential to increase the competitiveness of European industry and improve European economy.

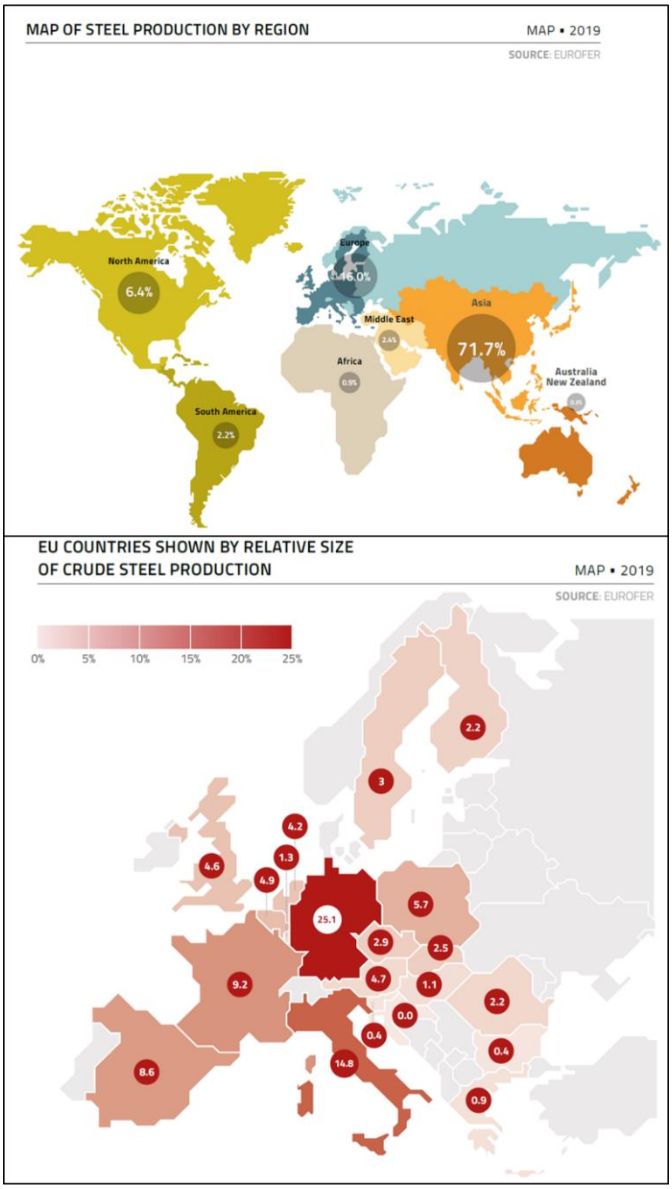


Figure 2. *Map of worldwide and EU steel production [3]*

2.1. Analysis of the current background

2.1.1. Steelmaking production routes

Steelmaking in EU includes two routes (**Figure 3**): the integrated route (based on Blast Furnace/Basic Oxygen Furnace) and Electric Arc Furnace (EAF)-based route, which exploit, respectively, virgin primary raw materials and ferrous scrap as main inputs. DRI production is very limited at the moment in EU, while is increasing worldwide in the last years (**Figure 4**) [4].

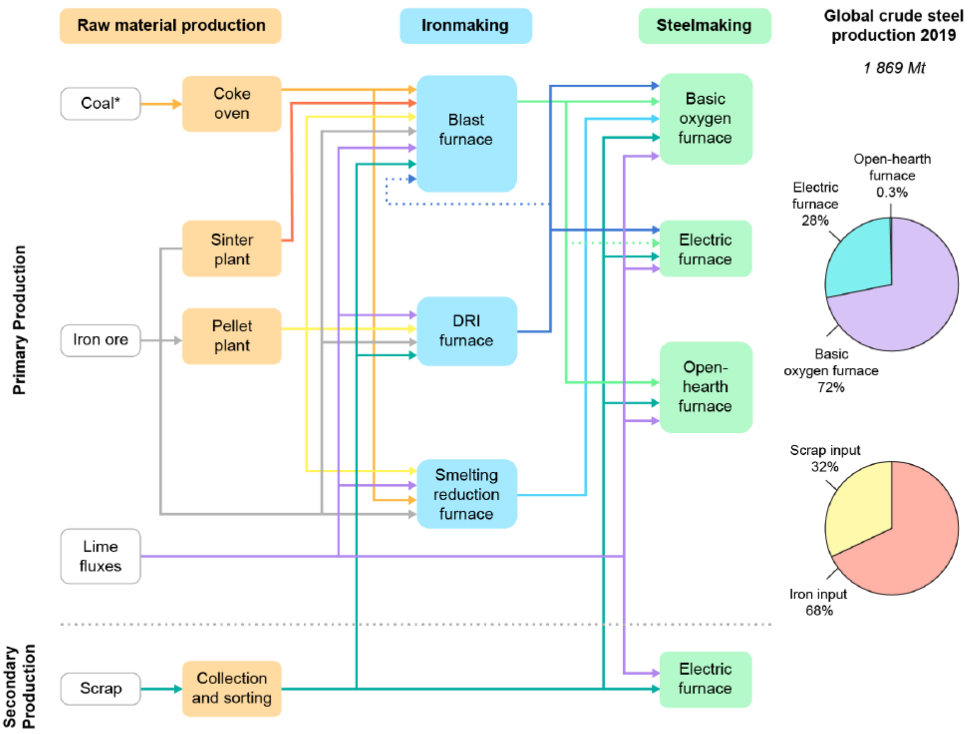
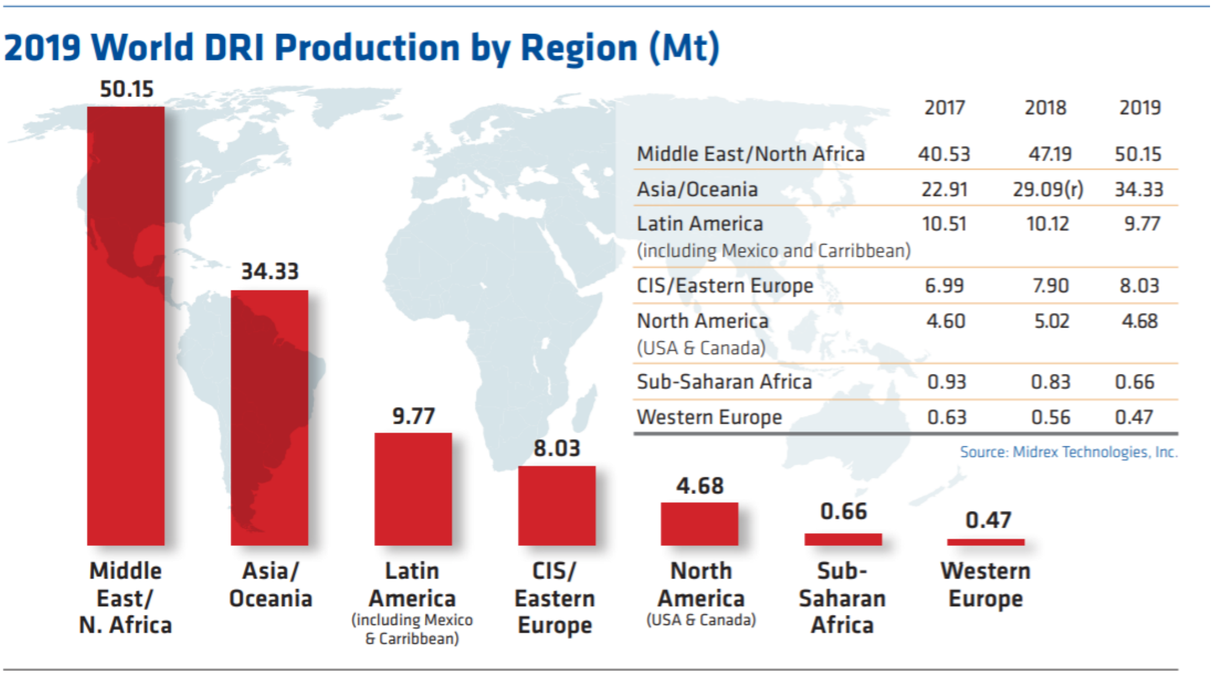


Figure 3. *Main steel production pathways and material flows in 2019 [5]*



	2017	2018	2019
Middle East/North Africa	40.53	47.19	50.15
Asia/Oceania	22.91	29.09(r)	34.33
Latin America (including Mexico and Carribbean)	10.51	10.12	9.77
CIS/Eastern Europe	6.99	7.90	8.03
North America (USA & Canada)	4.60	5.02	4.68
Sub-Saharan Africa	0.93	0.83	0.66
Western Europe	0.63	0.56	0.47

Source: Midrex Technologies, Inc.

Figure 4. *World DRI Production by Region [4]*

The two routes are synergistic, and today, the electric one represents about 29% of steel production worldwide. However, the share between the two routes is very different in the different countries, such as clearly shown in **Figure 5**.

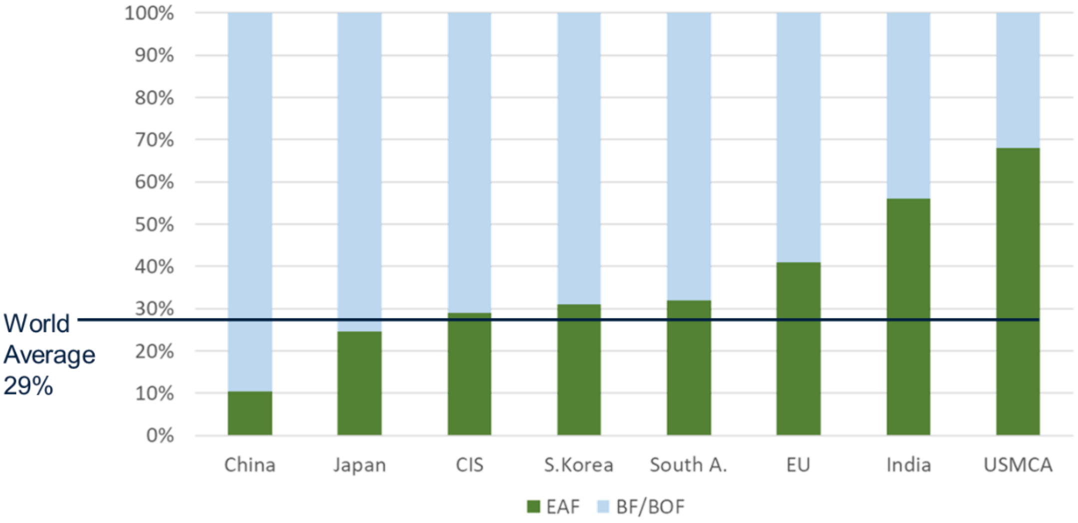


Figure 5. *Crude Steel Production by Process, 2019 [6]*

This is reflected in average CO_2 emissions related to steel production in different countries, as shown in **Figure 6**[2].

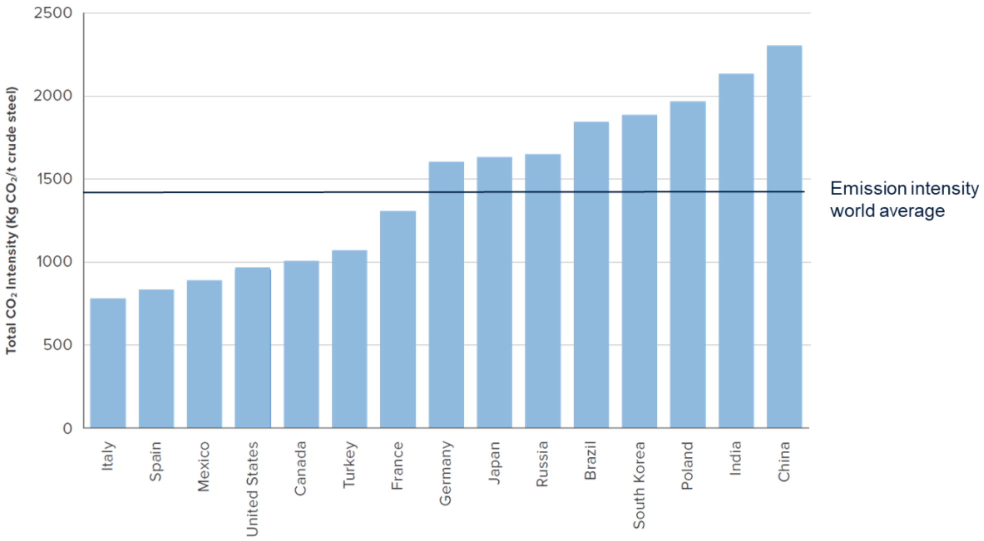


Figure 6. *Crude Steel CO_2 Emissions Intensity by Country, 2016 [7]*

In the European context, the production share between the two routes is stable in the last 10 years, and 41.4% of the total European steel production is currently provided by the EAF route (see Figure 7 [3]**).**

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[2] data are related to 2016 and for this reason there are some discrepancies with respect with data reported in **Figure 4**, e.g. for India

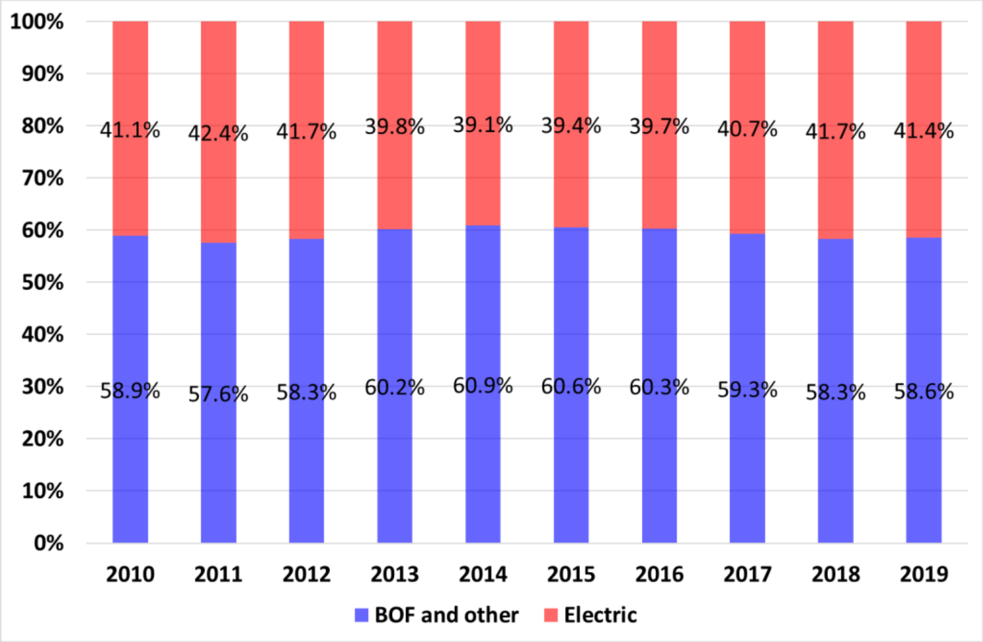

Figure 7. *BOF and Electric EU crude steel production shares in EU from 2010 to 2019 – data from [3]*

2.1.2. Envisioned scenario for scrap

EUROFER estimated that scrap will play a more important role in the EU steel strategy for the reduction of CO_2 emissions. Its availability towards 2050 was modelled by differentiating three sources of scrap: home scrap, prompt scrap and obsolete scrap. The calculation method and results of the scrap availability model are displayed in **Figure 8**. Home scrap and prompt scrap are expected to maintain their portion, while obsolete scrap is estimated to increase leading to a global increase of scrap availability.

Obsolete scrap characteristics are expected to drastically change and worse because of the increasing of the complexity and heterogeneity of available ferrous material (e.g. combination of steel with plastics and fibers, more complex joints, technical coatings, etc.) and of the repeated recycling and recycling rate.

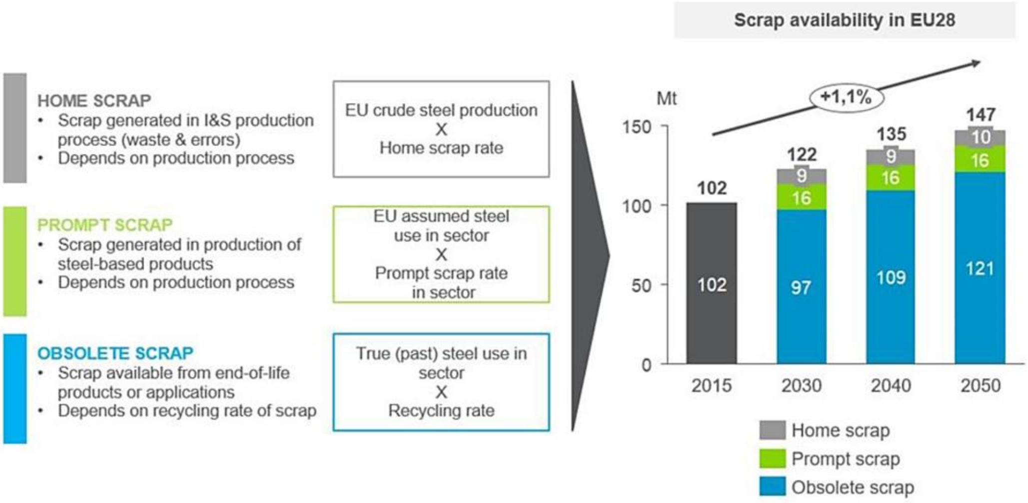

Figure 8. *Scrap availability in million tonnes by source [8]*

Currently, the worldwide steel recycling rate is around 85%, since there are some low-quality scraps that are being reused [9] [10]. Therefore, the steel production, together with the recycling rate of ferrous material, presently are important parameters to define the future recycling strategies (see **Figure 9**).

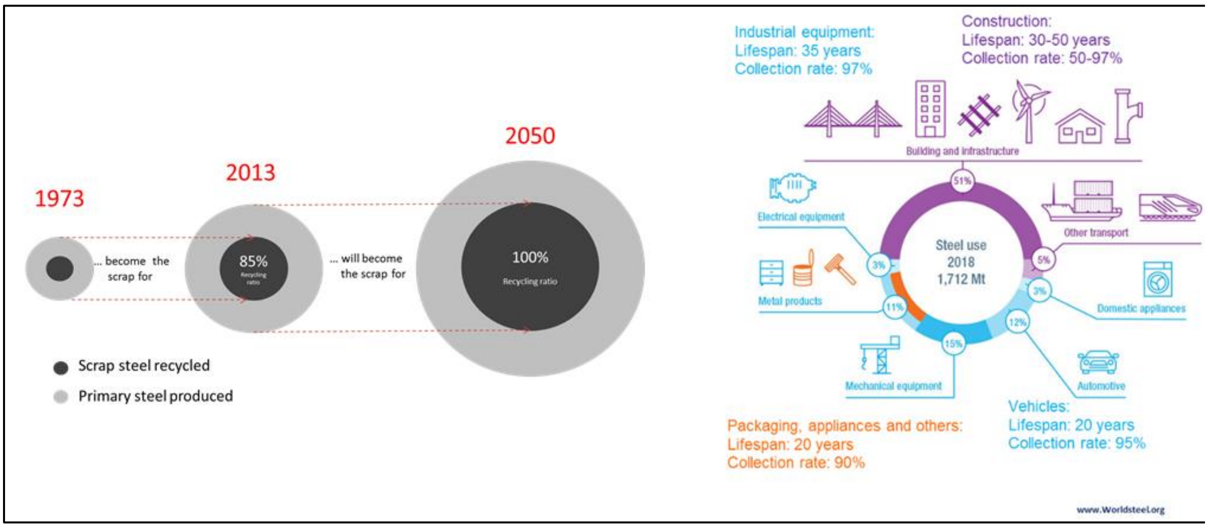

Figure 9. *Scrap Steel recycling rate analysis for future scrap availability estimate; left [11] and right [12]*

2.1.3. Steel production scenario in EU

The viability of both iron-ore and scrap production routes must be preserved, as they are both necessary to ensure the EU steel sector's capacity of delivering high-quality steel grades using different raw materials. In addition, it is necessary to consider that the availability of scrap at a certain point in time is defined by the past production and the ongoing recycling rate. Nevertheless, the EAF will continue to play a fundamental role for improving the EU strategic production of green steel, achieving the Carbon-Neutrality within 2050 [13], and meeting the targets of the European Green Deal, i.e. the "Clean Planet for All" strategy (**Figure 10**), and of the Paris Agreement.

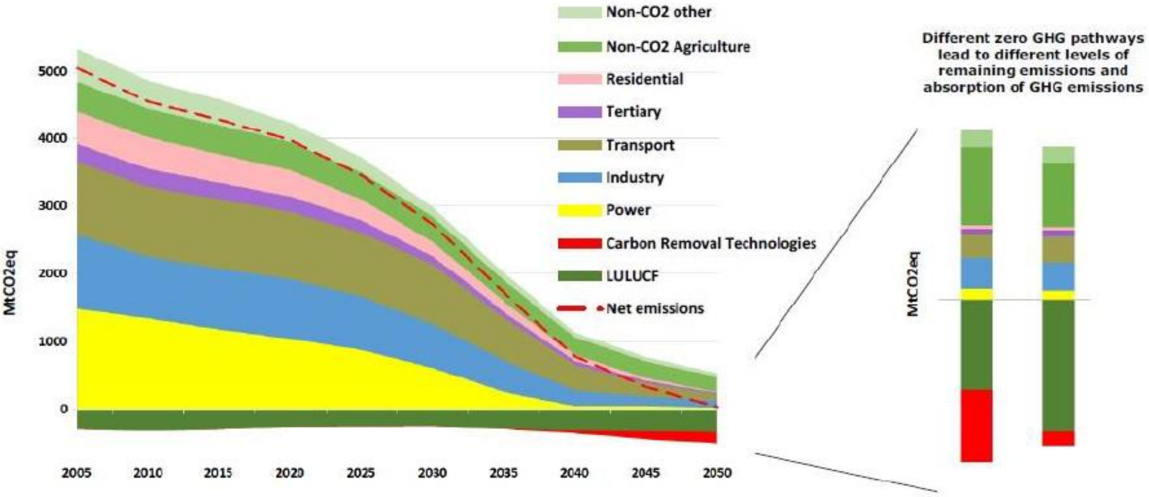

Figure 10. *GHG emissions trajectory in a 1.5°C scenario [14]*

In this context, the EAF will remain the main melting technology of ferrous scrap, and it will play a fundamental role in the iron ore route shift to exploitation of DRI route. Hence, R&D&I need to focus on existing issues to be solved, identification of new development potential and relevant implementation strategy.

2.2. The EU Circular Economy Scenario

The European Union, starting from 2011, took the leadership of the Circular Economy by implementing relevant policies through several programs and actions. The *Roadmap for a Resource-Efficient Europe* decouples resource consumption from economic growth. The *European Resource Efficiency Platform*, launched in 2012, provides high-level guidance to help the transition to a resource-efficient economy. In 2014 the *Circular Economy Package* was adopted, and, after different consultations and debates, the first *Circular Economy Action Plan* (fCEAP) was presented at the end of 2015. Finally, in December 2019 the EU Commission unveiled its *European Green Deal* (EGD) that includes the *new Circular Economy Action Plan* (nCEAP). EGD represents the last evolution of the Circular Economy-targeted development process [15] and it is Europe's new agenda for sustainable growth. It includes a set of policy initiatives facing the ambitious challenge of improving welfare and economy, by making Europe climate-neutral and by protecting our natural habitat by 2050 through application of green technologies, sustainable industries and transports as well as reduction of pollution (**Figure 11**). All the sectors are involved in this challenge: from energy to building, from industry to mobility. With a particular attention on industrial sectors, the EU will "*support industry to innovate and to become global leaders in the green economy*" [16].

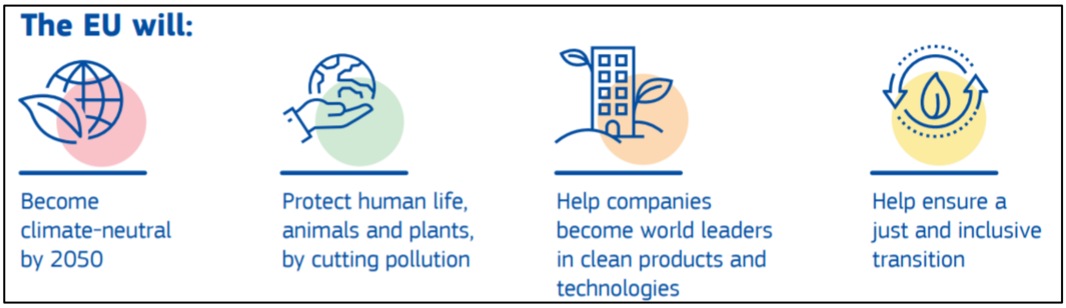

Figure 11. *Main objectives of European Green Deal [16].*

The nCEAP represents one of the main blocks of the EGD and addresses several measures along the entire life cycle of products [17]:

- make sustainable products the standard of the EU;
- make consumers and public buyers responsible;
- focus on the sectors that use most resources and where the potential for circularity is high;
- dramatically reduce wastes;
- encourage and support circularity work for people, regions and cities;
- lead global efforts on circular economy.

In the EU circular economy scenario, EAF steelmaking is well integrated. However, the promotion of ideas and actions devoted to the deployment of breakthrough technologies that allow further improvements of the processes (now considered already optimized from the thermodynamic point of view), can lead to an increase in EU support to facilitate the green transition of the steelmaking industry.

2.3. The Clean Steel Partnership

In the steelmaking context, a significant contribution to the EGD is provided by the Clean Steel Partnership (CSP), which is designed to tackle the challenges of climate change and sustainable growth in the EU [18] in the next seven years (2021-2027).

The general objective of the Partnership is to develop technologies at TRL8 to reduce CO_2 emissions stemming from EU steel production by 80-95% compared to 1990 levels by 2050, ultimately leading to climate neutrality.

Therefore, CSP is focused on promotion of carbon neutrality and CO_2 emissions reduction from the steel sector, by proposing 12 technological building blocks (BBs) that summarize R&D&I activities to provide solutions on six different areas of intervention/innovation (**Figure 12**).

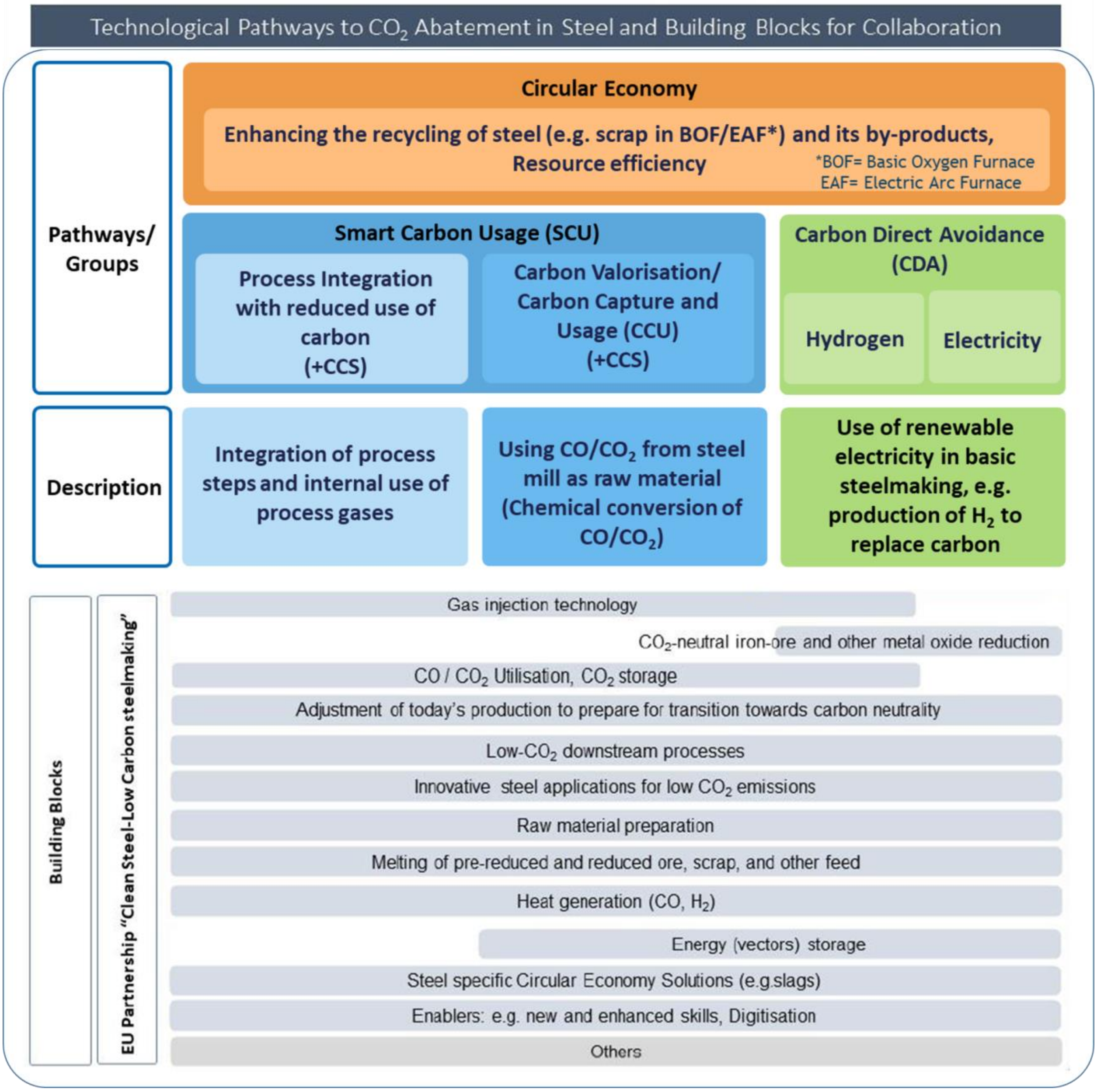

Figure 12. *Building Blocks mapped to the Technology Pathway of Clean Steel Partnership [18]*

The EAF route and technology is a key of the CSP strategy, by promoting the Circular Economy Pathway (CEP), through scrap utilisation via effective sorting technologies, and improved pollution removal through new technologies. It also includes processes related to not only internal but also external use of residues from steel production, such as dust in the non-ferrous sector or slags in the cement sector. Besides, CEP supports the substitution of fossil materials with alternative carbon-bearing materials and alternative reductants (e.g. biomass, plastic, rubber, syngas from wastes). Finally, CEP approaches encompass technologies that identify and make use of waste heat sources.

According to the EAF route nature it can be considered strategic for the application of Carbon Direct Avoidance (CDA) and Smart Carbon Usage (SCU) technologies in order to achieve considerable sustainability advantages.

2.4. Challenges and opportunities of EAF route

As above said, the role of EAF steelmaking is expected to increase in the near future and, as a consequence, some issues must be further addressed in order to achieve what declared in the vision statement, such as also underlined during the *Green Steel by EAF Workshop* [19].

2.4.1. Scrap

Scrap is regularly used as a raw material in steelmaking processes, and this fact has led to the development of a complete value chain for its valorization and a significant fluctuation of price. A situation that levered open new ferrous scrap markets (and in many cases, lower or highly variable quality), broadening the sources and the diversity of the ferrous scrap that is currently recycled.

As underlined in the Section 2.1, scrap is considered as a crucial resource by the EU steel strategy for the reduction of CO_2 emissions and thus, the relevant demand coming from BF/BOF and EAF steel production routes is expected to increase. In addition, and due to the limited overall availability of scrap, scrap quality is expected to decrease and, consequently, scrap costs to increase. Due to the high content of valuable resources, such as iron and energy used for its chemical reduction from iron ore, ferrous scrap must move to be part of the European Raw Materials Alliance (ERMA). In this way, according to the ERMA main objective of making Europe more resilient and competitive, a reliable, secure and sustainable access to ferrous scrap would be secured through the support in the recovery and recycling.

Scrap availability as well as cost and quality factors highlight the importance of implementing actions focused both on the scraps market and on optimal charge preparation and improved process control. Furthermore, R&D projects are needed for optimizing scrap quality by enhancing the cooperation between different stakeholders within the scrap management chain.

Moreover, there is still room for improving the yield of steelmaking route through the recovery of metal fractions from residues both by direct feeding in production processes or after a dedicated treatment.

2.4.2. Electric energy and energy sources

The growth of the electric route will increase the demand of electrical energy and, in particular, of renewable electricity as energy carrier, which will become ever more strategical in view of CO_2 emission reduction.

Figure 13 shows the expected CO_2 intensity of the electricity grid in the EU 28 up to 2050. Considering, for instance, the EU reference scenario, the CO_2 intensity of the EU 28 is 300 kg/MWh in 2015, 200 kg in 2030 and 80 kg in 2050.

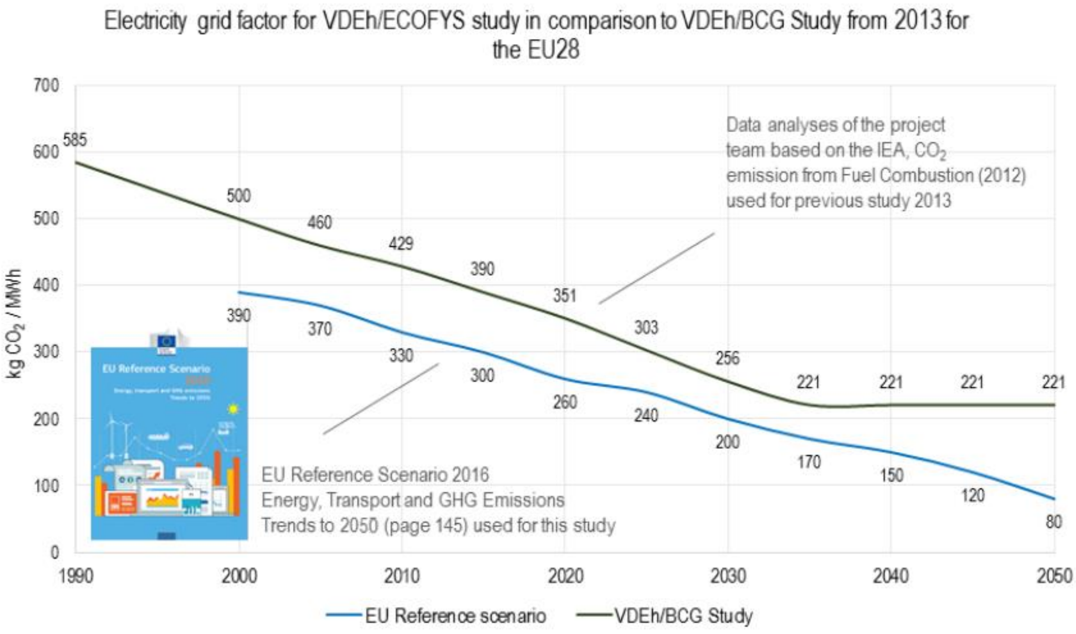

Figure 13. *Electricity CO_2 intensity of EU 28 (grid mix factor)*

Considering the today scenario of total (direct and indirect) emissions of CO_2 for the EAF route (**Figure 14**), the impact of the renewable energy can be relevant both on indirect and direct emissions. The use of CO_2-free electricity and CO_2-free fuels (e.g. green H_2) could lead to CO_2 emissions around 60 kg CO_2 /t tonne of liquid steel in the scrap-based EAF as well as for purely green hydrogen/electricity iron-ore based DRI/EAF. Levels of 60 kg CO_2/tonne of liquid steel are the operational minimum if the EAF uses graphite electrode and some carbon dioxide is coming from coal and the alloying material consumption.

Substitution of coal with carbon neutral feedstock can lead at an additional reduction of 50%.

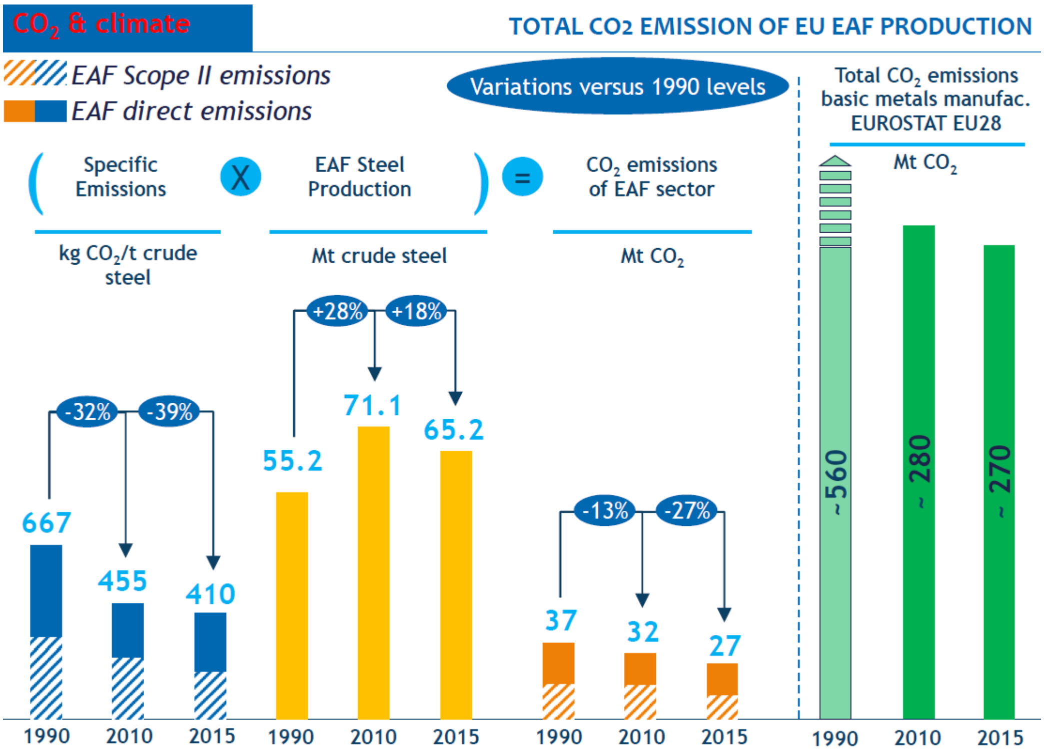

Figure 14. *Total CO_2 Emission of EU EAF Production [20]*

Nevertheless, energy efficiency must be improved, and attempts are required to integrate the use of existing resources in the production process such as, for example, by waste heat recovery and new sustainable and green energy sources, renewable energy and green H_2.

2.4.3. Industrial Symbiosis

Finally, adopting a holistic point of view the industrial symbiosis theme needs to be considered (**Figure 15**).

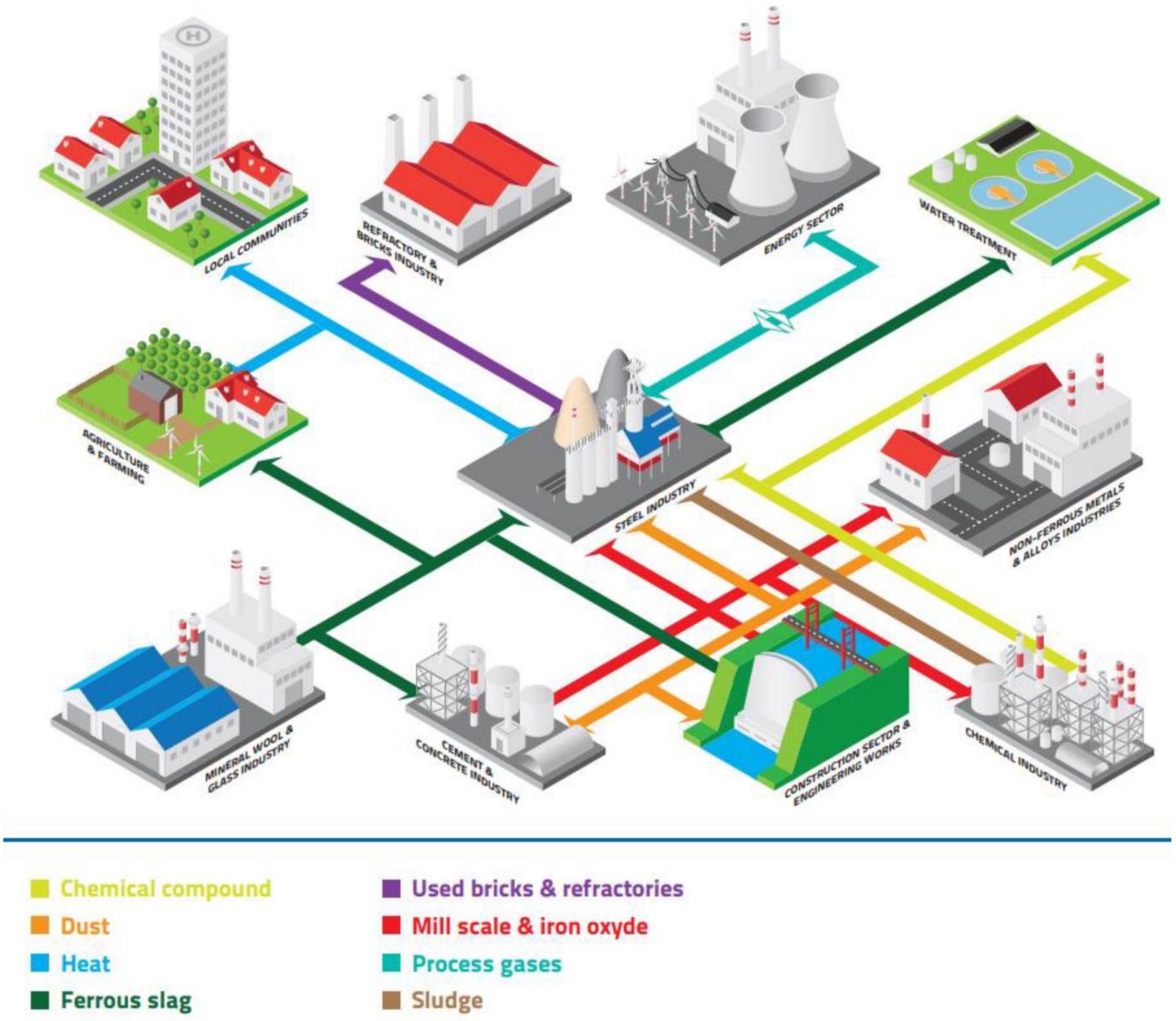

***Figure 15**. The industrial symbioses related to the EU steel sector [21]*

Although the scrap route is already included in the ecosystem, and some by-products are already internally or externally reused (such as schematically represented in **Figure 16** for the slag case), further opportunities for industrial symbiosis need to be investigated and created to reduce the consumption of primary resources by using secondary resources derived from residues.

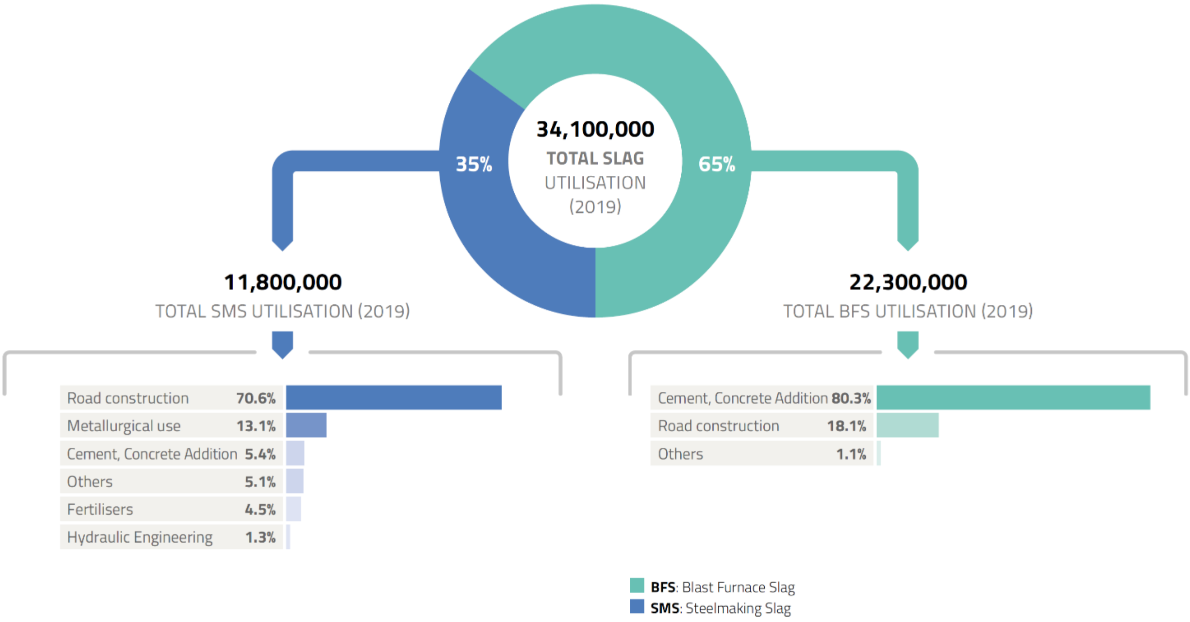

Figure 16. *Slag usage paths [3]*

2.4.4. Legislation and Societal issues

The awareness of the previous listed issues highlights challenges to be faced at both technical and regulation level. Therefore, EU level debates and legislative actions supporting companies in dealing with the described challenges are fundamental.

Moreover, although contributing to mitigation of climate change by reducing CO_2 emissions is fundamental, measures need to be implemented also addressing prevention and reduction of the local impact of the steelworks, to improve their coexistence with the surrounding communities. To this aim, emissions having a direct impact on the areas surrounding the facilities, (e.g. acoustic and diffuse dusts emissions) need to be mitigated, logistics aspects must be carefully addressed to minimize interferences with the mobility of the neighboring communities, and visual impact of the facilities needs to be improved. Industrial symbiosis and process integration solutions can be implemented to improve the synergies with local communities for, e.g., waste heat recovery and exploitation, water reuse and recycling. All these actions require a close cooperation and interaction with the local stakeholders.

Further legislative efforts are required to close the loop of recyclability and reuse of all the steel production residues in other sectors.

Tackling these challenges paves the way to new investments, job creation and increased competitiveness for the European steel industry and for the European activity sectors exploiting steel products.

Finally, contributing to the mitigation of climate change by reduction of emissions and wastes as well as of natural resource depletion will lead to benefits to the welfare, well-being and progress of present and future society.

3. Research and Innovation Strategy

Considering the current context and challenges, different priorities to be addressed for reaching what declared in the vision statement were selected during discussions and analyses, carried out in the framework of the ESTEP under the leadership of the Circular Economy Focus Group. Considering the whole value chain of the electric steelmaking route, the following macro-topics were identified:

- **scrap: pre-treatments to improve scrap quality and reduce tramp elements, on-line quality analysis and characterization, yard management and use of HBI/DRI**;
- **energy recovery and utilization**;
- **use of renewable energy sources and alternative non-fossil fuels: renewable electricity and direct use of renewable or green H_2**;
- **replacement of lump and pulverized coals as reducing or foaming agent with alternative C-bearing materials and reduced consumption of graphite electrodes**;
- **valorisation of wastes, residues and by-products for internal and external use**;
- **new tools and sensors for process improvements**.

In this chapter the identified priority topics are deepened and a strategy is identified to reach step by step the specific objectives.

Each paragraph addresses a specific topic and it is subdivided in a fixed number of sub-paragraphs to cover all the fundamental aspects and to provide a suitable plan/path to be followed.

After a brief introduction of the specific background of the EAF steelmaking process chain, where each topic will act (the topic target), the main key aspects on which it can contribute are analysed giving the importance and the scope description of the topic.

In addition, expected impacts and technical actions to be followed to reach the aim of each topic (i.e. a work program) are provided by defining three different consecutive steps (levels) with flexibly defined time horizons and milestones (in terms of reaching an established TRL), considering the indications given in **Figure 17**.

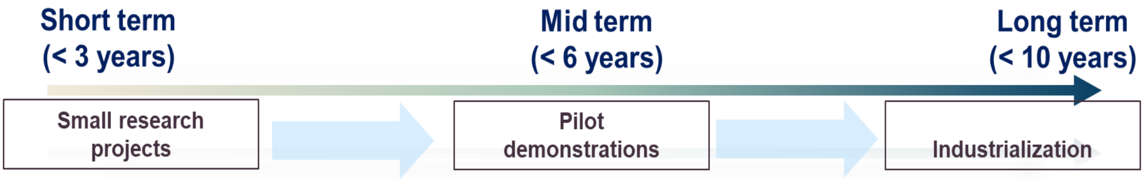

Figure 17. *Type of actions*

In addition, the risks estimate of the proposed plans is provided as well as a description of the resilience of the considered systems, to provide an idea on how they can resist on “black swans”[3].

Preliminary budget analyses related to the envisaged work plan are also provided.

The chapter considers possibilities of common objectives and, therefore, also the requirement of synergies among the different topics of the plan.

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[3] Black Swan means an event that has a major effect on results, yet occurs unpredictably. It considers the nature of the current markets and the industrial contexts according to the VUCA concept (Volatile, Uncertain, Complex and Ambiguous).

3.1. Scrap: pre-treatments to improve scrap quality and reduce tramp elements, on-line quality analysis and characterization, yard management and use of HBI/DRI

3.1.1. Specific EAF chain target

The strategic role of scrap management, as defined in Chapter 2, is also highlighted by the CSP Roadmap in the specific objective 4 entitled "*Increasing the recycling of steel scrap and residues to increase smart resources usage and further support a circular economy model in the EU*" and in the operational objective and the KPIs that are reported in **Table 1**.

Table 1. *Operational objective and KPI and related targets for the CSP objective "Increasing the recycling of steel scrap and residues to increase smart resources usage and further support a circular economy model in the EU" with focus on scrap management [18]*

Operational objective	KPI	Target Value
Enhancing the recycling of steel scrap	Scrap pre-treatment and cleaning technologies and scrap yard management procedures and techniques for: • Progressively increasing the uptake of low-quality scrap grades (post-consumer) into high-quality steel-grades • Progressively replace the use of pre-consumers grades with post-consumer grades • Progressively replace the use of solid pig iron with post-consumer grades	TRL6: Low-quality scrap input share over the total scrap input increased by at least 25% or more compared to the usual practice for a specific steel quality by 2024
		TRL8: Low-quality scrap input share over the total scrap input increased by at least 50% or more compared to the usual practice for a specific steel quality by 2030

From the quantitative point of view, today EU-28 sells on the worldwide market important volumes of its ferrous raw materials while imports nearly 100 Mt of iron ore [6]. According to the Bureau of International Recycling, the EU-28 exported 21.8 Mt of ferrous scrap in 2019 [3], mainly characterized by low quality type. For such reasons, it is important to better monitor the exported scrap by mapping scrap flows through EU, for instance developing dedicated advanced digital systems and tools aimed at this issue and at facilitating the access and the improvement of the transparency of the scrap market.

In addition, a valorization of low-quality ferrous scrap should be considered, as underlined by CSP, since an increased use of low-quality scrap will help to cover the expected rise of future scrap demand that will be the consequence of an increased share of EAF production to reach the CO_2 emission reduction target of more than 80% by 2050. This aspect is also important considering that in Europe the market for alternative ferrous materials, such as Hot Briquetted Iron (HBI) and Direct Reduced Iron (DRI), is limited.

In this background, it needs to keep in mind that the increase of low-quality or obsolete scrap use, the higher complexity of consumption goods (as cars which contain more and more electronic devices, resulting in more copper in scrap) and repeated recycling leads to higher levels of residual impurity elements entering in the steel-making process. Thus, the presence of tramp elements such as non-ferrous metals might limit the use of ferrous scrap for production of certain steel grades. Research efforts on this topic are necessary because, as said before, low-quality scrap streams are one of the key elements to foster the green transition of the steel production as a whole.

In particular, strategies are required and efforts must be spent for scrap sorting, pre-treatment, characterization, yard management and alternative ferrous material use in the electric steelmaking processes.

3.1.2. Key Aspects and Scope Description

The different international Steel Scrap Specifications define a set of scrap categories (qualities) by the source of the scrap and its physical characteristics, as well as its maximal content of undesirable elements and non-ferrous (sterile) materials.

These specifications reflect a compromise between the steelmakers' needs (high density for productivity, low percentages of tramp elements for metallurgical purity, reduced costs of low sterile contents) and the grade of purity that the industrial treatments can deliver with the technologies and equipment available at scrap recycling area. However, due to the widely varying quality of the scrap that is delivered to scrap processing plants, the suppliers will often provide materials with high variability between the minimum and maximum requirements defined in those specifications (mixtures of materials with different qualities, inadequate dimensions, hazardous elements, contamination with other constituents).

Therefore, an effective classification of steel scrap and the proper management of its variability is necessary.

This can be done by focusing on the following five key aspects.

Upgrading of scrap (cleaning, size control, tramp element elimination), standardization and market improvement

New scrap processing techniques that are more efficient and more aligned to the steel industry needs shall be developed and applied (individually or in integrated way) in the steel factories as well as in the scrap recycling facilities. Furtherly, new industrial solutions shall be developed for removing undesired elements in the ferrous recycled materials, such as, for instance, Cu from shredder scrap through physical-mechanical means.

In addition, the standard description of scrap with reference to its quality characteristics should be improved: information like provenience, typology, tramp element contents should be known by sharing such information. Therefore, following the trends of the digital transformation, during the purchase phase new approaches need to be considered for making negotiation transparent. To achieve this goal a self-ruled marketplace of scrap supported by eBusiness platform is in line with the general trend of the resource markets.

Inline characterization of ferrous materials

The implementation of a close control of scrap quality, both in origin and in destination, is a very complex task, due to its high heterogeneity, the large volumes involved, the different origins, the different pre-treatment processes, the blending quality, mix-ups at scrap suppliers, etc., which often create difficulties in controlling the scrap characteristics.

It is, therefore, necessary to have detailed information about the characteristics of EAF input raw materials for maximizing the overall performance of the steelmaking process. Several techniques for material characterization were investigated in recent projects, including: Laser-induced breakdown spectroscopy, LIBS (LCS [22] or IPRO [23], Prompt Gamma Neutron Activation Analysis [24], Pulsed Fast Thermal Neutron Activation, PFTNA, Muons tomography [25]. In addition, a recent HORIZON 2020 project, namely REVaMP [26], is focused on the development, adaptation and application of novel retrofitting technologies to face the increasing variability and to ensure an efficient use of the feedstock in metal making processes.

However, novel technologies for onsite characterization (chemical composition and physical properties) of ferrous materials need to be developed. This comprises characterization of small samples and surface analysis methods as well as bulk analysis and characterization of the whole scrap delivery, e.g. via trucks or wagons, in order to help all stakeholders to standardize their scrap managing practices. In the long term, new methodologies for better defining the different international scrap specifications should be derived.

Digitalization of scrap / charge material management and smart material usage

Digital system and tools for supporting scrap yard management activities shall be developed and implemented, aimed at maximizing the efficiency in the use of the available charge materials. This comprises the scrap yard inventory system, which tracks the availability of charge materials in the scrap yard, with detailed diversification of the different scrap types. The inventory data base must be automatically updated every time a scrap delivery is entering the plant, and every time a scrap basket has been loaded and charged to the furnace. For instance, visual systems are under development and some already implemented, whose data feeds AI and ML applications to classify scrap and suggest the best charge depending on the availability in the scrap yard.

On the other hand, a dynamic and robust charge mix optimization tool must be applied to determine the optimal charge mix for each individual steel grade with respect to quality restrictions of the crude steel as well as availability, purchase costs, yield and meltdown energy demand of the individual scrap types. This charge mix optimization must dynamically adapt the recipes or search an acceptable tradeoff when optimization is almost impossible by using up-to-date information on the characteristics (chemical composition, metallic yield, energy demand, bulk density etc.) of the scrap types, which are currently available on the scrap yard or can be delivered to the plant on a short term-basis. These characteristics can either be determined and tracked by appropriate inline sensors/characterization methods (see above) or by statistical methods, like multi-linear regression models which allow deriving the characteristics from analysis of liquid steel samples and temperature measurements performed before EAF tapping.

In this context, also new methods for assessing the real Value-In-Use of the different ferrous materials used in the EAF process shall be developed.

This key aspect is strictly linked with the macro-topic “*New tools and sensors for process improvements*” which is described in Section 3.6 and intended as the component of integrated scrap yard management systems in line with the melting operations.

Some examples of RFCS projects seeking the best and most economic use of scrap in steel making operations are CONOPT SCRAP [27], FLEXCHARGE [28], AdaptEAF [29], SUPERCHARGEEAF [30], and OptiScrapManage [31]. In addition, digitalization tools for supporting scrap yard management activities are under development and some already under implementation, aiming to maximize the efficiency in the use of the available charge materials [32] , [33], [34], [35].

Nevertheless, efforts are still needed to reach the industrialization.

Industrial residues beneficiation as C/Fe source

The new material treatment scenes to be developed in the upcoming years in different industrial sectors will generate residues that could be considered as C/Fe raw materials sources in EAF steelmaking. However, those residues must be analyzed to deploy their full potential of being transformed into by-products considering the legislation in the different countries of the EU.

Beneficiation of both scrap upgrading residues and other industrial residues are already under investigation; PROTECT [36], RIMFOAM [37], or URIOM [38] are good examples of recent researches to be considered as starting point for further improvements.

<u>Optimised use of alternative iron products (HBI/DRI) in EAF process</u>

Alternative iron sources like DRI/HBI or pig iron / hot metal can be used to compensate the increased content of impurities, such as tramp elements, which are especially introduced by post-consumer and obsolete scrap. However, the higher meltdown energy demand, the higher carbon content and the higher amount of EAF slag which is induced by these alternative charge materials, must be considered. Some current or previous projects can be taken into account.

For instance, LOWCNEAF represents a good example of project related to the application of this approach [39]. However, there are currently only two DR installations in the EU (i.e. in Germany and in Sweden) with a total production capacity of approx. 0.7 million ton per year [6, 40]. In addition, HYBRIT [41], H2H [42], SALCOS [43] or tkH2Steel [44] project are for instance dealing with DRI elaborated with Hydrogen.

3.1.3. Expected Impacts

Around 55 – 60% of the total costs for the electrical steelmaking route correspond to the input of metallic raw materials.

A better tracking of the different scrap grades and of their properties allows adapting optimal scrap grades blend and thus it has a big potential on reducing costs and environmental footprint and on improving performances of the EAF steel production site.

On the other hand, improving the available inline characterization technologies for ferrous material will allow a more precise control of the concentration of tramp elements and an increase of the used amount of cheap scrap with potentially higher tramp element concentration in an optimized mix with other higher quality materials, with consequent lowers the production costs.

The upgrading (cleaning, size control, tramp element elimination) of ferrous raw material as well as the standardization and market improvement would have the following impacts at different stage of the steelmaking process:

- In the material purchasing phase - The lack of knowledge in the chemical distribution (scrap + sterile) of material delivered to the steelmaker scrap yards leads to the risk of considering all inlet material as scrap. However, between 6 to 20% of the total input are sterile. Not paying sterile fraction as ferrous material through a better material characterization before material reception at the scrap yard, can represent costs saving up to 42€/t.
- Process efficiency - When non-ferrous materials are introduced to the EAF it is necessary to compensate the negative effects of those elements along the process. As shown in the **Figure 18**, the presence of 5% in Iron Oxide, Silica or Lime in scrap represents 7€/t, 40€/t or 10€/t respectively in extra process costs that can be avoid with improved knowledge of scrap and with its upgrade.

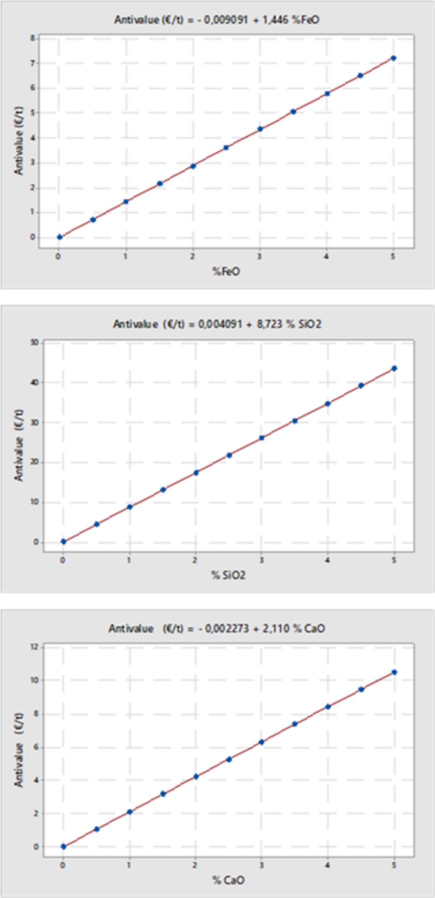

Figure 18. *Influence of FeO (Up) SiO_2 (Middle) and CaO (Down) on the material Value In Use [45]*

- Product quality - Poor quality scrap (coatings, electrical elements, paintings…) introduces tramp elements in steel products (e.g. Cu, Sn, Cr, P, etc.). This restricts the usage of those materials accordingly, forcing the steelmakers to take a conservative approach for ensuring the compliance with quality requirements throughout the manufacturing batch. Improved characterization and optimization of steel scrap and optimized use of alternative iron sources like DRI/HBI will allow limiting the introduced tramp elements so that also selected low alloyed steel qualities, which are at current state reserved to the production via the integrated route, can be produced via the electric steelmaking route. A replacement of the BF-BOF route by the scrap-based EAF route has the potential to reduce CO_2 emissions of about 80% per ton of crude steel, depending on the applied energy mix [46].

In addition to the upgrade of the scrap qualities, improved management operation within an installation, through plant digitalization and smarter management, control and usage of materials (**Figure 19**), will create additional opportunities for pushing further down the overall impact of EAF steel production from scrap purchasing to final product.

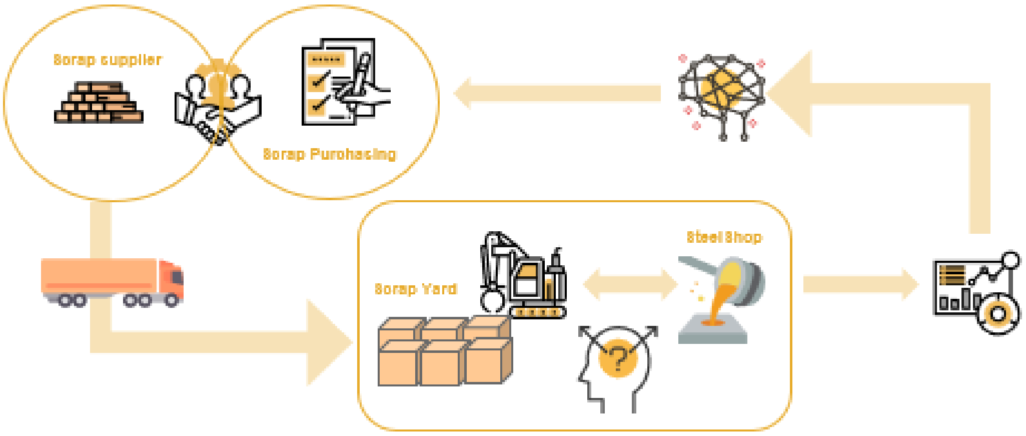

Figure 19. *Interrelation among the different steps of scrap usage in EAF steelmaking to be considered for process digitalization*

Another important impact to be considered is related to the industrial residue generation, not only along the steelmaking processes, but also those generated during the upgrading processes of scrap materials. If effective and efficient technologies for characterizing and sorting are applied to these residues, it is possible to conduct industrial beneficiation procedures to transform them into new Fe, C or high added value non-ferrous metal sources with an estimated value of 50 – 150 €/t [4] due to the following factors:

- reduction of steelmaking wastes/by-products generated by raw material lacks of quality;
- transformation of ferrous waste material of poor quality into raw materials for EAF steelmaking;
- enhancement of the recyclability of valuable raw materials contained in the scrap sterile.

3.1.4. Technical Actions

Considering the identified key aspects and the previous and ongoing researches for increasing scrap usage in steelmaking, the technical actions, under the scope of this document, can be split in the three level of actions listed and described in **Table 2**.

Table 2. *Overview of proposed technical actions for the improvement of scrap managements*

Research line	Short	Medium	Long
Upgrading of scrap, standardization and market improvement	Consolidation of existing knowledge: - European Ferrous scrap market understanding - Technical analysis of consolidated scrap upgrading methods (by materials topology) at industrial scale Improvement of standardization of scrap description and information sharing	New pilot technologies for scrap pre-processing Automatic quality monitoring (based on sensors) of the upgrading processes products Definition of self-ruled scrap marketplace supported by eBusiness platform	Industrial scale novel processes for tramp elements removal from the ferrous fraction of metal scrap Automated scrap sorting plants
Inline characterization of ferrous materials	Assessment of existing physical (density, volume, colorimetry…) and chemical (Hyperspectral, LIBs, XRF, OES …) characterization techniques for ferrous materials understanding	Lab demonstrator of techniques for real-time measurement of scrap buck chemical composition	Autonomous systems for chemical control of materials in scrap yards
Digitalization of scrap / charge material management and smart material usage	Definition of actions required for reducing human decision in material flows management	Tools for optimizing material monitoring and process control at the steelshop by dynamically	

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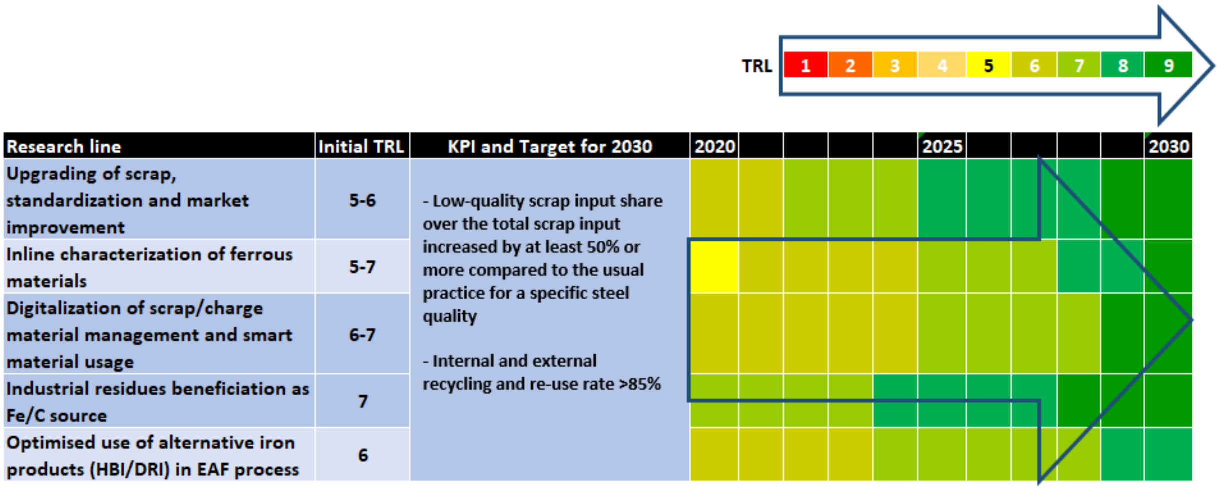
[4] The value is linked to the valorization of residues in the scrap after the cleaning process machines. Those residues present added value materials (e.g. Cu, Al, Cr) that can be sorted to be transformed into secondary raw materials.

	Optimization of scrap yard management operation by AI and process digitalization. Full traceability of raw materials from the scrap dealer to the steel shop.	adjusting the process based on scrap input data and availability AI algorithms for scrap/steel grade correlation	
Industrial residues beneficiation as Fe/C source	Exploration on the use of alternative carbonaceous residues obtained from the scrap beneficiation processes	Identification of new poor-quality Fe/C raw material markets	Industrial upgrading routes for low-grade iron ores and Fe-containing residues
Optimized use of alternative iron products (HBI/DRI) in EAF process	Exploration of the effects of massive use of HBI/DRI in EAF process	Development of technologies for pelletisation / sintering / agglomeration of by-products containing Fe Tools for optimizing the mix of HBI/DRI and low-quality scrap	Industrial upgrading of EAF route for producing low alloyed and high quality steel

3.1.5. Time Horizons Plans and Milestones

The following **Table 3** provides an overview of individual approaches regarding the increased use of scrap as well as their TRL development and research needs.

Table 3. *Temporal development frame for the improvement of scrap managements*



Research line	Initial TRL	KPI and Target for 2030	2020					2025					2030
Upgrading of scrap, standardization and market improvement	5-6	- Low-quality scrap input share over the total scrap input increased by at least 50% or more compared to the usual practice for a specific steel quality - Internal and external recycling and re-use rate >85%											
Inline characterization of ferrous materials	5-7												
Digitalization of scrap/charge material management and smart material usage	6-7												
Industrial residues beneficiation as Fe/C source	7												
Optimised use of alternative iron products (HBI/DRI) in EAF process	6												

3.1.6. Plans Risks and Robustness

Table 4 mentions main technical and economic risks related to actions devoted to the improvement of scrap managements. Probability of occurrence and impact quantification of the identified risks are estimated by considering a three-level scale (L for low, M for medium, H for High). While risk level is quantified through a five-level scale (1 very low risk level and 5 for very high risk level) in order to allow a more significant and easier comparison of the different risks providing them a “priority”. Countermeasures are also provided to counteract to the identified risks.

Table 4. *Risks and countermeasures related to actions devoted to the improvement of scrap management*

Risk	**Probability of occurrence**	**Impact quantification**	**Risk Level**	**Countermeasure**
Reluctance of new technology integration due to risks of productivity losses	M	H	5	Include in the conceptualization phase an exhaustive analysis of pre-existing physical plants at industrial scale
Higher occurrence of product quality issues due to residual impurities from scrap	H	M	5	Variation of process parameters
Lack of financial resources	L	M	2	Possible increased private funding in case public funding is too low
Policies and regulations affecting the availability and prices of raw materials	L	H	3	Social awareness in environmentally friendly operations
Lack of qualified staff	L	H	3	Find synergies among engineers, universities, R&D and industrial communities
Uncertainties on European steel market evolution in the coming years	M	L	2	Transparency of cooperation among companies and public institutions

3.1.7. Preliminary Budget Analysis

Although there is great expectation and hope for new technologies for accurate and continuous measurement of scrap properties, as well as for their upgrading, related residue beneficiation and automatic selection and smart material usage, and many promising results have been achieved, up to now no industrial routine applications are known. Their current TRL ranges from 5 to 7.

Considering the mean value of budget of the performed and proposed projects on this subject, a rough estimation of the efforts needed for achieving TRL8 by covering all the related projects is in the order of 20-30 M€ in ten years.

Technologies for improving the EAF process are more mature, however they present equivalent needs in terms of monitoring and control technologies. Hence a similar investment cost and time can be expected.

In total the cost for the development of robust solutions enabling a relevant increase of scrap usage in EAF can be estimated around 50 M€ by 2030. This amount, can be split as follows in the considered time horizon:

- 8 M€ for the period 2021-2023

- 17 M€ for the period 2024-2025
- 25 M€ for the period 2026-2030

3.2. Energy Recovery and Utilization

3.2.1. Specific EAF chain target

The energy recovery and utilization is considered fundamental in the CSP Roadmap as underlined with the specific objective 3 entitled “*Developing deployable technologies to improve energy and resource efficiency (SCU Process Integration)*” and by specifying that the usage of waste heat is also useful to support the CE. In particular, the operational objective and KPI, reported in **Table 5**, are defined.

Table 5. *Operational objective and KPI and related targets for the CSP objective “*Developing deployable technologies to improve energy and resource efficiency (SCU Process Integration)*” with focus on energy recovery and utilization [18]*

Operational objective	KPI	Target Value
Developing technologies to reduce the energy required to produce steel	Decrease the use of energy per tonne of steel for clean steel making	TRL7: > 5% specific energy consumption reduction for a dedicated process by 2024
		TRL7: > 10% specific energy consumption reduction for a dedicated process by 2030

It is generally estimated that EAF processes for steel production need about 650-750 kWh/tls [47] as energy input with a distribution as depicted in **Figure 20**.

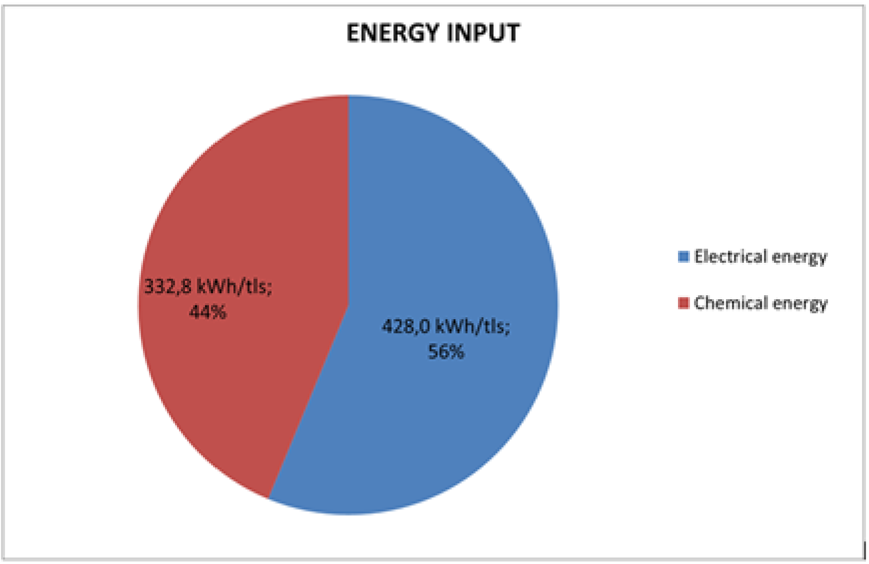


Figure 20. *Characteristic energy input in the EAF process charged by 100% scrap*

The biggest part of this energy, corresponding to about 50%, is directly transferred to molten steel. The other 50% is dissipated in the environment mainly by slag (about 10-15%), waste gas (about 25-35%), and cooling water (about 8 - 10%). Minor losses are related to heat radiation, electrical dissipation and moisture evaporation. This distribution is clearly reported in **Figure 21**.

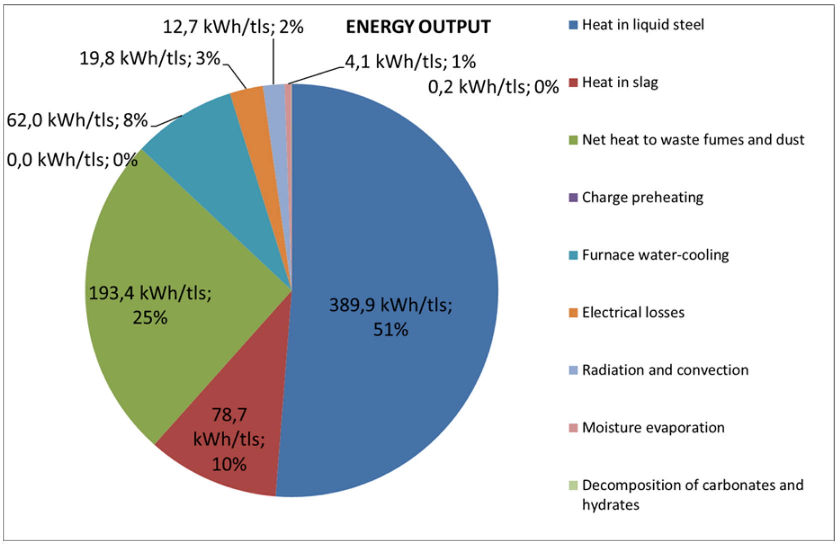


Figure 21. *Characteristic energy balance of the EAF process charged by 100% scrap*

These three main sources of energy loss are also the main drivers for energy recovery from the EAF that can be carried out through different approaches.

3.2.2. Key Aspects and Scope Description

Recovery up to 50% of the heat in the EAF is possible by state of art knowledge and recent developed technologies (e.g. iRecovery, Consteel, Ecoarc, Quantum, Sharc). However, although the heat recovery from EAF is a well proven technology, the high CAPEX involved, the low revenues expected by the energy at low temperature (hot water) and the low efficiency in the power generation are factors limiting its diffusion. Therefore, the main barrier which restrains the application of the energy recovery technologies applied to the EAF are the high CAPEX compared to the standard pay-back in the steel industry (3-years): the pay-back is even affected by the current decreasing standard fuel and energy prices.

Typically, the range of the pay-back time relevant to the investments in energy recovery is about 5-10 years not considering eventual grant from the authority. The EU countries developed different grant schemes for the valorization of the recovered energy, however the Carbon Emission Allowance (EUA) is the only recognized price premium across the EU for the investment in energy recovery, even if any single country is starting to manage different grant scheme to promote this project (e.g. TEE in Italy). The assessment of a common grant scheme across the EU for the energy recovery will lead to an easier development of the possible solutions.

Starting from these consideration, scope of R&D&I should be the increase of the recovered heat and its value with a decreasing of the investment costs, through:

- reviews of different technological solutions for the utilization of the energy carriers used in the heat recovery;

- analyzing the opportunity to define a unified premium price across the EU for the energy recovered which leads to avoid the carbon dioxide emission and improve the efficiency in the steel production processes.

This is required in all the key aspects and research lines that need to be considered for the increase of energy recovery and utilization and full implementation of the related state of the art technologies in EAF steelmaking route.

Off-gas heat recovery

The recovery of energy from off-gas is the most common and advanced possibility considered in EAF steelmaking. The consolidate way to recover heat from the off-gases is the direct use for scrap pre-heating before the charging in the EAF with a recovery of about 10-15% of energy. Another possibility is energy carrier production such as saturated steam or hot water generation. By considering the two possibilities, a global recovery of about 16-20% of EAF energy input could be obtained.

Different technologies have been developed for scrap preheating by hot off-gases such as Consteel, Quantum, SHARC, ECOARC. In addition, different projects across the EU (i.e. from GMH Gruppe, ESF – Feralpi, ORI-Martin, Acciaierie Arvedi, Celsa-Poland) were developed in the past ten/fifteen years to recover EAF off-gases thermal power in combination with scrap pre-heating or as standalone solution. In this second case, the heat recovery system is applied on the EAF off-gases primary directly interconnecting the heat exchanger to the EAF 4th hole.

Possible uses of saturated steam are the following:

- steel production purposes, directly as utility in the vacuum degassing process (i.e. VD, VOD and RH);
- power generation process through Rankine cycle in ORC turbine or standard steam turbine;
- heating/cooling system, directly through heat exchanger for district heating network or chiller for HVAC system;
- steam engine for compressor or ID-fan application.

On the other hand, the possible utilizations of hot water are:

- power generation at low temperature through thermoelectric elements;
- heating/cooling system, as mentioned above.

Molten salts can be a further possibility of energy carrier: a pilot project for waste gas heat recovery based on molten salts technology was realized in Stahlwerk Thüringen GmbH to ensure a higher temperature of the working fluid especially for producing overheated steam and increasing the performance of power generation.

However, it is still considerable the amount of energy dissipated in the environment through the fume treatment plant. Thus, actions are needed for more efficient and economic technologies and possibilities for maximizing the heat recovery from off-gases (also after their decrease of temperature) as well as for reducing dissipation (e.g. by improving EAF sealing) or for storing the recovered heat. The identification of better energy carriers and a plan for the conversion from dissipative cooling for all the technologies involved in the steel production process, could be also necessary.

Slag solidification waste heat recovery

Waste heat recovery from high temperature slags represents the latest potential way to remarkably reduce the energy consumption and CO_2 emissions of the EAF. The molten slags, in the temperature range of 1450–1659 °C, carry large amounts of high-quality energy. However, the heat recovery from slags faces several challenges, including their low thermal conductivity, inside crystallization, and discontinuous availability.

Cost-effective technologies are available for BF/BOF slags due to high quantities [48], while for EAF and LF slags investigations were carried out in H2020 project RESLAG [49] and under investigation in RFCS ECOSLAG [50] [51].

Figure 22 reports an example of the performed analysis assuming a heat recovery efficiency for slag cooling from 1600°C to 50°C by air coupled with an Organic Rankine cycle (ORC) for co-generation of electrical energy and hot water.

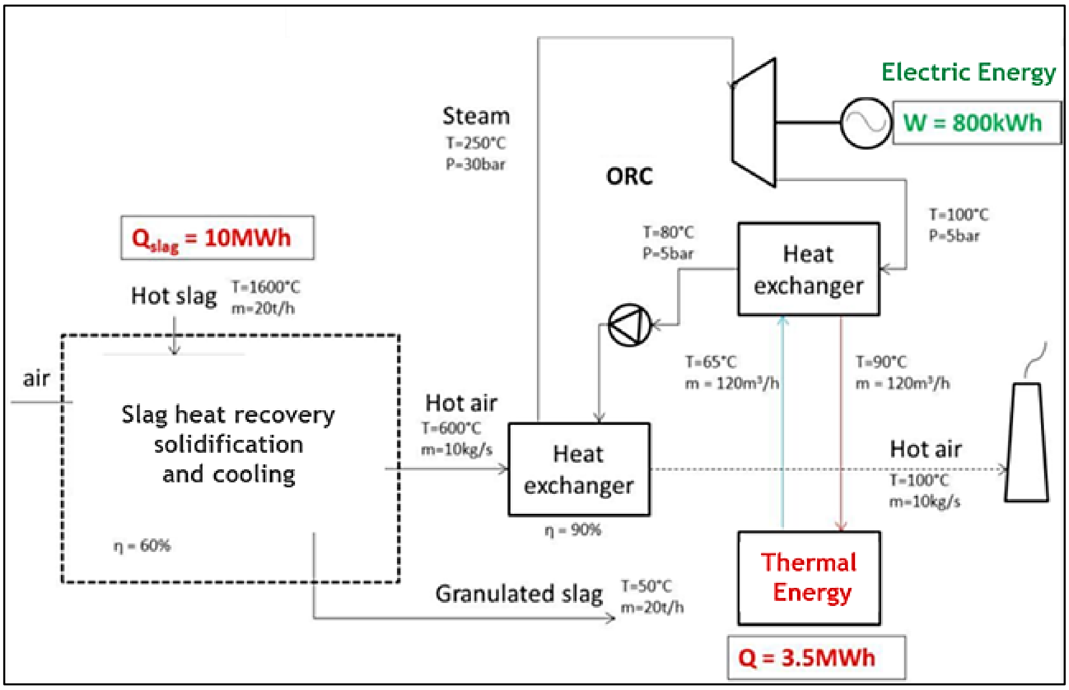


Figure 22. *Example of heat recovery from slag*

Low temperature cooling water heat recovery

Nowadays, few projects have been developed for recovery of the dissipated thermal power in EAF roof and shell [52] even if the amount of available heat is about 10-15% of the total energy input. Two projects are actually ongoing in Brescia (Italy) for the utilization of heat recovery from EAF shell and roof into a district heating network, respectively with and without the utilization of a heat pump.

Energy recovery from product and process

A significant amount of energy is dissipated by the steel product and during particular processes (e.g. continuous casting) and low efforts are until now spent for its recovery especially for the technological issues. However considerable benefits can be obtained if also this high amount of energy is recovered for instance from continuous casting machine (CCM) or slabs.

3.2.3. Expected Impacts

Beside the direct benefits of the heat recovery as the energy saving, even two other indirect benefits shall be considered: decreasing the carbon footprint of the steel production and the minimization of the water consumptions. Especially for the heat recovery through steam generation the water savings can be considerable because the water flow is generally even four time less than the dissipative cooling by water.

Based on the energy balance above mentioned, about 45-55% of the EAF energy input could be recovered as well as significant amount of CO_2 savings can be achieved with dedicated R&D&I actions as reported in **Table 6**.

Table 6. *Potential recoverable energy and CO_2 savings in EAF steelmaking thanks to the energy recovery*

Heat Recovery source	Energy Input percentage potentially recoverable		Potential energy savings [KWh/tls]		Potential energy recoverable [KWh/tls]		CO_2 savings for direct use of recovered heat [kg CO_2/tls]		CO_2 savings for conversion in power generation of the recovered energy [kg CO_2/tls]	
	min	max	min	max	min	max	min	max	min	max
Waste gas[a] and dust	30%	35%	195	228	150	175	27	31	7[d]	9 [d]
Slag[b]	8%	10%	52	65	42	52	7	9	1[e]	2[e]
Water cooled panel[c]	8%	10%	52	65	42	52	7	9	1[e]	2[e]

a. Input Temperature 1,200 – Output Temperature 200
b. Input Temperature 1,600 – Output Temperature 200
c. $\Delta T \approx 15$
d. based on ORC
e. based on Peltier technology

Considering that the current EAF steel production in EU is about 65 Mtls/a (Mtls = Millions of tons of liquid steel) [3] and taking into account all the three heat recovery sources reported in **Table 6**:

- the potential energy recoverable is about 15,000-18,000 GWh/a;
- the CO_2 savings for direct use of recovered heat are about 2.7-3.2 Mt CO_2/a;
- the CO2 savings for conversion in power generation of the recovered energy are about 0.6-0.8 Mt CO_2/a.

The amount of recoverable thermal energy is equivalent to the amount of saved/obtainable resources shown in **Table 7**. The green H_2 and O_2 potentially synthesizable, can be directly re-used in the steel production process with consistent reduction of the carbon footprint (see Section 3.3).

Considering all the benefits that can be achieved, efforts are continuously required for improving energy recovery and utilization in EAF steelmaking.

Table 7. *Amount of resources that can be saved or produced through the optimized recovery of energy in EAF steelmaking*

Medium		**Amount**
Saved Methane	MNm^3/a	1,500-1,800
Electrical Energy Production	*TWhe/a*	2.7-3.3
Green Hydrogen[5]	MNm^3/a	4,100-5,000
Green Oxygen[5]	MNm^3/a	2,100-2,500

3.2.4. Technical Actions

Actions on both decreasing of the investment cost and the increasing of the value of energy recovery are required in order to fully deploy the state of the art technology and further improving the recovery of energy. **Table 8** presents the technical actions foreseen for the energy recovery considering the different research lines and a target of about 30-35% and 8-10% of EAF energy input recovery respectively from waste gas and from other media.

Table 8. *Overview of proposed technical actions for implementation of EAF energy recovery and utilization strategies*

Research line	**Short**	**Medium**	**Long**
Off-gas heat recovery	Energy carrier analysis: water, steam, organic fluid Maximization of waste heat recovery from lowest off-gas temperatures Improvements of EAF sealing and post combustion control Direct use of energy carrier into technical gas or biomass production (e.g. hydrothermal pyrolysis)	Use of molten salts for higher efficiency (superheated steam) Steam Methane Reforming Development and use of ceramic heat exchangers for high temperature preheating of combustion air and fuels of other processes: - carbon fiber reinforced carbon (CFRC) for a reducing atmosphere - silicon infiltrated silicon carbide (SiSiC) for an oxidizing atmosphere	Power generation by high and medium temperature Peltier module (TEG) Power generation by Stirling engines Research for techniques for long-term energy storage for heating application Green H_2 and O_2 generation by heat recovery and SOEC technology
Slag solidification waste heat recovery	Heat recovery from slag by the application of different technologies (e.g. in dry slag granulation, the exiting hot air can be used for different heat recovery applications)		Power generation from EAF slag radiation using solar panels and/or TPV
Low temperature cooling water heat recovery			Power generation at low temperature by Peltier cells using the hot-water generated by heat recovery from EAF shell/roof and waste gas system Green H_2 and O_2 generation by heat recovery and SOEC technology
Energy recovery from product and process	Steam generation from CCM	Technologies for radiation heat recovery from slabs	Power generation from hot slab radiation using solar panels and/or thermophotovoltaics generators (TPV)

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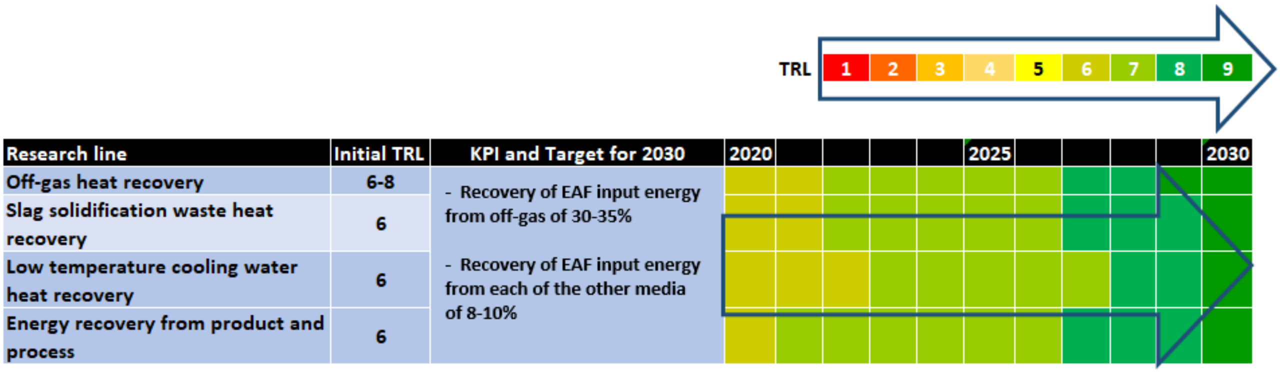
[5] Produced from the steam that can be generated by the recoverable amount of energy by using Solid Oxyde Electrolysis Cell (SOEC) technology

Considering that in most of the cases electricity can be produced by exploiting the obtained steam by the heat recovery, an investigation of electrical market is required for all the research lines in the short period.

3.2.5. Time Horizons Plans and Milestones

Table 9 provides an overview of the temporal development frame for the short, medium- and long-term actions.

Table 9. *Temporal development frame for implementation of EAF energy recovery and utilization strategies*



Research line	Initial TRL	KPI and Target for 2030	2020					2025					2030
Off-gas heat recovery	6-8	- Recovery of EAF input energy from off-gas of 30-35%											
Slag solidification waste heat recovery	6												
Low temperature cooling water heat recovery	6	- Recovery of EAF input energy from each of the other media of 8-10%											
Energy recovery from product and process	6												

3.2.6. Plans Risks and Robustness

Table 10 mentions main technical and economic risks related to the implementation of EAF energy recovery and utilization strategies. Probability of occurrence and impact quantification of the identified risks are estimated by considering a three-level scale (L for low, M for medium, H for High). While risk level is quantified through a five-level scale (1 very low risk level and 5 for very high risk level) in order to allow a more significant and easier comparison of the different risks providing them a “priority”. Countermeasures are also provided to counteract to the identified risks.

Table 10. *Risks and countermeasures for implementation of EAF energy recovery and utilization strategies*

Risk	Probability of occurrence	Impact quantification	Risk Level	Countermeasure
Technology tested during the project have a too short lifetime in the industrial environment	M	H	5	Variation on the materials and addition of protection
Technology tested during a project does not prove to be effective	M	H	5	Variation of tested process parameters and, if necessary, the process design
Lack of financial resources	M	H	5	Possible increased private funding in case public funding is too low
Low degree of pan-European cooperation between	L	M	2	Funding calls need to be tailor-made to force multi-player project consortia

companies (many single-firm projects)				between industry and science
Different legislation on electrical energy market across the EU	M	M	4	Unification of the grant system

To force the pan-European cooperation in R&D&I activities represents a robust strategy to face risks and barriers. By combining excellent expertise in the fields of basic and applied metallurgical research, process technology, and plant engineering, the possibility of risk occurrence can be minimized.

3.2.7. Preliminary Budget Analysis

Considering the scrap-EAF route, following budgets might be necessary to be in-line with the climate goal time horizon for developing projects related to EAF energy recovery and utilization solutions:

- 16 M€ for the period 2021-2023
- 21 M€ for the period 2024-2025
- 38 M€ for the period 2026-2030

This would give a total budget of 75 M€ for the period 2021-2030.

3.3. Use of renewable energy sources and alternative non-fossil fuels: renewable electricity and direct use of renewable or green H_2

3.3.1. Specific EAF chain target

CDA is one of the two main pathways for CO_2 mitigation in the steel industry (see **Figure 12** in Section 2.3); it covers the development of new processes to produce steel using renewable electricity and/or hydrogen from renewable energy (green hydrogen) to massively replace the current fossil feedstock (coal and/or natural gas).

Considering the CSP roadmap, it defines the specific objective, entitled "*Enabling steel production through carbon direct avoidance (CDA) technologies*". Two operational objectives are considered part of the specific objective; KPIs are included and some target values are defined, as reported in **Table 11**.

Table 11. *Operational objectives, KPIs and related targets for the CSP objective "Enabling steel production through CDA technologies" [18]*

Operational objective	KPI	Target Value
Replacing carbon by renewable energy	Decrease CO_2 emissions proven at a demonstration scale	TRL6: >35% CO_2 reduction compared with reference operation by 2024
		TRL8: >40% CO_2 reduction compared with reference operation at TRL6 by 2030
Development of H_2-based reduction and/or melting processes	Replacement rate of natural gas by H_2	TRL 6: > 70 volume-% by 2024
		TRL8: > 50 volume-% by 2030

Steel production via the EAF route uses large amount of chemical energy for the following process steps:

- melting phase where chemical energy is provided by natural gas (NG) burning and coal oxidation (the amount of chemical energy derived by metals oxidation will not be accounted in this evaluation);
- ladle and tundish pre-heating.

The progressive energy transition to reach the CO_2 reduction requires increased utilization of renewable electricity and substitution of NG by green H_2 for the EAF melting step. On the other hand, for ladle and tundish pre-heating, the use of H_2 in the burners or electrical heating solutions are required together with plant management optimization to avoid energy loss due to long ladle/tundish keeping in the pre-heating stage.

Table 12 reports the order of magnitude of NG utilization and an estimation of required hydrogen in case of NG substitution by the application of CDA technologies. The values derive from field experience and are compared with environmental declarations published by EU Steel Companies. An average EAF size of 1Mt of steel production per year was considered both for scrap bucket process and continuous one.

Table 12. *Natural gas utilization and estimated use of hydrogen*

	Continuous Charge		**Bucket Charge**		**Continuous Charge**		**Bucket Charge**	
	CH_4 Nm^3/tCS		CH_4 Nm^3/tCS		H_2 Nm^3/tCS		H_2 Nm^3/tCS	
	min	max	min	max	min	max	min	max
Liquid Steel (EAF)	**5**	**6.5**	**11**	**15**	**15**	**19.5**	**33**	**45**
EAF	1	1.5	7	10	3	4.5	21	30
Refractory heating	4	5	4	5	12	15	12	15

3.3.2. Key Aspects and Scope Description

Issues exists that need to be addressed for the acceleration of Hydrogen application as fuel in the steel sector as well as for the massive use of renewable electricity. Therefore, the elimination of fossil combustible requires a series of key aspects to be considered in order to obtain the essential techno-economic improvements.

Low carbon hydrogen and renewable energy production and supply

Large, continuous and reliable supply of low-carbon hydrogen with improvements of existing production technologies or developing of new ones is required. Production of hydrogen by water electrolysis with the exploitation of renewable energy is one of main possibilities, but the electrolysers' size shall be adapted to the double-digit MW range. Further possibilities should be the obtainment of hydrogen with partial oxidation and steam methane reforming with Carbon Capture and Storage (CCS) technologies and/or biomass or furtherly by extraction from off-gases. In addition, the H_2 storage and/or transportation should be addressed. Furtherly, availability of sufficient amounts of renewable energy, including infrastructure, are fundamental both for direct use or to be exploited in the production of hydrogen.

Adaptation of burners

Existing combustion systems and/or burners shall be adapted or ad-hoc developed, as well as related gas piping.

The NG in EAF provides further energy supply during scrap melting, to increase furnace productivity. The same injection system is then used to inject oxygen during refining stage in EAF. This aspect must be taken into account in burners adaptation activity.

NG is also largely used for refractory pre-heating (ladles and tundish) and oxy-cut. The order of magnitude of gas consumption is reported in **Table 12**.

The lower heating value of hydrogen and the subsequent need to use an amount of gas three times larger, may be partially compensated with optimized production process management, thanks to digitalization technologies.

Process changes evaluation

The introduction of hydrogen exploitation as fuel in the EAF steelmaking chain will lead to different changes that need to be investigated. Evaluation of the effects of the new combustion atmosphere with reduced (or eliminated) amount of CO_2 and increased amount of H_2O on the process is fundamental. Beside this, the impact on refractory material lifetime (reactions with H_2 and H_2O, possible corrosion mechanisms, locally higher radiative heat transfer peaks) also need to be investigated in detail. In addition, the effect of hydrogen use on the overall energy consumption of the electric arc furnace should be considered, as well as the analysis of safety and social impacts.

3.3.3. Expected Impacts

Expected impacts of use of renewable energy sources and green H_2 are the following:

- CO_2 reduction based on the consumption data given in **Table 12** is reported in **Table 13**.

Table 13. *Potential reduction of CO_2 by using renewable energy sources and green hydrogen*

	Continuous Charge		**Bucket Charge**	
	CO_2 kg/tCS		CO_2 kg/tCS	
	min	max	min	max
Liquid Steel (EAF)	**10**	**13**	**22**	**30**
EAF	2	3	14	20
Refractory heating	8	10	8	10

- Reduction of dependencies on import of fossil materials and subsequent price oscillations.
- Impacts on EU competitiveness - enhanced decarbonization of the EAF operation using H_2 or enhancing the use of green electricity will strengthen the leadership of the EU in sustainable steel production and will enhance its knowledge-based competitive advantage.

3.3.4. Technical Actions

Substitution of natural gas with hydrogen in the two cases mentioned in Section 3.3.1 and the enhancement of use of renewable energy sources requires a series of technical actions in short, medium and long period, as reported in **Table 14** considering each key aspect considered in Section 3.3.2.

Table 14. Overview of proposed technical actions for the use of renewable sources and alternative non-fossil fuels in EAF steelmaking chain

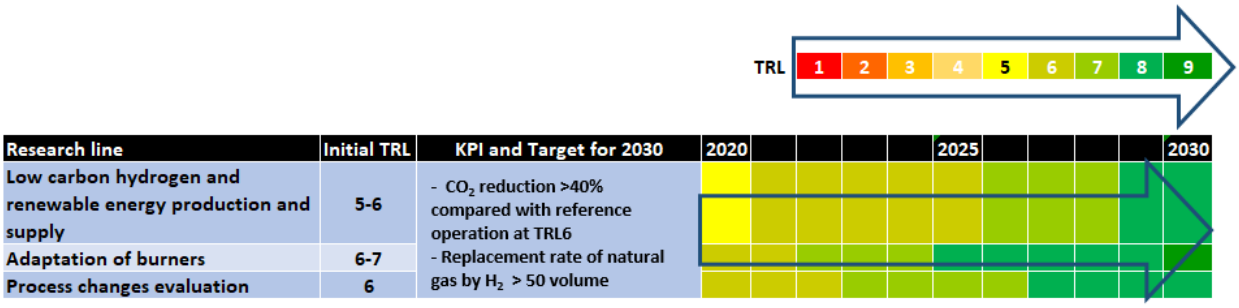
Research line	Short	Medium	Long
Low carbon hydrogen and renewable energy production and supply	Investigation of the best hydrogen production routes for the hydrogen use in EAF steelmaking heat purposes Analysis of renewable energy market Analysis of explosive properties of H_2 and development of safety concepts Flexible integration of use of renewable energy depending on its availability	Flexible integration of H_2 depending on the availability of renewable energy Extraction of hydrogen from off-gases	Implementation of internal hydrogen and renewable energy production
Adaptation of burners	Development of burners suitable for H_2	Flexible fuel handling through low emission multi-fuel burners technology coupled with ad-hoc control tools	
Process changes evaluation	Evaluation of refractory material lifetime in the new conditions Development of suitable hydrogen handling and storage procedures and solutions	Evaluation of the impact of feeding H_2 on the operational behavior and on productivity of the EAF	Adaptation of plant components Deployment of hydrogen use and management inside the plant (e.g. piping, storage, adapted components)

In order to implement the above scientific actions, support of legal and regulatory aspects are also required.

3.3.5. Time Horizons Plans and Milestones

Table 15 provides an overview of the time horizon and of evolution of the TRL with regard to the different research lines related to the use of renewable energy sources and green fuels.

Table 15. Temporal development frame with estimated progress of the TRL for the actions related to the use of renewable sources and alternative non-fossil fuels in EAF steelmaking chain



Research line	Initial TRL	KPI and Target for 2030	2020					2025					2030
Low carbon hydrogen and renewable energy production and supply	5-6	- CO_2 reduction >40% compared with reference operation at TRL6 - Replacement rate of natural gas by H_2 > 50 volume											
Adaptation of burners	6-7												
Process changes evaluation	6												

3.3.6. Plans Risks and Robustness

Table 16 mentions main technical and economic risks related to the use of renewable sources and non-fossil feedstock in EAF steelmaking chain. Probability of occurrence and impact quantification of the identified risks are estimated by considering a three-level scale (L for low, M for medium, H for High). While risk level is quantified through a five-level scale (1 very low risk level and 5 for very high risk level) in order to allow a more significant and easier comparison of the different risks providing them a "priority". Countermeasures are also provided to counteract to the identified risks.

***Table 16.** Risks and countermeasures related to the use of renewable sources and non-fossil fuels in EAF steelmaking chain*

Risk	Probability of occurrence	Impact quantification	Risk Level	Countermeasure
Long time (>2030) for effective transition to renewable energy at competitive price	M	H	5	Public investments Fiscal advantages
Slow adaptation of distribution network to new requirements of H_2 handling	M	M	4	Cooperation with gas companies and public institutions
Unavailability of GW size H_2 electrolyser installation for H_2 green production	H	M	4	On site dedicated production of H_2 based on modular electrolysers
Price increase in a short-term scenario and market competition	M	H	5	Fiscal advantages
Skill upgrade of technicians involved in production (used to work with fossil materials and consolidated technology)	M	H	5	Ongoing H2020 projects Involvement of Universities and research centers

3.3.7. Preliminary Budget Analysis

The decarbonization of the steel sectors requires the utilization of Hydrogen and large availability renewable energy. Projects dedicated to these issues requires to take into account different process and technologies and infrastructure for H_2 storage and transportation.

Considering the mean value of budget of the performed and proposed projects on this subject, a rough estimation of the efforts needed for achieving TRL8 by covering all the related projects is in the order of 120 M€ in ten years.

Technologies for H_2 fed burners are already mature, but the utilization in the steel production is not yet tested with relevant industrial trials. Moreover, the H_2 infrastructure is not yet available for steel sector.

This amount, can be split as follows in the considered time horizon:

- 20 M€ for the period 2021-2023
- 50 M€ for the period 2024-2025
- 50 M€ for the period 2026-2030

3.4. Replacement of lump and pulverized coals as reducing or foaming agent with alternative C-bearing materials and reduced consumption of graphite electrodes

3.4.1. Specific EAF chain target

The replacement of fossil coal as reducing or foaming agent is included in the technological pathway named SCU of CSP Roadmap (see **Figure 12** in Section 2.3). In particular, it is considered in the specific objective 2, **"***Fostering smart carbon usage (SCU – Carbon capture) technologies in steelmaking routes at a demonstration scale, thus cutting CO_2 emissions from burning fossil fuels (e.g. coal) in the existing steel production routes*" with the operational objective and KPI that are reported in **Table 17**. In addition, CSP specifies that also CEP supports the substitution of fossil carbon with alternative carbon-bearing materials and reductants.

Table 17. *Operational objective and KPI and related targets for the CSP objective "*Fostering smart carbon usage (SCU – Carbon capture) technologies in steelmaking routes at a demonstration scale, thus cutting CO_2 emissions from burning fossil fuels (e.g. coal) in the existing steel production routes*" with focus on replacement of coal as reducing agent [18]*

Operational objective	KPI	Target Value
Increasing the use of non-fossil carbon	Share of non-fossil carbon proven in reducing and/or melting process	TRL6: > 15% of non-fossil fuels/ reducing agent by 2024
		TRL8: > 20% of non-fossil fuels/ reducing agent by 2030

Excluding their use as energy sources, the carbon materials in EAF has indeed the following further main purposes:

- as slag foaming agent to maximize the electrical energy input efficiency;
- as reducing agent.

The utilization of coal is in the order of magnitude of 10 kg/t of produced steel. Coal can be charged as lump or pulverized and contribute at about 10% of total CO_2 emission and 30% of direct ones.

Fossil coal replacement in EAF route can be carried out using alternative carbon-bearing materials. Among them, the residues obtained from thermal treatment of biomass or also polymers, tyres, etc. can be mentioned. However, to obtain products with prices comparable with anthracite (order of magnitude of 150 €/t) and avoid the competition with food, it is necessary to use low grade biomass that currently in some countries is landfilled with a cost of about 300 €/t[6]. In addition, residues can be also obtained as by-products from gasification and power plant fed by biomass. In this case the problems to be solved are related to the available quantities and collection of material, pretreatment (generally, it is in the form of fine powder) and risk related to ignition and explosion during the transportation and handling.

On the other hand, graphite electrodes account for a significant portion of the cost of EAF steelmaking process and contributes to CO_2 emission. Electrode consumption can be divided into two types:

- side loss caused by oxidation with air and water vapour;
- tip loss caused by breakage, spalling, erosion in metal and slag, and sublimation caused by the high temperature of arc.

Reduced consumption of graphite electrodes can lead to different benefits. However, no specific operational objective and KPIs are included in CSP for this topic.

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[6] Average value in Italy.

3.4.2. Key Aspects and Scope Description

The utilization of alternative carbon-bearing materials has some technological and non-technological aspects to be considered. These aspects are related to:

- different characteristics of the alternative carbon-bearing materials, which requires adaptation of operating practices and injection systems;
- the values chain, which is not yet established for these materials for steel production and thus affects the current price and availability.

Regarding the reduction of electrodes consumption, a further effort in improvement of manufacturing process and understanding of erosion mechanism is necessary.

More details of above indicated issues are reported below.

Adaptation of the operating practice and injection systems

Char from biomass and in general alternative carbon-bearing materials (e.g. virgin biomass, polymers, wastes from other production cycles) has some differences in comparison to fossil carbon sources such as higher content of volatile matter, lower density and different chemical interaction with iron oxide rich slag. In addition, they may require pretreatment for agglomeration and densification into briquettes, if the scope is to charge them into basket with the scrap, or must be available in form of grains of suitable size (in the order of magnitude of 2-5 mm) for injection.

These aspects have been already investigated in previous RFCS projects (e.g. GREENEAF [53] and GREENEAF2 [54], RIMFOAM [37]). A significant experience has been gained but further improvements and adaptations are required. In addition, the injector for these specific materials, especially in case of their use as foaming agents, must be optimized yet. Some papers are available in literature [55, 56, 57, 58] and there are already running some EU funded: Onlyplastic [59] and POLYNSPIRE [60].

Material availability and cost

Among the non-technical aspects, char and alternative carbon-bearing materials availability and cost represent two main issues which can limit the utilization in the steel production and for this reason they constitute a key aspect to be addressed.

Considering the biochar, it is a char obtained from pyrolysis of biomass that is currently produced for specific sectors: agriculture, cosmetics, food, animal feed, small scale energy production. For this reason, the produced quantities are in general low (if compared with the need of EAF steel production) and with relatively high price. From updated market survey carried out by CSM, the costs reported in **Table 18** were collected for different biochar. Cost savings can be obtained from utilization of low-grade biomass and with tailored production on low grade biomass costs, costs are comparable to anthracite values [44].

Table 18. *Costs of different biochar*

Material	**Cost**
	€/t
Torrefied biomass (produced as pellets for home firing)	250-300
Pyrolyzed biochar (for home firing)	300-400

Biochar (for other applications)	Up to 1000

Figure 23 shows the simulation of the biochar price assuming the onsite production of char and three different prices of biomass.

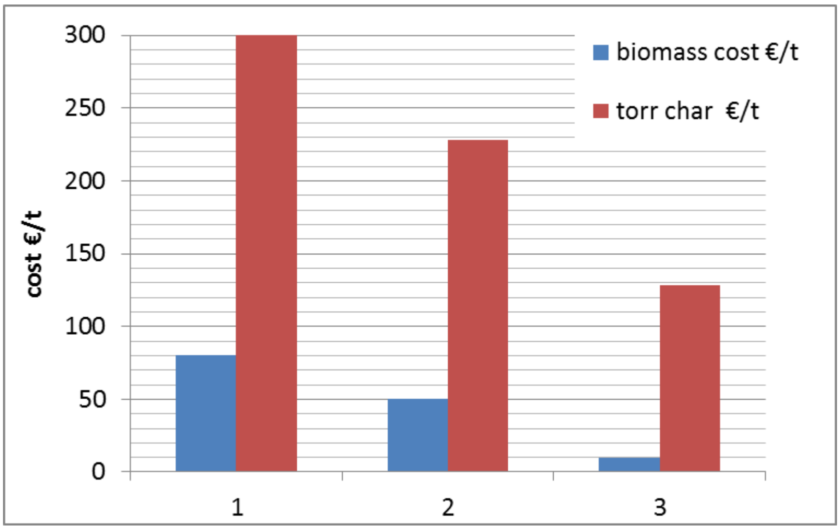

Figure 23. *Simulation of the biochar price considering three different biomass costs*

The value chain definition of the new alternative materials is required. Plastic grains are already available (for instance, in Italy grains are manufactured according to a technical regulation, UNI 10667-17 [61]) and it is reasonable to foresee few years for market stabilization. In case of biomass market and biochar for steel purposes, currently there is not a reference market although, as above mentioned, these products are already manufactured for different purposes, with higher costs.

<u>Reduced consumption of electrodes</u>

Electrodes consumption contributes to cost of steel production and also on CO_2 emission. Moreover, it must be taken into account that electrode preparation process is an energy intensive process.

Benefits can be obtained by starting from a deeper knowledge of electrodes wear process and continuing with EAF voltage tap profile modifications; however also the improvement of manufacturing electrodes process can lead advantages. Available literature shows for example that reduction consumption in the range of 20-40% are ambitious but achievable [62].

3.4.3. Expected Impacts

Table 19 reports the different contributions of CO_2 emissions in the EAF steel melting and the corresponding order of magnitude and percentage.

Table 19. *CO_2 emission sources in EAF steel melting*

Carbon source	Amount/t of steel	kg CO_2/t	%	Reference
Coal	10 kg/t	33	9	average value from field experience
NG	8.5 Nm^3/t	17	4	average value from **Table 12** (Bucket Charge)

C (charge material)	8 kg/t	29	8	average value from field experience
Electricity	450 kWh/t	293	76	[63]
Electrode	4 kg/t	15	4	average value from [63]
Total emitted CO_2		**387**	**kg CO_2/t of steel**	

Considering the CO_2 mitigation, the utilization of alternative carbon-bearing materials can avoid the emission of about 30-35 kg CO_2/t of liquid steel produced[7], depending of anthracite carbon content. Therefore, the utilization of alternative carbon-bearing material can allow a saving of about 10% of total CO_2 emissions.

The amount of saved CO_2 can be increased with reduction of electrode consumption as well as with larger utilization of renewable carbon into EAF cycle as energy provider, replacing (partially or in principle totally) of the NG burning. This last option requires availability of renewable carbon sources at competitive price and relevant amount.

In addition, the utilization of alternative carbon-bearing materials in EAF steel production will contribute to create new local economies and will reduce the impact of transportation of goods, specially from extra UE countries.

3.4.4. Technical Actions

The utilization of alternative carbon-bearing materials as reducing or foaming agent in replacement of fossil coal as well as the optimized consumption of electrodes are technically feasible, but some aspects need to be more studied as reported in **Table 8**.

Table 20. *Overview of proposed technical actions about the replacement of lump and pulverized coals as reducing or foaming agent with alternative C-bearing materials and reduced consumption of graphite electrodes*

Research line	**Short**	**Medium**	**Long**
Adaptation of the operating practice and injection systems	Analyses of effects of the use of alternative carbon-bearing materials having different features with respect to fossil carbon sources as charge materials (e.g. as reducing agent).	Adaptation of the operating practice in case of char charge in the scrap basket Definition of ad-hoc preparation procedures and pretreatments	Blending/agglomeration of C based material and Fe Oxide reach materials to direct charging/injection in EAF

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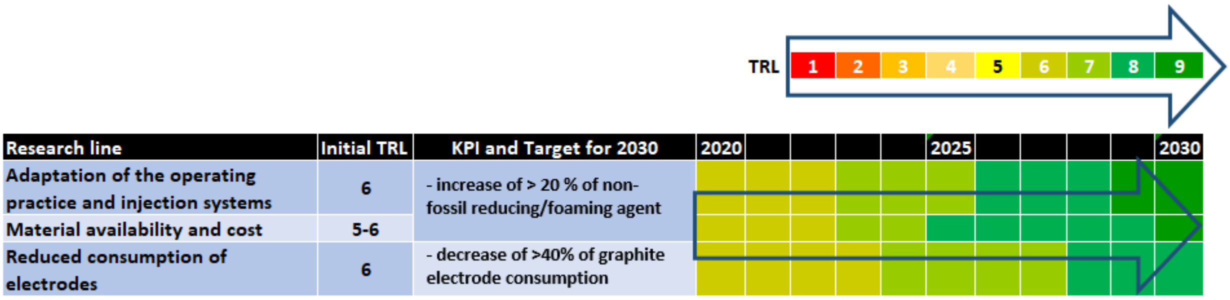
[7] Assuming an order of magnitude of 10 kg of anthracite per tonne of steel

	Investigation on mechanisms of slag foaming with alternative materials and with material mix	Design of tailored injection system	
Material availability and cost	Comparative assessment of the vast field of suitable alternative carbon-bearing materials (economy and LCA)	Pilot/demonstration of plant integrated upgrading technologies (e.g. drying, torrefaction, pyrolysis, hydrothermal carbonization) with utilization of waste heat (e.g. steam). Value chain definition of the new alternative materials	Industrialization of biochar onsite production by feeding the pyrolysis process with waste heat from the steel production
Reduced consumption of electrodes	Improvement of knowledge of electrodes wear process	Optimization of operating conditions and operating practices for reducing electrodes consumption	

3.4.5. Time Horizons Plans and Milestones

An overview of the time horizon of evolution of the TRL regarding the different research lines related to the replacement of fossil coal as reducing or foaming agent with alternative carbon-bearing materials and to the optimization of electrodes use is provided in **Table 21**. The table reports also a selection of KPIs to measure the achievement of interim milestones.

Table 21. *Temporal development frame for the replacement of lump and pulverized coals as reducing or foaming agent with alternative C-bearing materials and reduced consumption of graphite electrodes*



Research line	Initial TRL	KPI and Target for 2030
Adaptation of the operating practice and injection systems	6	- increase of > 20 % of non-fossil reducing/foaming agent
Material availability and cost	5-6	
Reduced consumption of electrodes	6	- decrease of >40% of graphite electrode consumption

3.4.6. Plans Risks and Robustness

Table 22 mentions main technical and economic risks about the replacement of fossil coal as reducing or foaming agent with alternative carbon-bearing materials as well as related on the application of operating practices that can allow the reduction of electrodes consumption. Probability of occurrence and impact quantification of the identified risks are estimated by considering a three-level scale (L for low, M for medium, H for High). While risk level is quantified through a five-level scale (1 very low risk level and 5 for very high risk level) in order to allow a more significant and easier comparison of the different risks providing them a “priority”. Countermeasures are also provided to counteract to the identified risks.

Table 22. *Risks and countermeasures about the replacement of lump and pulverized coals as reducing or foaming agent with alternative C-bearing materials and reduced consumption of graphite electrodes*

Risk	Probability of occurrence	Impact quantification	Risk Level	Countermeasure

Alternative carbon-bearing availability and organization of collection chain	M	H	5	Available studies report that waste biomass is potentially available for EAF steel production in Europe. The transition to utilization of alternative carbon-bearing materials needs to be pushed by CO_2 cost (trend is estimated to increases). Creation of interaction with different productive sector (projects, congress, associations..) could stimulate the organization of a collection chain.
Alternative carbon-bearing cost	M	M	4	Cost needs a scale factor to decrease at price comparable (or lower) to anthracite. Demo cases (as in funded projects) will favour this transition.
Operating practices for reducing electrodes wear are not in line to reach desired productivity and process yield	H	M	3	Use of compromise operating conditions Development of tailored process models including electrical component

3.4.7. Preliminary Budget Analysis

The utilization of alternative carbon-bearing materials requires the adaptation of operating practices, tailoring of basket charge operations and re-design of injection systems.

The design and installation of a tailored injection system has a cost ranging from 1-2 M€ (order of magnitude taken from SPIRE projects). A higher cost of biochar and in general of alternative carbon-bearing materials respect fossil coal should be considered for the first applications.

Considering the mean value of budget of the performed and proposed projects on this subject and on the investigation related on the reduction of graphite electrodes consumption, a rough estimation of the total efforts needed for achieving TRL8 is in the order of 20 M€ in ten years.

This amount, can be split as follows in the consider time horizon:

- 5 M€ for the period 2021-2023
- 6 M€ for the period 2024-2025
- 9 M€ for the period 2026-2030

3.5. Valorisation of wastes, residues and by-products for internal and external use

3.5.1. Specific EAF chain target

In the specific objective 4 of the CSP Roadmap, entitled "*Increasing the recycling of steel scrap and* residues to increase smart resources usage and further support a circular economy model in the EU" one of the operational objectives is related to valorization of residues as shown in **Table 23** where related KPI and targets are listed.

Table 23. *Operational objectives, KPIs and related targets for the CSP objective "*Increasing the recycling of steel scrap and residues to increase smart resources usage and further support a circular economy model in the EU*" with focus on residues valorization [18]*

Operational objective	**KPI**	**Target Value**
Enhancing the recycling and re-use of industrial residues of the steel production process	Re-use and recycling of solid residues co-generated during the steel production process and reduction of their landfilling rate	TRL6: internal and external recycling and re-use rate > 85% *(in total)* by 2024
		TRL8: internal and external recycling and re-use rate > 85% *(in total)* by 2030

According to the BAT document for Iron and steel production [64], 60-270 kg of slag and 10-30 kg of dust both per ton of crude steel are generated as main solid EAF residues. Considering the EU steel production via the EAF route, which was about 65 Mt in 2019 [3], 3.9-17.5 Mt EAF slag and 0.6-1.9 Mt EAF dust were generated being available as potential secondary resources, respectively.

Thus, accompanied with waste heat and energy recovery possibilities (see Section 3.2), two further main EAF output resources (i.e. dust and slag as visible in **Figure 24**) can be valorized for an internal and external use. To sum up, the specific EAF route R&D target can be defined to approach to a zero-waste steel production until 2030.

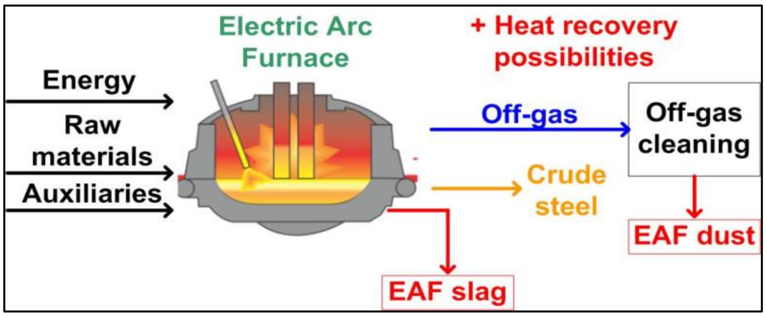


Figure 24. *Representation of main EAF inlet and outlet stream*

3.5.2. Key Aspects and Scope Description

The significant amount of wastes, residues and by-products generated in the EAF steel production route can be valorized both internally or externally to the steelmaking process by exploiting different approaches. However, several key aspects both technical and legislative need to be considered and different research lines can be so defined to boost these valorizations.

<u>Residues processing for material recovery and to make them useable in other resource-saving applications</u>

Most of the produced residues in EAF steelmaking have significant amount of valuable metal and mineral material fractions but ad-hoc processing is often required to recover these materials or to make them suitable to be used in other resource-saving applications. For instance, the combination of existing treatment processes (e.g. separation processes) or conditioning steps (e.g. fast dry cooling) shall be considered respectively for the maximization of the recovery of metal and mineral phases from liquid and solidified slags and/or for improving their properties. Besides existing treatments, new processes should be also developed to enhance the recovery of metals and oxides and consequently to lower the demand for primary resources directly in the melting process (e.g. solid or liquid iron) or in the value chain. For instance, Zn and Zinc oxide can be recovered from EAF filter dust, and new processes should be developed by starting from some technical examples in [65, 66]. Ferrous and non-ferrous materials (e.g. Zn) recovery from both dusts and slags can be enhanced through novel pyrometallurgical reducing processes; some starting examples can be found in literature for BOF slags and EAF residues [67, 68, 69, 70, 71]. Also process off-gas should be used to recover valuable substances, such as hydrogen to be internally reused (see Section 3.3).

Material recirculation and recycling

The direct reuse of steelmaking residues in existing EAF processes as secondary iron source is also a possibility by promoting and improving agglomeration and granulation [72] technologies or injection with suitable reductants. They can be also exploited as slag forming additive or foaming agent in the EAF to substitute primary slag foaming agents, such as coal (see Section 3.4). A further direct reuse should be also the exploitation of EAF off-gases as alternative energy source in EAF by their recirculation. However in this case it is needed the optimization of EAF internal atmosphere (e.g. by injection of oxygen or air) to obtain an enhancement of post combustion for further release of heat and consequent saving of electric energy (for energy recovery and utilization see also Section 3.2).

Carbonization of steel residues to sequester CO_2

Less explored but noteworthy, especially for future research, is the evaluation of carbonization of steel residues to sequester CO_2 with processes like steel slag-based carbon capture and storage (SS-CCS), explored for instance in [73].

Process adaptation and adjustment

The internal reuse of residues can be further improved by adaptation and adjustment of existing processes as well as of control and management procedures and tools. Processes should be tailored to accept a higher amount of recycled residues and to produce new secondary raw materials with features more suitable for the internal or external (e.g. in cement production) reuse. In addition, methods and tools shall be developed or improved (in case something is already applied) for dynamically optimizing the use of recovered materials, studying the behavior of existing process as well as for process control in new conditions and considering continuous analyses of the features of residues; a technical example can be found in [74].

This aspect is strictly linked with the macro-topic “New tools and sensors for process improvements”, which is described in Section 3.6.

Industrial symbiosis

Beside internal recycling, valorizing EAF residues (or recovered materials) externally within a cross-sectorial scenario shall be improved with related actions. Industrial symbiosis between ferrous and nonferrous industries for a use of valuable metal and mineral phases from EAF dusts and slags shall be improved (technical examples in [75] [76] [77]). Considering this aspect, legislation need to be upgraded as well as the development of secure web platforms is required to serve the marketplace of new secondary raw materials and valorized residues.

3.5.3. Expected Impacts

Competitiveness and resource efficiency of the steel industry are reached in case of recycling residues directly in the EAF, or via new valorization technologies for recovery of valuable fractions from EAF dust and slag. Cost-effective solutions for an increased by-product recycling rate will contribute to a lower demand on primary resources for steel production. Beside this, a market for secondary products derived from EAF residues targeting non-ferrous industries (industrial symbiosis / sector coupling with e.g. primary zinc production, construction and mineral industry) represents another possibility to increase the competitiveness of the steel sector. In addition to the solid and liquid residues, EAF off-gas can be used for a post-combustion process within the EAF to release heat and save electric energy or to recover valuable substances (e.g. H_2).

Some target values can be denoted under assumption of an annual EU steel production via the EAF-route of about 65 Mt [3]. For instance in **Table 24** are reported some figures; the last three rows are related to EAF dust as an exemplary EAF residue source [78].

Table 24. *Targeted impacts in case of improvement of residues valorization*

Material	**Recovered amount (RA) or Landfill Reduction (LR)**	**Note**
EAF Slag	RA: 99%	
Dust	LR: 3 times less	
Fe	300,000 t/a	
ZnO	270,000 t/a	12% of reduction of Zn imported to the EU

3.5.4. Technical Actions

Key breakthrough technologies for the scrap/DRI/HBI/hot metal EAF route regarding residue valorization mean solutions for a direct residue recycling in the EAF and recovery of energy (see Section 3.2) and valuable materials (metals and mineral fractions) from EAF residues. The technical actions, that are listed in **Table 25** in the three time frameworks, are necessary to reach the EAF chain targets (Section 3.5.1) and expected impacts (sub-section 3.5.3) by focusing on the key aspects and research lines defined in 3.5.2.

Table 25. *Overview of proposed technical actions for implementation of EAF residue strategies*

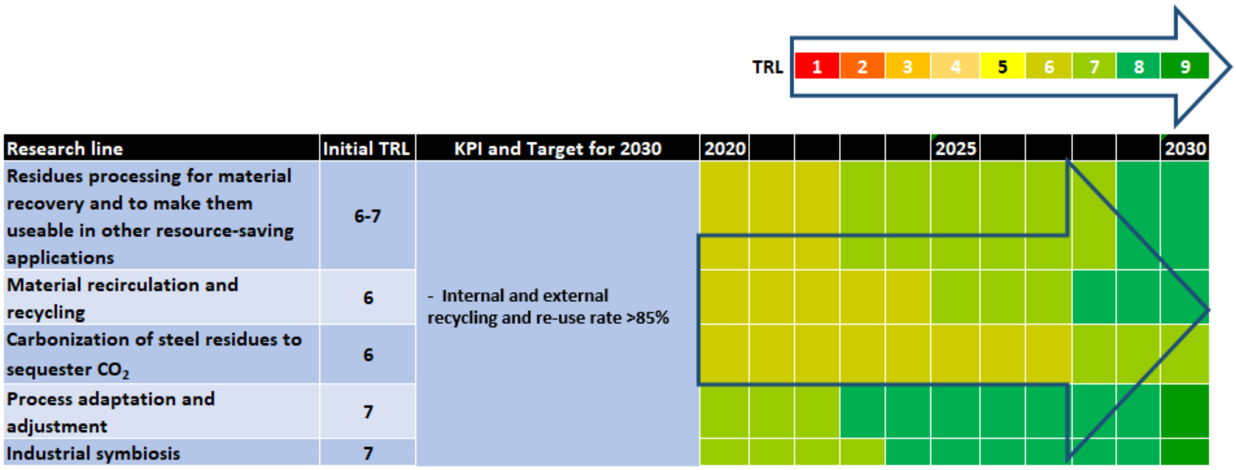
Research line	**Short**	**Medium**	**Long**
Residues processing for material recovery and to make them useable in other resource-saving applications	Evaluation of possible combination of existing treatment processes or conditioning steps	Development of new processes (e.g. pyrometallurgical) to enhance the recovery of ferrous and non-ferrous materials (e.g. Zn) Extraction of hydrogen from off-gases (see Section 3.3.5)	Industrialization of internal residues processing
Material recirculation and recycling	Investigation and optimization of requirements for off-gas post-combustion process within the EAF	Improvement of agglomeration, granulation and injection technologies to maximize materials recirculation Exploitation of off-gas post-combustion process within the EAF	

Carbonization of steel residues to sequester CO_2	Investigation of existing carbon capture technologies that can be suitable for the application with EAF steelmaking residues	Pilot/demo plant of carbon capture process with steel residues	Industrialization of carbon capture process with steel residues
Process adaptation and adjustment	Development or improvements of dynamic control and decision support tools for improving the recovery and valorization of residues (see Section 3.6)	Ad-hoc adaptation of process to accept high amount of recycled residues Adjustments of operating parameters to obtain residues more suitable for direct reuse (internally or externally)	
Industrial symbiosis	Upgrading of legislation for easier management and treatments of residues, waste and by-products and for better sharing of materials between different industries	Definition of self-ruled new secondary raw materials and valorized residues marketplace supported by secure web platform	

3.5.5. Time Horizons Plans and Milestones

Table 26 provides an overview of the time horizon and of evolution of the TRL with regard to the different research lines related to the valorization of residues for internal and external use.

Table 26. *Temporal development frame for implementation of EAF residue strategies*



TRL 1 2 3 4 5 6 7 8 9

Research line	Initial TRL	KPI and Target for 2030	2020					2025					2030
Residues processing for material recovery and to make them useable in other resource-saving applications	6-7	- Internal and external recycling and re-use rate >85%											
Material recirculation and recycling	6												
Carbonization of steel residues to sequester CO_2	6												
Process adaptation and adjustment	7												
Industrial symbiosis	7												

3.5.6. Plans Risks and Robustness

Table 27 mentions main technical and economic risks regarding the application of EAF residue strategies. the replacement of coal as reducing or foaming agent with residues or with carbon neutral materials. Probability of occurrence and impact quantification of the identified risks are estimated by considering a three-level scale (L for low, M for medium, H for High). While risk level is quantified through a five-level scale (1 very low risk level and 5 for very high risk level) in order to allow a more significant and easier comparison of the different risks providing them a “priority”. Countermeasures are also provided to counteract to the identified risks.

Table 27. *Risks and countermeasures for implementation of EAF residue strategies*

Risk	Probability of occurrence	Impact quantification	Risk Level	Countermeasure

Technology tested during a project does not prove to be effective	M	H	5	Variation of tested process parameters and, if necessary, the process design
Lack of financial resources	M	H	5	Possible increased private funding in case public funding is too low
Low degree of pan-European cooperation between companies (many single-firm projects)	L	M	2	Funding calls need to be tailor-made to force multi-player project consortia between industry and science
EU legislation hinders market uptake of secondary resources from EAF residues	M	M	4	Standardization measures need to be considered within R&D projects to gain product status for secondary resources

As already underlined in Section 3.2.6, also in this case the pan-European cooperation in R&D&I activities represents a robust strategy to combine expertise and to face and minimize risks and barriers. In particular, regarding the topic of residue valorization, sector coupling represented by the industrial symbiosis is an important pillar to approach a zero-waste concept in the steel industry.

3.5.7. Preliminary Budget Analysis

Considering the scrap-EAF route, following budgets might be necessary to be in-line with the climate goal time horizon for developing projects related to solutions for EAF residue valorization and utilization:

- 20 M€ for the period 2021-2023
- 25 M€ for the period 2024-2025
- 30 M€ for the period 2026-2030

This would give a total budget of 75 M€ for the period 2021-2030.

For the period 2021-2023, further improvements regarding residue processing for material recovery to make them useable are expected to reach a TRL7. Material recirculation and steel residue carbonization will be further optimized within TRL6. Process adaptation measures should reach TRL8 during that time. For the period 2024-2025, developments on material recirculation and recycling should be brought to TRL7. For the final period 2026-2030, all research lines mentioned in **Table 26** should be further developed reaching the next TRL. Some of them should be brought to TRL9, such as solutions and concepts dedicated to process adaptation and adjustment as well as to industrial symbiosis.

3.6. New tools and sensors for process improvements

3.6.1. Specific EAF chain target

The measures described in the previous sections must be accompanied and supported by the enhancement of management, monitoring and control of the EAF process. This can be addressed through the exploitation of novel tools and sensors which are also linked with concepts of digitalization included in the "*Industry 4.0*" definition.

The application of analytics and advanced statistical methods typical of big data analytics (although the involved data volumes not necessarily belong to the Big Data domain) are the way "*to extract value from data*" considering process, product and business data. Once they are transformed into "*good data*" obtained by plausibility check and synchronization processing, it is possible to use them for improving EAF process control and management. In this context, thanks to the availability of more and more powerful computing capacity both available on private and public clouds, it is possible to extend the plant *sensorization* through the development and implementation of new sensors to improve harvesting of useful data. As a premise, an important step is represented by the transition from the hierarchical ISA95-based pyramid of the IT landscape to flat, object-oriented paradigm typical of the Industry 4.0 paradigm. In this way, the collected data can be exploited through the most advanced modelling and simulation tools (analytical as well as based on machine learning and deep learning techniques) in order to develop soft sensors and to empower operators and decision makers.

Approaches such as Model Predictive Control (MPC) or Economic Model Predictive Control (EMPC) approaches or bio-inspired optimization methodologies can be exploited for control and optimization purposes devoted to the improvement of resource management (material and energy), and of the overall EAF metallurgical process performance and thus to the decrease of the environmental impact and the production costs.

The potential of the application of similar types of tools and sensors has already been proven in various RFCS projects and should be further developed and integrated in an overall concept for digitalization of the EAF process. The deployment of new tools and sensors integrated together can constitute cutting-edge decision support systems.

3.6.2. Key Aspects and Scope Description

The scope of the topic "*New tools and sensors for process improvements*" can be divided into five key aspects that are useful to identify what has already been done and the new research requirements.

Enhanced monitoring of the EAF process by data analytics as well as physical and soft sensors

Tools for big data analytics shall be applied to extract useful and usable information from EAF process data, which will increase the knowledge on the process behaviour and will allow to identify hidden correlations between process parameters. By this approach, measures could be identified, such as optimal patterns in electrical and chemical energy input to be applied for melt down of different charge mixes, or a typical evolution of energy losses via cooling water systems to determine the optimal charging time for the next scrap basket.

To further enhance the online monitoring of the EAF process, novel sensors shall be developed and applied to directly assess and acquire further information on the process behaviour. For instance, advanced and ad-hoc modified Laser-induced breakdown spectroscopy (LIBS) together with new camera systems can be used for inline characterisation of the charged scrap and the furnace slag as for example is under investigation in iSlag RFCS project [79]. In-line analysis systems based on immersed optical fiber-based or contactless systems like pyrometers and spectrometers should allow both measuring in real-time the melt level and temperature or even its composition and improving the capability of systems devoted to the real-time support of operators with simultaneous predictions and feedbacks. Novel optical sensors can be applied to monitor the fumes and off-gases regarding temperature, volume flow and composition to quantify the exploitable chemical energy and the losses during the process.

Further sensors shall be applied to support the predictive maintenance and safety issues of the furnace, e.g. camera systems to detect water leakages or scrap and slag skulls at the furnace walls or fibre optical systems to determine the wear status of the furnace hearth.

These physical sensors shall be complemented by soft sensors for the different process and plant parameters which are based either on analytical and / or data-based models derived by big data analysis or deep learning methods.

Application of advanced modelling and simulation tools for prediction of process behaviour

The process data and information collected by physical sensors shall be exploited through the most advanced modelling and simulation tools, to provide further information on the EAF process and plant status which cannot be directly assessed inline and in real time by sensors. This status information should cover (as long as not directly measurable):

- steel and slag temperature and composition;
- energetic status and efficiency of energy inputs;
- meltdown status of charged materials;
- performance of metallurgical reactions (e.g. decarburisation, dephosphorisation);
- status of foamy slag;
- status of the hot heel (i.e. weight/volume/depth);
- wear status of furnace hearth;
- condition monitoring of furnace equipment (e.g. burners, injectors, water-cooled panels)

Dynamic models (some already developed but still need improvement) allow monitoring status variables, by acting as soft sensors. On the other hand, they provide forecasting capabilities on process status and interactions among components and sub-processes. Therefore, models shall be more intensively used for optimal management of the whole production chain.

The modelling tools can be based either on analytical calculations, using energy and material balances and thermodynamic calculations, or on machine learning and deep learning techniques. In many cases hybrid solutions as a combination of both approaches may be the most suitable modelling approach.

Besides online monitoring and prediction, the modelling tools shall also be applicable for offline simulations, to perform investigations on different scenarios of EAF process control or for operator training. In this task, the models can also be combined with CFD and FEM simulations, to provide detailed information on fluid flow and wear conditions in the EAF.

Improved real-time control of the EAF process

The above described enhanced monitoring tools based on data analytics as well as physical and soft sensors, and the modelling and simulation tools shall be the basis for advanced real-time control of the EAF process, which shall be devoted to an optimised management of the resources (material and energy inputs) and of the overall EAF metallurgical process performance. This shall lead to a decrease of the environmental impact and the production costs as well as to an increase of productivity with reliable yield and quality of the produced crude steel. Some tools or sensors already exist but integrated, holistic and dynamic and real-time implementation of closed loop control solutions is often far to be achieved.

Real-time process control covers the continuous and / or event-triggered calculation of optimal set-points for material and energy inputs, as well as an end-point control of the EAF process, when the target values have been achieved. These set-point and end-point calculations shall be based on a dynamic prediction of the process behaviour by means of advanced models as described above, preferably embedded in Model Predictive Control tools.

Improved real-time process control of the EAF should provide enhanced solutions for the following functions:

- Management (control of amounts and timing) of materials charging, injection and addition with:
    - heat and steel grade individual scrap mix dynamic calculation, for loading the scrap baskets with the cost-optimal scrap mix in terms of purchase and meltdown energy costs for each scrap type;
    - determination of the optimal time of charging the next scrap basket;
    - addition of slag formers, e.g. for foamy slag creation or dephosphorisation;
    - addition and injection of carbonaceous materials (e.g. anthracite, biomass, recycling materials) for yield improvement and foamy slag creation;
    - addition of ferro-alloys;
    - addition and injection of recycling materials (e.g. dust, pellets, pressed or compound materials);
    - continuous charging of alternative iron sources (e.g. DRI, HBI).
- Management (control of amounts and timing) of energy inputs with:
    - electrical energy input with voltage steps, active power, total amount etc., not only according to predefined patterns, but dynamically depending on the actually charged scrap mix, with consideration of power demand control and intra-day electrical energy supply;
    - chemical energy input via oxyfuel burners with power and duration, not only according to predefined patterns, but dynamically depending on the actually charged scrap mix or sensor information (e.g. distance to scrap sensors or off-gas real-time analysis);
    - chemical energy input via oxygen lances, jets or tuyeres for scrap cutting, decarburisation, CO post-combustion and dephosphorisation, according to actual scrap charge, calculated carbon and phosphorus content resp. CO content of the off-gas.
- End-point control with simultaneous achievement of:
    - target tapping temperature (electrical and chemical energy input);
    - target carbon and oxygen content (oxygen input);
    - target phosphorus content (oxygen input, slag former additions);
    - target nitrogen and hydrogen content (Ar stirring, enhanced CO formation).

Enhanced management and optimisation with respect to resources, environmental impact, quality and productivity

To decrease the environmental impact as well as the production costs while improving the quality of liquid steel to be produced via the electric steelmaking route, appropriate multi-criterial optimisation strategies must be applied. Standard mathematical approaches but also bio-inspired optimization methodologies should be used. The optimization criteria must be well defined and should cover:

- minimising resource inputs (energy and raw materials);
- reducing emissions (e.g. off-gas, water) and produced residues (e.g. slag, dust);
- increasing the reuse of residues;
- reduce production time with less maintenance effort;
- improve liquid steel quality with extension to steel grades which were so far produced only via the integrated steelmaking route.

Weighting factors must be applied to balance the different optimisation criteria according to the situation at the individual plants.

For this optimisation task, not only the EAF but the complete EAF process route with secondary metallurgy and casting processes and also upstream processes (e.g. CO_2 emissions from raw materials preparation vs. residue recycling) have to be taken into consideration.

Enhanced monitoring and automation of the EAF operations to improve operators' safety

To optimise operational routines by automation of movements as well as minimising the exposition of personnel to risks of steelmaking operation by applying the "*no man on the floor*" philosophy, the real time awareness of the process and equipment status through the continuous monitoring of the EAF shop floor is necessary. In this context, sensoring should cover the different EAF phases:

- basket charging - automatic basket recognition, cranes movements automation, obstacles detection, dynamic trajectories of crane calculation and optimisation;
- refining - application of robots for sampling and temperature extraction, automatic slag door, cleaning, automatic deslagging;
- tapping operation - tilting control, dynamic volumetric control of ladle filling;
- turn around operation - automatic cleaning of Eccentric Bottom Tapping (EBT) and sand filling systems.

Starting from these key aspects, the first step is to assess the current situation in terms of research activities regarding EAF process monitoring and control tools as well as regarding sensors already developed and applied at the EAF. A very good overview on European research projects performed in the past years on EAF technology provides the dissemination project VALEAF [80], which was performed in 2015 in the frame of the RFCS research program. Within this project a roadmap for future developments of EAF technology was set up where especially the importance of in-line sensors and online process control tools was emphasized [81].

Some examples of recently finished or currently running European projects dealing with data analytics and sensors for monitoring of the EAF process as well as process modelling, control and optimization tools are EIRES [82], AdaptEAF [29], OptiScrapManage [31], SimulEAF [83], OSCANEAF [84] and OxyMon [85]. Their results are valuable starting points for further research activities finalized on the maximization of the impacts related to the digitalization (see next Section).

3.6.3. Expected Impacts

The expected impact of the application of the five above described key aspects cannot be assessed independently, as they, at least partly, rely on each other. In this sense, the 4th key aspect - *Enhanced management and optimisation of the EAF process* – can be regarded as a kind of overarching objective which covers the other key aspects dealing with sensors, models, and process control tools. Thus, quantifying the impacts is strongly depending on the available sensors and tools which are integrated and implemented.

The maximum impact can be obtained through an implementation of sensors and tools acting on all the main process steps to allow a holistic improvement of the EAF process management. Such target impact can be quantified according to the selection of sensors and tools to be implemented and will be validated during the execution of the project itself.

In general, the expected impact of an enhanced EAF process management will comprise the following general categories:

- Improvement of process performance, efficiency, and flexibility
    - Improved crude steel quality with reliable achievement of target steel analysis and temperature
    - Extension of steel grade portfolio to high quality grades
- Decrease of raw material consumption and related increase of resource efficiency
    - Increased use of low-quality scrap types
    - Improved metallic yield by reduced iron oxidation
- Decrease of energy consumption and related increase of energy efficiency
    - Increased efficiency of chemical and electrical energy inputs
    - Reduced energy losses via water cooling and off-gas
- Increased flexibility in the energy use for an optimal use of green or less expensive internal available energy (e.g. chemical energy by off gas)
- Reduction of the emissions (especially CO_2) and residues to dispose
- Increase of economic revenues
- Improved workers' health and safety as a consequence of better and leaner process management, monitoring and automation of EAF operations and maintenance.

3.6.4. Technical Actions

Considering the identified key aspects and the previous and ongoing research projects for sensoring, monitoring and model-based real-time control and optimization of the EAF process, the technical actions under the scope of these topics can be divided into short-, medium- and long-term research and development as well as pilot and industrial demonstration projects according to **Table 28**.

Table 28. *Overview of proposed technical actions in the field of sensoring and control of the EAF process*

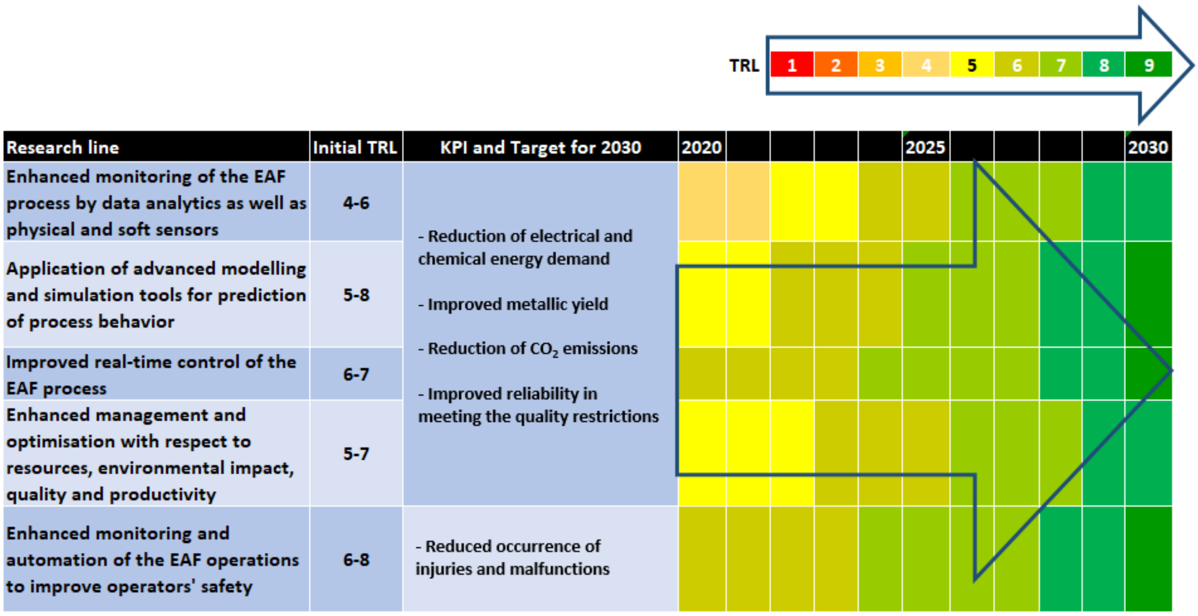
Research line	Short	Medium	Long
Enhanced monitoring of the EAF process by data analytics as well as physical and soft sensors	Further development and pilot application of novel soft and physical sensors for enhanced monitoring the EAF process behavior: - Development of novel sensor technologies for inline analysis of steel and slag composition and amount, off-gas composition and flow rate, etc. - Application of innovative methods of data analytics, e.g. machine learning and deep learning methods, for development of soft sensors to complement the physical sensors	Comprehensive digitalization of the EAF process by physical and soft sensors, to provide the basis for complete online monitoring and control of the EAF process. Exemplary application of a complete set of sensors at one industrial EAF to demonstrate the comprehensive monitoring of the EAF process behavior.	Industrial application of the sensor-based monitoring system at several EAFs for production of various steel grade groups, to demonstrate the applicability under different process conditions.
Application of advanced modelling and simulation tools for prediction of process behavior	Further development of analytical and data-based models for real-time application, to provide soft sensors for process parameters which cannot (yet) be assessed by physical sensors, and to allow an online prediction of the process behavior. Further extension of simulation models based on CFD, FEM, thermodynamics and reaction kinetics, to complete existing toolboxes for offline simulation of EAF process behavior.	Set-up of a digital twin for the EAF process, to support online monitoring and control and the performance of scenario calculations for process optimization.	Utilisation of the digital twin approach for online monitoring and control as well as for operator training and offline optimization purposes.
Improved real-time control of the EAF process	Further development and pilot application of real-time closed loop control tools for single EAF process parameters, as e.g. material additions, chemical energy input and comprehensive end-point control,	Set-up of a comprehensive real-time control concept for the EAF, to allow automatic closed loop control with minimization of operator interference.	Industrial application of the real-time closed loop control at several EAFs for production of various steel grade groups, to demonstrate the applicability

	based on novel sensors and predictive process models.	Exemplary application of the closed loop control concept at one industrial EAF to demonstrate its feasibility for real-time control of the EAF process behavior.	under different process conditions.
Enhanced management and optimisation with respect to resources, environmental impact, quality and productivity	Application of innovative multi-criterial optimisation tools for the different aspects of EAF steelmaking (e.g. environmental, productivity, costs, quality).	Combination of optimization tools with model-based real-time control, to allow an immediate reaction on changing process conditions.	Industrial application and demonstration of through-process real-time optimization for the complete route of electric steelmaking
Enhanced monitoring and automation of the EAF operations to improve operators' safety	Development and application of novel sensors and actuators, to monitor and automate single operations at the EAF from a remote position.	Set-up of a comprehensive condition monitoring and automation concept for remote control of all safety relevant operations at the EAF. Exemplary application and demonstration of the automation concept at one EAF plant.	Industrial application of the remote control and automation concept at several EAFs with various equipment.

3.6.5. Time Horizons Plans and Milestones

Table 29 provides an overview of the time horizon of evolution of the TRL with regard to the five different research lines, and a selection of KPIs to measure the achievement of interim milestones.

__Table 29.__ Temporal development frame with estimated progress of the TRL



Research line	Initial TRL	KPI and Target for 2030
Enhanced monitoring of the EAF process by data analytics as well as physical and soft sensors	4-6	- Reduction of electrical and chemical energy demand - Improved metallic yield - Reduction of CO_2 emissions - Improved reliability in meeting the quality restrictions
Application of advanced modelling and simulation tools for prediction of process behavior	5-8	
Improved real-time control of the EAF process	6-7	
Enhanced management and optimisation with respect to resources, environmental impact, quality and productivity	5-7	
Enhanced monitoring and automation of the EAF operations to improve operators' safety	6-8	- Reduced occurrence of injuries and malfunctions

3.6.6. Plans Risks and Robustness

Table 30 mentions main technical and economic risks regarding the implementation of new sensors and tools in the EAF steelmaking process. Probability of occurrence and impact quantification of the identified risks are estimated by considering a three-level scale (L for low, M for medium, H for High). While risk level is quantified through a five-level scale (1 very low risk level and 5 for very high risk level) in order to allow a more significant and easier comparison of the different risks providing them a "priority". Countermeasures are also provided to counteract to the identified risks.

Table 30. *Risks and countermeasures about for implementation new sensors and tools in the EAF steelmaking process*

Risk	Probability of occurrence	Impact quantification	Risk Level	Countermeasure
Reluctance of new sensor and control technology integration due to risks of productivity losses	M	H	5	Include in the conceptualization phase an exhaustive analysis of trial campaigns with application of the new technologies in industrial pilot scale
Lack of financial resources	L	M	2	Possible increased private funding in case public funding is too low
Lack of qualified staff with engineering and IT background	L	H	3	Find synergies among engineers, universities, R&D and industrial communities
Uncertainties on European steel market evolution in the coming years	M	B	2	Transparency of cooperation among companies and public institutions

3.6.7. Preliminary Budget Analysis

Although there is great expectation and hope for new technologies for online monitoring and closed loop control of the EAF process, and many promising results have already been achieved, up to now no comprehensive industrial applications are known. Especially for integrated and comprehensive solutions the current TRL ranges from 4 to 6.

Considering the typical budget of the performed and proposed projects on this subject a rough estimation of the investment needed for achieving at least TRL8 by 2030 is around 40 M€, allowing to finance 15-20 R&D and P&D projects within the next ten years.

This budget, can be split as follows in the considered time horizon:

- 5 M€ for the period 2021-2023
- 10 M€ for the period 2024-2025
- 25 M€ for the period 2026-2030

4. Conclusions

The path toward the electric steelworks of the future is challenging and can be successfully walked only through a unified effort of the whole European steelmaking sector. The EAF-based steelmaking route plays a fundamental role in reducing the emissions of the whole sector and achieving the ambitious targets stated by the EU for 2050. Therefore, research activities and related investments are required to pave the way to an evolution of this process route ensuring a sound socio-economic and environmental sustainability.

Figure 25 schematically represents the electric steelworks of the future, by summarizing its main features and by highlighting the complex network of material and energy streams that will need to be harmonized.

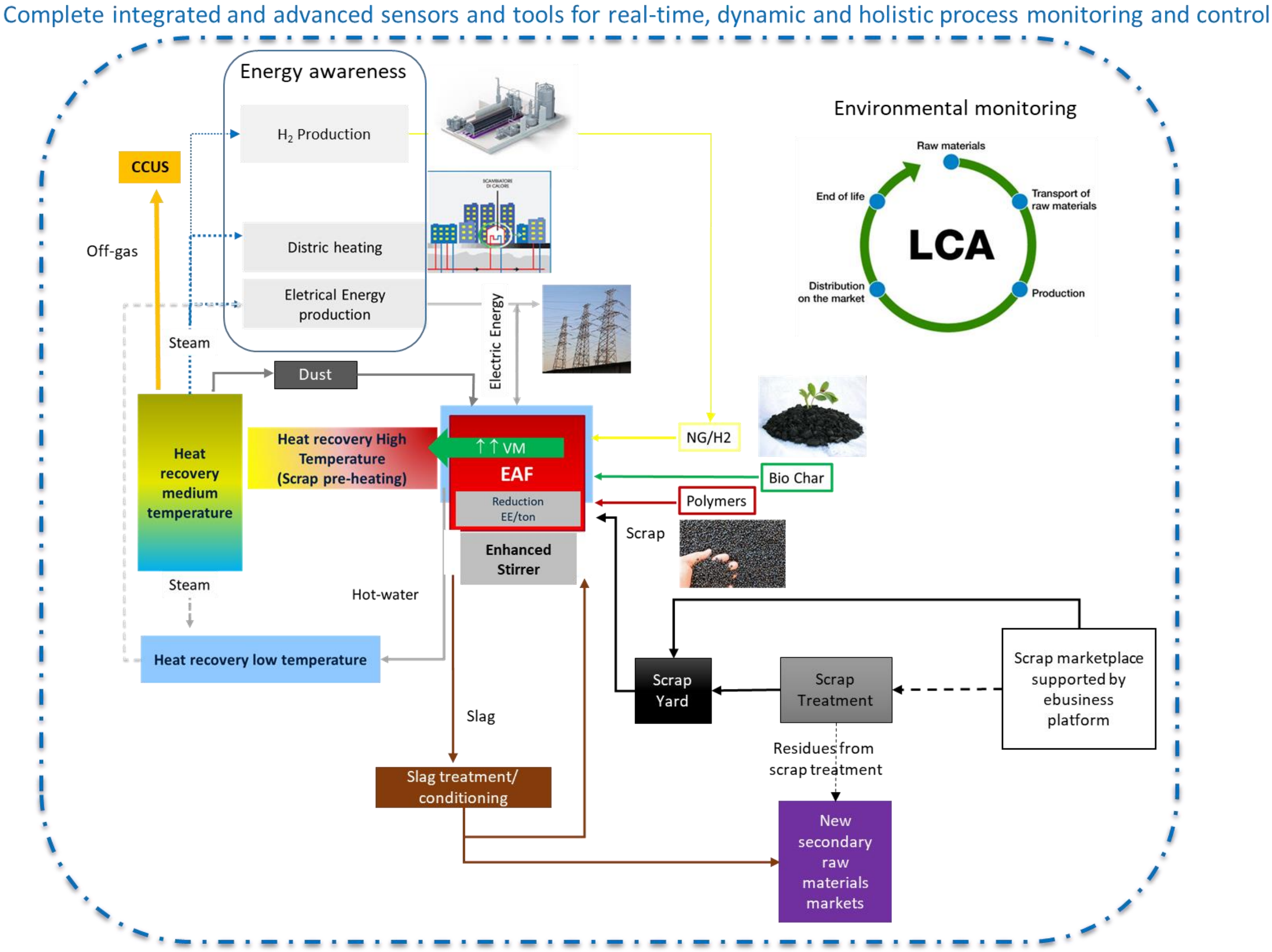

Complete integrated and advanced sensors and tools for real-time, dynamic and holistic process monitoring and control

Figure 25. Simplified representation of next generation EAF

Optimal exploitation and handling of scrap as well as of other raw materials and resources will be achieved. Energy efficiency needs to be targeted through the implementation of energy recovery measures, the exploitation of a suitable mix of energy sources, including renewable energy sources, alternative non-fossil feedstock, hydrogen and bio-gas. Waste minimization through optimal valorization of residues inside and outside the production cycle shall lead not only to reduced environmental impact, but also to improved competitiveness and shall create new business opportunities.

To achieve the above stated ambitious targets, an improved control of the all involved process stages as well as a more precise and up-to-date characterization of feedstock materials, products and residues along the production chain is needed. Therefore, sensing and monitoring equipment must evolve accordingly, by also exploiting Big Data and Artificial Intelligence, especially Machine Learning and Deep Learning for information and knowledge extraction from raw data, as well as for providing modelling and forecasting capabilities for energy awareness and environmental monitoring.

The new EAF-based route will be well connected with its own social environment, by providing a relevant positive contribution to the welfare, wellbeing and progress of the surrounding communities and by cooperating with all the stakeholders in the achievement of the ambitious targets of the European Green Deal.

Integration of all envisioned technologies in new EAF steel plants will also have an important impact on the further reduction of CO_2 emissions and an enhanced circular economy. **Table 31** reports an estimation of possible targets based on the following assumptions:

- SCOPE 1
    - Substitution of 50% limestone with recycled slag
    - Reduction of 50% pig iron by zero or lower C content material (e.g. Natural Gas based DRI)
    - Substitution of NG with green H_2
    - Substitution of 50% coal/anthracite with alternative material with zero CO_2 emission
- SCOPE 2
    - Reduction of electrical energy consumption by 15%
    - Reduction of grid factor based on data in **Figure 25** (black line): 0.376 kgCO_2/kWh (today) to 0.25 kgCO_2/kWh
- SCOPE 3
    - Substitution of 50% limestone with recycled slag
    - Reduction of 50% pig iron by zero or lower C content material (e.g. Natural Gas Based DRI)
    - Substitution of NG with green H_2
    - Substitution of 50% coal/anthracite with alternative material with zero CO_2 emission
    - Reduction of oxygen by 10%

***Table 31.** Estimation of CO_2 reduction with the application of all the envisioned technologies in new EAF steel plants*[8]

TODAY								
			Emission Factor - Scope 1 WSA	Scope 1	Grid Factor EE Scope 2	Scope 2	Upstream CO_2 value Scope 3 WSA	Scope3
			kg CO_2/t	kg CO_2/tCS	kg CO_2/kWh	kg CO_2/t_{CS}	kg CO_2/t	kg CO_2/t_{CS}
EE EAF/LF/Aux	kWh/t_{CS}	580,0			0,376	218,1		
Antracite	kg/t_{CS}	12,0	2,461	29,53				
Limestone	kg/t_{CS}	50,0	0,440	22,00			0,95	47,5
Electrodes	kg/t_{CS}	2,0	3,663	7,33			0,65	1,3
PigIron	kg/t_{CS}	100,0	0,172	17,20			1,855	185,5
Fe Cr	kg/t_{CS}	4,0	0,275	1,10			5,987	23,9
Fe Manganese	kg/t_{CS}	5,0	0,183	0,92			2,789	13,9
Natural Gas	Nm3/t_{CS}	15,0	2,052	30,78				0,0
Oxygen	Nm3/t_{CS}	40,0		0,00			0,335	13,4
TOTAL				108,9		218,1		285,6
					326,9			612,5

2030 ENVISIONED TARGET								
			Emission Factor - Scope 1 WSA	Scope 1	Grid Factor EE Scope 2	Scope 2	Upstream CO_2 value Scope 3 WSA	Scope3
			kg CO_2/t	kg CO_2/tCS	kg CO_2/kWh	kg CO_2/t_{CS}	kg CO_2/t	kg CO_2/t_{CS}
EE EAF/LF/Aux	kWh/t_{CS}	493,0			0,250	123,3		
Antracite	kg/t_{CS}	6,0	2,461	14,77				
C substitute	kg/t_{CS}	6,0						
Limestone	kg/t_{CS}	25,0	0,440	11,00			0,95	23,8
Recycled slag	kg/t_{CS}	25,0						
Electrodes	kg/t_{CS}	2,0	3,663	7,33			0,65	1,3
PigIron	kg/t_{CS}	50,0	0,172	8,60			1,855	92,8
DRI/NG	kg/t_{CS}	50,0	0,073	3,65			0,78	39,0
Fe Cr	kg/t_{CS}	4,0	0,275	1,10			5,987	23,9
Fe Manganese	kg/t_{CS}	5,0	0,183	0,92			2,789	13,9
Green Hydrogen	Nm3/t_{CS}	50,0						
Oxygen	kg/t_{CS}	36,0					0,334	12,0
TOTAL				47,4 -56%		123,3 -43%		206,7 -13%
					170,6 52%			377,3 38%

Figure 26 provides an overview of the presented Roadmap, by including main topics, impacts and estimated requirements in terms of budget.

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[8] **Scope definitions** from [86]:
Scope 1 emissions (according to greenhouse gas protocol): Direct emissions from site chimneys determined by the carbon balance methodology
Scope 2 emissions (according to greenhouse gas protocol): Upstream emissions or credits related to procurement/delivery of electricity and steam from site. Upstream emissions of exported co-product gas considering the potential savings in electricity generation.
Scope 3 emissions (according to greenhouse gas protocol): Other upstream emissions or credits related to procurement/delivery of pre-processed materials/co-products from site.

Scrap: pre-treatment and separation of tramp elements, quality analysis and characterization, yard management and use of HBI/DRI

Upgrading of scrap, standardization and market improvement	**Inline characterization of ferrous materials**	**Digitalization of scrap / charge material management and smart material usage**	**Industrial residues beneficiation as Fe/C source**	**Optimized use of alternative iron products (HBI/DRI) in EAF process**

Impacts

Costs saving of up to 42€/t due to better scrap characterization before yard and consequent payment of the only ferrous fraction	Avoidance of extra process costs for negative effects of non-ferrous materials	Production of low alloyed high steel qualities by EAF route and consequent reduction of CO_2 emissions of about 80%	Profit from high added value non-ferrous metal sources (e.g. Cu, Al, Cr): 50-150 €/t

Budget

2021-2023: 8M€	2024-2025: 17M€	2026-2030: 25M€	Total: 50M€

Replacement of lump and pulverized coals as reducing or foaming agent with alternative C-bearing materials and reduced consumption of graphite electrodes

Adaptation of the operating practice and injection systems	**Material availability and cost**	**Reduced consumption of electrodes**

Impacts

Reduction of CO_2 emissions of about 30-35 kg CO_2/tls	Creation of new local economies	Reduction of the impact of transportation of goods, specially from extra UE countries

Budget

2021-2023: 5M€	2024-2025: 6M€	2026-2030: 9M€	Total: 20M€

Energy Recovery and Utilization

Off-gas heat recovery	**Slag solidification waste heat recovery**	**Low temperature cooling water heat recovery**	**Energy recovery from product and process**

Impacts

Recovery of about 45-55 % of EAF energy input	Potential energy recoverable of about 15,000-18,000 GWh/a	CO_2 savings for direct use of recovered heat of about 2.7-3.2 Mt CO_2/a	CO_2 savings for conversion in power generation of the recovered energy of about 0.6-0.8 Mt CO_2/a	Saved Methane of about 1,500-1,800 MNm^3/a	Saved Electrical Energy Production of about 2.7-3.3 TWhe/a	Green Hydrogen Production of about 4,100-5,000 MNm^3/a

Budget

2021-2023: 16M€	2024-2025: 21M€	2026-2030: 38M€	Total: 75M€

The EAF-based steelmaking route of the future is a sustainable seamless production chain, integrated in the society in terms of optimal use of raw materials and resources, including energy and its flow, contributing to welfare and progress of the surrounding communities and of the society as a whole.

Valorisation of wastes, residues and by-products for internal and external use

Residues processing for material recovery and to make them useable in other resource-saving applications	**Material recirculation and recycling**	**Carbonization of steel residues to sequester CO_2**	**Process adaptation and adjustment**	**Industrial symbiosis**

Impacts

Recovery of 99% of EAF slag	3 times less landfilled dust	300,000 t/a of recovered Fe from dust	270,000 t/a of recovered ZnO from dust (12% of reduction of EU imported Zn)	Improvement of industrial symbiosis

Budget

2021-2023: 20M€	2024-2025: 25M€	2026-2030: 30M€	Total: 75M€

Use of renewable energy sources and alternative non-fossil fuels: renewable electricity and direct use of renewable or green H_2

Low carbon hydrogen and renewable energy production and supply	**Adaptation of burners**	**Process changes evaluation**

Impacts

CO_2 reduction: 10-13 CO_2 kg/tCS (continuous charge) 22-30 CO_2 kg/tCS (bucket charge)	Reduction of dependencies on import of fossil materials	Confirmation of the leadership of the EU in sustainable steel production

Budget

2021-2023: 20M€	2024-2025: 50M€	2026-2030: 50M€	Total: 120M€

New tools and sensors for process improvements

Enhanced monitoring of the EAF process by data analytics as well as physical and soft sensors	**Application of advanced modelling and simulation tools for prediction of process behavior**	**Improved real-time control of the EAF process**	**Enhanced management and optimisation with respect to resources, environmental impact, quality and productivity**	**Enhanced monitoring and automation of the EAF operations to improve operators' safety**

Impacts

Improvement of process performance, efficiency, and flexibility	Decrease of raw material and energy consumption and related increase of resource efficiency	Increased flexibility in the energy use for an optimal use of green or less expensive internal available energy	Reduction of the emissions (especially CO_2) and residues to dispose	Increase of economic revenues	Improved workers' health and safety

Budget

2021-2023: 5M€	2024-2025: 10M€	2026-2030: 25M€	Total: 40M€

Figure 26. *Overview of the Roadmap for an improved EAF scrap route*

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List of Acronyms

Acronym	Explanation
AI	Artificial Intelligence
BB	Building Block
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture Utilization
CDA	Carbon Direct Avoidance
EE	Electric Energy
EUA	Carbon Emission Allowances
CRFC	Carbon Fiber Reinforced Carbon
CE	Circular Economy
CEP	Circular Economy Pathway
CS	Crude Steel
CSP	Clean Steel Partnership
CFD	Computational Fluid Dynamics
CCM	Continuous Casting Machine
CCUS	Carbon Capture Utilization and Storage
DRI	Direct reduced iron
EBT	Eccentric Bottom Tapping
EMPC	Economic Model Predictive Control
EAF	Electric Arc Furnace
EU	European Commission
EGD	European Green Deal
ERMA	European Raw Materials Alliance
ESTEP	European Steel Technology Platform
FEM	Finite Element Method
fCEAP	first Circular Economy Action Plan
GHG	Greenhouse Gases
HVAC	Heating, Ventilation and Air Conditioning
HBI	Hot Briquetted Iron
ID	Induced draft
LCA	Life Cycle Assessment
ML	Machine Learning
Mtls	Millions of tons of liquid steel
MPC	Model Predictive Control
NG	Natural Gas
nCEAP	new Circular Economy Action Plan
ORC	Organic Rankine Cycle
P&D	Production and Development
R&D	Research and Development
R&D&I	Research, Development and Innovation
RH	Ruhrstahl Heraeus
SiSiC	Silicon Infiltrated Silicon Carbide)
SCU	Smart Carbon Usage
SOEC	Solid Oxyde Electrolysis Cell
SS-CCS	Steel Slag Carbon Capture and Storage
tCS	Tonne of crude steel
TRL	Technology Readiness Level

TEG	Thermo-Electric Generator
TPV	Thermophotovoltaic
TEE	Titoli di Efficienza Energetica
tls	tonne of liquid steel
VD	Vacuum Degassing
VM	Volatile Matter
VOD	Vacuum Oxygen Decarburisation
VUCA	Volatile, Uncertain, Complex and Ambigous
WSA	World Steel Association

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