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Review

Future Research and Developments on Reuse and Recycling of Steelmaking By-Products

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Abstract: In the steel sector, sustainable management of by-products is a key challenge to preserve natural resources and achieve the zero waste goal. In this paper, the main trends of future research and development on reuse and recycling of by-products of the steel industry are presented in the form of a roadmap, which is the outcome of a dissemination project funded by the European Union based on the analysis of the most relevant and recent European projects concerning reuse and recycling of by-products from the steel production cycle. In particular, the developed roadmap highlights the most important topics of future research activities and challenges related to reuse and recycling of by-products from the existing or alternative steelmaking routes. A time horizon of 10 years has been considered, taking into account the European Commission targets to achieve carbon neutrality in a circular economy context. In addition, current technological trends derived from past and ongoing research projects are analysed. Research needs are based on the main categories of by-products and residual materials. Due to the different pathways to reduce CO_2 emissions, each category is divided into subcategories considering both current and novel process routes targeting decarbonization of steel production. This work identifies the most urgent and demanding research directions for the coming years based on a survey targeting the steel companies, services providers of the steel industry and research organizations active in the field.

Keywords: by-products; circular economy; future research; reuse; recycling; steel industry

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1. Introduction

Steel is currently produced through two main production routes, iron-ore-based and scrap-based. In the first one, which is primarily represented in the European Union (EU), iron ore is processed to produce iron sinter or pellets. These materials are reduced and melted in a blast furnace (BF) using coke to produce pig iron, which is afterwards processed (decarburisation and refining of the chemical composition) in a basic oxygen furnace (BOF) to produce steel. In the scrap-based route, steel is produced by melting steel scrap in an electric arc furnace (EAF). In 2021, 152.6 million tonnes of crude steel were produced in Europe (EU28): 86 million tonnes (56.4%) via the BF/BOF route and 67 million tonnes (43.6%) via the scrap-based route [1]. In addition, about 32.9% of the worldwide steel production output is made up of by-products, mainly consisting of slags, dusts and sludge, as well as gases and other materials, which can be used in several processes inside and outside the steel production cycle [2].

In 2019, around 52 million tonnes of steelmaking by-products/residual materials were produced (~40 million tonnes from the BF/BOF route and ~12 million tonnes from the

EAF route). Around 426 kg of residues are produced per tonne of liquid steel from the BF/BOF route, while 185 kg of residues are produced per tonne of liquid steel from the EAF route [3]. In 2021 in Europe, 25.2 million tonnes of BF slag and 16.8 million tonnes of steel furnace slag were produced [4]. About 77% of the total production of by-products in the steel sector consists of slags. Dusts and sludges from gas cleaning systems amount to 15%. Mill scale makes up 2% and refractories 7% of the total by-product amount. As the residue production is relevant, the steel sector is committed to their valorisation both in the steelmaking process and externally in other sectors as raw materials according to the concept of industrial symbiosis (IS) [5]. IS consists of establishing synergies across different industries covering the economic, social and/or environmental dimensions. In particular, concerning environmental aspects, the synergy is mainly focused on efficient material exploitation and emissions reduction to promote resources preservation and to reduce environmental impacts [6]. In order to implement circular economy (CE) in the EU, IS is a potential pathway where waste, energy, by-products and water are the main streams exchanged among different industries [7]. To this aim, specific technologies and processes for each type of material are required to purify and separate the valuable fractions. Some solutions can be applied directly, while other ones require multi-step processing.

Concerning driving IS for by-products valorisation, further reasons for increasing residues and by-products valorisation are represented by:

- increasingly stringent legislation on waste/residues disposal;
- high content of metal oxides in residues, which can be used to (partially) replace costly virgin raw material;
- chemical and physical properties of steel residues and by-products that make them useful in other sectors.

This paper presents a part of the work carried out during the project titled "*Dissemination of results of the European projects dealing with reuse and recycling of by-products steel sector (REUSteel)*", which was funded by the EU through Research Fund for Coal and Steel (RFCS). The aim of this dissemination project is to identify, organize, combine and integrate the most relevant and promising results of several EU-funded projects, focusing on reuse and recycling of by-products from the iron and steelmaking processes and on exploitation of by-products from other industrial sectors in the steel sector as alternative sources of carbon (e.g., biomass and plastics). The project also developed a roadmap for future research, promoting the exploitation of results and strengthening synergies with other industrial sectors according to the concepts of CE and IS.

The paper is organized as follows: Section 2 presents the current industrial utilization of steel by-products, while Section 3 presents the information gathering for the developed analysis; Section 4 provides an overview of the achieved results and the discussion on future research and developments in reuse and recycling of by-products. Finally, Section 5 includes some concluding remarks.

2. Current Industrial Utilization of Residues Derived from the Steel Sector

The current industrial generation and utilisation of the different by-products and residues represents the starting point for the pursued analysis on future research needs [8]. In Table 1, various by-product streams and their uses addressed are summarized.

Concerning slag, different types are generated during steelmaking process with different chemical and physical properties depending on the process, input material (ore/scrap) or addition of fluxes. In particular, BF slag includes granulated BF slag (GB slag) and air-cooled BF slag (AB slag). Steelmaking slags comprise BOF slag, EAF slag from carbon steel production (EAF C slag), EAF slag from high grade steel production (EAF S slag) and secondary metallurgical slags, which include ladle furnace slag (LF slag), vacuum degassing slag (VD slag), argon oxygen decarburization slag (AOD slag) and vacuum oxygen decarburization slag (VOD slag). As shown in Figures 1 and 2, in 2021, 17.9 M tonnes of BF slag were produced in Europe and 12.5 M tonnes of steelmaking furnace slag [4].

Table 1. By-products streams and their uses.

By-Products	Utilization	Quantities
BF slag (GB/AB slag)	Cement/concrete, road, others	17.9 M tonnes (2021)
BOF slag	Cement/concrete, road, hydraulic engineering, fertilizer, metallurgical use, others	12.5 M tonnes (2021)
EAF C slag	Landfill replacement, landfill building material, aggregate	
EAF S slag	Landfill replacement, landfill building material, metal extraction, aggregates (e.g., unbound mixtures)	
LF slag	Acid mine drainage prevention, treatment, remediation; soil stabilization and road base reclamation; sludge solidification and stabilization; hazardous waste stabilization; flowable fill and excavatable backfill.	
Sinter dust	Internal recycling as sinter raw material	167.7 M tonnes (2018)
BF dust (coarse)	Internal: mixed and granulated in sinter raw material, pelletized/ briquetted in BF burden or injected to BF via tuyere	
BF sludge (fine)	Internal: dezincing pre-treatment by hydro cyclone, afterwards: mixed and granulated in sinter raw material, briquetted in BF External: dezincing (Shaft furnace—Oxycup, DK Recycling—Waelz process); sent to the landfill	
BOF dust (coarse)	Internal: used in the sinter plant, BF and BOF	
BOF dust/sludge (fine)	External: dezincing (Shaft furnace process); sent to the landfill	
EAF C dust	External: zinc recovery through the pyrometallurgical Waelz process (rotary kiln).	
EAF S dust	External: processed to recover Cr and Ni in the form of ferroalloys.	
Mill scale	Internal: recovering metal to be reused in the steel production External: cement sector, cement clinker manufacturing, used in counterweights, ferroalloy production, production of friction agents, production of refractories, welding electrodes, iron salts and iron oxides.	0.3–1.3 M tonnes/year
Refractories	As slag conditioners in EAF and BOF; as a substitute of the lime and dololime in EAF and BOF; disposed in landfill.	Consumption: 8–10 kg/t (BF/BOF) 5–7 kg/t (EAF)
Secondary raw materials	Biomass: replacing fossil fuel and carbon Plastic: as alternative carbon source in steelmaking	

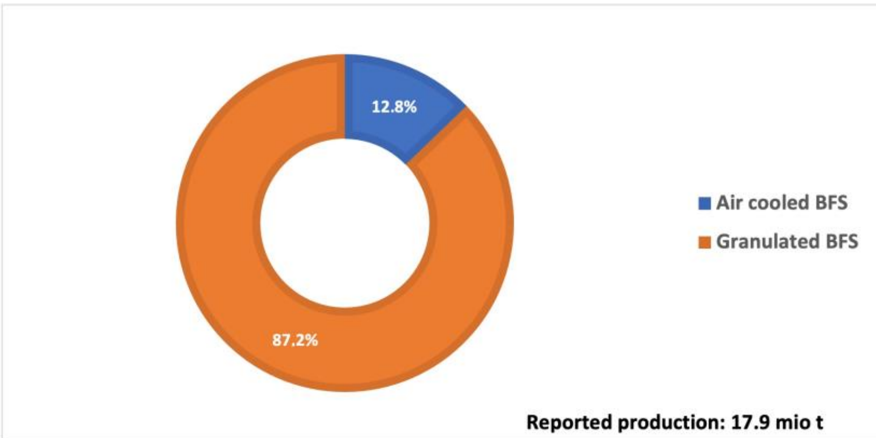

Figure 1. Production of BF slag in Europe in 2021 [4].

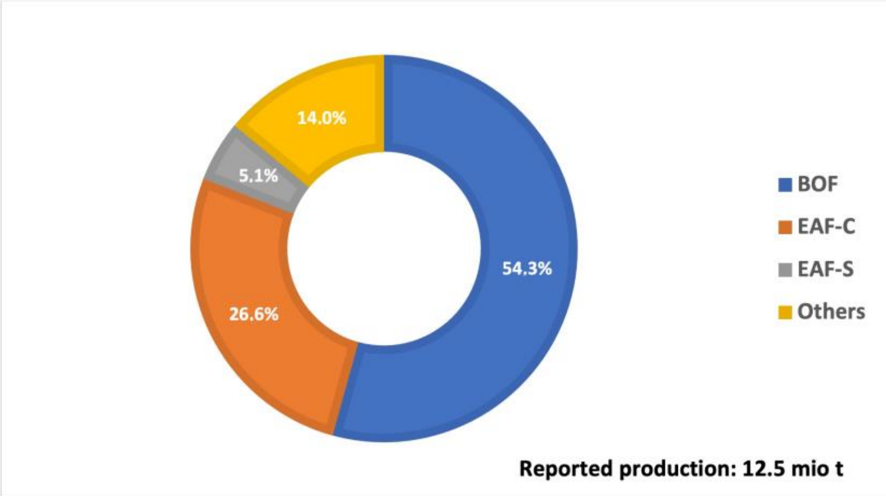

Figure 2. Production of steel slags in Europe in 2021 [4].

The utilization rate of slags depends on slag type, country or individual steelworks. According to Euroslag [4], in 2021 in Europe, all BF slag was used as cement/concrete addition [9], in road construction [10] or in other applications (Figure 3). In addition, about 76% of steel slags were used in cement/concrete addition [11], road construction, hydraulic engineering, fertilizer, metallurgical use or other applications [12] (Figure 4).

Some examples of different applications in the EU for specific steel slags can be provided. Carbon EAF (EAF C) slag can be used for landfill replacement, landfill building material, aggregate [13] (e.g., unbound and hydraulically bound mixtures, bituminous mixtures, concrete, mortar, armourstone, gabions, railway ballast, roofing, embankments and fill, sealants, wastewater treatment, air quality control). Stainless EAF (EAF S) slag can be used for landfill replacement, landfill building material, metal extraction, aggregates (e.g., unbound mixtures). EAF slag as "slag sand" can be used in acid mine drainage prevention [14], treatment and remediation, soil stabilization and road base reclamation, road base and sub-base construction, general construction engineered fill, embankment and backfill, sludge solidification and stabilization, hazardous waste stabilization, flowable fill and excavatable backfill, cement and concrete, asphalt, blasting material. LF slag can be used for landfill replacement, landfill building material, liming material (pH adjustment and plant available silicon), replacement of lime in EAF and cement replacement. In addition, LF slag as "slag sand" can be applied in acid mine drainage prevention, treatment and remediation, soil stabilization and road base reclamation, sludge solidification and stabilization, hazardous waste stabilization, flowable fill and excavatable backfill.

The fact that some slag applications are technically possible does not automatically imply that the steelwork/slag processor can use the slag for these applications. The use of slag can depend on several factors, such as the slag chemical and physical properties, the availability of applications within an acceptable distance (due to costs of transportation), abundance of natural resources in the area of the steelwork, the cost of utilization compared to costs of disposal, the lack of regulations or the existence of limiting ones. Taking these issues into account, research activities are needed both on new utilization paths and on increasing the amount of slag used within the known applications.

Dusts and **sludge** derive from the gas and wastewater abatement equipment in different processes. Over the last few years, significant improvements have been achieved, resulting in a decreased amount of materials sent to landfills by increasing the material volume that is internally reprocessed. An example of generation and utilization of dust and sludge in EU is provided by results from a survey carried out in 2018 by the FEhS Building Materials Institute (Figure 5) involving 27 plants holding BF/BOF- and EAF-based routes in Germany, Netherlands and Austria [15].

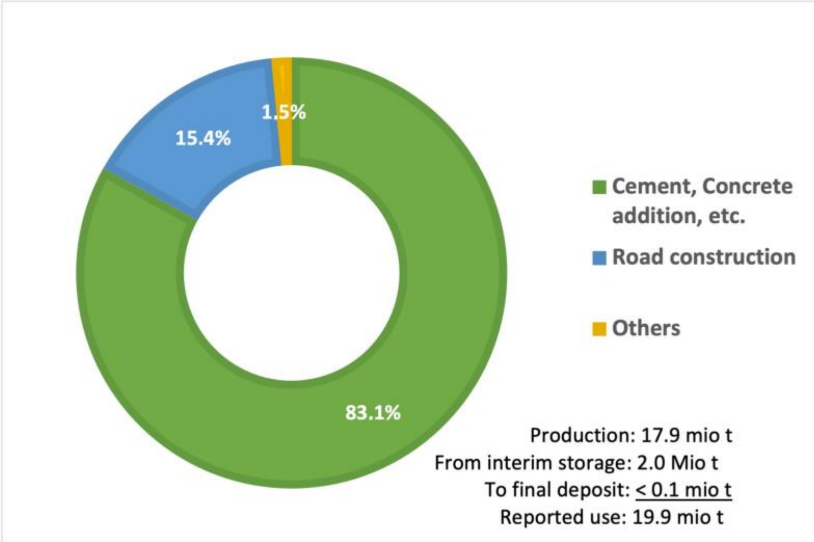

Figure 3. Use of BF slag in Europe in 2021 [4].

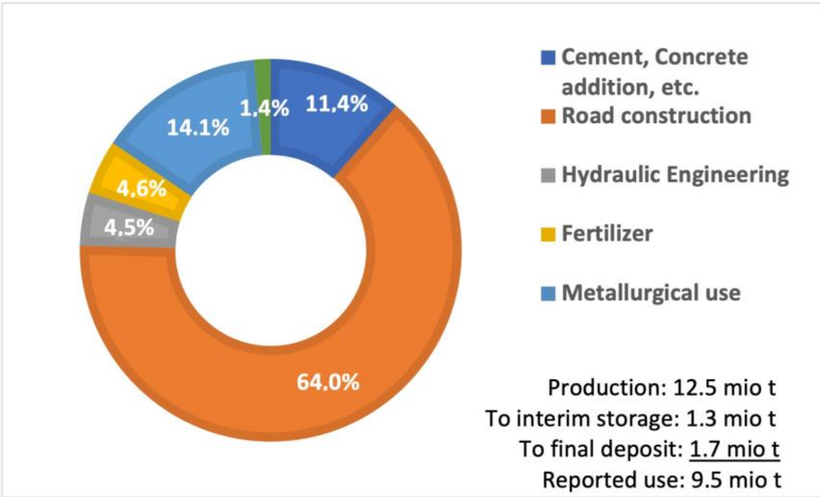

Figure 4. Use of steel slags in Europe in 2021 [4].

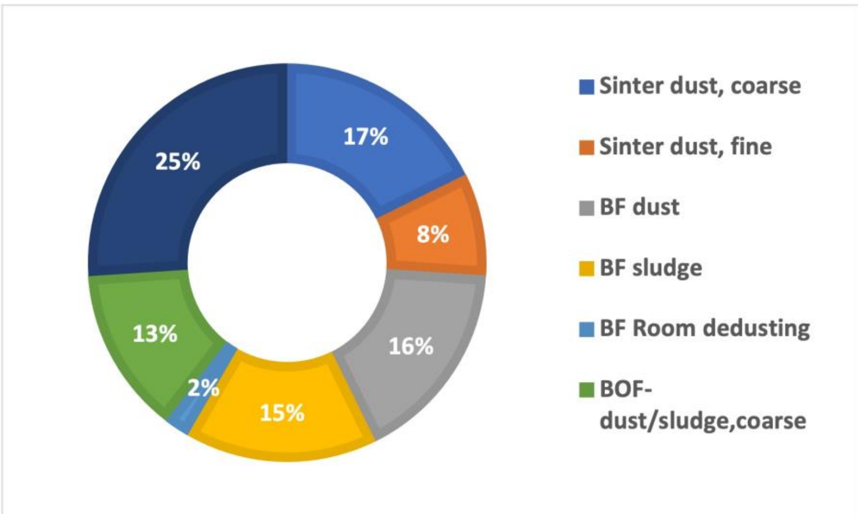

Figure 5. Production of dust/sludge BF in 2018.

This survey showed that around 80% of steel dusts and sludges are internally recycled or used for other purposes, while more than 18% are still disposed in landfills (Figure 6).

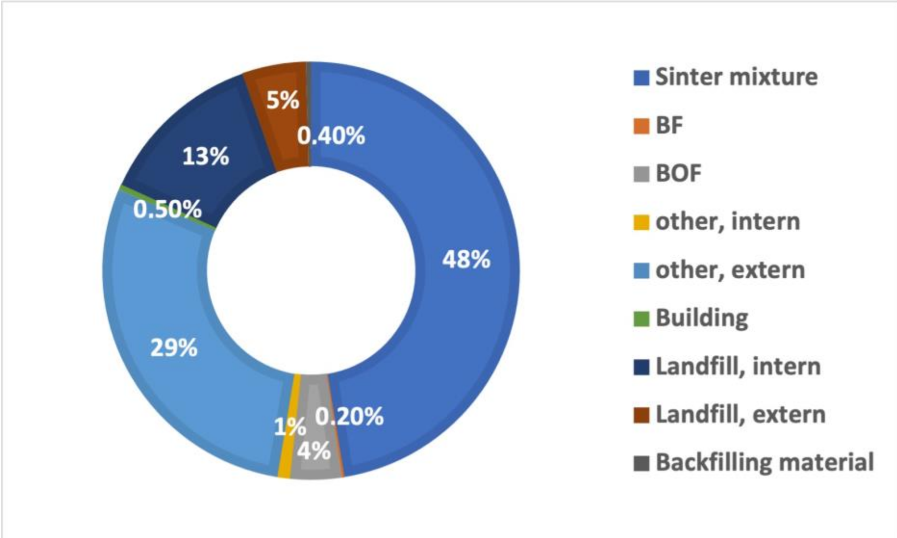

Figure 6. Industrial utilization of dust and sludge in 2018.

According to EU production of crude steel (LS) in 2018 (167.7 M tonnes from BF/BOF and the EAF route), the amount of sludge and dust is estimated to be 6.8 M tonnes/year in EU [16]. Dust and sludge streams and their uses addressed are summarized in Table 1.

Concerning the **BF/BOF route**, pellets or sinter are produced from fine ores and iron-containing residues following the reduction of ores, sinter and pellets to hot metal (pig iron) in the BF and refining in BOF and the secondary metallurgy to steel. In the European steel industry [16], dust and sludges from BF/BOF route are used in different ways [3,17,18]. Dust and sludge are mainly used for internal processes or moved to external sites for further processing. However, some, such as parts of the sinter dust, are still sent to landfill due to high heavy metals and metal chlorides content in fine fractions. Sinter dust and sludge are mainly recovered within the integrated steel plant, and a part is recycled back to the sinter plant, where it is used as sinter raw material. The rest is landfilled, as mentioned above. BF dust (coarse) can be internally used due to its high iron carbon content (mixed and granulated in sinter raw material, pelletized/briquetted in BF burden or injected to BF via tuyere). BF sludge (fine) is used internally (dezincing pre-treatment by hydro cyclone, afterwards mixed and granulated in sinter raw material, briquetted in BF), externally (dezincing: shaft furnace—Oxycup, DK Recycling—Waelz process) or sent to the landfill. BOF dust (coarse), with low zinc content, is internally used in the sinter plant, BF and BOF. BOF fine dust/sludge can be used externally (dezincing: shaft furnace (Oxycup, DK Recycling) process) or sent to the landfill due to high zinc levels and fine particles that are problematic to charge [17].

The dust generated in the **EAF-route** is around 15–30 kg per tonne of crude steel. It is collected by primary and secondary dedusting systems and generally separated by bag filter systems [18]. EAF dusts mainly contain iron oxide, with an iron content of up to 45% Fe for carbon/low alloyed steel production and up to 65% Fe for high alloyed and stainless steel production. In addition, all EAF dusts contain CaO (usually up to 20%), MgO, MnO, SiO_2 and Al_2O_3 (which are important compounds for slag forming). Depending on the scrap charge composition, EAF dust from carbon/low alloyed steel production contains a large amount of zinc oxide (21–43% Zn), and the Pb content can also be high. Consequently, EAF dust can be a resource for Zn recovery. On the other hand, EAF dust from high alloyed or stainless steel production contains lower amount of Zn and Pb but high amounts of alloying components, such as Cr and Ni, which can be recovered.

In the last few years, the fraction of produced EAF dust that was recycled has increased. In particular, in 2018 in central Europe, almost 97% of the EAF dust was externally recycled, mainly for metal recovery [15]. EAF dust, coming from carbon steelmaking, is usually externally processed for zinc recovery through the pyrometallurgical Waelz process (rotary kiln). The Waelz process accounts for around 80% of the total worldwide recycled EAF dust, recovering around 90% of the total zinc content in the EAF dust. Compared to others, Waelz process presents several advantages, such as simplicity (one-step process) and low energy consumption. Some remarkable disadvantages of the Waelz process are represented by the relatively low quality of the produced zinc (Waelz oxide still contains significant amounts of chlorides and fluorides) and the high amount of the newly generated iron-bearing slag (approx. 700–800 kg/t of charged EAF dust), which cannot be used to recover iron. However, the Waelz process is the most economical when operating on a large scale, hence serving several mills [19]. EAF dust from high alloy/stainless steelmaking is usually externally processed (by pyrometallurgy in submerged arc furnace (SAF) or plasma furnace (e.g., SCANDUST®)) to recover Cr and Ni in the form of ferroalloys.

During steelmaking, 2 to 8 kg of **mill scale** per tonne of crude steel are generated, and the total annual amount of mill scale is 0.3 and 1.3 million tonnes per year. The mill scale is generated during steel slabs reheating in pusher furnaces or bogie hearth furnaces. Due to the high temperatures in this environment (above 1200 °C), the iron surface of the steel slabs reacts with the atmospheric oxygen by forming iron (II)/(III) oxide (scaling), called "primary scale". When the scaling process takes place in the slabs' hot rolling, the resulting mill scale is called "secondary scale". Mill scales and their uses addressed are summarized in Table 1. Primary and secondary scale differ in their grain size and grain composition: primary scale is coarse-grained and porous, while secondary scale is rather fine-grained [20]. As secondary scale is produced during hot rolling, it contains oil due to contact with the rolling emulsion. Collecting the primary and secondary scales separately, the oil-free scale can be directly recycled via the blending beds as a ferrous secondary raw material in the sintering process. For reusing the oil-containing secondary scale, different processing technologies have been tested/investigated via the BF or the (Linz–Donawitz) LD converters, for instance, as an injection agent into the BF or as mill scale briquettes that can be used in an LD converter. However, the reuse of oily mill scale is limited, and treatments are required for removing oil and other components. Usually, washing treatment followed by material preparation for dosing the treated mill scale in the metallurgical units of an integrated steelwork can be applied [20]. In order to recovery metal from mill scale, the IPBM (in-plant by-product melting process) project [21] aimed at transforming mill scale and other by-products into value-added products with a smelting reduction vessel while recovering metal to be reused in the steel production. Furthermore, mill scale can be externally used in other sectors [22]. In the cement sector, mill scale is added to the combustion area when manufacturing cement clinker converts unwanted and potentially dangerous hydrocarbon gases into less volatile gas products. In addition, mill scale can be used in cement clinker manufacturing by mixing it with feedstock materials before introducing raw material into the heated rotary kiln. Furthermore, mill scale can be used in counterweights (used in cranes, elevators, draw bridges, lift trucks), ferroalloy production, production of friction agents as well as production of refractories, welding electrodes, iron salts and iron oxides.

In the steel industry, **refractories** have different compositions and can be used for different purposes, such as vessels, furnaces, components for flow control and for different operating practices. Refractories used in steel industry present a common composition, with high alumina, magnesia, dolomitic and silico-aluminous classes of such materials. The annual production of refractories amounts to around 35–40 million tonnes, with 4.3 million tonnes of products supplied to EU countries and 2.6–3.0 million tonnes supplied to the steel industry [23]. In the electric route, there is a refractory consumption of about 5–7 kg/t, while, in integrated route, there is a 30–40% higher demand, with a consumption of 8–10 kg/t [24].

The main way to recycle spent refractories is to use them as slag conditioners in different steel furnaces, such as EAF and BOF [25]. Refractories streams and their uses addressed are summarized in Table 1. Metallurgical and dolomitic lime is commonly used in the EAF slag to reduce the corrosion of the MgO-based refractories lining the internal part of the furnace. For this reason, dolomitic lime is often replaced by spent MgO-C refractory [26]. This approach has been pursued in different industrial applications since the early 2000s within the EU and in other countries as well. For instance, in Italy, special injectors for the introduction of mixes of ladle slag/spent refractories (from dolomitic ladle and tundish linings and from EAF hearth) in the EAF are used [27,28]. In addition, in Sweden, ground and sized (5–25 mm) MgO-C bricks are used and charged together with the scrap charge in partial substitution of calcined dolomite [29]. On the other hand, the addition of recycled MgO-C aggregate as the component of new type of MgO-C refractories does not deteriorate their properties [30]. More recently, the interest for the spent refractories reuse was confirmed by the H2020 Integrated Refractory and Steel Recovery (ReStoRe) project started in 2019 [31]. An industrial process, the ReStoRe technology was developed, consisting of a series of steps from spent refractories to obtain materials that can be reused in steelmaking to replace raw materials, such as lime and dololime, bauxite and even metallic scraps. The achieved benefits in the ReStoRe process can be summarized as follows [32]:

- Basic materials in spent refractories (around 50% of granular materials recycled) can be used in EAF or converted as a substitute of the lime (usually containing calcium oxide and/or calcium hydroxide) and dololime (mainly containing calcium and magnesium oxides). The possible partial substitution of fired lime and calcined dolomite with adequate quantities of granulated materials obtained from spent refractories (refer to Table 2, Fines 1, Fines 2 and Fines 3) with the aim of obtaining EAF slags with characteristics suitable for the process has been theoretically evaluated within the project activities.
- Aluminous materials contained in spent refractories (around 40% of high alumina fluxes restored in the process) can be used as substitute of alumina fluxes for slag conditioning/forming.
- Spent refractories, containing about 5% of steel scrap, after separation, can be directly reused in the steelmaking process.
- Only 5% of the collected refractory materials are disposed in landfill.

Table 2. Average chemical analysis of materials reused in ReStoRe project compared with fired lime and calcined dolomite used in steelworks [31].

	MgO [%]	CaO [%]	Al_2O_3 [%]	SiO_2 [%]	Fe_2O_3 [%]	Details
Fines 1	50	46.1	0.8	2.2	0.9	Granulated dolomia based (5/50 mm) from exhaust refractories
Fines 2	88.1	1.6	7.1	1.1	1	Granulated magnesia based (5/50 mm) from exhaust refractories
Fines 3	86.3	1.7	8.7	1.4	1	Granulated magnesia based (5/50 mm) from exhaust refractories
Ref-1	0.8	99	0.3	1	0.2	Fired lime 5/50 mm
Ref-2	27	72	0.4	1	0.2	Calcined dolomite 5/50 mm

Although the closed loop presents significant advantages from a circular economy perspective (e.g., reducing landfilling, saving raw materials, reducing CO_2 emissions), with this approach, it is difficult to meet the high quality demands of refractory producers. This is due to the typical contamination of the refractories after their use [33]. To this aim, the closed-loop approach requires an initial classification and pre-sorting stage, aiming at a first fundamental separation of all the residues included in the spent refractories stream. The pre-sorting per refractory type stage is a manual operation, requiring adequate knowledge of the refractory characteristics (e.g., the colour) and related expertise of operators [34]. In the last few years, laser-induced breakdown spectroscopy (LIBS)-based systems were also used to this aim. For instance, the European FP7-project REFRASORT aimed at developing a new LIBS system purposely designed to avoid/minimize the disturbance of material identification caused by surface contamination [35]. After the pre-sorting step, a process consisting of crushing/grinding/sieving/purifying of the pre-selected spent materials is carried out to obtain the materials to be reused. This process must be more selective as a high purity degree of the recycled products is needed to obtain valid substitutes of virgin materials.

Residual materials from other industries and businesses can be used as **secondary raw materials** in the steelworks. These materials are alternative carbon sources (e.g., biomasses [36] and plastics) and residual material from the base metal industry.

Concerning **biomass** as secondary raw material, the S2Biom ("Delivery of sustainable supply of non-food biomass to support a "resource-efficient" Bioeconomy in Europe") project [37] is based on non-food biomass material from different sources, such as forestry, agriculture and wood industries, that have been calculated based on harvest levels in a 50-year period. The amount of residues in 2020 within EU28 included:

- 39 million tonnes for forestry
- 88 million tonnes for secondary residues from wood industry
- 90 million tonnes for biowaste
- 16 million tonnes for post-consumer wood.

Due to the increasing interest of many industries in replacing fossil fuel and carbon with biomass, residual materials are less available for using in steelmaking processes. For instance, it has been estimated that, in 2045 in Sweden, the total demand of biomaterials will be 30% higher than their availability [38].

Concerning smart carbon utilization (SCU), the fossil carbon is progressively substituted by using alternative carbon materials that do not affect either the process (e.g., energy) or the quality of the product. In particular, alternative source of carbon can be either biogenic or goods at their end of life. Other external residual materials include sludge and other waste material from the pulp and paper sectors [39,40].

Biomass coming from agriculture or forestry before application needs to be processed (e.g., torrefaction [36] or biochar production) to improve its performance. On this subject, a new system to inject biochar in EAF is currently settled and evaluated [41]. Both biomasses and sludges containing carbon need to be upgraded with a pre-treatment before being used as carbon source in iron and steel production [42]. Different thermal pre-treatment techniques are available [43]. Torrefaction of the biomass, in an inert atmosphere with mild pyrolysis, results in friable and dusty material, which is pelletised after adding a binder [44]. Hydrothermal carbonization (HTC) is a thermal pre-treatment performed in a pressure vessel at 200–300 °C and resulting in hydrochar. Compared to torrefied biomass, hydrochar is less dusty and no binder is needed to produce a pellet [44]. Thermally pre-treated biomass is torrefied biomass used for injection in the BF [45,46], while torrefied sawdust was tested as addition in the briquettes to BF [47] and briquettes containing an addition of hydrochar pellets produced by HTC technology, charged at the top of the BF during hot metal production [48].

Plastic as secondary raw material can be considered as alternative carbon source in steelmaking. In the last decade, plastics production has grown by 50%, and this growth is expected to continue in the next few years. In advanced economies, packaging represents a major use, followed by construction and automotive sectors. The current annual use of plastics in Europe is around 100 kg/person and in North America is around 140 kg/person. The amount of post-consumer waste plastic collected in Europe was 27.1 million tonnes, of which about 27.3% was disposed [49]. This includes low grade mixed plastic products with no market application. Using waste plastic (WP) in steel production can contribute to waste recycling and CO_2 emission reduction due to additional hydrogen input. However, the inhomogeneity of WP physical and chemical properties must be considered. Furthermore, different polymer types can contain different metallic and mineral impurities, including harmful elements [50]. In this regard, WP can be used in ironmaking technologies as follows:

- Gasification and subsequent injection of generated reducing gas [51];
- Embedding in raw materials (self-reducing pellets, composites, coal blend for coke-making, fuel for sintering) [52];
- Direct use by injection via tuyeres [50].

Up to now, the use of unexploitable fraction of WP for EAF operations represents the new challenge for steel production in the near future.

3. Information Gathering

In the REUSteel project, 45 projects were selected for review (among which 36 had final reports available) dealing with different research topics that are linked together by an overarching framework [53]. In particular, the number of research topics per residue/by-product (i.e., slag, sludge, dust, refractory, mill scale, other residual materials, secondary raw materials) in the projects was subdivided by internal, external and other use (Figure 7). Projects funded by other European, national or regional resources or carried out by companies without public funding were not taken into consideration in the evaluation work as they were out of the scope of the project.

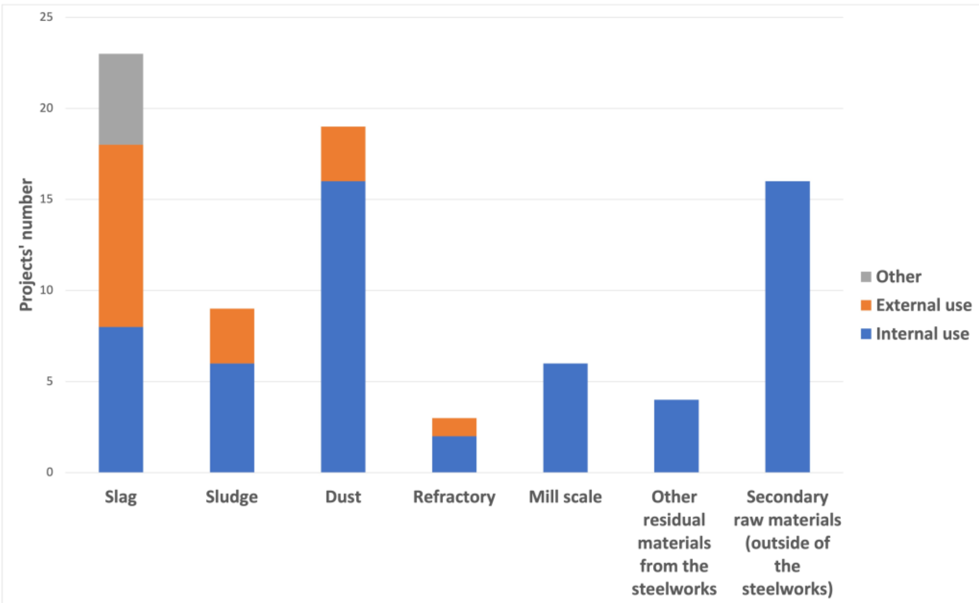

Figure 7. By-products based on type of use/recycling [54].

Concerning the research topics in the assessment of EU projects, the number of projects dealing with slag, dust or secondary raw materials from outside the steelworks was similar. The number of slag research projects was the highest because slag is by far the residual material that is produced in greatest quantity by steelworks. For slag, the applications were divided into internal, external and other slag uses. Concerning sludge and dust, the number of research topics was also high, which meets the demand and is geared to the internal utilisation. In addition, the mill scale research topics are mainly oriented towards their internal use. The number of research topics on secondary raw materials from outside the steelworks was also high, even if it does not include topics on scrap recycling.

After the critical analysis of EU research projects in the last 15 years, feedback from seminars and workshops held within the project were considered for future work of the projects [54,55]. In particular, in order to identify the areas of reuse and recycling of by-products and residuals in the steel sector that are in the greatest need of research, a questionnaire was set up involving specialists from industry and research institutes. They were provided the option to vote for any number of given topics and to make remarks in an open text on their current interests in the different research topics.

The questionnaire was set up to identify areas of reuse and recycling of by-products and residues in the steel sector for which the research demand is higher. The survey was launched during the REUSteel webinars, which were held in June 2021, and through the network of the European Steel Technology Platform (ESTEP) and the European research institutes working in the steel sector. The survey was also used to identify the most relevant topics for future research activities.

The questionnaire included the question “In which areas do you see a need for research?” to provide an assessment for which materials the respondents identify as greatest needs, enabling the selection of the following recycling uses. The participants could then choose which use they envision for the respective materials:

- internal slag recycling and valorisation outside the steel production cycle;
- extraction of valuable material from waste and wastewater;
- internal and external recycling of Fe-bearing by-products different from slag
- internal and external recycling of by-product with other beneficial and valuable contents, such as metals, coal and lime.

Other research needs to be applied to all categories of by-products and residual materials could be chosen:

- elimination of harmful elements;
- minimisation of waste generation and landfill;
- process integration solutions for by-products management;
- modelling and simulation.

The type of organisations involved and their business areas were investigated, reaching 66 valid answers from experts working in large companies (50%) or research institutes (41%). Most participants (77%) work in the steel sector, while the remaining 23% is distributed among other sectors, such as cement, chemical, base metals, ceramics, waste management and renewable energies.

The short-term research needs of the steel industry were based not only on the literature review and survey results but also on interviews with relevant stakeholders in the steel sector. In order to identify the research needs related to each category of by-products and residuals material in the next 10 years, the designed roadmap is based on evaluation of current industrial utilisation, the challenges based on the CE targets and prevention of CO_2 emissions as well as the results of the questionnaire and interviews. In particular, research needs were designed according to the main categories of by-products and residual materials. The main categories were structured into subcategories by analysing research needs for both the existing production routes (BF/BOF route and EAF route) and new process routes for decarbonised steel production. In addition, research needs on modelling and simulation techniques to be applied to all categories of by-products and residual materials were considered and analysed by considering the most significant achievements in recent years [54].

4. Research and Development Projections

The results of this work were mainly focused on the roadmap for by-products and residual materials, which is based on the industrial research needs and refers to the next 10 years. Although the roadmap is highly affected by the roadmap for CO_2 emissions reduction, it focuses on optimizing internal recycling or external valorisation of residues and by-products as well as on reducing harmful elements and recovering valuable components from residues and landfilling [56]. In the short term, the existing integrated steel plant route cannot include novel C-lean technologies; it will continue to operate on a carbon basis. However, the main challenge consists of implementing process-integrated solutions enabling economic low-carbon steel production. For instance, some possible solutions consist of using:

- hydrogen-rich auxiliary reduction gases (C_nH_m) injected via the tuyere;
- charging scrap via the burden;
- biogenic/alternate carbon sources that can partly replace fossil carbon resources.

Consequently, the amount of used residues and by-products will be affected and will require both revision of current recycling routes and implementation of new ones. In the next 10 years, new processes to produce natural-gas- or hydrogen-based direct reduced iron (DRI) and the subsequent melting in electric furnaces will be implemented. This will require further studies on the features and operational behaviour not only of possible raw materials but also of generated by-products and residues. In addition, in the medium- and long term, new production routes will also be developed, such as alternative smelting reduction processes, e.g., the iron bath smelting reduction (IBSR) and hydrogen-plasma smelting, as well as iron ore electrolysis that can be operated on a CO_2 lean process mode. Moreover, these new production routes will produce residues and by-products with new properties. Therefore, new methods for the internal utilization and based on existing knowledge and available processes must be developed. In addition, further investigation will be needed to meet the requirements for external by-product recycling. Considering the differences among existing and new process combinations, future significant research will need to deal with many possible options.

By providing an overview of research needs, the outcomes of the questionnaire, carried out within the REUSteel project (overview of the results shown in Figure 8), help in identifying the perceived demands for future research investigations concerning by-product/residual materials [54]. As shown in Figure 8, all steelmaking slags (BOF, EAF, LF) are of interest. In addition, all EAF-related topics are of major concern, such as slag, dust and sludge. In particular, EAF is the category in the greatest need for research activities according to the participants' indications. Furthermore, among the other categories, refractory and oily mill scale stand out.

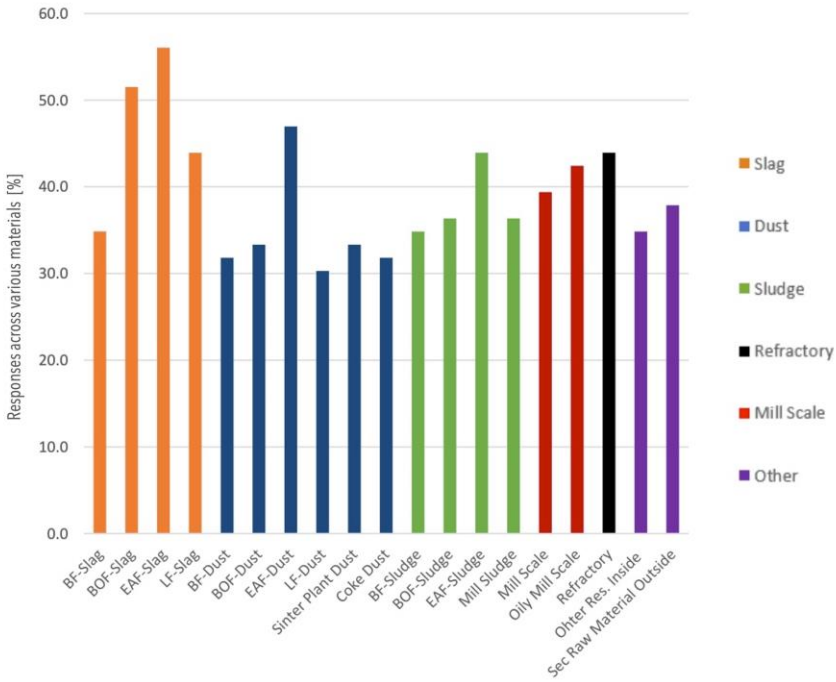

Figure 8. Responses providing an overview of research needs across by-products/residual materials [54].

The main results are presented in the following sub-chapters, which concern the identified by-products categories, e.g., slag, dust/sludge, mill scale, refractory and secondary raw materials. Furthermore, modelling and simulation provide general research needs that can be applied to all categories.

4.1. *Slag*

Past and current research activities, such as RFCS projects, have been mainly dedicated to the currently produced slag, in particular BOF slag. In the near future, the EAF route will increase its production, which will result in increased EAF slag production and decreased BOF slag production. In addition, research needs will include all processes without carbon-based metal reduction. Consequently, research needs in the short term should be focused on recycling and using the currently produced slag. In particular, specific solutions should be found taking into account economic, regulatory, physical and environmental issues. For instance, research activities should be focused on hot slag reduction for metal recovery, modifying the slag oxides to a clean high value slag product with high CO_2-saving potential, co-processing slag with other residues and heat recovery from the hot slag. On the other hand, it will be crucial to investigate next generation slag coming from the steel production with reduced CO_2 footprint, including metal recovery from slag, which was also one of the most investigated topics in the past. However, it will be even more important in the future due to the foreseen increased production of EAF slag, which has a higher iron content than BOF slag.

Future research demands on slag, presented extensively in the following paragraphs, are summarised in Figure 9.

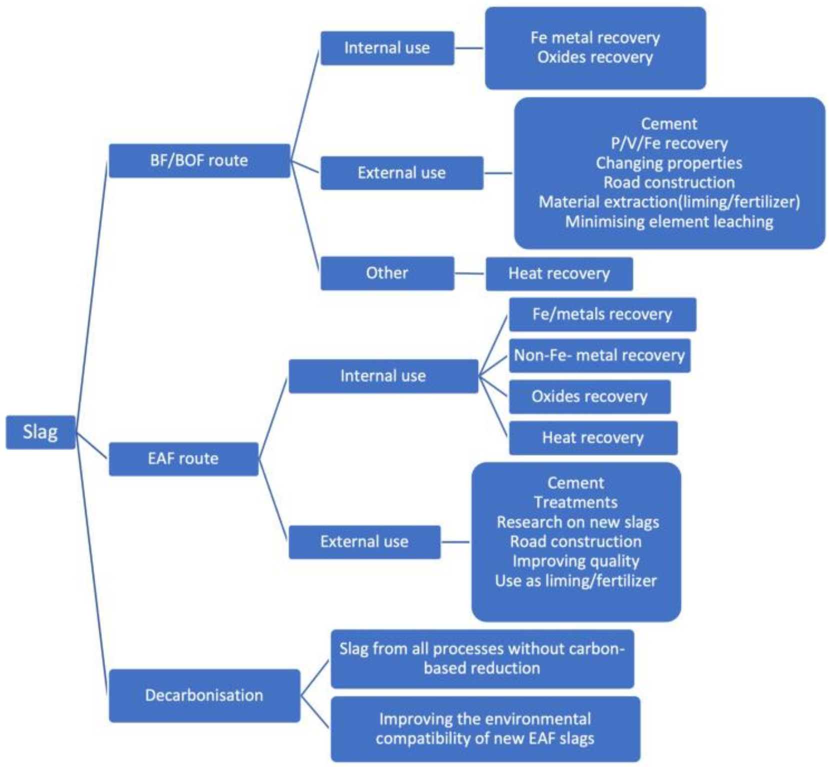

Figure 9. Future research needs on slag.

4.1.1. BF/BOF Route Slag

The current external use of BF and BOF slags includes cement and road construction. Therefore, slags management in liquid and/or solid phase aims at achieving the chemical and physical requirements. Although in the future the BF route will be stopped due to the decarbonization process, it is necessary to continue research in this area during the long transition period. The current research is mainly focused on new solutions to reduce the amount that will be disposed in landfills. Furthermore, sectors that currently use these slags will be pushed to search for new solutions to use the new slags. In this regard, to enhance recycling of BF and BOF slag, the following examples can be provided:

- Internal utilisation:
  - Recovery of Fe metal (e.g., Fe from BOF slag as scrap substitute, such as recycling into the BOF as iron carrier and cooling material);
  - recovery of oxides (e.g., FeO/Fe_2O_3 from BOF slag as iron ore substitute in sinter plant or BF).
- External utilisation:
  - cement;
  - P recovery/V/Fe and a slag product for the cement industry;
  - changing BOF slag properties to be like granulated BF slag;
  - road construction;
  - extraction of valuable material (liming/fertilizer);
  - improvement of the quality to better meet utilization requirements of slag for specific applications;
  - investigation of processes for crystallization to minimize the leaching of certain elements to reduce the amount of slag to be landfilled;
  - industrial processes for producing material for the building industry.
- Other:
  - industrial processes for heat recovering from slag.

4.1.2. EAF Route Slag

EAF slag is currently used in external applications, mainly in road construction, and it needs to be prepared in the liquid and/or solid phase to meet the chemical and physical requirements. With a view to decarbonisation, in the future, part of the EAF slag will have different chemical compositions. However, the current EAF slag still needs to be recycled to reduce its disposal and to increase its substitution of virgin materials. In particular, research demands concerning internal and external use can be summarised as follows:

- Internal slag utilisation
  - Recovery of Fe and other metals
    - Fe recovery without carbon-based reduction or with biogenic carbon;
    - Recovery of Fe for internal utilization (e.g., recycling in the EAF);
  - Recovery of non-Fe metal (e.g., hot slag reduction for Ni/Cr/Fe/Mn (stainless slag) or P recovery/V/Fe/Mn (C steel) and for the cement industry);
  - Recovery of oxides (e.g., substitution of lime with LF slag to EAF, LF slag internal recovery for refractory applications);
  - Heat recovery from EAF and LF slag.
- External slag utilisation
  - cement;
  - treatment (reduction, modification, granulation) to create hydraulic properties for Portland cement and to reduce CO_2 emissions in cement industry;
  - research on slag during transitions to H_2 ironmaking;
  - construction materials for road construction, earthworks, rail and hydraulic engineering (e.g., improving properties by decreasing leaching of specific elements, volume stability, etc.);
  - improving the slag quality to better meet requirements for its recycling;
  - investigation of slag use as liming/fertilizer material on long-term effects on soil and plants.

4.1.3. Decarbonisation

The current use of slag is mainly focused on external applications. Thus, slag (both in liquid and dry form) adjustment aims at meeting requirements (chemical or physical properties) for specific applications in different countries. In the near future, due to the commitment of the steel sector to decarbonisation, new technological processes will be implemented and new slags will be produced. For this reason, new research needs for new technologies will arise to evaluate the chemical, environmental or physical properties of these new slags to meet the requirements or new utilization paths.

In the near future, DRI-based EAF slag and slag from the submerged arc furnace (SAF) will mainly be produced. In particular, due to the high demand from the cement industry for by-products and due to the decreasing amounts of granulated BF slag, there will be a need for metallurgical treatment of new slags to meet these demands. On this subject, in view of the decarbonisation process, some relevant research trends on slag utilization to increase its recycling rate are as follows:

- Research on slag from all processes without carbon-based reduction:
    - slag from a DRI–EAF route, considering slag conditioning and treatment as well as the utilization of low-grade ore and recycling material as feedstock;
    - slag from DR/SAF/BOF route, considering also slag conditioning and treatment as well as the utilization of low-grade ore and recycling materials as feedstock, to produce a material similar to granulated BF slag;
- Research to improve the environmental compatibility of new EAF slags for different applications.

4.2. Dust and Sudge

As for the other by-products, research needs on dust and sludge recycling will be focused, in the short term, to increase their utilization within next generation steel production processes with reduced CO_2 footprint. Through the analysis of European research projects as well as the questionnaire to relevant stakeholders, both continue research trends (particularly on their internal recycling to use the high iron and carbon contents) in the short term and new needs have been identified. In addition, new research on recycling of dust and sludge will aim at developing new measurement and data collection methods to support the operator and to improve processes.

Future research demands on dust and sludge, presented extensively in the following paragraphs, are summarised in Figure 10.

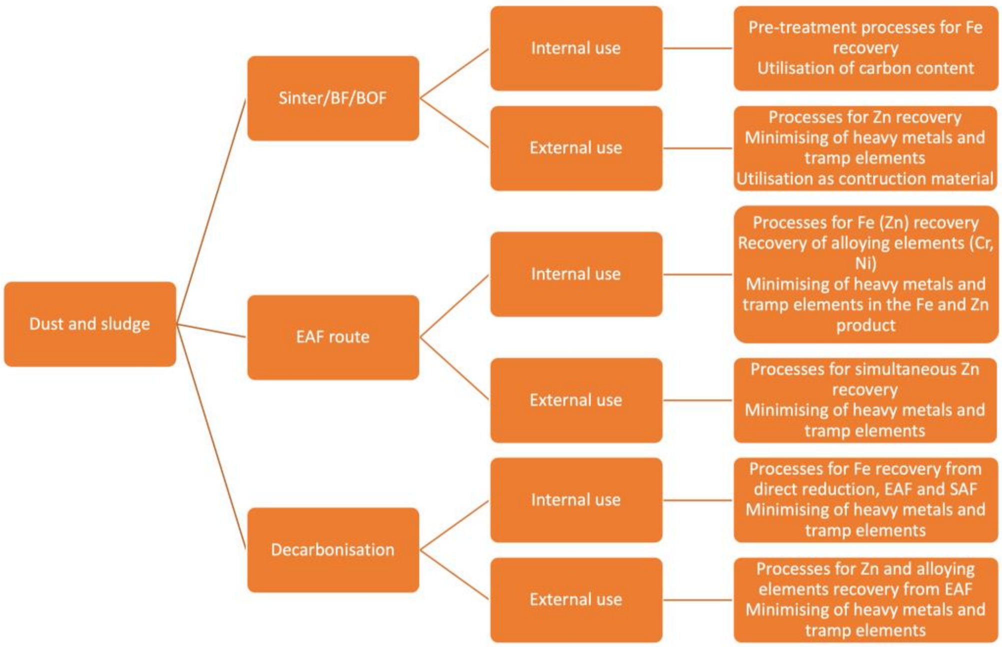

Figure 10. Future research needs on dust and sludge.

4.2.1. BF/BOF Route Sludge and Dust

Evaluating the EU research projects showed that the internal recycling of dust and sludge in the sinter plant, BF or BOF, through the addition into the processes after upgrading, is already in progress and applied. However, the survey results revealed that the research on internal recycling of BF and BOF dust and sludge is considered important, followed by the research on harmful elements elimination.

- Internal utilization

One of the challenges consists of improving the use of sinter, BF and BOF dust and sludge with low zinc content to recover Fe metal, oxidic and carbon components in the sintering raw mixture. Research is still needed to optimize the agglomeration of challenging material with different chemical compositions, morphological surface properties and wide ranges of particle size and form as well as optimizing the use of binder and adapted to the boundary conditions. Coarse dust with high iron percentage, on the other hand, can be used as raw materials in sintering and BF or BOF.

For the internal utilization in the BF or BOF, different briquetting processes have been investigated, including different Fe-bearing residues and reactive carbon containing sources, as well as binders for improved briquette properties, such as increased hot strength. These pre-treatment processes still need to be optimized according to plant-specific boundary conditions. In addition, one of the future aspects will include the use of biogenic CO_2-neutral alternative carbon carriers to reduce CO_2 emissions and optimize the BF process.

In addition, the research on injection of residues from BF and BOF for the recovery of iron and other oxides, as well as the injection of alternate carbon sources into the tuyeres of the BF, has to be continued. Furthermore, this research will include suitable preparation of residues for conveying and injection. The effort should be focused on chemical and thermal utilization within tuyere, raceway and within the furnace.

There is also need for research on the internal use of the fine fractions of dust and sludge, containing high fractions of iron and carbon, as well as zinc, a valuable is component detrimental to the iron making process. Other dusts and sludges are also contaminated with further detrimental components, such as phosphorus and alkalis (i.e., oxides or chlorides). In addition, recycling dust into BOF or secondary metallurgy will be based on the generation of self-reducing pellets, replacing scrap charging to the BOF or adding alternative additives for metal treatment.

- External utilization

Investigation on the recycling via external upgrading processes is recommended to be continued in the near future. One of the main problems is the zinc content in fine dust fractions and sludges, which reduces recycling of valuable compounds, leading to disposal in the landfill. For this reason, applying mechanical and thermal treatment and pyro- and hydrometallurgical processes should be developed to remove zinc and produce a valuable zinc product and iron-rich fraction to be recycled. In addition, it is fundamental to improve hydrometallurgical, dry and hydro-mechanical magnetic and thermal separation processes in order to reduce heavy metal, alkali and chloride content of residuals from sinter plant, BF and BOF off gas cleaning.

4.2.2. EAF Route Sludge and Dust

Concerning the EAF route, some aspects and related technological issues can be highlighted as follows:

- Pyrometallurgical processes
  - optimizing the separation of iron from other (high volatile) oxides using dedicated furnaces operating in reducing conditions;
  - using briquettes and/or pellets, including EAF dust and other fine steel by-products;

    - self-reducing briquettes using carbon from alternative sources (e.g., biochar). Using innovative technologies for facilitating the reduction process of reducible oxides (e.g., FeO);
    - optimization of the synergy between procedures allows obtaining hot metal and/or metallic alloys to be reused internally, inert slag to be reused externally, ZnO-enriched dust to be treated for valuable metal recovery;
    - innovative microwave heating technologies allowing the efficiency increase of the pyrometallurgical process;
    - the use of devoted reducing furnaces for pyrometallurgical processes operating in parallel with EAF as a valid option to be implemented for serving single steel mills.
- Hydrometallurgical processes
    - different leaching solutions can be proposed, i.e., based on ammonium chloride ready for industrial implementation;
    - an integrated pyro/hydro metallurgical process to obtain the pre-selection of the different fractions, thus on the yield of obtained product (metallic zinc having high purity as main objective);
    - recovering residues from the different stages of the hydro process, containing Pb, Ni, Cd, Cu, Al, Si as oxides or as different species according to the different leaching methods (e.g., sulphates);
    - considering possible new options facilitating the leaching process (e.g., the ultrasound-assisted sulphuric leaching that allows maintaining the process efficiency as dissolution of franklinite at lower acid concentration);
    - implementing hydrometallurgical plants fitted for serving a single steel mill.

Finally, an integrated pyro/hydro metallurgical process can be a valuable possibility to recycle EAF dust and other steel by-products. Designated pyro/hydro metallurgical plants working in parallel with the EAF are the best solution. Furthermore, a hydrometallurgical or a combined process with zinc electrowinning at final stage presents significant advantages. In particular, the zinc product (zinc metal) can be reintroduced into galvanizing plants in steelworks, resulting in CE improvement in the steel industry.

The external use of EAF dust is usually conducted in large centralized plants (e.g., Waelz process), resulting in the enriched zinc oxide production, used as raw material in zinc metallurgy. However, this use should be further investigated to achieve a more efficient process. Future iron recovery from the EAF dust will become more important to reach the "zero-waste" goal. In particular, this could support large-scale recycling technologies, such as the rotary hearth furnace (RHF) or the multiple hearth furnace (MHF), that, compared to the Waelz process, can recover iron in the form of DRI. In addition, research could be needed for iron recovery from Waelz slag. Further investigations concern use of carbon-based processes that, combined with carbon capture and utilisation/carbon capture and storage (CCU/CCS) technologies, can avoid CO_2 emissions and are appropriate for zinc separation (e.g., HiSarna/Reclamet process).

4.2.3. Decarbonisation: Sludge and Dust

Research needs for improving and increasing residue and by-product use, according to the decarbonization of integrated steelworks, include investigations on pre-treatment and utilization of BF dust and sludge, as follows:

- partial replacement of fossil coal and coke by pre-treated biomass and plastic wastes;
- partial replacement of iron oxides by suitable scrap as secondary raw material;
- injection of hydrogen-rich reduction gases or other carbon sources in the BF.

In the near future, the (hydrogen-based) DR/EAF route is expected to replace the BF/BOF route. Consequently, future recycling topics will be focused on internal use of dust or sludge from the DR plant, as follows:

- recovering the contained iron after application of agglomeration (palletisation, briquetting) for recycling these fine-grained residues into the DR plant or the EAF.
- recycling of DR plant dust/sludge to the same plant through briquetting technology [3], involving tests of new organic or inorganic binder systems to optimize the size of briquettes, the thermal stability and reducibility as well as the selection of a continuous agglomeration device, such as a roller press.
- The implementation of the DR/EAF route would result in the newly upcoming DR-dust and in an increased amount of produced EAF or SAF dust. Nevertheless, this EAF dust will contain low zinc, which can be recycled back to the DR plant or the EAF.

Finally, in order to mitigate CO_2 emissions, electrical processes (e.g., electric furnaces such as EAF, SAF, plasma furnace or hydrometallurgical electrowinning) would be advantageous as they are nearly carbon neutral, especially when they use 100% "green" electricity.

4.3. Mill Scale

Concerning the mill scale, Figure 11 summarises its future research demands.

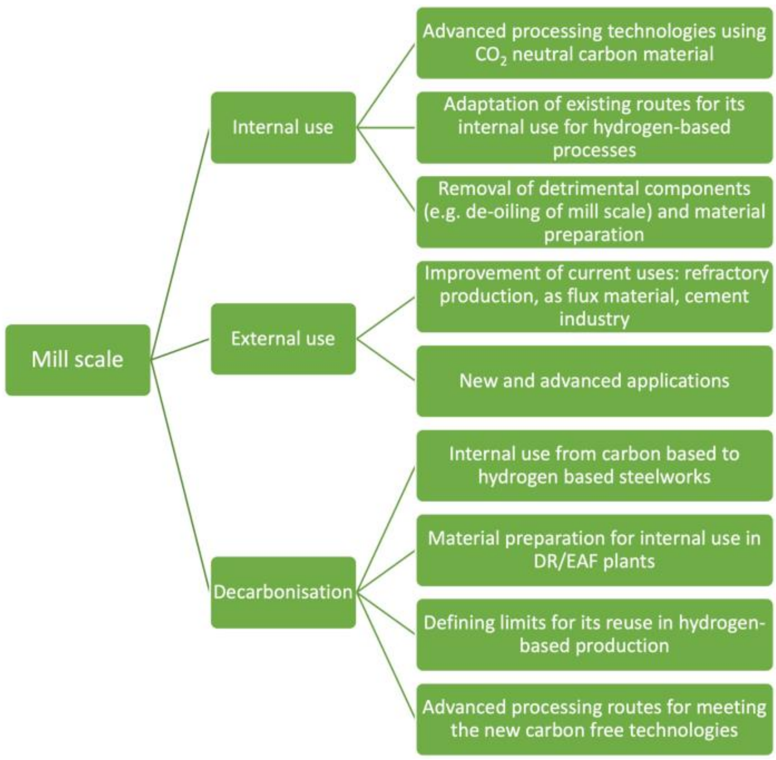

Figure 11. Future research needs on mill scale.

Internal utilization

Concerning the mill scale, the outcomes of the REUSteel questionnaire showed that, in the steel sector, research demands focus on its internal recycling. This topic was highlighted by 23% of the participants especially with respect to CO_2 neutral solutions, while other topics concern extraction of valuable materials from mill scale (18%) and process integration solutions (17%). In particular, advanced compacting and processing technologies and processes using CO_2-neutral carbon material (e.g., biomass) must be investigated. In addition, existing routes for mill scale (and other waste iron oxides) internal utilization will need to be adapted for hydrogen-based steelmaking processes. However, topics of past projects need to be further investigated as well. In particular, removal of detrimental components (e.g., de-oiling of mill scale) and material preparation for dosing in metallurgical units represent relevant topics.

External utilization

Past applications for external utilization of mill scale are its use in the refractory production as flux material or in the cement industry for manufacturing of cement clinker. However, new and advanced applications for external utilization of mill scale represent an important challenge for future research activities, as shown by the outcomes of the questionnaire, where the external valorisation of mill scale was indicated as an important topic (20%) for research in the steel sector.

Decarbonisation

Although new reduction technologies, such as hydrogen-based DR, will replace in the next few decades the conventional carbon-based BF, this will not directly affect the amount of mill scale coming from the integrated route as the rolling process will continue to operate. Nevertheless, the internal utilization will change due to technological shift targeting CO_2 mitigation, such as hydrogen-based DR technology. New research activities will be developed for new internal utilization routes of mill scale. In this regard, future topics for research activities can be summarised as follows:

- developing internal utilization routes for mill scale and other waste iron oxides from carbon-based to hydrogen-based integrated steelworks involving processing of these residues in the DR plant (shaft furnace) or in the electric furnace for DRI melting (EAF or SAF);
- developing advanced material preparation processes for internal utilization of mill scale in DR/EAF plants;
- defining limits for metallurgical reuse in hydrogen-based steel production due to presence of detrimental components;
- developing advanced processing routes for the mill scale to meet the new carbon free metallurgical technologies.

4.4. Refractory

Refractory is recycled by open-loop as slag conditioners/slag formers in the main steelmaking processes. On the other hand, in the future, the focus will be on closed-loop recycling, involving the reuse of spent refractories to produce new ones. This can result in possible abatement of CO_2 emissions deriving from processes for obtaining basic material components from raw materials (e.g., MgO from raw $MgCO_3$). In this regard, the following technological issues to be addressed by research can be identified:

- Open-loop recycling (for internal recycling):
    - developing/refining processes to select spent materials for a proper selection of the adequate mixtures to be used in different applications (e.g., grinding/sieving and sorting of the spent material);
    - evaluating through laboratory tests the behaviour of mixtures, such as slag formers and fractions from spent refractories. They include dissolution kinetics with the support of theoretical models;
    - developing/refining theoretical models for calculating kinetics and thermodynamics aspects of the mixtures, including spent refractories. These models should aim at selecting proper mixtures ensuring slag formation in due time and with adequate fluidity;
    - possible external reuse of selected fractions of spent refractories, such as cement and ceramics.
- Closed-loop recycling (suitable for internal and external recycling)
    - refining/optimising of automatic systems for identifying different classes of spent materials for a more efficient and objective sorting (e.g., methods based on cameras/laser systems, such as LIBS);

- ○ developing/refining intelligent software systems to be coupled with the optical devices. In particular, application of artificial intelligence (AI), machine learning (ML) as well as Big Data and edge computing are expected;
- ○ optimizing methods for purification of materials coming from spent refractory to achieve a purity level comparable to the correspondent virgin material.
- ○ demonstrative projects involving the use of refractories from recycled refractories, showing adequate performance in real operating conditions, to overcome the mistrust still present in stakeholders and refractory producers.

In addition, the possible use of spent refractories to produce new refractories for external industries could represent a further interesting aspect.

Decarbonization

Refractories contribute to the overall CO_2 emissions of steel production by about 3%, mainly due to the carbon content (as both graphite and pyrolytic carbon are used) to improve their resistance against thermal shock [57]. In particular, this is fundamental in processes with fast temperature changes, such as in converters, EAF and ladles, where magnesia carbon bricks are used. In addition, the thermal conductivity related to the carbon contained in the refractories materials is important [58]. Consequently, better insulation properties of the material will save energy and reduce CO_2 emissions, particularly when the electricity mainly derives from conventional sources. In order to decrease carbon content in refractories, some studies are based on the use of nano-carbon [59] allowing refractories production, such as MgO-C with proper characteristics but containing about half of the total carbon content of conventional refractories.

Research needs in the field of refractory for steelmaking processes are as follows:

- development of refractory materials with reduced carbon or carbon-free content;
- identifying adequate materials to be used as substitutes, such as graphite, pet-coke, tar-pitch, petroleum pitch;
- laboratory- and pilot-scale studies on needed refining of the new materials' chemical composition, focusing also on the possible impact on steel quality;
- laboratory- and pilot-scale studies to identify possible refinements of chemical composition to be used in process conditions involving use of hydrogen;
- developing new refractory materials and new process routes also requires adaptation of the processing methods for recycling refractory materials;

Such context is integrated in the closed-loop recycling of spent refractories, particularly improvements in selection methods for the different components of spent materials that would be beneficial to be used in new developed refractories.

4.5. Secondary Raw Materials

According to the questionnaire, a strong interest and demand for research on recycling of secondary raw material from other industries within steelmaking is perceived. In particular, biomass, polymeric residues and slags/residues from other metal industries are mentioned as well as ash from waste incineration processes and waste tires.

Concerning the use of secondary raw material from outside steelworks, the exploitation of carbon-bearing material aims at reducing the use of fossil carbon and, consequently, the fossil footprint of steelmaking processes. On this subject, it is important to consider the differences between alternative carbon-bearing materials and fossil carbon sources. These can be related to volatile matters, density and chemical interaction with iron-oxide-rich slags. Other aspects involve the required pre-treatment for possible uses, for example, agglomeration/densification forming briquettes to be charged with scrap or obtaining grains of suitable size for injection.

A smarter carbon usage, leading to a progressive decarbonization, concerns the use of biomass and biochar as substitute of fossil coal in steelmaking operations (e.g., in EAF). This will progress in the next few years, particularly managing biomass/biochar for proper charging operations. However, there is still room for optimizing injection of these specific materials, in particular for their use as foaming agents. In addition, the use of non-recyclable fractions of waste plastics is expected to increase in importance due to its thermal properties.

Concerning the research in the medium/long-term period, significant pilot/demonstration research activities of integrated technologies (e.g., pyrolysis/torrefaction of biomass with utilization of waste heat) followed by industrial implementation of biochar onsite production should be considered, particularly in EAF [60]. Some topics needing further research for implementing alternative carbon sources in EAF steelmaking were identified as follows:

- using real plastic material waste streams;
- integrating biomass treatment and upgrading with EAF processes (e.g., use of waste heat from the EAF process for biomass processes);
- charging and EAF operation when materials with high volatile matter are used (to ensure the efficient use of the alternative carbon as an energy source);
- increasing the amount of polymers blended with fossil coke for injection carbon.

In addition, using lime-containing residues can reduce the fossil footprint, the energy required and the environmental impacts due to mining operations when the need for primary lime decreases. On this subject, further research is needed to confirm the technical possibilities to use these residues at a larger scale and to study the overall environmental performance (also based on Life Cycle Assessment) and the energy aspects [39]. Finally, results from the questionnaire show that further research is needed concerning utilisation of residues from other metal industries. In particular, these residual materials can contribute to fulfil the demand for valuable metals within the steel cycle by reducing natural resource depletion and overall generation of residual materials and waste.

4.6. Modelling/Simulation for By-Products

Over the last few decades, several research activities have focused on continuous production process monitoring and control to enhance recovering and recycling of residues and by-products. This can be achieved by exploiting suitable sensing tools and advanced information processing techniques also based on AI, ML or hybrid solutions, coupling these advanced techniques with physics-based modelling.

On this subject, modelling and simulation approaches within monitoring solutions based on data analytics, as well as physical and soft sensors, represent the basis for constructing digital twins that support process advanced real-time control and optimal resource management (material and energy inputs). In particular, process data and information collected by physical sensors can be exploited by modelling and simulation tools to gather process information (e.g., status of processes, such as energetic status and efficiency of energy inputs, meltdown status of charged materials, performance of metallurgical reactions, etc., and status of by-products, such as slag temperature and composition, etc.) that cannot be assessed inline and in real time by sensors. Modelling tools can be based on analytical calculations using energy and material balances and thermodynamic calculations and on ML and deep learning (DL) techniques. Often, the most suitable modelling approach consists of combining these approaches.

Some examples of advanced simulation tools applied to improve the environmental performance of steelmaking processes concern advanced flow sheeting models developed through the Aspen Plus® suite, which are exploited to assess the viability of process integration solutions to improve by-products handling and water efficiency in integrated steelworks [61–63]. In a further application, an Aspen Plus®-based model was tuned through genetic algorithms by exploiting experimental data to test and validate innovative treatments for BF gas washing waters [64]. Furthermore, by combining advanced modelling and monitoring of the environmental impact through key performance indicators (KPI), a tool was developed to evaluate different scenarios and operating conditions for increasing slag reuse inside the electric steel production route [65].

In recent years, there is a growing consensus toward solutions for complex science and engineering problems, which integrate traditional physics-based modelling approaches with state-of-the-art ML techniques [66]. This field, also known as *physics-guided ML*, *physics-informed ML* or *physics-aware AI*, covers many scientific disciplines and includes approaches where the application of AI and ML is integrated and guided by scientific knowledge to improve performance and ensure consistency with the basic physical and chemical principles. The exploitation of these inter-disciplinary approaches for improving material reuse and recycling needs to be applied in the short/medium term.

Future research will also be focused on material characterisation and include raw materials and by-products. In particular, knowing the chemical composition of materials is crucial for materials having variable properties, such as EAF scrap. Furthermore, a careful characterization of by-products is fundamental for their future appropriate valorisation. In this regard, an ongoing EU-funded project named iSlag is currently being developed concerning online characterization of EAF slag at solid and liquid stage as well as model-based estimation of slag composition [67]. However, further research will be focused on other by-products, and AI and ML approaches represent fundamental tools for supporting material characterization. On the other hand, advanced process modelling, control and optimization tools can allow adapting both single processes and the whole production chain, management for residues valorisation and waste and costs minimization while saving and improving steel products quality [68]. Modelling, simulation and optimization approaches can be used to determine the optimal route for by-products reuse and to find information on treatments by supporting selection and validation of potential solutions to overcome technical, economical and environmental issues affecting the by-products recycling rate [69]. In addition, the combination of by-products and waste management simulations and optimization can be used by plant managers and operators for improving by-products management, such as identifying the most suitable activities for potential internal or external recovery and for their reuse. Different approaches, such as model predictive control (MPC), economic model predictive control (EMPC) or bio-inspired optimization methodologies, can be applied to improve material and energy management. In addition, advanced AI- and ML-based techniques implementation can help operators in decision making.

Coupling these optimization tools to the ever-increasing deployment of cyber–physical systems, Internet of Things (IoT), Big Data technologies and edge computing aims at improving flexibility and reliability of steelmaking processes and product quality control. Such technologies, relying on a network of sensors that collect data and tools for interpreting them, can be applied to monitor the environmental impact of production processes as well as to control the processes themselves. Furthermore, coupling such tools to advanced modelling and simulation approaches aims at supporting control and scenario analyses to evaluate environmental advantages and technical and economic feasibility of process changes and new operative practices.

Sensoring and control activities in the short-, medium- and long term aim at improving resource management and optimisation, environmental impact, product quality and productivity. The application in the short term of innovative multi-criterial optimisation tools can target different impacts. Moreover, in the medium term, the combination of optimization tools and model-based real-time control can enable rapid reaction to changing process conditions and enhanced flexibility with respect to variable external factors (e.g., raw material prices, market demand for by-products). Following such a path, in the long term, industrial demonstration and full deployment of through-process real-time optimization can be achieved.

The collected data will be used to model new processes, with the aim of assessing the viability of such processes and of the related new operating practices. This can lead to reduce the relevance of secondary working operations by providing ready-to-sell resources according to market requirements. Different modelling tools can be exploited after tuning through process data by enforcing resource and energy efficiency [70–72]. Furthermore, such modelling tools can also be embedded into processes of digital twins and advanced monitoring systems to improve energy and resource efficiency in steelworks [73,74].

To sum up, modelling and simulation show a relevant potential to support further improvements in resources and energy efficiency by contributing to environmental and economical sustainability of the steel sector and, on the other hand, by promoting cooperation with other sectors. Such approaches, in the context of IS and CE, help to establish the network facilitating the transaction of by-products and unrecovered energy. This will lead to reduce disposal of by-products and residues as well as CO_2 emissions by preserving natural resources and increasing revenues.

5. Conclusions

The present work, as part of the Roadmap developed within the REUSteel project, identifies the most urgent and demanding research directions in the coming years in the field of residues and by-products related to the steel sector. In particular, the main trends and challenges in future research and development on reuse and recycling of by-products from existing or alternative steelmaking routes were highlighted. The provided overview can be used as a support for both steel companies and companies providing services to the steel industry. This can be crucial in the investments selection mainly focused on research and development related to reuse and recycling of by-products from iron- and steelmaking. In addition, the developed overview can be a tool for policymakers, helping them to identify research topics demanding public support. This can help them to implement activities that can overcome regulatory gaps across EU countries from the perspective of CE and IS solutions. Finally, this work, as a part of dissemination activities also outside the EU of the REUSteel Roadmap, represents a valuable tool for the scientific and technical community beyond the formal project conclusion.

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References

1. European Steel in Figures 2022. Available online: https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2022/European-Steel-in-Figures-2022-v2.pdf (accessed on 20 September 2022).
2. World Steel in Figures 2021, Worldsteel.org. Available online: https://worldsteel.org/media-centre/press-releases/2021/world-steel-in-figures-2021-now-available/ (accessed on 20 September 2022).
3. Rieger, J.; Colla, V.; Matino, I.; Branca, T.A.; Stubbe, G.; Panizza, A.; Brondi, C.; Falsafi, M.; Hage, J.; Wang, X.; et al. Residue Valorization in the Iron and Steel Industries: Sustainable Solutions for a Cleaner and More Competitive Future Europe. *Metals* **2021**, *11*, 1202. [CrossRef]
4. Euroslag Statistic 2021. Available online: https://www.euroslag.com/products/statistics/statistics-2021/ (accessed on 23 February 2022).
5. European Steel Technology Platform–ESTEP. Strategic Research Agenda (SRA). Available online: https://www.estep.eu/assets/SRA-Update-2017Final.pdf (accessed on 20 September 2022).
6. Axelson, M.; Oberthür, S.; Nilsson, L.J. Emission reduction strategies in the EU steel industry: Implications for business model innovation. *J. Ind. Ecol.* **2021**, *25*, 390–402. [CrossRef]
7. Branca, T.A.; Fornai, B.; Colla, V.; Pistelli, M.I.; Faraci, E.L.; Cirilli, F.; Schröder, A.J. Industrial Symbiosis and Energy Efficiency in European Process Industries: A Review. *Sustainability* **2021**, *13*, 9159. [CrossRef]
8. Branca, T.A.; Colla, V.; Algermissen, D.; Granbom, H.; Martini, U.; Morillon, A.; Pietruck, R.; Rosendahl, S. Reuse and Recycling of By-Products in the Steel Sector: Recent Achievements Paving the Way to Circular Economy and Industrial Symbiosis in Europe. *Metals* **2020**, *10*, 345. [CrossRef]
9. Saranya, P.; Nagarajan, P.; Shashikala, A. Eco-Friendly Ggbs Concrete: A State-of-the-Art Review. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2018; p. 012057.
10. Vacková, P.; Kotoušová, A.; Valentin, J. Use of recycled aggregate from blast furnace slag in the design of asphalt mixtures. *Waste Forum* **2018**, *1*, 60–72.
11. Jiang, Y.; Ling, T.-C.; Shi, C.; Pan, S.-Y. Characteristics of steel slags and their use in cement and concrete—A review. *Resour. Conserv. Recycl.* **2018**, *136*, 187–197. [CrossRef]
12. Rodgers, K.; McLellan, I.; Cuthbert, S.; Masaguer Torres, V.; Hursthouse, A. The potential of remedial techniques for hazard reduction of steel process by products: Impact on steel processing, waste management, the environment and risk to human health. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2093. [CrossRef]
13. Skaf, M.; Pasquini, E.; Revilla-Cuesta, V.; Ortega-López, V. Performance and durability of porous asphalt mixtures manufactured exclusively with electric steel slags. *Materials* **2019**, *12*, 3306. [CrossRef]
14. Sellner, B.M.; Hua, G.; Ahiablame, L.M.; Trooien, T.P.; Hay, C.H.; Kjaersgaard, J. Evaluation of industrial by-products and natural minerals for phosphate adsorption from subsurface drainage. *Environ. Technol.* **2019**, *40*, 756–767. [CrossRef] [PubMed]
15. Drissen, P. Aufkommen und Verbleib von Stäuben, Schlämmen und Walzzunder der Eisen- und Stahlindustrie, Report. *Wiss. Des FEhS-Inst.* **2019**, *2*, 13–17.
16. Worldsteel Association. Steel Statistical Yearbook 2019 Concise Version. Available online: https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2019-concise-version.pdf (accessed on 20 September 2022).
17. Rieger, J.; Schenk, J. Residual processing in the European steel industry: A technological overview. *J. Sustain. Metall.* **2019**, *5*, 295–309. [CrossRef]
18. Roudier, S.; Sancho, L.D.; Remus, R.; Aguado-Monsonet, M. Best Available Techniques (BAT) Reference Document for Iron and Steel Production: Industrial Emissions Directive 2010/75/EU: Integrated Pollution Prevention and Control (No. JRC69967). Joint Research Centre (Seville Site). 2013. Available online: https://op.europa.eu/en/publication-detail/-/publication/eaa047e8-644c-4149-bdcb-9dde79c64a12/language-en (accessed on 20 September 2022).
19. Stewarts, C. Sustainability in Action: Recovery of Zinc from EAF Dust in the Steel Industry. In *Proceedings of the International Lead and Zinc Study Group (ILZSG)*; ILZSG: Liverpool, UK, 2015.
20. Thiel, S.; Thomé-Kozmiensky, E.; Senk, D.G.; Wotruba, H.; Antrekowitsch, H.; Pomberger, R. *Mineralische Nebenprodukte und Abfälle 7:-Aschen, Schlacken, Stäube und Baurestmassen*; RWTH Publications: Austria, Germany, 2020.
21. IPBM (In-Plant By-Product Melting Process). Available online: https://op.europa.eu/en/publication-detail/-/publication/dedc7d6a-9ac2-435e-9c39-89255e447725 (accessed on 20 September 2022).
22. Mill Scale, Sales and Information, Mill Scale. Available online: https://millscale.org/ (accessed on 20 September 2022).
23. Buhr, A.; Bruckhausen, R.; Fahndrich, R. The steel industry in Germany–trends in clean steel technology and refractory engineering. *Refract. Worldforum* **2016**, *8*, 57–63.
24. Chetlapalli, S.; Cappel, J. High Value added Refractories for high Quality Steelmaking. In Proceedings of the Value Enhancement through Refractories IREFCON16, Hyderabad, India, 20–22 January 2016.
25. Horckmans, L.; Nielsen, P.; Dierckx, P.; Ducastel, A. Recycling of refractory bricks used in basic steelmaking: A review. *Resour. Conserv. Recycl.* **2019**, *140*, 297–304. [CrossRef]
26. Conejo, A.N.; Lule, R.G.; Lopéz, F.; Rodriguez, R. Recycling MgO-C refractory in electric arc furnaces. *Resour. Conserv. Recycl.* **2006**, *49*, 14–31. [CrossRef]
27. Porisiensi, S. Recycling of ladle slag and spent refractories by injection into EAF. In Proceedings of the Iron & Steel Society International Technology Conference and Exposition 2003, Indianapolis, IN, USA, 27–30 April 2003.

28. Memoli, F.; Brioni, O.; Mapelli, C.; Guzzon, M.; Sonetti, O. Recycling of Ladle Slag in the EAF: A Way to Improve Environmental Conditions and Reduce Variable Costs in the Steel Plants—The results of Stefana SpA (Italy). In Proceedings of the Iron & Steel Technology Conference Proceedings (AISTech), Warrendale, PA, USA, 1–4 May 2006.
29. Viklund-White, C.; Johansson, H.; Ponkala, R. Utilization of spent refractories as slag formers in steelmaking. In Proceedings of the Sixth International Conference on Molten Slags, Fluxes and Salts, Stockholm, Sweden, 12–17 June 2000.
30. Ludwig, M.; Śnieżek, E.; Jastrzębska, I.; Prorok, R.; Sułkowski, M.; Goławski, C.; Fischer, C.; Wojteczko, K.; Szczerba, J. Recycled magnesia-carbon aggregate as the component of new type of MgO-C refractories. *Constr. Build. Mater.* **2021**, *272*, 121912. [CrossRef]
31. European Commission, CORDIS, H2020. Integrated Refractory and Steel Recovery, ReStoRe Project. Available online: https://cordis.europa.eu/project/id/859087 (accessed on 22 September 2022).
32. ReStoRe (REfractory and STeel REcovery). Available online: https://www.deref.com/index.php/it/restore (accessed on 22 September 2022).
33. Ellen MacAuthor Foundation. *Towards the Circular Economy Vol. 1: An Economic and Business Rationale for an Accelerated Transition*; Ellen McArthur Foundation: Isle of Wight, UK, 2013.
34. Lule, R.G.; Conejo, A.N.; Lopez, F.A.; Rodriguez, R. Recycling MgO-C Refractory in the EAF of IMEXSA. In Proceedings of the AISTech-Conference, Association for Iron & Steel Technology, Charlotte, NC, USA, 9–12 May 2005.
35. European Commission, CORDIS FP7. Innovative Separation Technologies for High Grade Recycling of Refractory Waste Using Non Destructive Technologies (REFRASORT Project). Available online: https://cordis.europa.eu/project/id/603809/de (accessed on 22 September 2022).
36. Kieush, L.; Rieger, J.; Schenk, J.; Brondi, C.; Rovelli, D.; Echterhof, T.; Cirilli, F.; Thaler, C.; Jaeger, N.; Snaet, D.; et al. A Comprehensive Review of Secondary Carbon Bio-Carriers for Application in Metallurgical Processes: Utilization of Torrefied Biomass in Steel Production. *Metals* **2022**, *12*, 2005. [CrossRef]
37. S2Biom: Delivery of Sustainable Supply of Non-Food Biomass to Support a "Resource-Efficient" Bioeconomy in Europe. Available online: https://www.s2biom.eu/index.html (accessed on 27 September 2022).
38. Fossilfritt Sverige. Bio-Strategy. Available online: https://fossilfrittsverige.se/en/start-english/strategies/biostrategy/ (accessed on 27 September 2022).
39. Jarnerud, T. *Application of Wastes from Pulp and Paper Industries for Steelmaking Processes*; KTH Royal Institute of Technology: Stockholm, Sweden, 2021.
40. Nosek, R.; Holubcik, M.; Jandacka, J.; Radacovska, L. Analysis of paper sludge pellets for energy utilization. *BioResources* **2017**, *12*, 7032–7040. [CrossRef]
41. RETROFEED–H2020 EU Project. Available online: https://retrofeed.eu/ (accessed on 28 September 2022).
42. Mousa, E.; Wang, C.; Riesbeck, J.; Larsson, M. Biomass applications in iron and steel industry: An overview of challenges and opportunities. *Renew. Sustain. Energy Rev.* **2016**, *65*, 1247–1266. [CrossRef]
43. Suopajärvi, H.; Umeki, K.; Mousa, E.; Hedayati, A.; Romar, H.; Kemppainen, A.; Wang, C.; Phounglamcheik, A.; Tuomikoski, S.; Norberg, N.; et al. Use of biomass in integrated steelmaking–Status quo, future needs and comparison to other low-CO2 steel production technologies. *Appl. Energy* **2018**, *213*, 384–407. [CrossRef]
44. Hoekman, S.K.; Broch, A.; Warren, A.; Felix, L.; Irvin, J. Laboratory pelletization of hydrochar from woody biomass. *Biofuels* **2014**, *5*, 651–666. [CrossRef]
45. Orre, J.; Ökvist, L.S.; Bodén, A.; Björkman, B. Understanding of blast furnace performance with biomass introduction. *Minerals* **2021**, *11*, 157. [CrossRef]
46. Sundqvist Ökvist, L.; Lundgren, M. Experiences of bio-coal applications in the blast furnace process—Opportunities and limitations. *Minerals* **2021**, *11*, 863. [CrossRef]
47. Mousa, E.; Lundgren, M.; Sundqvist Ökvist, L.; From, L.E.; Robles, A.; Hällsten, S.; Sundelin, B.; Friberg, H.; El-Tawil, A. Reduced carbon consumption and CO2 emission at the blast furnace by use of briquettes containing torrefied sawdust. *J. Sustain. Metall.* **2019**, *5*, 391–401. [CrossRef]
48. Jarnerud, T.; Karasev, A.V.; Wang, C.; Bäck, F.; Jönsson, P.G. Utilization of Organic Mixed Biosludge from Pulp and Paper Industries and Green Waste as Carbon Sources in Blast Furnace Hot Metal Production. *Sustainability* **2021**, *13*, 7706. [CrossRef]
49. PlasticsEurope, E.P.R.O. 2019. Plastics—The Facts 2019. An Analysis of European Plastics Production, Demand and Waste Data. Available online: https://www.plasticseurope.org/en/resources/publications/1804-plastics-facts-2019 (accessed on 28 September 2022).
50. Knepper, M.; Babich, A.; Senk, D.; Buergler, T.; Feilmayr, C.; Kieberger, N. Waste plastics injection: Reaction kinetics and effect on the blast furnace process. In Proceedings of the 6th International Congress on the Science and Technology of Ironmaking-ICSTI, Rio de Janeiro, Brazil, 14–18 October 2012.
51. Pietruck, R.; Buchwalder, J.; Harp, G. Gasification of Waste Materials to Reducing Gas for Reduction of Iron Ore, Muenster. 2008. Available online: https://books.google.de/books?id=Nxp1zQEACAAJ (accessed on 28 September 2022).
52. Hanrot, F.; Sert, D.; Delinchant, J.; Pietruck, R.; Bürgler, T.; Babich, A.; Fernández López, M.; Álvarez García, R.; Díez Díaz-Estébanez, M.A. CO_2 mitigation for steelmaking using charcoal and plastics wastes as reducing agents and secondary raw materials. In Proceedings of the 1st Spanish National Conference on Advances in Materials Recycling and Eco–Energy, Madrid, Spain, 12–13 November 2009.

53. REUSteel Public Deliverable 2.1. Available online: https://www.reusteel.eu/deliverables.html (accessed on 24 February 2023).
54. REUSteel Public Deliverable 5.1. Available online: https://www.reusteel.eu/deliverables.html (accessed on 24 February 2023).
55. REUSteel Public Deliverable 4.2. Available online: https://www.reusteel.eu/deliverables.html (accessed on 24 February 2023).
56. Colla, V.; Branca, T.A.; Pietruck, R.; Morillion, A.; Algermissen, D.; Martini, U.; Granborm, H.; Rosendahl, S. Reuse and recycling of residual materials in iron and steelmaking: Analysis of relevant results, trends and perspectives. In Proceedings of the ESTAD Symposium REUSteel, 5th ESTAD (European Steel Technology and Application Days), Stockholm, Sweden, 30 August–2 September 2021; 2021.
57. Brachhold, N.; Aneziris, C.G.; Stein, V.; Roungos, V.; Moritz, K. Low carbon content and carbon-free refractory materials with high thermal shock resistance. *Keramische Zeitschrift* **2012**, *64*, 109–114.
58. Mohoamed, E.; Ewais, M. Carbon based refractories. *J. Ceram. Soc. Jpn.* **2004**, *112*, 517–532.
59. Bag, M.; Adak, S.; Sarkar, R. Study on low carbon containing MgO-C refractory: Use of nano carbon. *Ceram. Int.* **2012**, *38*, 2339–2346. [CrossRef]
60. Echterhof, T. Review on the use of alternative carbon sources in EAF steelmaking. *Metals* **2021**, *11*, 222. [CrossRef]
61. Matino, I.; Colla, V.; Branca, T.A.; Romaniello, L. Optimization of by-products reuse in the steel industry: Valorization of secondary resources with a particular attention on their pelletization. *Waste Biomass Valorization* **2017**, *8*, 2569–2581. [CrossRef]
62. Matino, I.; Colla, V.; Romaniello, L.; Rosito, F.; Portulano, L. Simulation techniques for an efficient use of resources: An overview for the steelmaking field. In Proceedings of the World Congress on Sustainable Technologies (WCST), IEEE, London, UK, 14–16 December 2015.
63. Colla, V.; Matino, I.; Branca, T.A.; Fornai, B.; Romaniello, L.; Rosito, F. Efficient use of water resources in the steel industry. *Water* **2017**, *9*, 874. [CrossRef]
64. Matino, I.; Colla, V.; Branca, T.A. Extension of pilot tests of cyanide elimination by ozone from blast furnace gas washing water through Aspen Plus® based model. *Front. Chem. Sci. Eng.* **2018**, *12*, 718–730. [CrossRef]
65. Matino, I.; Colla, V.; Baragiola, S. Internal slags reuse in an electric steelmaking route and process sustainability: Simulation of different scenarios through the EIRES monitoring tool. *Waste Biomass Valorization* **2018**, *9*, 2481–2491. [CrossRef]
66. Willard, J.; Jia, X.; Xu, S.; Steinbach, M.; Kumar, V. Integrating scientific knowledge with machine learning for engineering and environmental systems. *ACM Comput. Surv. CSUR* **2021**, *55*, 1–37. [CrossRef]
67. Petrucciani, A.; Zaccara, A.; Matino, I.; Colla, V.; Ferrer, M. Flowsheet Model and Simulation of Produced Slag in Electric Steelmaking to Improve Resource Management and Circular Production. *Chem. Eng. Trans.* **2022**, *96*, 121–126.
68. Matino, I.; Branca, T.A.; Colla, V. Addressing the right by-product recovery steps in steelmaking chain: Support tools for slag recovery, recycle and reuse. In Proceedings of the Residue Valorization in Iron and Steel Industry—Sustainable Solutions for A Cleaner and More Competitive Future EUROPE, Virtual Workshop, ESTEP, Brussels, Belgium, 6–27 November 2020.
69. Matino, I.; Branca, T.A.; Fornai, B.; Colla, V.; Romaniello, L. Scenario Analyses for By-Products Reuse in Integrated Steelmaking Plants by Combining Process Modeling, Simulation, and Optimization Techniques. *Steel Res. Int.* **2019**, *90*, 1900150. [CrossRef]
70. Porzio, G.F.; Colla, V.; Fornai, B.; Vannucci, M.; Larsson, M.; Stripple, H. Process integration analysis and some economic-environmental implications for an innovative environmentally friendly recovery and pre-treatment of steel scrap. *Appl. Energy* **2016**, *161*, 656–672. [CrossRef]
71. Colla, V.; Matino, I.; Cirilli, F.; Jochler, G.; Kleimt, B.; Rosemann, H.; Unamuno, I.; Tosato, S.; Gussago, F.; Baragiola, S.; et al. Improving energy and resource efficiency of electric steelmaking through simulation tools and process data analyses. *Matériaux Tech.* **2016**, *104*, 602. [CrossRef]
72. Schneider, C.; Lechtenböhmer, S. Industrial site energy integration: The sleeping giant of energy efficiency? Identifying site specific potentials for vertical integrated production at the example of German steel production. In Proceedings of the ECEEE Industrial Summer Study Proceedings, Stockholm, Sweden, 11–13 June 2018; pp. 587–598.
73. Colla, V.; Cirilli, F.; Kleimt, B.; Unamuno, I.; Tosato, S.; Baragiola, S.; Klung, J.S.; Quintero, B.P.; De Miranda, U. Monitoring the environmental and energy impacts of electric arc furnace steelmaking. *Matériaux Tech.* **2016**, *104*, 102. [CrossRef]
74. Matino, I.; Alcamisi, E.; Colla, V.; Baragiola, S.; Moni, P. Process modelling and simulation of electric arc furnace steelmaking to allow prognostic evaluations of process environmental and energy impacts. *Matériaux Tech.* **2016**, *104*, 104. [CrossRef]

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