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Review

Residue Valorization in the Iron and Steel Industries: Sustainable Solutions for a Cleaner and More Competitive Future Europe

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Abstract: The steel industry is an important engine for sustainable growth, added value, and high-quality employment within the European Union. It is committed to reducing its CO_2 emissions due to production by up to 50% by 2030 compared to 1990′s level by developing and upscaling the technologies required to contribute to European initiatives, such as the Circular Economy Action Plan (CEAP) and the European Green Deal (EGD). The Clean Steel Partnership (CSP, a public–private partnership), which is led by the European Steel Association (EUROFER) and the European Steel Technology Platform (ESTEP), defined technological CO_2 mitigation pathways comprising carbon direct avoidance (CDA), smart carbon usage SCU), and a circular economy (CE). CE approaches ensure competitiveness through increased resource efficiency and sustainability and consist of different issues, such as the valorization of steelmaking residues (dusts, slags, sludge) for internal recycling in the steelmaking process, enhanced steel recycling (scrap use), the use of secondary carbon carriers from non-steel sectors as a reducing agent and energy source in the steelmaking process chain, and CE business models (supply chain analyses). The current paper gives an overview of different technological CE approaches as obtained in a dedicated workshop called "Resi4Future—Residue valorization in iron and steel industry: sustainable solutions for a cleaner and more competitive future Europe" that was organized by ESTEP to focus on future challenges toward the final goal of industrial deployment.

Keywords: circular economy; steelmaking residues; clean steel

1. Introduction

The steel industry is an important engine for sustainable growth, adding value, and high-quality employment within the European Union. It is committed to reducing its CO_2 emissions from production by up to 50% by 2030 compared to 1990′s level by developing and upscaling technologies. The Clean Steel Partnership (CSP, a public–private partnership of the European steel sector), which is led by the European Steel Association (EUROFER) and the European Steel Technology Platform (ESTEP), defined technological CO_2 mitigation pathways comprising Carbon Direct Avoidance (CDA), Smart Carbon Usage (SCU), and a circular economy (CE). CSP targets the development of technologies at technological readiness level (TRL) 8 to reduce CO_2 emissions stemming from EU steel production by 80–95% compared to 1990's levels, ultimately leading to climate neutrality [1].

To reach a sustainable iron and steel industry, CE is one of the important pillars. Solid and sludgy residues from steelmaking processes represent secondary resources with considerable amounts of valuable materials, such as metals and minerals. Therefore, several technologies for the valorization of residues can lower the demand for primary resources and a reduced landfill volume, as well as produce economic savings for steel plant operators.

The current review article gives an overview of the amounts of steelmaking residuals generated in Europe and describes methods for CE approaches to close material cycles, create ideas for industrial symbiosis, and increase the internal residue recycling within the steelmaking processes. The latest ongoing research activities dedicated to CE in the steel sector were presented at a workshop called "Resi4Future-Residue valorization in iron and steel industry-sustainable solutions for a cleaner and more competitive future Europe." This event was organized by the focus group "Circular Economy" from the European Steel Technology Platform (ESTEP) and gave an overview of the possible technical solutions contributing to the overall goals defined in the New EU Circular Economy Action Plan (CEAP, [2]) and the European Green Deal (EGD, [3]). Furthermore, an overview of the current technological development status of residue treatment solutions will be given. Finally, the CE approaches presented will be linked to the CSP roadmap.

1.1. ESTEP at a Glance

ESTEP was formed in 2003 as one of the first European technology platforms and brings together all the major stakeholders in the European steel industry. The members comprise major steel manufacturers, universities, and research institutions that are active in steel research; major users of steel, such as car manufacturers; and public bodies, such as the European Commission and national governments. Since 2018, ESTEP has been a non-profit organization according to Belgian law (international ASBL) [4]. The mission of ESTEP is to engage in collaborative EU actions and projects on technologies that are tackling EU challenges (notably on renewable energy, climate change, i.e., low-carbon emissions, and CE) to create a sustainable EU steel industry. This is done by disseminating the results of projects, facilitating a supportive environment for collaborative projects, and the active network of ESTEP's community. Figure 1 shows the organizational structure of ESTEP [4].

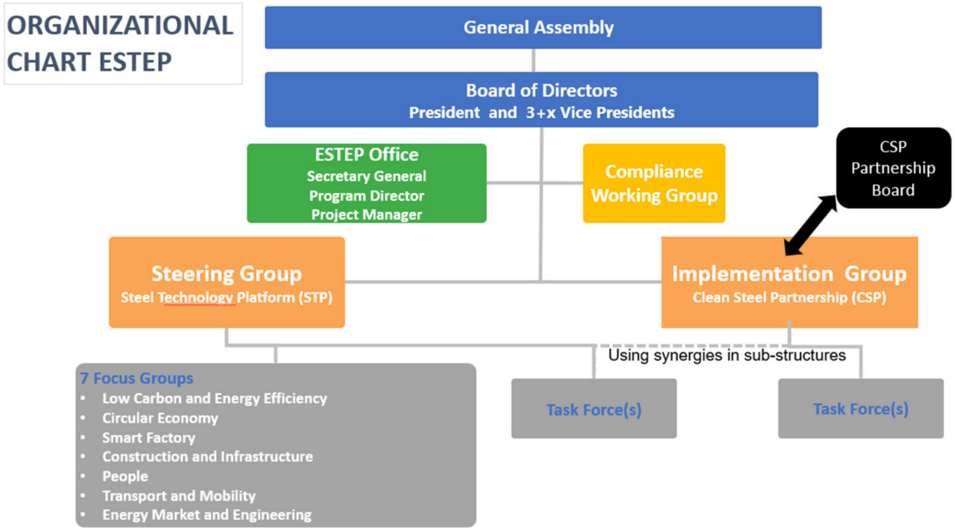

Figure 1. Organizational structure of ESTEP [4].

ESTEP is governed by a board of directors. The steering group pilots the overall ESTEP research program. It reviews the activities of the focus groups, ensures that planning is in line with the SRA, and coordinates the working groups. Seven focus groups (FG) actively work on issues that deal with the implementation of ESTEP's Strategic Research Agenda (SRA) in different domains. Two of these FGs deal with steel production, which are low carbon and energy efficiency and circular economy. The former works on the development of safe, clean, energy-efficient, and innovative technologies, while the latter deals with innovative solutions to increase the circularity of steel. Of major concern here is reducing CO_2 emissions, conserving resources, and boosting waste recovery. Three FGs cover steel applications: steel solutions for transport and mobility, steel solutions for construction and infrastructure, and steel solutions for energy markets, including engineering. FG People deals with activities for attracting people to the steel industry, skills development, education and training programs, and occupational safety. FG Smart Factory covers issues for intelligent and integrated manufacturing, applying developments in the field of information, and communication techniques [4].

The Implementation Group deals with all issues in regard to the CSP, which supports the transition of the EU steel industry toward climate neutrality. CSP is explained in further detail in Section 4.

1.2. Steelmaking by-Product Generation within the European Union

In 2019, 158.8 million tonnes of crude steel were produced in Europe (EU28), 93.9 million tonnes (59.1%) of which was via the blast furnace (BF)-basic oxygen furnace (BOF) route and 64.9 million tonnes (40.9%) was via the scrap-based electric arc furnace (EAF) route [1]. A total of 87.0 million tonnes of hot metal (HM) was produced in 2019, representing a 54.8% share of the entire crude steel production [5]. Table 1 shows the specific amounts of by-products generated via the BF- BOF and EAF routes.

A total of 426 kg of residues per tonne of liquid steel (average values, sum of residues per tonne of HM and LS without desulphurization slag, ladle furnace slag, and mill scale) are generated via the BF-BOF route according to Table 1, whereas 185 kg of residues are generated per tonne liquid steel from the EAF process. Considering the above-mentioned specific by-product quantities and steel production figures for 2019, approximately 52 million tonnes of steelmaking by-products were generated (~40 million tonnes from the BF/BOF route and ~12 million tonnes from the EAF route). The largest part of the by-products is covered by the slag fractions (slags mainly from BF, BOF, and EAF; see Figure 2).

Table 1. Specific amounts of steelmaking by-products [6–10].

by-Product	Specific Amount	Average
BF slag	150 to 347 kg/t hot metal (HM)	249 kg/t HM
BF dust	3 to 18 kg/t HM	11 kg/t HM
BF sludge	2 to 22 kg/t HM	12 kg/t HM
Desulphurization slag	3 to 40 kg/t liquid steel (LS)	22 kg/t LS
BOF slag	85 to 165 kg/t LS	125 kg/t LS
BOF dust	1 to 24 kg/t LS	13 kg/t LS
BOF sludge	15 to 16 kg/t LS	16 kg/t LS
EAF slag	60 to 270 kg/t LS	165 kg/t LS
EAF dust	10 to 30 kg/t LS	20 kg/t LS
Ladle furnace slag	10 to 80 kg/t LS	45 kg/t LS
Mill scale	2 to 8 kg/t LS	5 kg/t LS

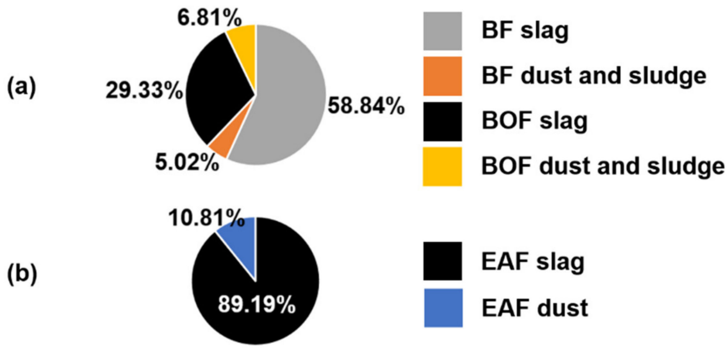

Figure 2. Percentage of generated slags, dusts, and sludges from hot metal and crude steel production via the BF-BOF route (**a**) and the EAF route (**b**).

Regarding by-products from the BF/BOF route, 88.17% slags (BF + BOF slag + secondary metallurgy) are produced. The remaining 11.83% represent dusts and sludges from gas cleaning systems. For the EAF route, besides the 89.19% as slags from EAF and secondary metallurgy, the dust from dry gas cleaning systems represents 10.81%.

2. Methods for CE Approaches

To achieve a sustainable steel industry, CE must be addressed by different technical solutions contributing to European initiatives, such as the European Green Deal (EGD [3]) and the New EU Circular Economy Action Plan (CEAP [2]), which were launched by the EU in 2020. There are several main actions envisaged under the umbrella of the EGD and the CEAP and appear particularly significant for the steel sector [11]. These are the introduction of a sustainable product policy framework supporting the design of sustainable products, the empowerment of consumers in the selection of "green" products, strengthening circularity in production processes, the enhancement of a waste policy oriented toward prevention, the circularity and elimination of toxic compounds, and the enforcement of a market for secondary raw materials. Steel fits well with this ambition due to its inherent properties and because the steel industry established circular practices decades ago [11].

However, these opportunities need to be materialized and the steel sector has already defined some priorities to be capable of fully exploiting such chances. An ongoing RFCS dissemination project entitled "Dissemination of results of the European projects dealing with reuse and recycling of by-products in the steel sector" (acronym REUSteel, grant agreement number 839227) [12] concerns the evaluation of the most important results on the reuse and recycling of by-products achieved in the last few decades in relevant EU-funded projects. The activities of REUSteel are based on an in-depth and critical integrated analysis of relevant projects and aim at results exploitation according to the concepts of CE and industrial symbiosis by promoting an increase in reuse and recycling of by-products, as well as the synergies between the steel industry and the other sectors [12].

The recovery, recycling, and reuse of steelmaking residues are sometimes hampered by a lack of knowledge related to missing ad hoc legislation or because pre-treatment needs to be customized to obtain the desired recovery of materials. In this context, digitalization and Industry 4.0 are identified as enablers of CE. To overcome the lack of information and support decision making, simulation and optimization tools can provide some of the additional knowledge required. Simulation tools and related scenario analyses can exemplarily allow the consequences of the internal reuse of slags in steelmaking aggregates to be evaluated, such as when using the EAF process [13,14]. Moreover, the combination of different simulation and optimization tools can support the evaluation of slag pre-treatment steps and the optimization of the internal or external reuse of separated fractions with or without a combined use of further by-products. The potential of these systems lies in the possibility to make preliminary evaluations to address specific solutions before a real application by avoiding both unnecessarily great efforts and undesired consequences [13].

Industry 4.0, which employs the combined use of smart sensors and data analytics, is also a possibility for implementing the real-time monitoring and control of, e.g., an electric steel plant. Information exchange between machines and services has huge potential and machine learning is extensively applied to optimize processes [15]. Special emphasis is given to the classification and tracking of steel scrap, which represents an important secondary resource for the steel industry. One possible method is a convolutional neural network (CNN), which is applied for the automatic classification of metal scrap to store it in dedicated areas depending on its quality and supplier. A charge optimization model can be coupled with this scrap-sorting approach. Finally, an online tool for dynamic environmental impact assessment can be connected to physical detection systems (sensors) of environmental parameters. This tool combines digital models, innovative sensors, and data from an internal inventory system. It will be able to provide information based on life cycle assessment (LCA) toward a full CE concept that is dedicated to enhanced scrap use for steel production and toward eco-conscious management of traditional production batches [15]. Technological developments that are dedicated to steelmaking residue valorization for internal use, resource usage from non-steel sectors, and industrial symbiosis are presented later in this paper.

2.1. Valorization of Steelmaking Residues

Figure 3 shows the basic aggregates of the BF-BOF and EAF routes (coupled with direct reduction as a prior upstream primary process), with the main residues and their place of generation. In the following subsections, different processes for residue valorization that are currently under investigation are mentioned.

2.1.1. Pyrometallurgical Processes

Dusts from iron and steelmaking that are separated by gas cleaning systems contain considerable amounts of valuable metals, such as iron and zinc. Several European research initiatives focus on the development of solutions to recover these metals for both internal uses in the steelmaking process (e.g., iron fraction as a secondary resource for the BF) and external uses of zinc in other industries.

Within the framework of the European project Reclamet (funded by EIT Raw Materials, project number 17209; see Figure 4), iron and zinc recovery from the HIsarna process is investigated [16].

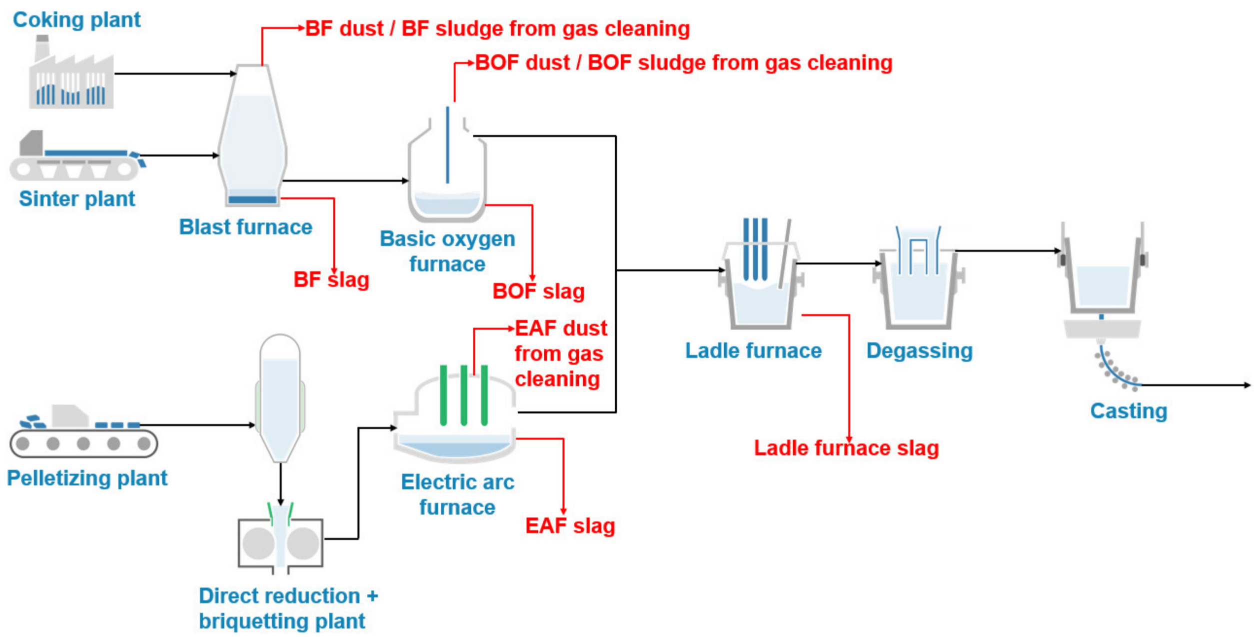

Figure 3. BF-BOF and EAF routes (with a direct reduction process for iron ore reduction) for primary steel production and the place of generation for the main steelmaking residues.

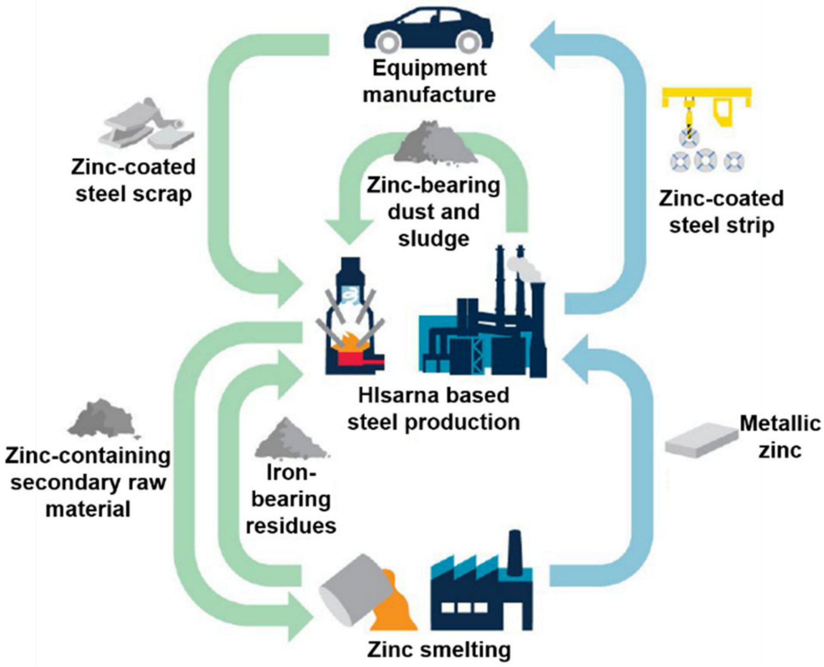

Figure 4. Concept of the Reclamet project [16].

HIsarna is a smelting reduction process using iron ore, which is almost directly converted into liquid iron (pig iron). The HIsarna process maintains a temperature above the melting point of iron throughout so that the injected iron ore immediately melts and is converted into liquid hot metal. The process combines two aggregates, a cyclone converter furnace for ore melting and pre-reduction and a smelting reduction vessel for the final reduction stage to liquid iron. The very high temperature of the process gases in the smelting vessel is further increased in the cyclone at the top of the reactor by the addition of pure oxygen, which reacts with the carbon monoxide that is present [17]. The process does not require the manufacturing of iron ore agglomerates, such as pellets and sinter, and uses only fine coal as a reducing agent in the smelting reduction vessel. Within the Reclamet project, zinc-rich residues, such as BF and BOF sludge, BOF dust, and zinc-rich steel scrap, are treated in the HIsarna process. The preparation of the fine residues is a crucial step; therefore, micro-granulation, briquetting, and extrusion are adapted regarding the specific residue properties and cost effectiveness of the process. The dissolution behavior of the obtained briquettes and scrap was studied through pilot melting tests. Within the scope of the testing at the HIsarna plant, zinc concentrate was separated with a bag filter at the end of the process gas cleaning with a target zinc concentration of >50 wt.% and an iron content of <15 wt.% [16].

The use of an induction furnace is another possibility for treating zinc- and iron-bearing residues by applying melt bath injection technology (see Figure 5 [18]).

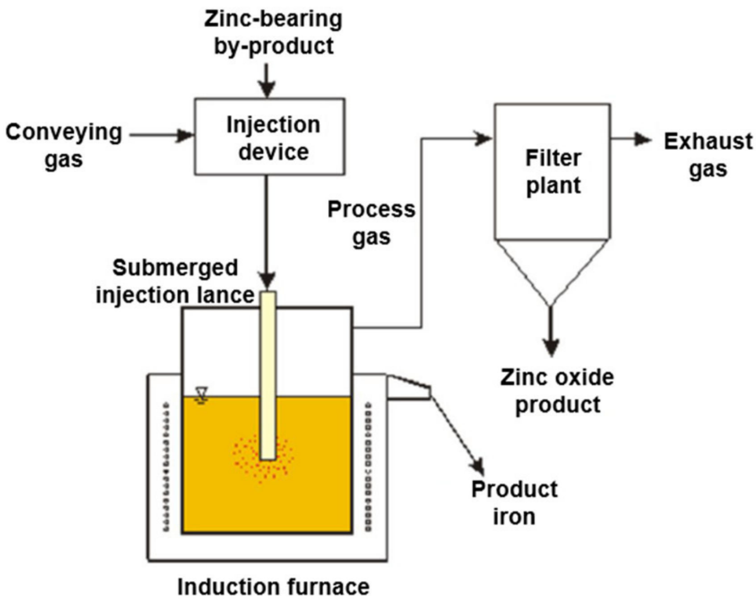

Figure 5. Scheme of the melt bath injection process [18].

Pneumatic conveying and injection via a submerged lance into the iron melt bath are suitable approaches for using fine-grained residues as feed materials, such as special zinc-containing cupola furnaces or BF dusts, with nitrogen as the conveying medium. This injection technology was built and implemented in an industrial 30 t induction furnace, where operational trials led to a very good zinc recovery and yielding a high-quality zinc oxide product (>60% Zn content) [18].

Another approach is the RecoDust process, in which BOF dust is processed pyrometallurgically (see Figure 6 [19–21]).

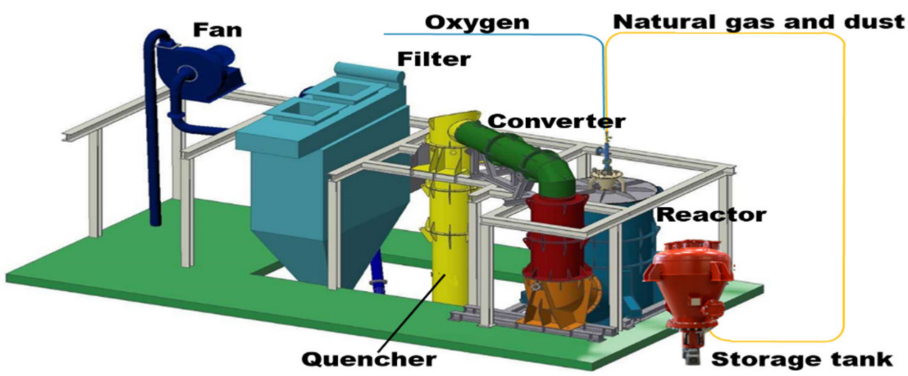

Figure 6. Schematic view of the RecoDust process [19].

The process is funded within the Austrian COMET program K1-MET and is currently in the pilot plant stage (300 kg/h throughput) and transfers the iron content into a slag phase to be used as a secondary iron resource for the sintering plant or the BF. The zinc content in this product stays below 0.5 wt.% [19–21]. The crude zinc oxide, which is separated with a bag filter (representing the second product), is treated using a leaching step and shows a low halide content (chlorine and fluorine ~0.1 wt.% each). With upscaling to 1000 kg/h being the current focus of the development project, a new pneumatic conveying system was installed; it uses natural gas as the conveying medium. The main benefit of RecoDust is that no carbonaceous solid reducing agents are required since the reducing atmosphere is only adjusted via the natural gas/oxygen flame [19–21].

The treatment of EAF dust with a sequence of oxidizing and reducing atmospheres is the basis of the two-step dust recycling (2sDR) process funded within the framework of EIT Raw Materials [22,23] (see Figure 7).

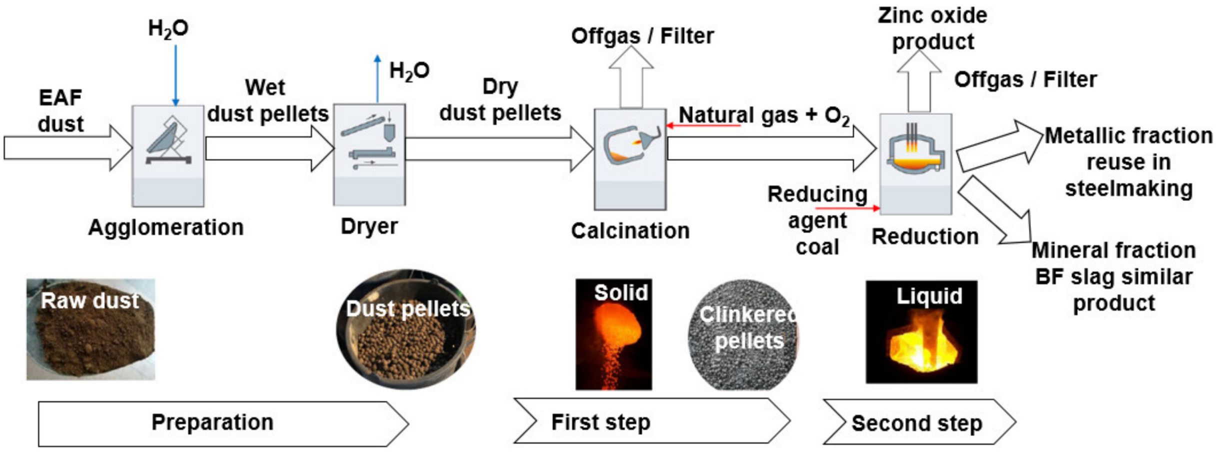

Figure 7. The 2sDR process steps that are used to take EAF dust from its raw state to the final products [23].

In a first step (clinkering step under an oxidizing atmosphere), fine EAF dust with a typical partial size below 5 µm is formed into small pellets with water and then dried to a humidity level below 6% to be charged into a drum furnace, where the halogens and lead are vaporized by means of a natural gas burner at temperatures around 1100 °C. In a second step, the clinkered dust is treated under reducing conditions in an electric arc furnace, where, in addition to a high-quality zinc oxide (ZnO), a metallic fraction is generated, which can be reused in steelmaking. A mineral fraction, which can be used in the construction industry, is also generated. Coal is injected into the furnace as a reducing agent. The main benefit of the 2sDR process, besides the fact that is a zero-waste approach, is that the produced ZnO product has very low halogen contamination and, therefore, can be directly used in the primary zinc industry without further treatment. The development of the 2sDR process has been finalized and successfully proven in lab-scale and pilot-scale testing [22,23].

2.1.2. Hydrometallurgical Residue Treatment

New branches of extractive metallurgy treatment via leaching are an environmentally friendly and CO_2-free alternative to pyrometallurgical treatment for metal recovery from steelmaking residues [24,25]. Within the scope of the EIT Raw Materials project SAMEX (project number 19205, https://eit-samex.eu/, accessed on 16 May 2021), an ammoniacal process is being developed to treat fine BOF sludge (see Figure 8 [26]).

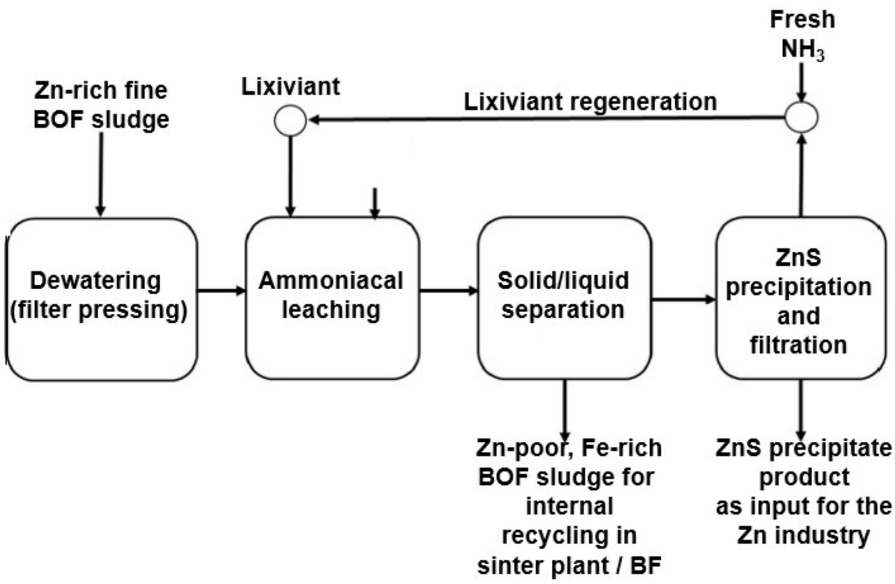

Figure 8. Schematic flow chart of the SAMEX process [26].

The main advantage of the ammoniacal leaching procedure is its selectivity for Zn over Fe. The NH_3 solution and $(NH_4)_2CO_3$ (salt) chemicals that are used for this ammonia–ammonium–carbonate (AAC) leaching method are relatively cheap. Furthermore, they do not lead to the corrosion of equipment (unlike the use of strong acids), thus offering favorable operational expenditures (OPEX). This is also the main difference with respect to traditional acid-based processes. The cleaned iron-rich residue can be fed into the BF, resulting in cost savings for primary iron ore, while the zinc (76% yield) in the saturated leach solution can be recovered as a zinc sulfide precipitate product to be used in the zinc industry. Even though AAC leaching can only dissolve zinc from a zincite/wustite solid solution and not from the refractory zinc ferrite (franklinite) phase, the process offers many advantages that need to be demonstrated at higher scales since up-to-date testing at a 1 L reactor scale are available. As part of the SAMEX project (https://eit-samex.eu/, accessed on 16 May 2021), Tecnalia (Spain), ArcelorMittal (Spain), and KU Leuven (Belgium) shall upscale the ammoniacal leaching process to TRL7, with the aim of engineering and building a pilot plant [26].

2.1.3. Mechanical Processes

Pyrometallurgical and hydrometallurgical residue treatment concepts induce a certain additional demand for energy (to provide a required temperature level in the corresponding pyrometallurgical reactors) and chemicals (e.g., for leaching steps). Concepts that employ mechanical residue treatment, such as cold-bonded briquetting, offer a possibility to recycle fine-grained iron-oxide-containing residues. Direct reduction processes, such as MIDREX®, generate various iron-containing fine-grained residues, which can be screened in terms of oxide fines and dried sludge [19,27]. To be in line with the idea of a CE, briquetting via the use of a cold-bonded process generates agglomerates, which can be reused in the MIDREX® shaft. An important question related to the production of briquettes for the MIDREX® shaft is the use of an appropriate binder. The briquettes should have a certain mechanical strength (compressive strength of >35 MPa and abrasive strength R30 >85% according to [19,27]). Besides this, metallurgical properties (reducibility in terms of reduction degree >80% and oxygen release during reduction with a residue O_2 content of <5%) must also be considered [19,27].

2.1.4. Slag Valorization

As shown in Figure 2, slags represent the largest residue fraction from steelmaking (88.17% slags from the BF-BOF route and 89.19% from the EAF process). Therefore, slag valorization technologies are of high importance to be able to use the slag as a secondary resource, not only for the steel sector but also for other sectors, such as construction or the cement industry.

Wet and dry granulation technologies are used to transform steelmaking slag into a secondary raw material. The wet granulation of slag guarantees fast cooling and high production rates but requires water treatment [28]. Dry slag granulation provides an opportunity to have no wastewater and a reduction in costs, with the possibility to recover heat, but it can have limitations regarding the flow rate. Different dry granulation solutions exist that can be adopted for specific needs for EAF or ladle furnace (LF) slag granulation [28]. To generate a mineral product that can serve as a secondary resource for the cement industry, slag cooling and granulation are crucial since the solidified granules must have a certain glass content to trigger cement hydraulic reactions during solidification.

One concept for the dry slag granulation (DSG) of BF slag operates with a rotating disc that is placed in a reactor with water-cooled walls (see Figure 9 [29,30]).

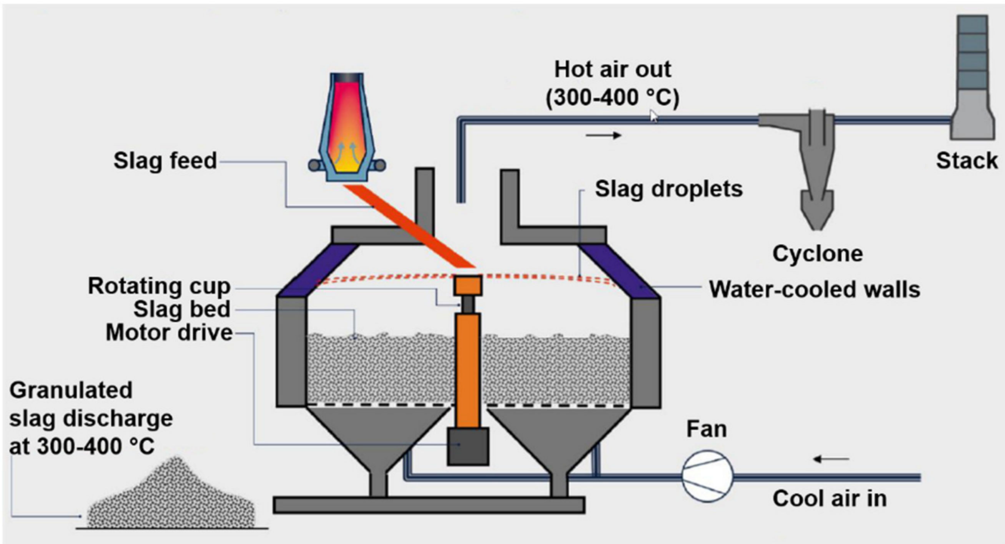

Figure 9. Schematic of the DSG process flow [29,30].

Particle formation takes place through the rotating principle. Air is used to create a fluidized bed condition at the bottom of the granulator and to solidify and cool the product in it. BF slag granules from the DSG process are characterized by a round and smooth surface with properties that are similar to wet granulated slag in terms of its cement hydraulic properties (compressive strength and hydration heat). The DSG process was tested in operational trials with a slag flow of up to 1 t/min with a coupled possibility to recover heat from the BF liquid slag through steam generation; the technology is currently in a pre-commercialization state [29].

A second concept for the dry granulation of EAF and LF slag is based on air blowing to avoid any contact between the hot liquid slag and metal or refractory parts that can require heavy maintenance (see Figure 10).

Figure 10a shows the material properties of dry granulated LF and EAF slag. The presence of FeO (EAF slag) or calcium difluoride CaF_2 interferes with the formation of the amorphous phase, which is instead promoted by fast cooling. As shown in Figure 10a, there is no strong influence of the binary basicity index 2 (IB2—concentration ratio of the slag components CaO + MgO/SiO_2) on the formation of the amorphous phase. Therefore, the amorphous content of a granulated material can be controlled by the cooling rate; this is essential regarding latent hydraulic properties for the use of the slag, e.g., as a secondary additive for cement production. Figure 10b illustrates the schematics of different dry slag granulation plant layouts using the concept of a forced-air jet. A screen is collocated at a distance, where the slag is expected to be solidified and the product can be collected. The proper gas slag ratio (GSR) and the distance between the fan exit and the screen can be selected to adjust the final properties of the product, in particular, the fraction of the amorphous content [28].

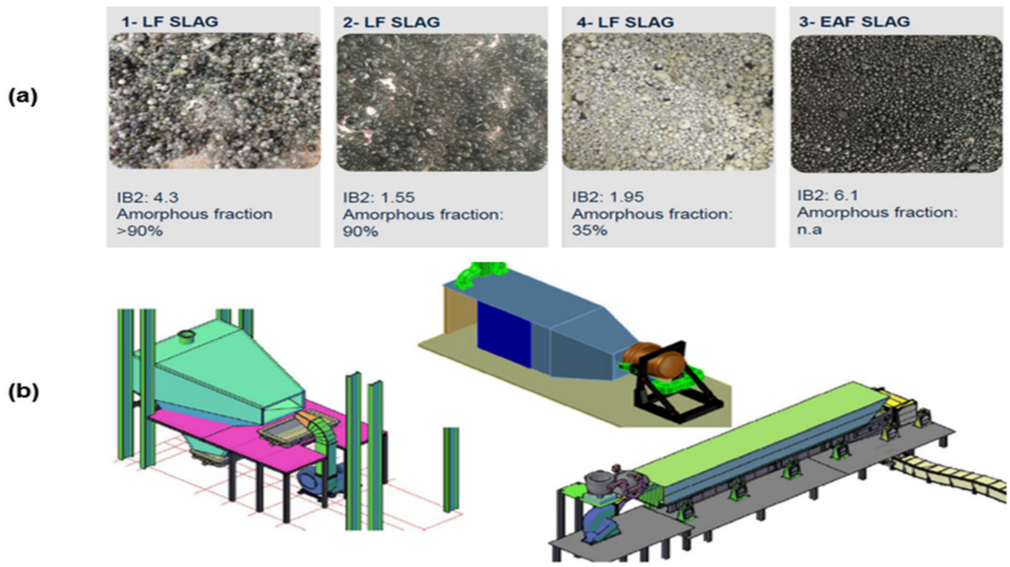

Figure 10. Dry slag granulation results (**a**) and different plant layouts (**b**) [28].

BOF slag has different applications depending on the legal regulations in each EU member state [31]. In Italy, for example, the use of BOF slag for agriculture in Italian soils is being investigated [32]. Italian coastal soils are typically rich in alkalies and might have excess sodium due to intrusions from coastal aquifers and irrigation with saline water. The potential of BOF slag as a possible soil conditioner can be assessed using column and lysimeter tests. Results showed the positive effects of this slag on the investigated soil; BOF slag increased the cation exchange capacity of the soil, which resulted in higher nutrient retention [32]. In lysimeter tests, the application of BOF slag was evaluated in terms of its effect on tomato growth. It was shown that a replacement of Na ions took place due to the competition of Ca ions supplied by the slag for the sorption sites in the soil, leading to a higher tomato yield [33]. The use of BOF slag in agriculture, compared to other chemicals (e.g., gypsum [34]), can reduce natural resource exploitation, and induce cost reductions and other savings, such as energy and water consumption in mining activities [32].

EAF slag can also be valorized in different applications, e.g., cement and aggregates for concrete or blasting material [35]. New application fields must be developed in anticipation of an expected higher share of steel production via the EAF in Europe in the future. In previous years, when EAF slag was investigated for its use in the cement industry, the need for too much energy and high amounts of treating agents limited such a possibility. DRI-based EAF slags have different properties than other EAF slags, e.g., lower Cr content, which opens up opportunities for EAF slag use in fields that up to now have been limited for slag with higher Cr content. Future research initiatives will focus on the creation of new possible markets and reflect on the necessary standardization measures and economic conditions to implement cost-effective EAF slag treatment technologies [35]. Close cooperation is inevitable between the steel sector and other industries that will be the target sectors (cement, fertilizer, etc.).

For future steel production, material flexibility will be one important issue. Variations in feed material sources (sintered and pelletized ore and scrap of different qualities, HBI, etc.) will have an impact on future plant designs. In particular, while it is clear that the use of green hydrogen is the way to decarbonize steelmaking, utilizing a direct reduction reactor in combination with an EAF (which is the traditional method) would pose two main constraints. First, the utilization of high-grade iron ore pellets for DRI (direct reduced iron) production, and second, a slag composition similar to the current EAF slag, and therefore, a limited salability capacity.

The first constraint, namely, the utilization of high-grade DRI pellets, is born from the fact that the EAF can manage and treat only a limited quantity of slag per batch heat. This is because it is a technology that is optimized for the fast batch melting of scrap and not for the treatment of continuous big quantities of metal and slag (such as the blast furnace). Different studies demonstrated that high-grade DRI pellets are rare due to the type of ores available, and these pellet grades are not able to fulfill the worldwide production needs [36,37]. Therefore, the "green solution" for steelmaking must be capable of processing normal, BF-grade minerals with higher levels of gangue, which results in DRI with a higher gangue content.

The use of an OSBF (open slag bath furnace; see Figure 11) to replace the "traditional" EAF allows for the production of iron ore at a defined percentage of carbon while using 100% hydrogen as a reducing gas [36].

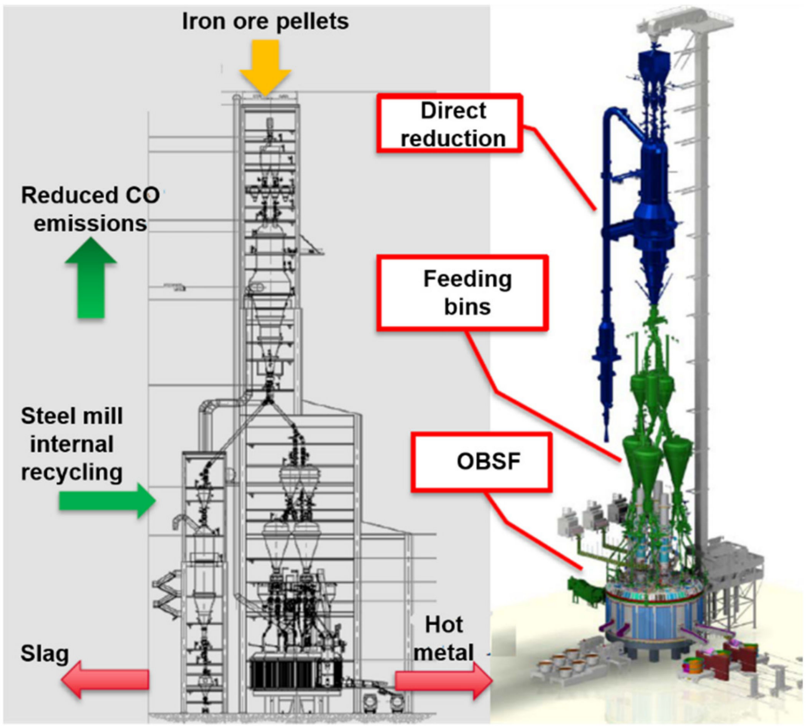

Figure 11. Schematic of an OBSF combined with a direct reduction plant [36,37].

The OSBF technology is very well known in the ferroalloys industry and producers have been operating such furnaces for more than a century all over the world. The OSBF has the same ability as a BF to run long continuous campaigns, but with higher flexibility (possibility to switch on and off) and the possibility of running a continuous process (vs. the batch process of the typical EAF). The DRI reactor and the OSBF can be operated coupled as one unit or can work separately during the maintenance of one of the two units.

In addition to the DRI (hot metal) produced, the DRI reactor with the OSBF process generates a slag with the same or better quality than BF slag, resulting in a material that can be valorized in concrete, cement, mortar, or as aggregates. The OSBF slag will contain a much lower percentage of sulfur and phosphorus than the BF slag (within the BF, these elements are transferred to the slag and the hot metal from the metallurgical coke, which is not used in DRI reactors). This process enables a 100%-DRI-fed furnace to produce high-quality hot metal and a slag with chemical/physical properties in the same range as the BF slag, thus making it fully compatible with cement and concrete production.

A DRI reactor coupled with an OBSF plant is currently built in Canada and there are other projects in other countries in the study phase [36,37].

Generated within secondary metallurgy, LF slag represents another valuable resource to be reused for addressing the idea of CE. Different valorization solutions are conceivable for LF slag, ranging from internal use as EAF feedstock, external use to substitute lime, to cement production and road construction. At the moment, landfilling is also utilized within the EU as a final step. The challenges in using LF slag are related to the legislation, technology, production rate, market, and economy. As an example, technical challenges include volume instability, volatile composition, and disintegration, e.g., due to the unstable free calcium oxide content in the LF slag. A new framework for the LF slag value chain was developed based on single steelmakers considering regional perspectives [38]. Figure 12 illustrates the processing of LF slag and possible application fields through the lime production process [38].

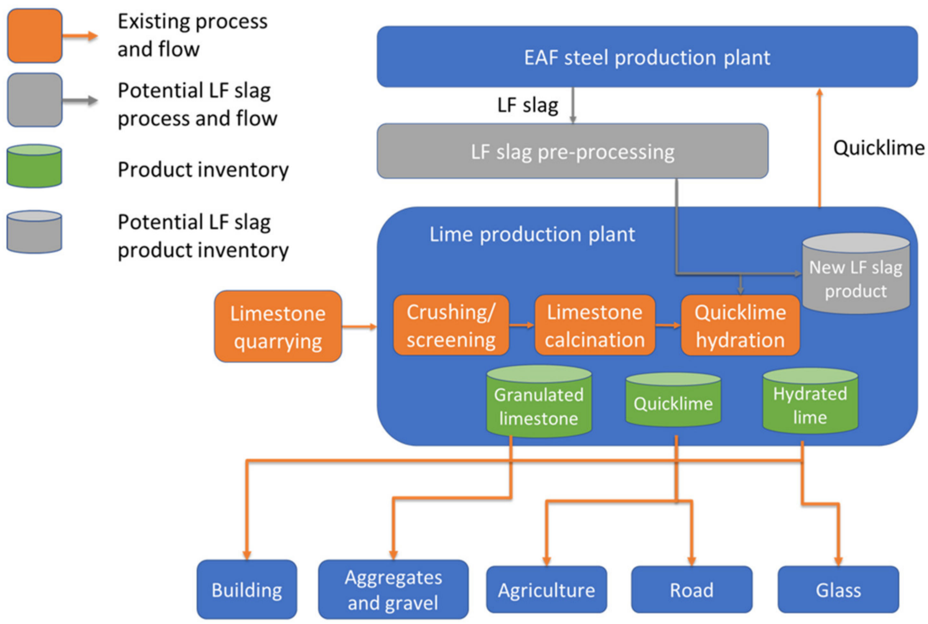

Figure 12. General framework for LF slag utilization [38].

The possible integration of LF slag use in the lime production process represents the central part of Figure 12. The orange boxes are the typical steps for a lime production plant that sells its products to different industrial sectors (shown as blue boxes at the bottom of Figure 12). LF slag cannot be used in an as-received form in the lime production process, which is why a pre-processing phase (shown as the grey box "LF slag pre-processing" in Figure 12) is required. Based on the final aim of LF slag use, the pre-processing phase can be carried out in the steel plant, the lime production plant, or through an external actor. The pre-processed LF slag can subsequently be used, either in one of the existing production phases or to generate a new product (preferred by the user industries, mainly due to its reasonable price).

2.2. *Secondary Sources from Non-Steel Sectors*

Alternative reducing agents and carbon substitution for primary steelmaking is one application field in which non-steel sectors are important partners for the steel industry. Waste plastic is a commonly used alternative reducing agent for the BF process. The gasification of waste plastic to generate syngas is one possible approach, whereas the syngas produced can partially substitute metallurgical coke and pulverized coal (see Figure 13 [39]).

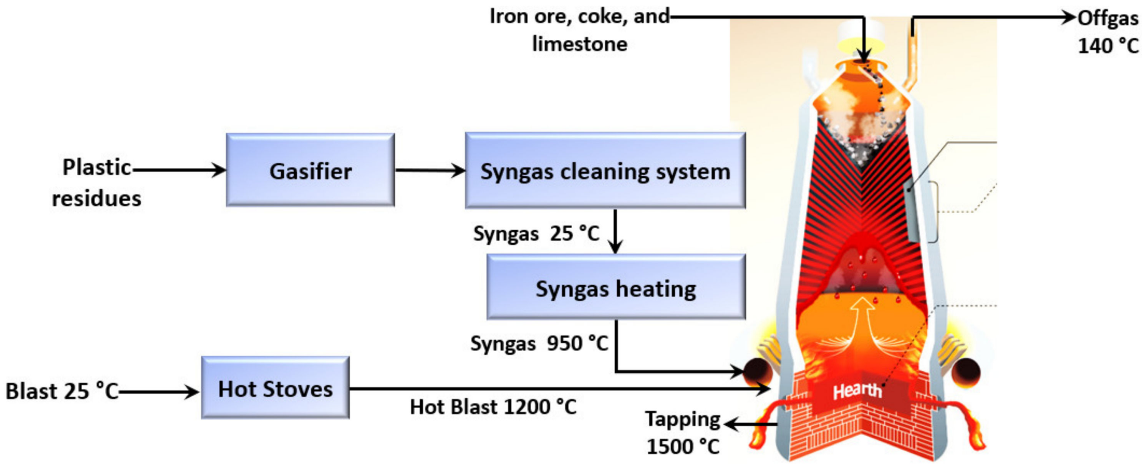

Figure 13. Principal layout of syngas injection into the BF [39].

A study revealed that the syngas can substitute ~0.18 kg coke + pulverized coal per Nm^3 syngas [39]. Waste plastic can also be injected directly into the BF without being gasified beforehand (see Figure 14 [40]).

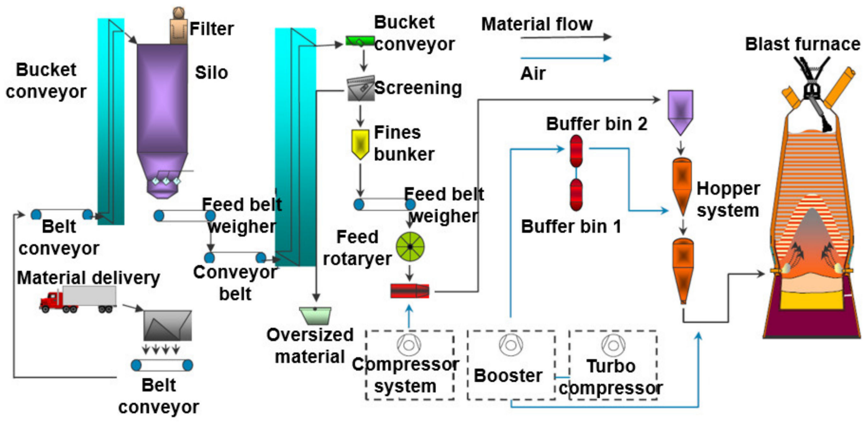

Figure 14. Flowchart of a waste plastic injection plant at a blast furnace [40,41].

Densified and pre-treated waste plastics (pellets, as well as granulate with a grain size <10 mm) coming from household waste and automotive shredder residues (ASRs) represent possible waste fractions that can be injected into the BF via the tuyères with an injection level of ~20–30 kg plastic per tonne of hot metal. No negative effects on the BF performance and environment are known [40,41].

Secondary resources from non-steel sectors can also be used in the EAF. Within the framework of the RIMFOAM RFCS project "Recycling of industrial and municipal waste as slag foaming agent in EAF" briquetted ASR pieces (~3–5 cm length) were charged into the EAF via the basket. The use of polymers in the EAF charge in baskets as a substitute for the carbon is possible but needs a homogeneous distribution in the basket to avoid rapid reactions that can create uncontrolled reactions. In the ongoing OnlyPlastic RFCS project "EAF working with polymers derived from plastic residue in substitution of fossil fuel" (cooperative research project between Feralpi Siderurgica, Euromec, Tenova, i.Blu, Rina-CSM, and Strane Innovation), an injection system for polymers that was obtained using waste plastic at an EAF was developed and tested at an industrial scale. Good process stability and slag foaming were obtained [42]. The polymer injection in an EAF as a substitute of coal requires the adaptation or substitution of carbon lance due to the lower density and higher reactivity of the material and the development of a proper injection practice and control system [42]. Furthermore, end-of-life carbon-fiber-reinforced polymers (CFRPs) can serve as an alternative carbonaceous reducing agent in the EAF process [43].

Another approach toward residue recycling from non-steel sectors is the reuse of refractory waste. EAF MgO-C bricks, high alumina bricks for the ladle, and isostatically pressed bricks from the continuous casting (CC) plant can serve as a refractory repairing source, for example [44]. In two EU-funded projects, "Systematic and integral valorization of refractories under the "5R" approach" (5RefrACT; co-funded by the LIFE financial instrument of the EU, contract number LIFE17 ENV/ES/000228) and "Management of ladle refractory brick waste " (E-CO-LadleBrick; funded by RFCS, grant agreement number 847249), several potential applications (waste refractories based on magnesia and alumina base) were developed; an EAF gunning mass and refractory for the ladle ring were tested and generated recycling rates between 65–70% [44].

2.3. Good Practice Examples for Supply Chain Analysis and Industrial Symbiosis

Using resources from non-steel sectors as described in the previous section follows the idea of industrial symbiosis (sector coupling). The word "symbiosis" is usually associated with relationships in nature, where two or more species exchange materials, energy, or information in a mutually beneficial manner. Industrial symbiosis is a form of brokering to bring companies from different industrial sectors together in innovative collaborations to find ways to use the waste from one company as raw material for another company to improve business and the processes used.

Industrial symbiosis is the focus of the currently ongoing EU-funded project CORALIS (H2020 SPIRE Program, grant agreement number 958337) [45]. CORALIS will create new value chain relations through novel approaches that facilitate long-term industrial symbiosis. Three industrial use cases will be studied within the CORALIS project. In the Brescia (Italy) case (see Figure 15), a steel producer, a foundry, and a partner from the aluminum industry are cooperating to recover metal fractions from waste, along with evaluating the use of the residue as secondary raw materials. Furthermore, biochar utilization as a carbon substitute will be investigated and waste heat utilization potentials will be analyzed [45].

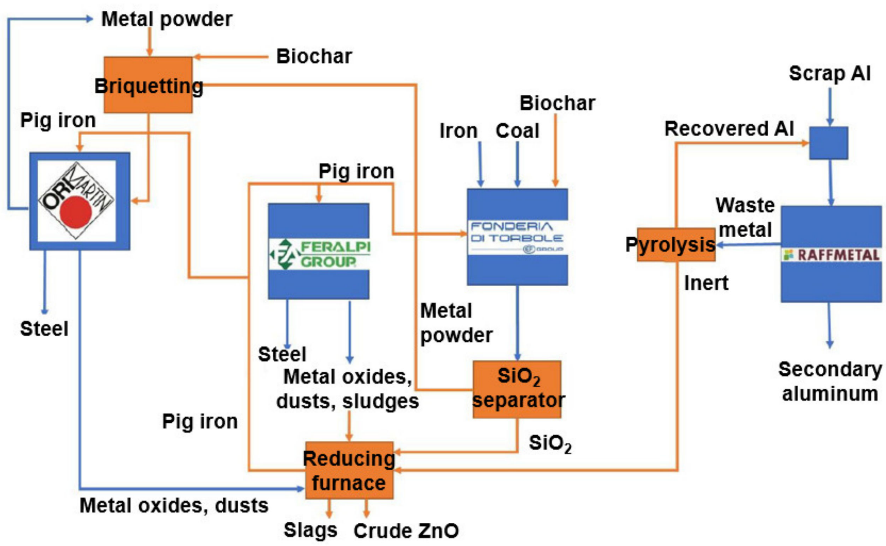

Figure 15. Brescia use case for industrial symbiosis within the CORALIS project [45].

3. Current Technological Development Status and Future Challenges

Technology readiness levels (TRLs) are a commonly used method for following the maturity status of technological developments during a phased program and comparing technologies with each other. As part of the Horizon 2020 program, a TRL scale was defined for funded research projects, which include the following stages [46]:

- TRL1—Basic principles observed;

- TRL2—Technology concept formulated;
- TRL3—Experimental proof of concept;
- TRL4—Technology validated in a lab;
- TRL5—Technology validated in a relevant environment (industrially relevant environment in the case of key enabling technologies);
- TRL6—Technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies);
- TRL7—System prototype demonstration in an operational environment
- TRL8—System complete and qualified;
- TRL9—Actual system demonstrated in an operational environment (competitive manufacturing in the case of key enabling technologies).

Table 2 summarizes the technological developments presented in the previous sections, with special emphasis on their technological maturity status and indicates the main challenges for future research.

Table 2. Current technological development statuses and open challenges of the latest ongoing European research initiatives on CE approaches in the steel industry.

Process/CE Approach	Current TRL Status	Open Challenges for Future Research
Use of carbon-fiber-reinforced polymers in EAF [43]	3–4	Scale-up of pilot plant
RecoDust for Fe and Zn recovery from BOF dust [19]	4	Optimized dust feeding Increased energy efficiency
Leaching process for Zn recovery from BOF sludge [26]	5	Pilot plant engineering and operation
Digitalization tools for CE focusing on monitoring (slag reuse scenarios [14,32,35,38], dynamic environmental impact analysis/online LCA [15]), and simulation for optimization (by-product pre-treatment evaluation [14])	5	Evaluation with experimental data for model improvement Implementation in a real industrial process environment
Zn recovery from HIsarna filter dust [16]	6	Pilot erection and operation, including raw material preparation
Induction furnace and bath injection for Zn recovery from filter dust [18]	6	Full sets of operational and economic data Improved carbon (post) combustion Energetic optimization (heat recovery)
Mechanical MIDREX® residue agglomeration for reuse in DR * [19]	6	Improved agglomerate stability Continuous agglomeration process
Waste plastic gasification for syngas production (partial substitution of coke and pulverized coal in BF) [39]	6	Erection and operation of a syngas pilot plant and long-term campaigns at an industrial BF
Slag utilization strategies [28,32–38]	7	Engineering and operating of demo plants for slag treatment Developing market strategies for secondary products while considering national legislation in the EU member states
Two-step dust recycling of EAF dust [23]	8	Final design layout for industrial plant
Reuse of waste refractories [44]	8	Complete economic evaluation of use cases Minimize the percentage of waste refractories that are dispatched to landfill
Scrapyard management via scrap handling/tracking using sensors and machine learning tools [15]	9	Implementation of innovative sensors in a steel plant environment Link between scrap-sorting algorithms and EAF-charging strategy
Dry granulation of BF slag [29]	9	Commissioning of first industrial plant
Charge of granulated waste plastic in BF [40]	9	Process parameter variation in case of changing waste qualities
Charge of lump waste plastics in EAF bucket [42]	9	Final industrial scaling-up of a waste plastic injection process

* DR—direct reduction.

4. Circular Economy in the European Clean Steel Partnership

The steel sector plays an important role regarding the CE; in a well-structured CE, steel has significant competitive advantages over competing materials. Four keywords define these advantages, namely, reduce, reuse, remanufacture, and recycle (see also Figure 16 [47]).

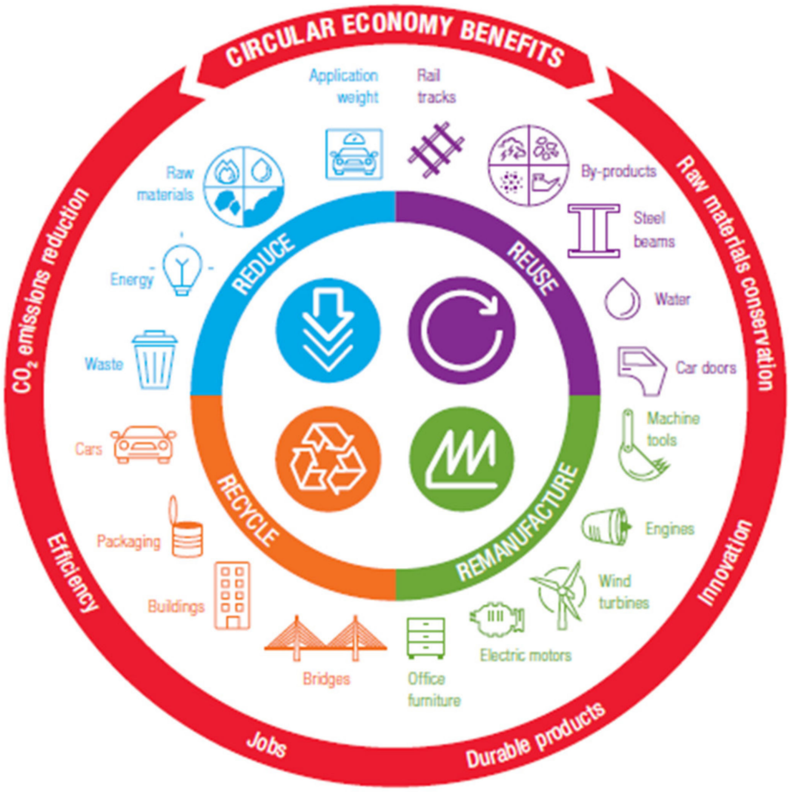

Figure 16. Steel in the circular economy: the 4 R's [47].

Reduce means decreasing the amount of material, energy, and other resources that are used to create steel and reducing the weight of steel used in products. Reuse covers the use of an object or material again, either for its original purpose or for a similar one, without significantly altering the physical form of the object or material. Remanufacture stands for the process of restoring durable used steel products to an as-new condition. Finally, recycle means melting steel products at the end of their useful life to create new steel. Recycling alters the physical form of the steel object so that a new application can be created from the recycled material [47].

During the technical workshop "Resi4Future-Residue valorization in iron and steel industry-sustainable solutions for a cleaner and more competitive future Europe," which was organized by the focus group "Circular Economy" from the European Steel Technology Platform (ESTEP), possible technical solutions were presented and discussed that fit into the overall goals defined in the Circular Economy Action Plan and the European Green Deal. The currently ongoing research initiatives within the EU are in line with the roadmap of the Clean Steel Partnership (CSP) [1]. The CSP, which is the public–private partnership of the European steel sector and is led by the European Steel Association (EUROFER) and ESTEP, defined technological CO_2 mitigation pathways comprising carbon direct avoidance (CDA), smart carbon usage SCU), and the circular economy (CE). CSP targets the development of technologies at a technological readiness level (TRL) 8 to reduce CO_2 emissions stemming from EU steel production by 80–95% compared to 1990 levels, ultimately leading to climate neutrality. Within the CSP roadmap, R&D&I activities supporting the achievement of the CSP's objectives are classified according to two levels, six areas of intervention (AoIs), and twelve specific building blocks (BBs). The following shows the six AoIs [1].

The aforementioned technological pathways comprising CDA, SCU, and CE represent four of the six AoIs. CDA means steel production using hydrogen or renewable "green" electricity. SCU is separated into two sub-parts: CCUS (carbon capture, utilization, storage) and PI (process integration). CCU (carbon capture, utilization) encompasses technologies that use CO and CO_2 in steel plant gases or fumes as raw materials for production or integration into valuable products. PI allows for the reduction of fossil fuel (coal, natural gas, etc.) that is used in both BF-BOF and EAF steel production to reduce the CO_2 emissions generated by the steel industry. Besides the CE, enablers are another AoI. This field includes the integration of technologies such as artificial intelligence and digital solutions into industrial production. The development of new measurement techniques and digital tools for monitoring and control in the new steel production processes, new predictive and dynamic models, and strategic scheduling tools are examples of enablers that will ensure the planning, assessment, and optimization of the industrial transition process toward a climate-neutral steel sector. The last AoI (denoted as "combination" in Figure 17) defines research initiatives in which the different pathways interact with each other [1].

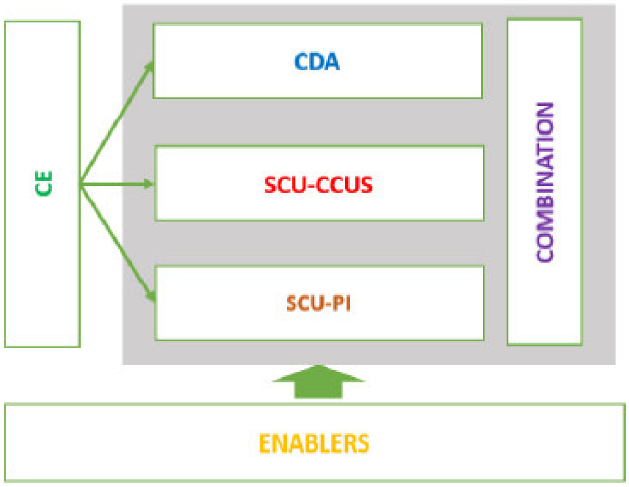

Figure 17. Areas of intervention and their interactions [1].

R&D&I activities contributing to the above AoIs focus on 12 technological BBs (see Figure 18) and/or a combination thereof.

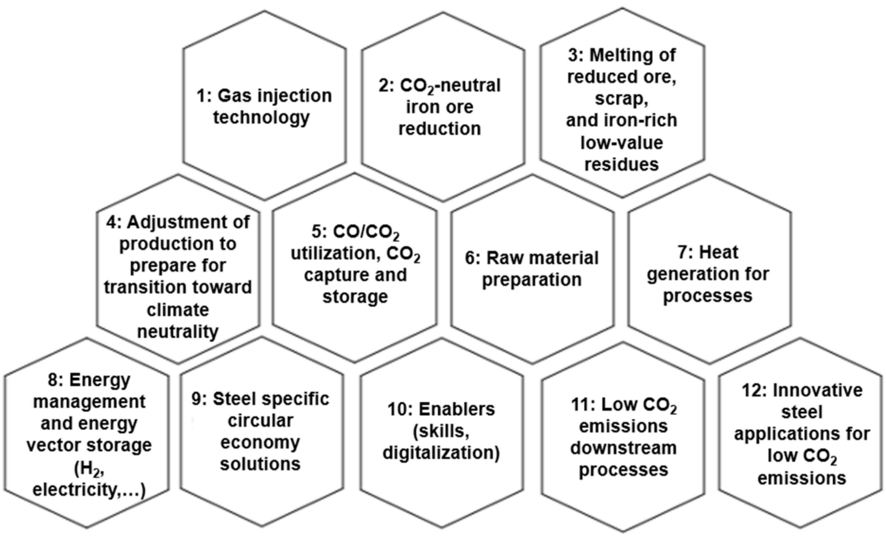

Figure 18. The twelve building blocks of the Clean Steel Partnership [1].

The CE dedicated research initiatives presented in this paper clearly address some of the BBs from the CSP. In the following, the relevant BBs are mentioned, where the descriptions of the BBs are taken from [1].

BB 1 refers to gas injection technologies of media into the BF and EAF, such as natural gas, coke oven gas, BOF gas, or hydrogen-enriched gas streams, which can significantly contribute to a CO_2 reduction during steel production. In addition to new process technologies for co-injection into BF, DRI plants, and EAF, BB 1 also includes new control technologies that were developed by considering process requirements, safety issues, and economic aspects.

BB 2 includes R&D&I activities that are related to the metal reduction processes using hydrogen, renewable energy, or biomass. However, direct reduction with high amounts of hydrogen is a key component. The effects on the DRI properties and the process conditions of downstream processes are also considered as part of BB 2.

BB 3 includes technologies for melting ferrous feedstock with variable carbon content and variable metallization, including low-grade iron-based sources. Furthermore, the demonstration of new reduction process technologies is addressed to recover the metal content to be used as scrap substitutes from low-value residues through pre-reduction or reduction smelting with hydrogen, biogas, low CO_2 electricity, and carbonaceous residues.

BB 4 deals with R&D&I activities to adapt the energy and material cycles of today's integrated steel mills to new and alternative melt reduction processes. The focus is on the conversion to climate-neutral steel production, which contributes to reducing the CO_2 footprint. Flexible and modular heating concepts are part of this BB along with techniques and tools for immediate reduction of the CO_2 footprint at the industrial level. Techniques and planning tools are also considered, which support the later steps of decarbonization at the industrial level.

BB 6 relates to the two most important raw materials for iron and steel production, namely, iron ore and scrap. The aim is to produce iron and steel of the best possible quality while reducing CO_2 emissions. Iron ore can be upgraded using low-carbon technologies. The sorting of scrap materials can be done according to different quality criteria, together with scrap charge optimization to achieve high-quality finished products.

BB 9 covers three fundamental topics that will help to achieve the CO_2 reduction targets. The first topic addresses strategies for upgrading low-value scrap and recovering certain non-ferrous fractions from scrap; the second one is material recycling to increase iron and steel production yields by recovering metals from metal oxides; the third topic is residue recycling, focusing on the use of residues in other industrial sectors.

BB 10 addresses the requirements of digitalization, CE, and sustainability regarding the decarbonization of steel production. This ensures sustainable steel production under the conditions of the new technical and organizational boundary conditions along the steel production chains. Regarding digitalization, the related activities will ensure that the potential of the latest technologies, such as artificial intelligence and machine learning, is fully exploited. The activities will also consider the key aspects of systems that these technologies require to ensure their economic application in industrial production.

Table 3 illustrates the link of CE-related activities to the BBs of the CSP roadmap.

Table 3. Link of currently ongoing European CE research initiatives to the Clean Steel Partnership.

Process/CE Approach	Link to a BB of the CSP Roadmap
Scrapyard management via scrap handling/tracking using sensors and machine learning tools [15]	BB 6—Raw material preparation
Zn recovery from HIsarna filter dust [16]	BB 2—Adjustment and processing of slag chemistry for H_2 metallurgy BB 4—Use of slags in the cement industry BB 9—New processes to lower demand on primary resources; conditioning the properties of the minor slag phases; reduce landfill volume
Induction furnace and bath injection for Zn recovery from filter dust [18]	
RecoDust for Fe and Zn recovery from BOF dust [19]	
Two-step dust recycling of EAF dust [23]	
Leaching process for Zn recovery from BOF sludge [26]	
Mechanical MIDREX® residue agglomeration for reuse in DR * [19]	
Slag utilization strategies [28,32–38]	
Dry granulation of BF slag [29]	
Waste plastic gasification for syngas production (partial substitution of coke and pulverized coal in BF) [39]	BB 1—Development and demonstration of gas injection technology for the BF BB 3—Design of new solid raw material injectors for use of alternative material BB 9—Auxiliary reducing agent and slag foaming material
Charge of granulated waste plastic in BF [40]	
Use of carbon-fiber-reinforced polymers in EAF [43]	
Charge of lump waste plastics in EAF bucket [42]	
Reuse of waste refractories [44]	
Digitalisation tools for CE focusing on monitoring (slag reuse scenarios [14,32,35,38], dynamic environmental impact analysis/online-LCA [15]), and simulation for optimization (by-product pre-treatment evaluation [14])	BB 10—Development of a tool for continuous monitoring of the effects of circular approach/solutions on CO_2 emissions

* DR—direct reduction.

5. Conclusions

The presented activities comprise the entire European steel industry and related sectors and clearly demonstrate that technical solutions are required to contribute to European initiatives, such as the Circular Economy Action Plan and the Green Deal. CE approaches ensure competitiveness through increased resource efficiency and sustainability and comprise different issues, such as the valorization of steelmaking residues (dusts, slags, sludges) for internal recycling in the steelmaking process, enhanced steel recycling (scrap use), the use of secondary carbon carriers from non-steel sectors as reducing agent and energy source in the steelmaking process chain, and CE business models (supply chain analyses). Through an intensive collaboration between industry and science, research activities have the chance to be upscaled to semi-industrial and industrial scale in the near future to maintain and increase sustainability and competitiveness of the European steel sector.

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