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Project title: Dissemination of results of the European projects dealing with reuse and recycling of by-products in the Steel sector

Deliverable 5.1

Road map for future research and development directions

Table of contents

1 Executive summary

In the Deliverable 5.1 a roadmap is developed to highlight the relevant topics and directions in which research and development efforts will be concentrated to implement the reuse and recycling of by-products at the existing BF/BOF- and EAF steelmaking routes, as well as on alternative production routes for low carbon steel making of the future. The roadmap covers a time horizon of 10 years, i.e. up to 2030, which is the first milestone set up by the EU Commission in the path of achieving the Carbon Neutrality, which has a considerable impact on the endeavour towards a circular economy.

The main envisaged target audience for this document is the EU steel sector, i.e., steel companies, companies providing services to the steel industry and research organisations in identifying the most urgent and demanding research directions for the coming years.

The Deliverable is based on the current industrial utilization, on the future targets and challenges to be faced, as well as on current technological trends derived from the valorised research projects and questionnaires carried out in the project. In detail the Deliverable 5.1. comprises the following chapters.

Chapter 2 **"Current industrial utilization"** of by-products summarizes the current production of the main by-products and residual materials such as slag, dust/sludge, mill scale, refractory and secondary raw materials and provides an overview of the internal and external utilization. As an example, the production volumes and utilisation data for 2018 for the above categories were compiled from the literature.

In chapter 3 **"Targets and challenges"** a short overview over legislative challenges for by-products and residuals such as the "Directive on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)" as well as example of technological challenges of the main categories is given. The targets and pathways for the reuse and recycling of the by-products will be also strongly influenced by the measures of the EU for low-carbon steelmaking to achieve CO2 emissions reduction from production by up to 50% by 2030 compared to 1990s level and a climate neutrality in the EU by 2050.
There are two main technological pathways for CO2 reduction in the steel sector. These are Smart Carbon Usage (SCU) comprising modifications of existing ironmaking/steelmaking processes based on fossil fuels to reduce the use of CO2 emission and Carbon Direct Avoidance (CDA) comprising Hydrogen-based metallurgy. This will lead to a research need in various areas.

In chapter 4 the **"Trends from assessed EU Projects and Questionnaire"** were assessed based on the 36 valorised EU-research projects and applications which were carried out over the last 15 years sorted in the main categories. The evaluation of the results achieved in the EU research projects in the first part of chapter 4 delivers detailed research topics for the internal and external utilisation of all main categories of by-products and residual materials.
In the second part of chapter 4 trends were assessed from an online questionnaire, which was created and presented to the audience during the webinars and the conferences. Furthermore, individual interviews with relevant steel industry stakeholders who participated in the research were carried out to find current interests of members of the iron and steel industry on different research topics. The evaluation of the questionnaire and interviews gives tendencies of research demand in the listed categories. As an example, for slag utilization, the research need was prioritized for external utilization, while for sludge and dust utilization, the highest research need was seen in internal utilization and processing.

The Research needs for each category of by-products and residuals material are described in chapter 5 **“Research needs – Road map”** which cover a 10-year time horizon. The roadmap is based on the evaluation of current industrial utilisation, the challenges based on the targets of the circular economy and the prevention of CO2 emission, the trends derived from the reviewed EU projects and the results of the questionnaire and interviews.

The research needs are structured according to the main categories of by-products and residual materials. Due to the different pathways to reduce CO2 emission, i.e., comprising modifications of existing ironmaking/steelmaking processes or applying for example Hydrogen-based metallurgy, each of the main categories are additionally structured into subcategories discussing research needs for the existing production routes (BF/BOF route and EAF route) as well as research needs of new process routes for decarbonised steel production

In addition, a sub-chapter on "Modelling/Simulation for By-Products" contains a general research need that can be applied to all categories of by-products and residual materials.

In chapter 6 **“Target audience and dissemination of the roadmap”** the target audiences comprising the EU steel sector but also companies proving services to the steel industry are described. Further, a statement is given how the deliverable is of added value for the dissemination activities.

2 Current Industrial utilization

2.1 Introduction

The majority of European steel is made via the primary route. It involves processing iron ore to produce iron sinter or pellets, and then melting these in a blast furnace (BF) with coke to make pig iron. This is processed in a basic oxygen furnace (BOF) to create steel. The rest of Europe's steel comes from the secondary route. It produces steel from scrap metal by heating it in an electric arc furnace (EAF).

In 2018, 167.7 million tonnes of crude steel were produced in Europe (EU28), 98.6 million tonnes (58.2%) of which was via the blast furnace (BF)-basic oxygen furnace (BOF) route and 69.1 million tonnes (41.8%) was via the scrap-based electric arc furnace (EAF) route [1].

Worldwide, about 32.9% of the steel production output is by product and consists of slags, dusts and sludge, gases and other materials, which is utilized internally or externally in several processes [2] (**Figure 1**).

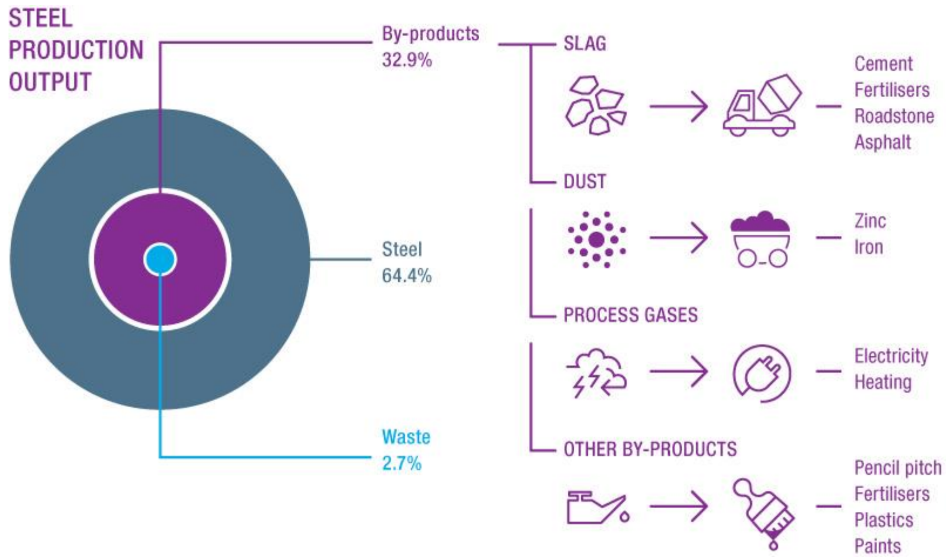


Figure 1. Distribution of products and waste [2]

In the EU in 2018, approximately 46 million tonnes of slag, dust and sludge, mill scale and spent refractory were produced [3]–[7]. The largest part of the by-products is covered by the slag fractions with about 77%. The remaining 23% represent dusts and sludges from gas cleaning systems amounting 15 %. The mill scale comprising 2 % and the refractory comprising 7%.

The industrial need is to revalorize the by-products and residuals either in the steelmaking process or as raw materials via industrial symbiosis or internal cascading use, for several reasons [8]:

- The tightening environmental legislation with the aim to reduce and avoid the landfill disposal of wastes
- The high content of iron and metal oxides makes residues valuable as raw material
- The chemical and physical properties allow re-use of residues and by-products of the steel plant in other industries or contexts.

In the following the current industrial generation and utilisation of by-products and residues is comprehensively summarized as one basis to derive the future research need.

2.2 Slag utilisation

Different types of slags (e.g., BF, BOF, EAF and LF slag) are generated during steelmaking as a by-product of the process. Depending on the process, the input material (ore/scrap), or addition of fluxes, the resulting slag has different chemical, mineral and physical properties.

In 2018, 19.2 M tons of blast furnace slag was produced in Europe and 15.7 M tons of steel making furnace slag (**Figure 2)** [3]. The BF slag includes granulated blast furnace slag (GB slag) and air-cooled blast furnace slag (AB slag).

The steel furnace (SF) slag includes basic oxygen furnace slag (BOF slag), electric arc furnace slag from carbon production (EAF C slag), electric arc furnace slag from steel production (EAF S slag) and secondary metallurgical slag (including ladle furnace slag (LF slag), vacuum degassing slag (VD slag), argon oxygen decarburization slag (AOD slag) and vacuum oxygen decarburization slag (VOD slag)).

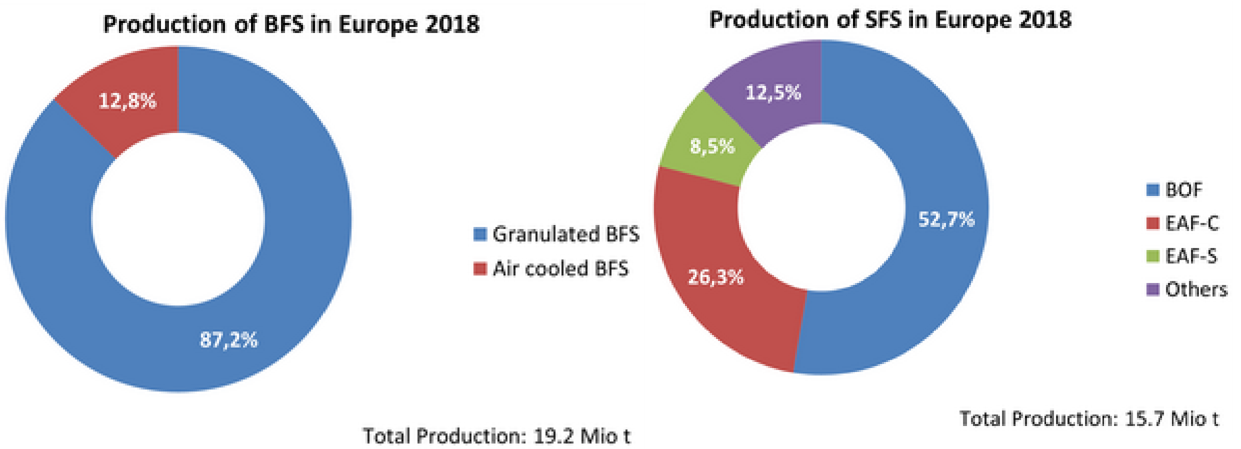


Figure 2. Production of BF slag (left) and SF slag (right) in Europe in 2018 (Euroslag) [3]

The utilization rate of the slag can depend on the type of slag, country, or specifically individual steelwork. In 2018 all of BF slag was used in Europe either as cement/concrete addition, in road construction or other applications (**Figure 3**). About 73 % of SF slag was used in cement/concrete addition, road construction, hydraulic engineering, fertilizer, metallurgical use or other applications (**Figure 3**).

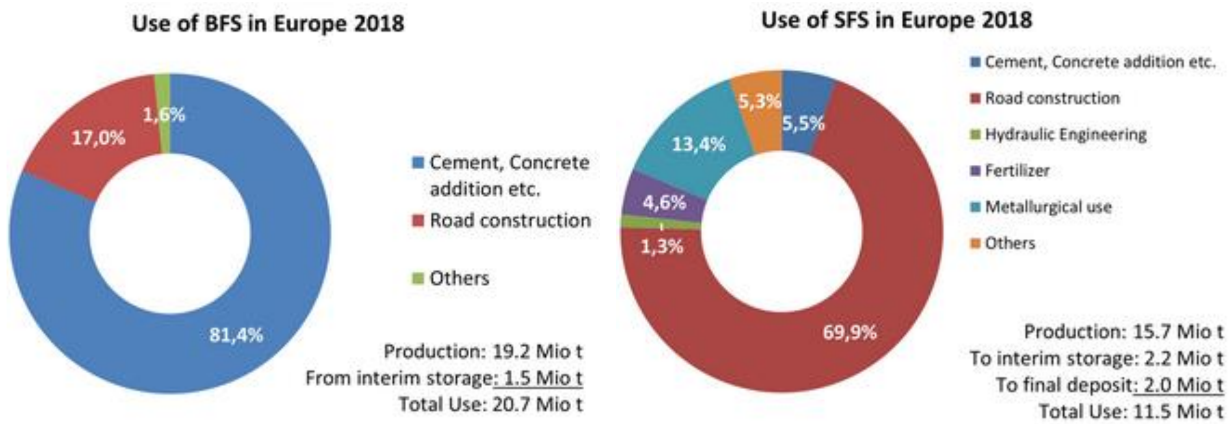


Figure 3. Industrial utilization of BF slag (left) and SF slag (right) in Europe in 2018 (Euroslag) [3]

Some specific examples of different types of applications for specific slags currently found in Europe (referenced from iSlag project):

- Carbon EAF (EAF C) slag
  - Landfill replacement
  - Landfill building material
  - Aggregate
    - unbound and hydraulically bound mixtures
    - bituminous mixtures
    - concrete
    - mortar
    - armourstone
    - gabions
    - railway ballast
    - roofing
    - embankments and fill
    - sealants
    - waste-water treatment
    - air quality control
- Stainless EAF (EAF S) slag
  - Landfill replacement
  - Landfill building material
  - Metal extraction
  - Aggregate
  - Unbound mixtures
- EAF slag as "slag sand"
  - Acid mine drainage prevention, treatment and remediation
  - Soil stabilization and road base reclamation
  - Road base and sub-base
  - 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
  - Landfill replacement
  - Landfill building material
  - Liming material (pH adjustment and plant available silicon)
  - Replacement of lime in EAF
  - Cement
- LF slag as "slag sand"
  - 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

Because certain applications might be available it does not mean that the steelwork/slag processor is able to utilize the slag due to chemical properties of the slag, physical properties of the slag, available applications within acceptable distance (costs of transportation), cost of utilization compared to costs of landfilling, lack or limiting regulations. With respect to these issues, it is necessary to conduct research not only on new utilization paths but also on increasing amount of slag that qualifies for the currently available utilization paths.

2.3 Dust/Sludge utilisation

Dusts and sludge are mostly coming from the pollution abatement equipment that clean the gases and wastewater discharges from the various iron and steelmaking processes. In the past years, significant improvement has been realised reducing the level of materials sent to landfills. These residues are being reprocessed internally, at least at the integrated steelmaking route.

In 2018, the FEhS – Building Materials Institute made a survey on the occurrence and utilization of dusts, sludges and mill scale from the iron and steel industry. 27 plants from BF/BOF and EAF route from Germany, Netherlands and Austria have contributed to this collection of data [4]. These data are shown in Figure 5 as an example of the generation and utilization of dust and sludge in Europe.

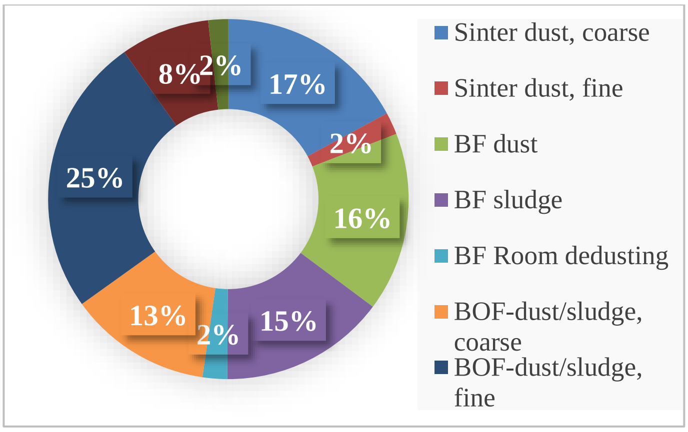


Figure 4. Production of Dust/Sludge BF, 2018 [4]

While around 80 % of the dusts and sludges from the steelworks are sent to internal recycling or used for other purposes, more than 18% per year are still disposed in landfills (**Figure 5**).

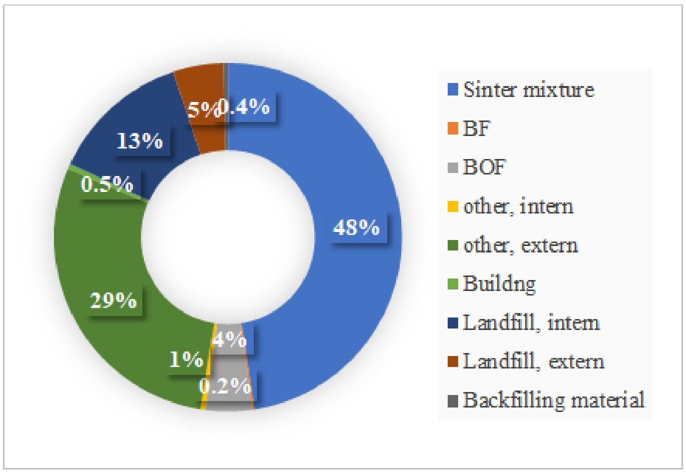


Figure 5. Industrial utilization of Dust and Sludge, 2018 [4]

Based on the dust and sludge production data from 27 plants of the BF/BOF route and EAF route and the yearly European production of crude steel (LS) in 2018 of 167.7 M ton (BF/BOF and the EAF route) the amount of sludge and dust is estimated on 6.8 M ton/year in Europe [9]. In the following example for the utilisation of the dust and sludge are given for BF/BOF route and the EAF route.

BF/BOF-route

The current most common steel making technology is the BF/BOF route. It involves production of pellets or sinter from fine ores and iron containing residues, the reduction of ores, sinter and pellets to hot metal (pig iron) in the blast furnace and refining in BOF and the secondary metallurgy to steel.

The range of specific amounts of produced dust and sludge from the sinter plants, of the BF and BOF are given in the **Table 1**.

Table 1. Specific amounts of steelmaking residuals [1], [5], [10]

Byproduct	Specific amount (range)
Sinter dust	0.2 to 4 kg/tons sinter
BF dust	3 to 18 kg/tons hot metal
BF sludge	2 to 22 kg/tons hot metal
BOF dust	1 to 24 kg/tons crude steel
BOF sludge	15 to 16 kg/tons crude steel

In the following the actual applied industrial, plant specific utilization strategies in the European steel industry [9] for dust and sludge from BF/BOF route are summarized [1], [5], [10]:

Sinter dust

- Partly recycled internally as sinter raw material
- Landfill

BF dust (coarse)

- Internal use
  - Mixed and granulated in sinter raw material.
  - Pelletized/ briquetted in blast furnace burden
  - Injection in blast furnace via tuyere

BF sludge (fine)

- Internal dezincing pre-treatment by hydro cyclone, afterwards
  - Mixed and granulated in sinter raw material
  - Briquetted in blast furnace
- External use:
  - Dezincing: Shaft furnace (Oxycup, DK Recycling), Waelz process
- Landfill

BOF dust (coarse)

- Internal use in sinter plant, BF, BOF

BOF fine dust/sludge

- External use
  - Dezincing: Shaft furnace (Oxycup, DK Recycling), process
- Landfill

Whilst slag tends to be used ‘internally’ or 'externally' to site, dust and sludge utilisation is on the major part recovered using 'internal' processes but still there is material sent to landfill or to external sites for further treatments.

Sinter dust and sludge are mainly recovered within the integrated steel plant, and a part is recycled back to the sinter plant. Fine sinter dust and sinter sludge is sent to landfill. The recovery rate of sinter dust is limited mainly due to the high heavy metal and metal chloride content in fine fractions [10].

The coarse fraction of BF dust is almost fully recovered internally utilizing the high iron as well as the carbon content. The main recovery route is the BF itself and the sinter plant. The recycling rate of the fine fraction is limited by concentration of zinc and alkali metals. BF fine dust and sludge is often sent to landfill, internally or externally [11] but also pyrometallurgical dezincing processes are applied in industrial scale in shaft furnaces as the DK shaft furnace process and the Oxycup at tkSE in Duisburg and the Waelz process.

In integrated steel plants with BFs operating mainly on pellet-based ferrous burden, there is no on-site sinter plant and the recycling cannot be achieved via this route. The recycling within such plants can be achieved via top-charged cold-bonded briquettes and injection of in-plant fines via the BF tuyeres.

Coarse BOF dust with low zinc content is recovered to a high extent in sinter plant, BF and BOF. The fine fraction and the sludge is partly recovered externally in pyrometallurgical dezincing processes as the DK shaft furnace, but often the sludge is landfilled due to high zinc levels and fine particles that are problematic to charge [5].

EAF-route

The specific amount of EAF dust generated by electric steelmaking is between 15-30 kg per tonne of crude steel produced. The EAF dust is collected by primary and secondary dedusting systems and finally usually separated by bag filter systems [10].

A large part of all EAF dusts is 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. Besides this, all EAF dusts contain a considerable amount of slag forming compounds like CaO, MgO, MnO, SiO_2 and Al_2O_3, where CaO is dominating with contents up to 20 %.

Especially the EAF dust from carbon/low alloyed steel production contains a large amount of zinc oxide (21-43% Zn), which stems from charged zinc coated scrap. Depending on the scrap charge composition, also the lead content can be elevated. This makes the EAF dust an interesting resource mainly for Zn recovery [10].

In contrast, the EAF dust from high alloyed or stainless-steel production contains a significantly lower amount of Zn and Pb. However, here the content of alloying components like Cr and Ni is elevated, which makes this EAF dust a valuable resource for recovery of these elements [10].

In the early 2000s, the situation in Europe regarding EAF dust recycling can be summarized by **Figure 6**, which source data are obtained from the work of Raggio [12]. All the EAF dust was recycled externally by Waelz process (see later in the Chapter) whereas the residual part of the produced dust was sent to waste disposal. The group of nations in central Europe including Denmark, Benelux, Austria, Switzerland, and Germany were the ones with higher recycling rates with an average around 85% (around 58% as average for the set of countries investigated excluding the data of England). It is also worth mentioning that Italy has an apparently anomalous situation in terms of overall dust production that is the highest; this is because Italy has around 85% of its total steel production by scrap/EAF route.

The situation in the following years moving towards the present continued evolving with an increase of the fraction of produced EAF dust that was recycled (see the example related to Pontenossa plant that is described later in the Chapter).

In 2018 in central Europe (data from Germany, the Netherlands, Austria and Switzerland), nearly all the EAF dust (97 %) is used for external recycling, in particular for metal recovery (recovery of Zn respectively alloying components). Only a negligible amount of 3 % is deposited [4]. The high recovery rates in Europe can be considered as a virtuous situation considering that on a worldwide level, an important quantity of the produced EAF dust is still reported to be not recycled, hence landfilled (different sources reported about 50% or even about 67%) [13], [14].

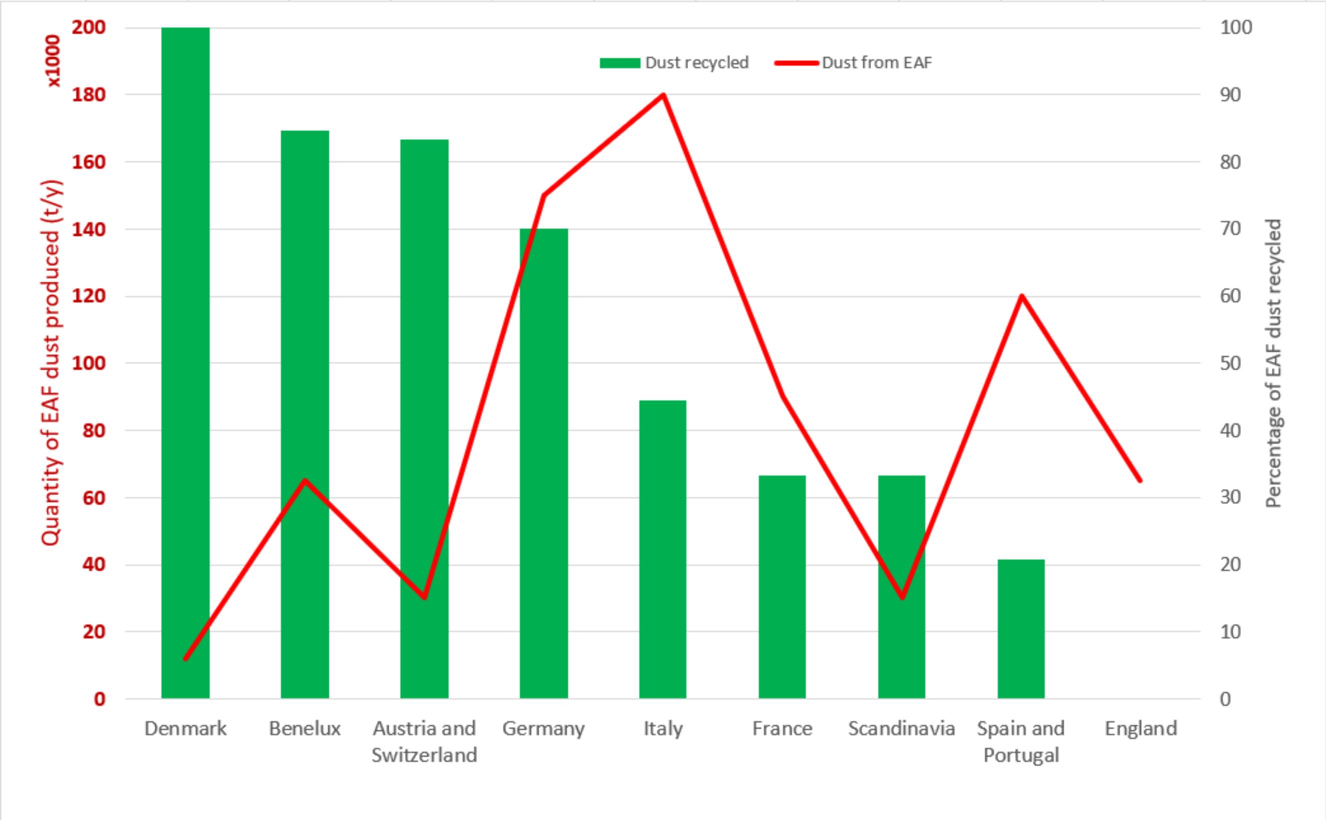


Figure 6. Situation of EAF dust recycling in the early 2000s

EAF dust from carbon steelmaking usually is externally processed for zinc recovery. Here, the most widely used process is the pyrometallurgical Waelz process (rotary kiln), which was invented in 1910. The Waelz process accounts for around 80% of the total recycled EAF dust quantity worldwide. This process has undergone several improvements, so that the energy efficient SDHL technology actually is state-of-the-art concerning this process. The Waelz process usually recovers about 90 % of the contained zinc in the EAF dust. [15]

The main advantages of the Waelz process are the simplicity of this one-step process and the low energy consumption compared to alternative processes. However, this process also has some remarkable disadvantages like the relatively low quality of the zinc product (Waelz oxide still contains significant amounts of chlorides and fluorides) and the high amount of the newly generated iron containing slag (approx. 700-800kg/t of charged EAF dust), which is not usable for iron recovery. The “appeal” of Waelz process is overall due to the fact that this is the most economical when operating on a large scale hence serving several mills [16]. As an example, the Waelz plant of Pontenossa SpA located in the north of Italy had a relevant increase of its capacity to process the dust coming from steelmaking passing from the initial capacity of 70.000 t/y in

1994 to the current 150.000 t/y serving about the 70% of the Italian dust production from steelmaking [17].

Some other (one-step) pyrometallurgical processes have been developed and are partly operated in commercial scale, like the multiple hearth furnace (PRIMUS® process), the rotary hearth furnace, the induction furnace technology (PIZO) respectively the electric arc furnace technology. In contrast to the Waelz process, all these alternative technologies, besides zinc recovery, are able to recover the contained iron in the EAF dust by producing either a DRI product (direct reduced iron) or a hot metal.

EAF dust from high alloy/stainless steelmaking usually is externally processed for recovery of Cr and Ni in the form of ferroalloys. Here, the plasma shaft furnace technology and the submerged arc furnace technology are commercially used processes [18].

2.4 Mill scale

As mentioned before, in 2018, approximately 167.7 million tonnes of crude steel were produced in Europe (EU28). If the specific amount of mill scale generated during the steelmaking is within the range of 2 to 8 kg per tonne of crude steel, the total annual amount of mill scale is in the range of 0.3 and 1.3 Million tonnes per year.

The mill scale is produced during the reheating of steel slabs in the pusher-type furnaces or bogie hearth furnaces. At the high temperatures in the reheating furnaces (above 1,200 °C), the iron surface of the steel slabs reacts with the atmospheric oxygen to form iron (II)/(III) oxide (scaling). The scale produced in the reheating furnaces is also called primary scale. The process of scaling also takes place during the actual hot rolling of the slabs into heavy plate. The resulting mill scale is referred to as secondary scale. Primary and secondary scale differ essentially in their grain size and grain composition. If the primary scale is coarse-grained and porous, the secondary scale is rather fine-grained. [19]

Since the secondary scale is produced during hot rolling, it contains oil due to contact with the rolling emulsion. When the primary and secondary scales are collected separately, the oil-free scale can be directly recycled via the blending beds as a ferrous secondary raw material directly in the sintering process. In order to be able to reuse the oil-containing secondary scale, a variety of processing technologies have been tested/investigated via the blast furnaces or the LD converters, for example as an injection agent into the BF or as mill scale briquettes, which can then be used in a LD converter. But, the metallurgical reuse of oily mill scale is limited, due to the presence of disturbing components. Thus, there is still an industrial need for removal of oil and disturbing components e.g., by washing treatment followed by material preparation for dosing the treated mill scale in the metallurgical units of an integrated steelwork. [19]

Primary mill scale with larger particle size and low oil content (<1%) are already reused internally as an additive to the iron ore sinter mixture. [19]

Furthermore, new processes for metal recovery from mill scale and other by-products of the steel industry have been developed. For example, the IPBM (in-plant by-product melting process) project [P2] aimed to develop a flexible process outside the main metallurgical line allowing total transformation of mill scale, as well as other in-plant by-products into value-added products with a smelting reduction vessel while recovering metal to be reused in the steel production. Besides those smelting reduction processes, mill scale by principle can also be processed to a solid iron product (sponge iron, DRI) or a hot metal by reducing treatment e.g., in rotary kilns, rotary hearth furnaces respectively in special cupola furnaces. Due to the fine-grained nature of mill scale, in all these cases a preceding agglomeration (pelletising or briquetting) is necessary – if necessary, in combination with a reductant (e.g. carbon). But, since the cost/profit situation is greatly influenced by factors like investment costs for the new process, environmental legislation and alternative solutions, the economical operation of such processes on industrial scale is quite difficult to realize and must be evaluated continuously.

Beside the industrial needs and trends for internal utilization of mill scale in an integrated steelwork, there are established external utilization routes outside the steel industry. In the following a list of industrial use cases is given [20], [21]**:**

- cement industry: Adding mill scale to the combustion area when manufacturing cement clinker converts unwanted and potentially dangerous hydrocarbon gases into less volatile gas products. Further, it can be used as a raw material for manufacture of cement clinker by mixing it with feedstock materials before introduction of the raw material into the heated rotary kiln.
- counterweights used e.g., in cranes, elevators, draw bridges, lift trucks
- ferroalloy production
- production of friction agents
- production of refractories: Refractory material is made by crushing dolomite and mixing it with a flux suspension liquid or paint. Mill scale can be used as flux material that is combined with the liquid binder and ultimately used to produce the refractory material.
- production of welding electrodes
- production of iron salts and iron oxides

2.5 Refractory

Refractories in steel industries have a variety of compositional range and types being used for different purposes e.g., vessels, furnaces, components for flow control and for different operating practices. The mostly used refractories in steel industry include high alumina, magnesitic, dolomitic and silico-aluminous classes of such materials. As examples of different use for different purposes, high alumina and silico-aluminous are used for blast furnaces, magnesitic for EAF. Furthermore, special classes of materials such as zirconia based are used for special components for flows control.

The annual global production of refractories is around 35–40 million tonnes, with fluctuations largely dependent on the steel market demand since the major share of around 60-70% is employed by the steel and iron industry. In the EU countries the refractory industry supplied a total of 4.3 million tonnes of products; the supply of refractory materials for the steel industry of 2.6 -3.0 million tonnes [6], [7].

The electrical steel mills melting scrap have a refractory consumption of about 5-7 kg/tRS, whereas integrated mills have a 30-40% higher demand of 8-10 kg/tRS [6].

During the operation, depending on the working conditions, a given refractory is subjected to the action of a hostile environment that could include case by case slag, steel, hot metal. This situation implies that the material after use has a certain degree of “contamination” including slag and metal residues. The situation is even more complicated by the possible use in operation of shaped (bricks) and unshaped (monolithics) refractories; as a matter of fact, monolithics in comparison with bricks are more prone to contamination, are more complicated to crush and may have anchors.

The aforementioned aspects must also be considered in the light of the design criteria applied by the refractory producers that are managed to obtain the maximum performances (to guarantee a proper life in service of the lining or of the component) not considering is such a process the possibility of recycling.

The logic consequence of this situation is that the main and easier way of spent refractory recycling is their use as slag conditioners in the steel industry (e.g., for EAF and BOF slags), hence in an open-loop recycling approach [22]. The practice of adding metallurgical and dolomitic lime in the EAF slag to reduce the corrosion of the MgO based refractories used for lining the internal part of the furnace is rather common; the replacement of dolomitic lime by spent MgO-C refractory has been shown to be efficient for such purpose [23]. Other examples of industrial application of this type of approach are present since the early 2000s in Europe and outside Europe. Some of them are in the following:

- Ferriere Nord and Stefana (Italy)
  - Use of special injectors for the introduction of mixes ladle slag/spent refractories in the EAF. The spent refractories come from dolomitic ladle and tundish linings and from EAF hearth. [24], [25]
- SSAB Lulea (Sweden)
  - Use of ground and sized (5-25 mm) MgO-C bricks charged together with the scrap charge in partial substitution of calcined dolomite. [26]
- Daido Steel (China)
  - Spent refractories (about 900 tons per month) are crushed and then reused for additions in ladle slag and in EAF slag. [27]
- USA department of energy jointly with Steel Manufacturers Association and different steelmaking/refractory companies (USA)
  - Research on the optimization of procedures for the use of spent MgO-C refractories as slag modifiers in EAF. The attention is focused in particular on the individuation of the optimal grain size of the recycled material in order to favour the dissolution in slag. [28]

The current interest for such kind of approach of spent refractories reuse is confirmed by the H2020 Integrated Refractory and Steel Recovery (ReStoRe) project started in 2019 and still on-going [29]. Deref S.p.A. developed an industrial process called ReStoRe technology that consists in a series of steps starting from material pre-selection and following by grinding/sieving of the spent refractories, separation of the metal residues to be reused in steel production, selection of the different chemistry of the obtained fractions with the proper grain size according to the steel producer's needs. The materials obtained from the process can be reused in steelmaking cycle in substitution of raw materials such as lime and dolo-lime, bauxite and even metallic scraps. Purposely devoted ancillary activities included in the project are devoted to the optimization of the mixtures recycled refractories/raw materials to be used in the different cases (e.g. addition in EAF) and to the kinetic of dissolution of the recycled mixtures. The benefits achieved from the ReStoRe process (by Deref) can be summarized as follows [30]:

- Basic materials contained in spent refractories are around 50% of granular materials recycled. These can be used in EAF or converter in substitution of the lime.

- Aluminous materials contained in spent refractories are around 40% of high alumina fluxes restored in the process. These can be used in substitution of alumina fluxes for slag conditioning/forming.
- Spent refractories contain about 5% of steel scrap. Once separated, these can be directly reused in the steelmaking process.
- Only 5% of the collected refractory materials must be disposed in landfill.

The open-loop recycling approach for refractories as summarized above is undoubtedly a valuable and relatively easy to do option to reduce landfilling and save raw materials with advantages also regarding CO2 emission savings. On the other hand, additional advantages could also be achieved by a parallel adoption of a closed-loop recycling way [22], namely the reuse of exhaust materials to produce new ones. It is worth mentioning that this last way is complicated by the difficulty to meet the high-quality demands of refractory producers for the making of materials that can guarantee adequate performances. The main difficulty related to such approach is due to the typical contamination of the refractories after use for the causes previously discussed that includes also the consequence of the practice of tear-out this last resulting in mixtures that are difficult to separate by type and grade and by variety of contamination. On the other hand, closed-loop has the advantage to a possible framing in the context of circular economy approach; the functionality and therefore the value of the material must be kept as high as possible over an as long as possible time period [31].

The logic consequence is that the closed-loop approach requires a fundamental initial step that is aimed at obtaining a proper sorting of the different refractory wastes. This initial step, classified as pre-sorting, is aimed at having a first fundamental separation of all the residues included in the spent refractories stream. The pre-sorting per refractory type stage is typically done in manual mode, operation this last requiring of adequate knowledge of the refractory characteristics and related expertise of the operator(s). A typical reference characteristic useful for this purpose is the colour [32]. In the latest years, LIBS based systems have also been used for this purpose and demonstrated their potentiality; as an example, the European FP7-project REFRASORT has been aimed to the development of a new LIBS system purposely designed to avoid/minimize the disturbance of material identification caused by surface contamination [33]. The pre-sorting step is then followed by a process consisting in crushing/grinding/sieving/purifying of the pre-selected spent materials to obtain the materials to be reused. Logically, this process must be for its proper nature, much more selective than the one done for obtaining slag conditioners (described above in the paragraph) considering the final aim of the process. In fact, a high purity degree of the recycled products is needed to obtain valid substitutes of virgin materials.

2.6 Secondary raw materials

In the projects that have been studied there has also been an interest for residual materials coming from other industries and businesses, i.e., from outside the steel work, that can be used as secondary raw materials inside the steel work. Examples of such materials are alternative carbon sources (e.g. biomasses and plastics) and residual material from the base metal industry. The most important secondary raw material is steel scrap; however, this will not be dealt with in this project due to the large content of the topic.

Biomass as secondary raw material

Within the EU funded research project S2Biom on non-food biomass for resource efficiency in Europe that ended in 2016, residual biomass material from different sources such as forestry, agriculture and wood industries have been calculated based on harvest levels in a 50-year period. Within EU28, the amounts of residues for 2020 were calculated to be

- 39 million tons for forestry, i.e., logging residues from final felling, thinning and stumps
- 88 million tons for secondary residues from wood industry, i.e., sawmill, pulp and paper and other wood processing industries
- 90 million tons for biowaste, i.e., biodegradable garden and park waste, food and kitchen waste from households, restaurants, catering and retail premises and comparable waste from food processing plants
- 16 million tons for post-consumer wood, i.e., wooden material at the end of its use as a product, e.g., packaging materials, demolition wood and timber from building sites.

Available residual materials vary between the member countries (**Figure 7**) [34] which might also lead to regional differences in research interest regarding different biomass materials.

Since many industries are interested in replacing fossil fuel and carbon with biomass, the available residual materials for use in steelmaking will be lower than the total availability. In the case of Sweden, the total demand for biomaterials in 2045 is estimated to be 30 % higher than the availability [35].

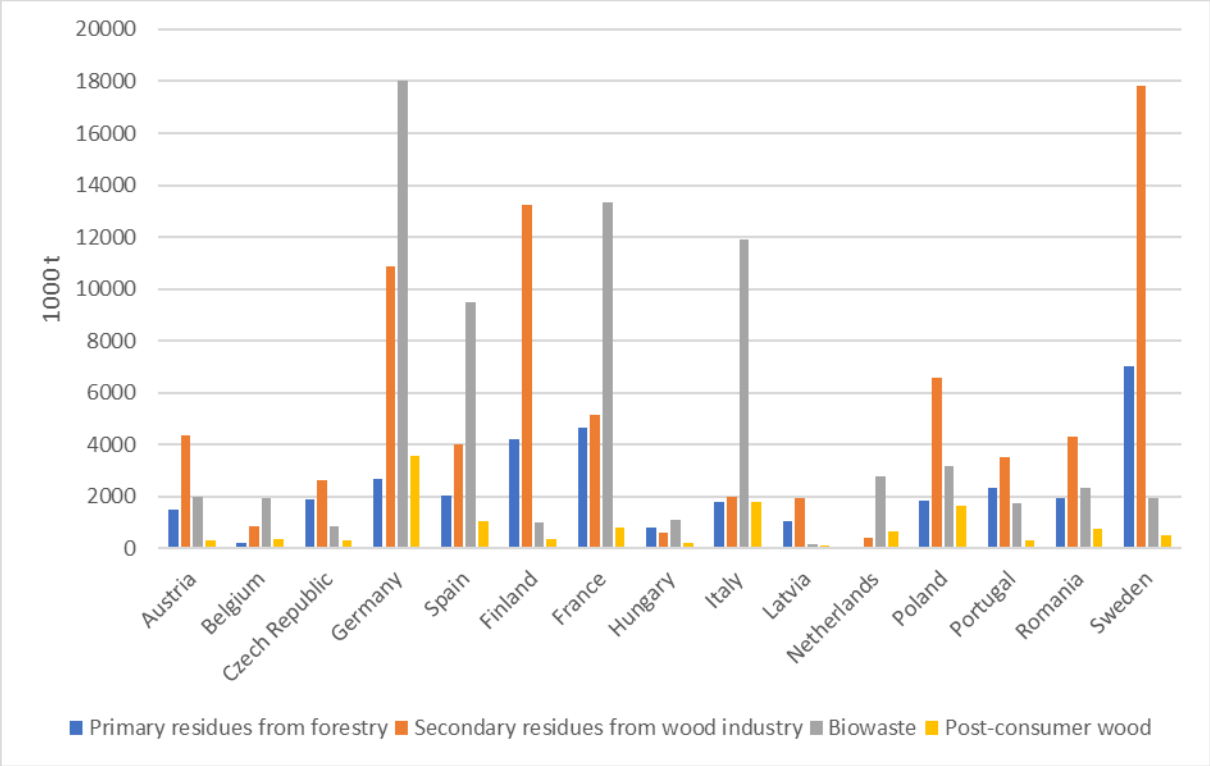


Figure 7. Estimated yearly production of residual biomass material for 2020 [34]

Within Smart Carbon Utilization (SCU) the fossil carbon is progressively substituted by the use of alternative carbon materials without affecting neither the process (e.g. energy) nor the quality of the product. The alternative source of carbon individuated as feasible for this task is either biogenic or goods at their end of life.

Biomass from agriculture or forestry should be submitted to proper processes such as torrefaction or bio char production, which will be described below, in order to improve their performances. The torrefied biomass and biochar demonstrated their potential in devoted projects that have been done in the latest years with the aim to evaluate the feasibility of the EAF process using such solutions (see **Figure 8**).

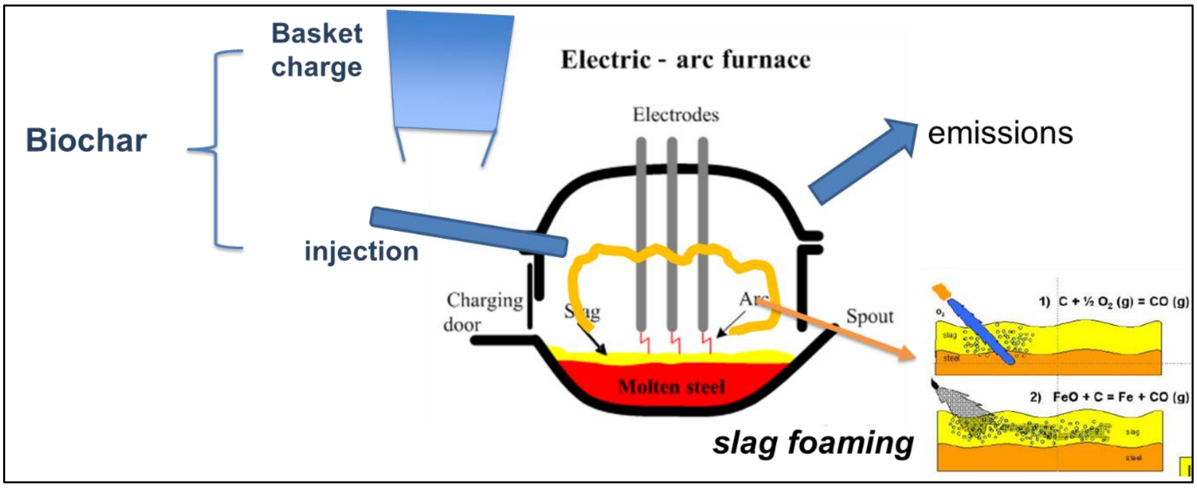


Figure 8. Sketch showing the approach of using biomass/biochar instead of coal for EAF operations

Different Italian steel producers demonstrated a clear interest on these subjects also considering the adoption of the new procedures on common daily practices. As an example, Ferriere Nord is setting and evaluating a new system to inject biochar in EAF [36]. In case of satisfactory results, the system will be used in operation on a permanent basis.

Another external residual material of interest is sludge and other waste material from the pulp and paper industries [37]. In Europe over 11 million tons of such material was produced yearly in 2017 and due to high costs of landfill there is an interest of finding utilization for the material [38].

As mentioned before, biomasses and therefore also sludge containing carbon, needs to be upgraded before it can be used as carbon source in the iron and steel production. The upgrading is done as a pre-treatment resulting in for example an increase of energy content and mass density of the biomass. The pre-treatment can be done by biochemical or thermochemical conversion; however, the biochemical conversion is rather slow thus thermal pre-treatment is mostly used [39]. Several thermal pre-treatment techniques are available and used depending on the biomass and the intended utilisation. The reaction atmosphere and the temperature and heating rate is what separates the different techniques [40]. Torrefaction of the biomass is done in an inert atmosphere with mild pyrolysis, the result becomes friable and dusty, and an additional binder is often needed in order to pelletise the material [41]. Another thermal pre-treatment is hydrothermal carbonization (HTC). HTC is performed in a pressure vessel at 200-300 °C and results in a product called hydrochar. The hydrochar is less dusty than torrefied biomass and no binder is needed to produce a pellet [41]. When using biomass sludge, which is wet, HTC can be a good alternative as it can produce a carbonaceous product that is solid without having to firstly dewater or drying the material [37]. Examples of utilization of thermally pre-treated biomass are torrefied biomass that has been studied for injection in the blast furnace [42], [43] torrefied sawdust tested as addition in the briquettes used in BF [44] and briquettes containing an addition of hydrochar pellets produced by HTC technology, which has been charged at the top of the blast furnace during hot metal production [45].

Plastic as secondary raw material

Plastic materials are starting to be explored as alternative carbon sources in steelmaking. Plastics production has grown by 50% in the past decade, to just under 350 million tonnes per year worldwide and the growth is expected to continue (**Figure 9**). In advanced economies, packaging is a major use, followed by construction and automotive.

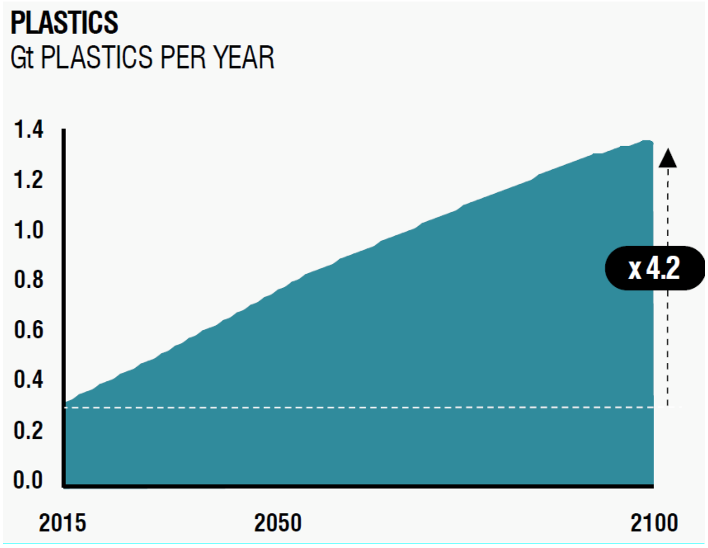


Figure 9. Calculated scenario of plastic production growth hypothesizing that all world regions will converge to 120 kg/person within 2100 [46]

In Europe, current annual use of plastics is about 100 kg/person, while North America is at about 140 kg/person. In 2016 the demand of plastic in Europe was 50 million tonnes. The amount of post consumer waste plastic collected in Europe was 27,1 million tonnes of which about 27.3% was landfilled [47]. This includes low grade mixed plastic products with no market application.

Use of waste plastic (WP) in the steel industry may contribute to both waste recycling and carbon dioxide emission mitigation due to additional hydrogen input. However, the inhomogeneity of the physical and chemical properties of waste plastic has to be considered. In addition to different polymer types waste plastic can contain various metallic and mineral impurities, including harmful elements [48]. There are three ways to use WP in ironmaking technologies:

- Gasification and subsequent injection of generated reducing gas [49]
- Embedding in raw materials (self-reducing pellets, composites, coal blend for cokemaking, fuel for sintering)[50]
- Direct use by injection via tuyeres [48]

Injection of WP has already been conducted at several BFs in Germany, Japan and Austria; typical injection rates are 40 kgWP/tHM, although values of 60–80 kgWP/tHM have been reached. Up to 110,000 tons of plastics per year were injected as a reducing agent [48].

The use of such, up to now, unexploitable fraction of waste plastic for EAF operations is the new challenge for the near future of steel production.

3 Targets and Challenges

Targets were developed in the context of the EU goal and policies to achieve climate neutrality by 2050 - the European Green Deal, the Clean Planet for All strategy and the Paris Agreement, to fighting climate change and moving towards climate neutrality by 2050, a zero-pollution ambition for a toxic-free environment and a circular economy using digital technologies as an enabler and new forms of collaboration. Steelmakers are committed to reducing their emissions and thereby contributing to the achievement of the EU climate targets.

3.1 Challenges by regulations and technology

Legislative challenges for by-products and residuals

The recovery of by-products and residues must be in compliance with the environmental regulations and its application. There are several regulations which are always being further developed, such as the Directive on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and how they interact, the Directive on industrial emissions (IED) which establishes the main principles for permitting and controlling large industrial installations based on an integrated approach and the application of best available techniques (BAT).

In addition, the EU Circular Economy Action Plan, waste prevention programmes, work on non-toxic and resource-efficient recycling and a forthcoming EU strategy for a toxic-free environment in 2018 are important for the industry to follow.

The European Pollutant Release and Transfer Register gives public access to detailed information and provides easily accessible key environmental data from industrial facilities in European Union Member States. Each industrial facility provides information to their national authority on the quantities of pollutants released to air, water and land.

The following are examples of Instruments and Regulations with a potentially significant impact for the steel industry:

- Integrated Pollution Prevention and Control (IPPC) permits,
- the Industrial Emissions Directives called (IED), which is the revision of this IPPC directive with the implementation of the BAT conclusions (Best Available Techniques) being the legal reference for permitting of installations,
- the new product and waste legislation (guided by the Life Cycle Assessment approach and eco-design as well as PEF, the product environmental footprint),
- thematic strategies on natural resources, waste prevention and recycling,
- European Fertilizer Regulation; Regulation (EU) 2019/1009
- the EU legislation on chemicals ('REACH', Registration, Evaluation, Authorisation and Restriction of Chemicals)
- Circular Economy

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

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

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

Steelmaking results in useful by-products, such as ferrous slag, which substitute natural resources and is mainly utilized in external sectors and contribute to resource efficiency. Ferrous slag is used in a range of applications (e.g., civil engineering like road construction, fertilizer, and cement production etc.), saving millions of tons of natural resources annually.

However, the rules for slag utilization in Europe are complicated as they depend on regulations in each country and sometimes also regional applications apply. Often the regulations are very different from each other (different leaching test, different elements requested, different limiting values, different physical properties required, etc…) and the steelwork/slag processer must comply with regulations at the destination of where the slag will be used. Example of limiting values (class 1 with least restrictions in application) for leaching in Germany and Italy are presented in Table 2 (data reference from SLACON project). Some countries outright forbid certain utilizations of slag, while others make the regulations in a way as to make utilization of slag impossible for the companies. With respect to this the steel industry and related entities have conducted research to show beneficial uses of slag and their safety with respect to humans and the environment.

Table 2. Summary of limiting values in Germany and Italy determined with slag leaching (EN 12457-2, or DIN EN 12457-4, DIN 19528 or DIN 19529, 2-4 mm grain size) (SLACON project)

Parameter	Unit	Germany	Germany	Italy
		DIN EN 12457-4	DIN 19528/ DIN 19529	EN 12457-2
solid: liquid ratio		1:10	1:2	1:10
pH		10-12.5	9-13	5.5-12
EC*	µS/cm	≤ 1500	≤ 10000	
COD **	mg/l			≤ 30
As	mg/l			≤ 0.05
Ba	mg/l			≤ 1
Be	mg/l			≤ 0.01
Cd	mg/l			≤ 0.005
Co	mg/l			≤ 0.25
$Cr_{(total)}$	mg/l	≤ 0.030	≤ 0.110	≤ 0.05
Cu	mg/l			≤ 0.05
Hg	mg/l			≤ 0.001
Mo	mg/l		≤ 0.055	
Ni	mg/l			≤ 0.01
Pb	mg/l			≤ 0.05
Se	mg/l			≤ 0.01
V	mg/l	≤ 0.050	≤ 0.180	≤ 0.25
Zn	mg/l			≤ 3
Cl^-	mg/l			≤ 100

CN^-	mg/l			≤ 0.05
F^-	mg/l	≤ 0.750	≤ 1.1	≤ 1.5
NO_3^-	mg/l			≤ 50
SO_4^{-2}	mg/l			≤ 250

* EC= electrical conductivity

** COD = chemical oxygen demand

Whilst slag tends to be used ‘internally’ or 'externally' to site, dust and sludge is on the whole recovered using 'internal' processes but a minor part is sent to landfills or to external sites for further treatments.

Dust is formed in most of the steel industry’s processes, especially where sinter or pellet plants, blast furnaces, basic oxygen furnaces and electric arc furnaces but also material handling and storage are concerned. The dust emissions are distinguished in primary emissions from exhaust systems and in secondary emissions from distributed locations, in process industries mostly from handling and transport of solid granular materials all-over the plants.

The development of abatement strategies and improved dedusting technology, filters and ventilation systems, in the last decades have resulted in that the primary dust emissions have been sharply reduced. This is based on environmental legislation such as the Directive on industrial emissions (IED) and described in the application of best available techniques (BAT). Thereby residues are generated containing considerable quantities of valuable metals and materials. This opens up the need of reuse and recycling taking into account among others the EU legislation on chemicals (REACH) as well as the European concept of Circular Economy to prevent waste and instead re-use, repair and recycle the residues.

In Italy as a second example steelmaking dust as well as mill scale are classified as dangerous wastes and framed into specific CER categories (see **Table 3** as an example). This implies that these types of steel by products must be treated only by specific companies that have a certification to do that. In principle, a given steel production site could do the request in order to obtain the authorization to process e.g. the dust. An example of that is given by the Acciaierie di Verona [51] that has a specific plant for the physico-chemical inertization treatment of dust that can be directly managed after having obtained the authorization of specific environmental compatibility by the Italian Ministero per l’ambiente (ministry for the environment).

Table 3. Examples of Italian CER rules related to steelmaking dust and mill scale

CER 10.02.07 – Dust from fumes in steelmaking production	Powders collected in devoted filtering systems. The collected powders must be directly loaded on vehicles to be transported to authorized plants of treatment or disposal.
CER 10.02.10 – Mill scale	Scale that is mainly made of Fe oxides is sent to authorized plants for recovery to be used in the sectors of cement production, chemistry production, counterweights production

Technological challenges for dusts and sludges

The composition of the various dusts and sludges is very heterogeneous. Besides dry dusts, flowable sludges are generated in gas cleaning devices. There are also strong differences, e.g. in the carbon content. Zinc contents vary between less than one percent and double-digit values (**Table 4**).

Table 4. Example of composition of dust and sludge [10]

wt.%	Fe	C	CaO	SiO2	Al2O3	Zn	Pb	Cl	K
Sinter dust	43-50	3-6	10-11	5-8	0.5-2.2	0-0.3	/	3-25	3-9
BF Dust	15-40	25-40	2-8	4-8	0.2-3.7	0.1-0.5	< 0.07	/	/
BF Sludge	7-35	15-47	3.5-18	3-9	0.8-4.6	1-10	< 2.0	/	/
BOF Coarse dust	30-85	1.4	8-12	/	/	< 0.4	< 0.04	/	/
BOF Fine dust	54-70	0.7	3-11	/	-	3-11	< 1.0	/	/
BOF sludge	48-70	0.7-4.6	3-17	/	/	0.2-4.1	< 0.14	/	/
Mill Scale	56-72	0.6-0.8	0.2-5	0.7-7	< 2.2	< 0.04	/	/	/
EAF carbon steel	10-45	0.4-3.3	3-17	0.6-5	0.3-3	21-43	0.4-10	0.8-5	0.1-2
EAF stainless steel	20-65	0.05-1.3	8-20	3-9	0.4-2	2-25	0.2-4,5	Cr2O3 9-20	Ni 1-8

The composition of the various dusts and sludges of the sinter plant, BF, BOF and the EAF are very heterogeneous. The compositions depend strongly on the raw material and the scrap charged in the device. Besides dry dusts, flowable sludges are generated in gas cleaning devices. Often there are differences between coarse dry dust and fine dusts/sludge due to the formation processes of dust. In these fine dusts/sludges the concentration of elements with low boiling point is higher, but the concentration of valuable elements worth to be recovered in these dusts is often at a limit of an economic recovery operations. The varying composition of the dust and sludge require a detailed adaption of the recycling process which is often specific for a production plant.

In the sinter plant many dusts and sludges of the BF/BOF route are recycled. The recycling is limited by harmful components like sodium, potassium, zinc, lead or oil at higher concentrations. Due to the input materials the sinter plant the dusts have higher contents of sulphur and chlorine compounds. This leads to high a salt content as potassium chloride and high content heavy metal in the dust and make recycling more difficult.

The BF dust which is emitted via the top gas is often cleaned in tow steps a dry gas cleaner, creating a coarse fraction called BF dust (or primary dust) and a wet-scrubbed, fine fraction, called BF sludge (or secondary dust)

The BF dust is characterised by high iron and carbon content and the wide particle size distribution and is usually recycled to a large extent via the sinter plant or the BF. The size distribution is affecting pre-treatment processes as granulation or briquetting process. The recycling rate is also limited by concentration of zinc and alkali metals in the dust, which is low in comparison to the sludge.

The BF sludge contains also high a iron and a carbon content but also by high moisture and zinc content as well as heavy metal and high content of small particle which is limiting the recycling rate. Most BOF dusts and sludges are collected in the secondary/fine systems. Often the sludge is landfilled due to the high effort for upgrading.

The particular emission of the BOF can be divided in primary (coarse) and secondary (fine) BOF dusts and sludges. Regarding the BOF fine dust fraction alkali and zinc content are main constrains and at the BOF sludge practical and technical also constraints appear due to zinc and moisture content and the high content of fine particle. The carbon levels associated with BOF dusts and sludges are low compared to BF dusts and sludges. Investigations have shown that the fine fraction is much richer in zinc and lead than the coarse BOF sludge contains much less sulphur than BF.

A large part of all EAF dusts is 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. Besides this, all EAF dusts contain a considerable amount of slag forming compounds like CaO, MgO, MnO, SiO2 and Al2O3, where CaO is dominating.

Especially the EAF dust from carbon/low alloyed steel production contains a large part of zinc oxide (21-43% Zn), which stems from charged zinc coated scrap. Depending on the scrap charge composition, also the lead content can be elevated. This makes the EAF dust an interesting resource mainly for Zn recovery.

In contrast, the EAF dust from high alloyed or stainless-steel production contains a significantly lower amount of Zn and Pb. However, here the content of alloying components like Cr, Ni is elevated, which makes this EAF dust a valuable resource for recovery of these elements.

Technological challenge to use of spent refractory for the production of new ones

The variety of refractory types used in steelmaking industry **(Figure 9**) implies a variety of both chemical composition and of related thermo-mechanical properties of the components that must suit the different operating conditions. The largest consumption is noted in refractories used for steel ladle and BOF linings and for Blast Furnace casthouse.

The already explained problems (see Chapter 2.5) related to these aspects of the spent refractories push a certain type of “easier” recycling as slag conditioners because this allows a less refined approach of material sorting. This approach is already used and is expected to increase in the next years.

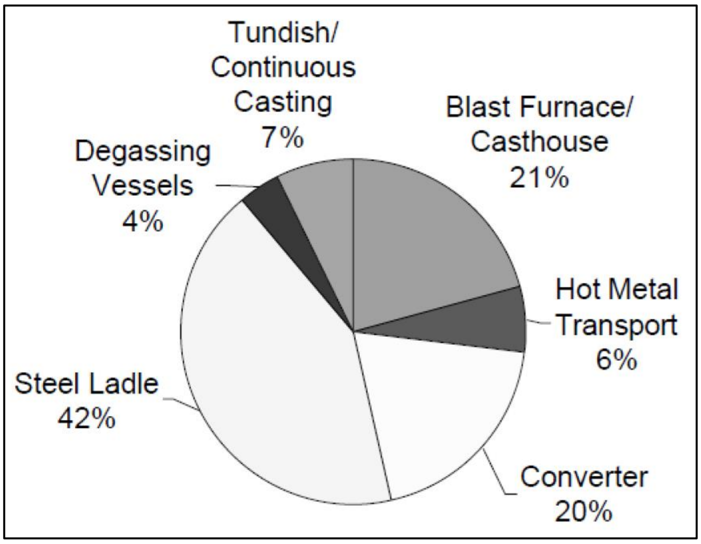


Figure 10. Consumption of different types of refractories in integrated European mills

The possibility to have a recycling of spent materials to produce the new ones is the real technological challenge to face and overcome. Spent refractories contain some pollution due to the process they have been exposed to. However, in most cases this pollution is not so important in terms of overall chemical composition (see **Table 5**) despite this being one of the causes hindering reuse of such materials for producing new ones that must have high performances. What can be considered as challenging is a proper sorting and selection of the spent materials after use. Automatic systems based of optic devices controlled by specialized software (e.g. AI) can be considered as a reliable step forwards to reach the target.

Table 5. Comparison of chemical composition between new and spent MgO/C refractory for EAF

MgO+C	Al_2O_3	CaO	FeO	MgO	SiO_2	C	N_2
New	4.40	0.99	0.37	84.74	4.47	9.49	0.20
Spent	6.07	1.99	0.56	86.06	0.93	6.61	0.41

Technological challenge to use alternative carbon source as secondary raw material in the place of fossil coal in EAF operations

Biomass or materials directly derived from biomass have been demonstrated as feasible substitutes of coal in EAF operations.

The challenges related to such operations are not only technical but also of an organizational nature. The technical challenges have been mostly solved by recent devoted projects [P22, P31] that optimized the modalities of biogenic carbon addition together with scrap and started to optimize the injection systems to obtain a proper slag foaming.

Biochar obtained from biomass torrefaction (see **Figure 11**) has been indicated as a better material to be used. Obviously, the biomass torrefaction implies additional efforts as a devoted plant is needed. In such case, the additional costs related to biochar production affects the convenience of the operation in an economic point of view being strongly related to the cost of coal on the market. The highest benefit has been estimated when the torrefaction plant is close to steel plant. More stringent rules on emissions and considering that the EU quota for carbon permits an increase by 146.33% since the beginning of 2021, indicates a change of the situation in the next period.

The torrefaction plant is composed by the following treatment stages:

- collection of biomass, grinding and homogenization,
- drying stage: the biomass is dried using the heat from hot gases in a conveyor belt, closed into a tunnel,
- torrefaction: biomass is thermally treated in a rotating drum with hot gas having a temperature in the range 250-350°C
- production of a hot gases stream; the boiler is heated up by the syngas from the torrefaction drum and from the gas developed in a second reactor in which an amount of residual biomass is burned,
- briquetting stage to compact material by pressure, obtaining a final product having a size according to final destination and a density of about 600 kg/m3.

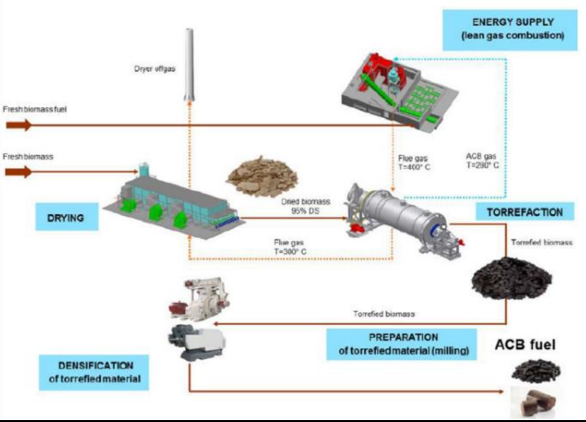


Figure 11. Biochar production plant starting from biomass (Study from project GreenEAF2 [P31])

Biochar production can then be included in what has been defined as a challenge of organizational nature in the start of the present paragraph. Hence, this organizational approach should include logistic aspects that must also be related to geographical factors. The Friuli region in Italy is a good example for stressing such a concept. This region has a large variety and availability of biomass of different nature such as forest residues, ligneous species, and agricultural residues. A study of ENEA in 2012 about the biomass situation in Friuli highlighted the possible CO2 avoided in tons/year by using the available biomass sources. The situation of Friuli region is particularly favourable for nearer steelmaking plants (e.g. Ferriere Nord) making the whole operation much more convenient from an economic point of view.

biomass type	ton	energy (tep*/year)	CO_2 avoided (t/year)
forest residues	218100	40100	93000
ligneous species	66200	12200	28000
agricultural residues	355100	100200	233000
biomass from cultivation	300000	95000	220000
tot	**939400**	**247500**	**574000**

Figure 12. Study by ENEA about energy and related CO2 avoided exploiting the biomass sources in Friuli (year 2012, cited in project GreenEAF [P22])

The use of waste plastic materials in substitution of coal can be considered in a similar way as biomass/biochar regarding the technological challenges. The main problem is related to the optimization of a proper way for plastic injection. Plastic materials in general have chemical characteristics and related physical properties that differs significantly from anthracite **[52]**. The problem is in particular due to the high amount of volatile matter in the material (higher than 80%) with a carbon content significantly lower than that in coal (see **Table 6**). This aspect implies the need of new and specifically optimized injection systems for such materials to ensure proper EAF operations.

Table 6. Comparison between a plastic material and coal [52]

Parameter	Plastic residue	anthracite (reference material)
HHV** (MJ/kg)	32.37	26-30
Ash (% dry)	9.50	1-10
Cl (% dry)	0.38	<0.01
S (% dry)	0.03	0.5-1.5
H (% dry)	10	0.5-1.5
N (% dry)	1.1	0.2-0.3
C (% dry)	65.0	80-85
O (% dry)	14.88	0.1-0.5
Volatile matter (%)	88.50	1-10
Fixed carbon (%)	1.5	75-80

3.2 Targets and challenges to achieve climate neutrality by 2050

Reducing the CO_2 intensity of the energy intensive industries in general and the global steel sector in particular is crucial for meeting the objectives of the Paris agreement and the EU's own climate targets. The EU steel industry currently accounts for 221 Mt GHG emissions annually (including both direct and indirect emissions). This is 5.7% of total EU emissions.

The EU steel industry has already reduced emissions by 26% since 1990, driven by energy efficiency improvements and higher recycling rates. It is committed to reducing its CO_2 emissions from production by up to 50% by 2030 compared to 1990s level by developing and upscaling technologies. Achieving climate-neutrality by 2050, however, requires radical changes to the way steel is produced.

The overall transformation would be enabled by hydrogen-based steelmaking, by adapting of fossil fuel-based steelmaking through process integration, and through the capture, eventually storage or use of waste carbon to produce chemicals. Further, the transformation will be driven through increased recycling of steel scrap and steel by-products (e.g., through the EAF route). In all cases a shift to fully decarbonised electricity will be imperative.

There are two main technological pathways for CO_2 reduction in the steel sector. These are Smart Carbon Usage (SCU) and Carbon Direct Avoidance (CDA). These pathways, shown in **Figure 13**, seek to substantially reduce the use of the carbon compared to the current means of steel production or to avoid carbon emissions entirely. There are overarching circular economy projects, such as enhancing recycling of steel and its by-products and the further improvement of resource efficiency. Within each pathway are groups of technological approaches [53].

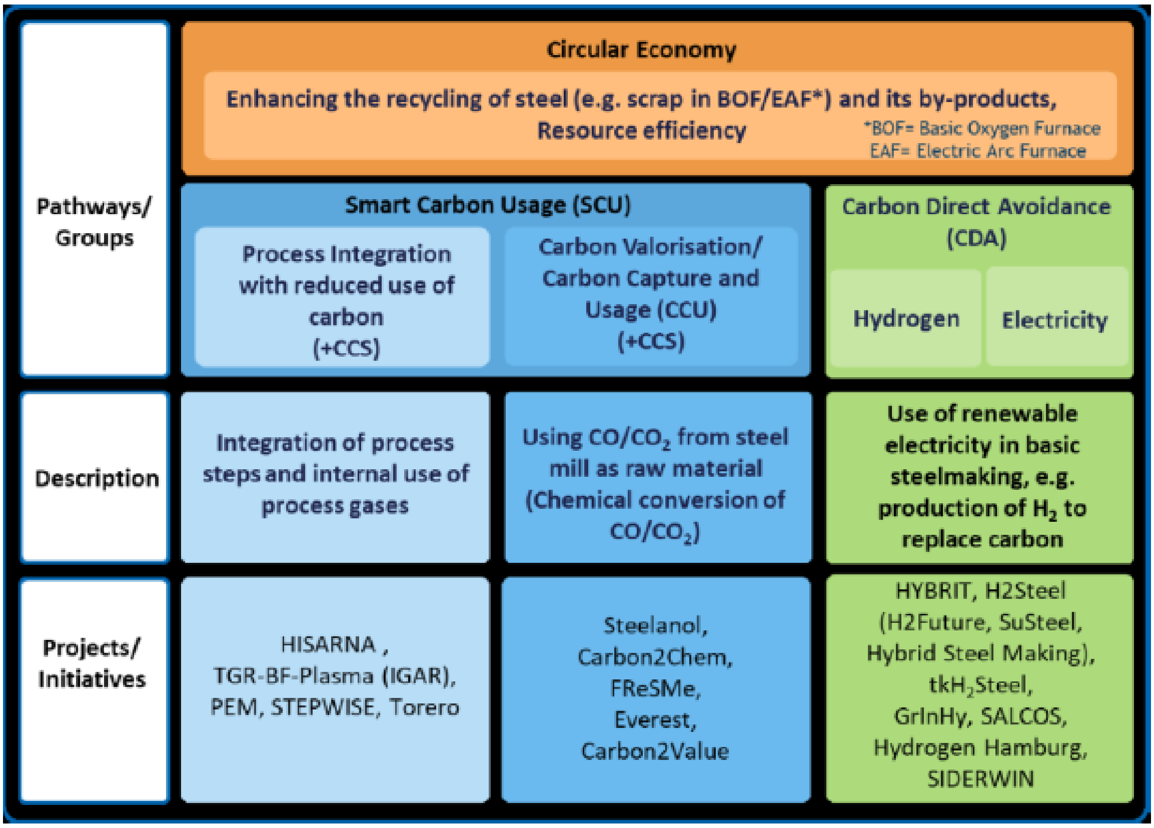
Smart Carbon Usage (SCU) includes:

- Process integration (PI), which looks at modifications of existing ironmaking/steelmaking processes based on fossil fuels that would help reduce the use of carbon in, and thus the CO_2 emissions of, a state-of-the-art EU plant.

- Carbon Valorisation or Carbon Capture and Usage (CCU), which includes all the options for using the Hydrogen, CO and CO_2 in steel plant gases or fumes as raw materials for the production of, or integration into, valuable products.

Carbon Direct Avoidance (CDA) includes:

- Hydrogen-based metallurgy, which uses hydrogen to replace carbon as the main reduction agent for the iron ore reduction stage. This hydrogen could be produced using renewable energy.
- Electricity-based metallurgy, which uses electricity instead of carbon as reduction agent for the iron ore reduction, with greater focus on renewable energy.



Source: Eurofer

Figure 13. The EU steel industry's strategic technological pathways for low-carbon steelmaking, which identifies both the main pathways to be pursued and a sample of the proposed or ongoing projects in each pathway [53]

Actual technologies and initiatives (projects) of the EU steel industry regarding CO_2 mitigation within the main technology pathways are described in [54], [55] and summarised as follows:

- SCU - Process integration pathway
  - Technology routes based on optimised BF-BOF (optional: combination of technologies for maximised CO_2 mitigation)
    - Recycling or increased utilization of steel plant gases (e.g. recycling of BF top gas as an auxiliary reducing agent; TGR-BF-Plasma, IGAR project),

    - Partial replacement of coal by either natural gas, hydrogen injection or biomass (Torero project)
    - Increase of scrap/hot metal ratio, and the replacement of iron ore by hot briquetted iron (HBI).
  - Carbon based smelting reduction
    - Iron bath reactor for smelting reduction (HIsarna). This process is operated with oxygen and therefore well suited to be combined with CO_2 capture for CCU or CCS. Further, HIsarna is capable for recycling of fine-grained iron and zinc bearing residues (Reclamet project).
  - Final storage of captured carbon (CCS; e.g. Everest CCUS projects network). CCS is applicable for the BF-BOF route, as well as for the carbon-based smelting reduction.
- SCU – CCU pathway

  Aim of CCU is to bond CO_2 originated from steel process and waste gases and to use the carbon for producing base chemicals e.g., via catalytic conversion processes. The production of various CO_2 based products requires hydrogen, whereas for CO_2 lean H_2-production, the availability of renewable energies and their volatility are important factors. Many different CCU products are existing at different TRLs. Main CCU projects basing on the BF/BOF route are mentioned as follows:

  - The Steelanol and Carbon2Value projects deal with the conversion of the CO and H_2 in the blast furnace gas by using microbes into ethanol
  - The Carbon2Chem project deals with methanol production, as well as production of polyalcohols, polymers, and oxymethylene ether (OME)
  - The FresMe project deals with methanol production from steel plant process gases
- CDA pathway
  - Hydrogen based direct reduction route (H_2-DR/EAF route)

    The H_2-DR/EAF route includes the hydrogen based direct reduction of iron ores in a shaft furnace processes and the melting of the produced DRI in an electric arc furnace (e.g., HYBRIT, H2Stahl, SALCOS projects).

    In the direct reduction process, the direct reduction of iron ores with hydrogen shaft furnace processes will be used. In these furnaces the iron ores, mostly in the form of pellets, are reduced in the “dry” stage by CO and H_2 from cracking of natural gas. No liquid phases occur and no slag metallurgy is done. The produced DRI contains all the gangue materials from the iron ores, so that the slag metallurgy must be done in the subsequent electric arc furnace during crude steel production. To keep the slag volume at low level, so-called DR pellets with especially low amount of gangue components, are charged to the DR plant.

    The slag of the electric arc furnace cannot be used for production of granulated slag like the blast furnace slag.

    Another process option for DRI melting is the submerged arc furnace (SAF), which produces hot metal, being further processed in the oxygen converter. The SAF process can also apply slag metallurgy for adjustment of slag properties towards the desired composition for recycling and refining of the hot metal to liquid steel in the oxygen converter.

Many leading European integrated steel plants, in their environmental declarations besides individual PI and CCUS measures, have already committed to follow mid-term transition paths to replace the blast furnace process successively by the H_2-DR/EAF route [56]–[61]. At first this may include the use of natural gas as reductant as long as green hydrogen is not available in sufficient amount and at acceptable price.

- Hydrogen plasma smelting reduction, which currently is investigated in technical scale (SuSteel project). Potential industrial deployment is not expected before 2050 [55].

  Iron electrolysis technologies, which comprise alkaline electrolysis (e.g. SIDERWIN project) and molten oxide electrolysis. Both are still in development at different levels. Potential industrial deployment is not expected before 2040 for alkaline electrolysis respectively 2050 for molten oxide electrolysis [55].

During the time scope of the REUSteel project only a few low-carbon steel production technologies are expected to be at technological maturity, and it is not yet clear which process will dominate steel production in the future. As worked out in the GREENSTEEL [55] projects, in short-term (up to 2030/35) some process integration and CCS technologies based on the conventional BF/BOF route are expected to reach industrial deployment. This is further expected for a few CCU technologies (e.g., methanol, ethanol production), also based on the BF/BOF route. During this time, also the transformation of primary steelmaking towards the hydrogen-based direct reduction (DR)/EAF route is expected to start, which will replace several blast furnaces plants. Some initial industrial scale DR plants in the EU will be started-up in the period until 2030 – some with the option to operate also with natural gas in a transition phase.

The industrial deployment of the mentioned SCU technologies (including CCU) is not expected to have a substantial effect on the amount or quality of the produced dusts and sludges, since the basic BF/BOF process route remains unchanged. However, the deployment of the CDA pathway in the form of the hydrogen-based DR/EAF process route will lead to a changed amount and quality of the produced dust, sludge and slag in contrast to the BF/BOF route and changed options of internal recycling of residues.

From the DR/EAF route new dust or sludge will arise from the DR plant. Further, a new type of EAF dust (or dust from similar electric furnaces) from the DRI melting step will arise. Both will have a different composition compared to the dusts and sludges from integrated steelmaking as well as compared to dusts from scrap based electric steelmaking.

For instance, the electric furnace dust from DRI melting is expected to have a low zinc content due to the absence of zinc containing feedstock. This may imply a different recycling strategy compared to the high-Zn EAF dust from scrap based electric steelmaking.

The slag produced from the DRI melting step will also differ very much from the current blast furnace slag, for which utilisation in the cement industry is well established. To enable a further slag utilisation in the cement or construction sector, this implies an appropriate adjustment of the newly produced electric furnace slag.

4 Trends from assessed EU Projects and Questionnaire

Based on the critical analysis of EU research projects of the last 15 years carried out in WP2 and feedback from the seminars and the workshop held within WP4, the industrial trends listed in Chapter 4.1 are derived, taking into account the recommendation for future work of the projects. When assessing the trends, it must be borne in mind that the reviewed EU projects represent only a limited, even though significant, thematic part of the research activities carried out within the borders of the EU during this period. Topics and projects funded by other European, national or regional resources or carried out by the companies without public funding were not included in the evaluation. Within the description of the EU projects, associated project numbers [P#] are being used which can be found in Appendix 9.

To check the current state of the topics of the EU-projects, it was reviewed whether the topics were continued in following ups or other research projects in the last few years. A summary is given in Appendix 10.

To find out the current interests of members of the iron and steel industry on different research topics, an online questionnaire was created and presented to the audience during the webinars and the conferences. The answers received are analysed and summarised in the Chapter 4.2 “Questionnaire”. The questionnaire is shown in the Appendix 11 Questionnaire.

4.1 Trends on the basis of the assessed EU research projects

In Project REUSteel, 45 projects were selected for review from which 36 projects has final reports available. The list of the reviewed projects is given in Appendix 9. The projects almost always deal with several different research topics that are linked together by an overarching framework. Therefore, the sum of projects dealing with the research topics is significantly higher than the number of projects reviewed.

In **Figure 14** the number of research topics per residual/by-product in the projects is broken down by internal, external and other use.

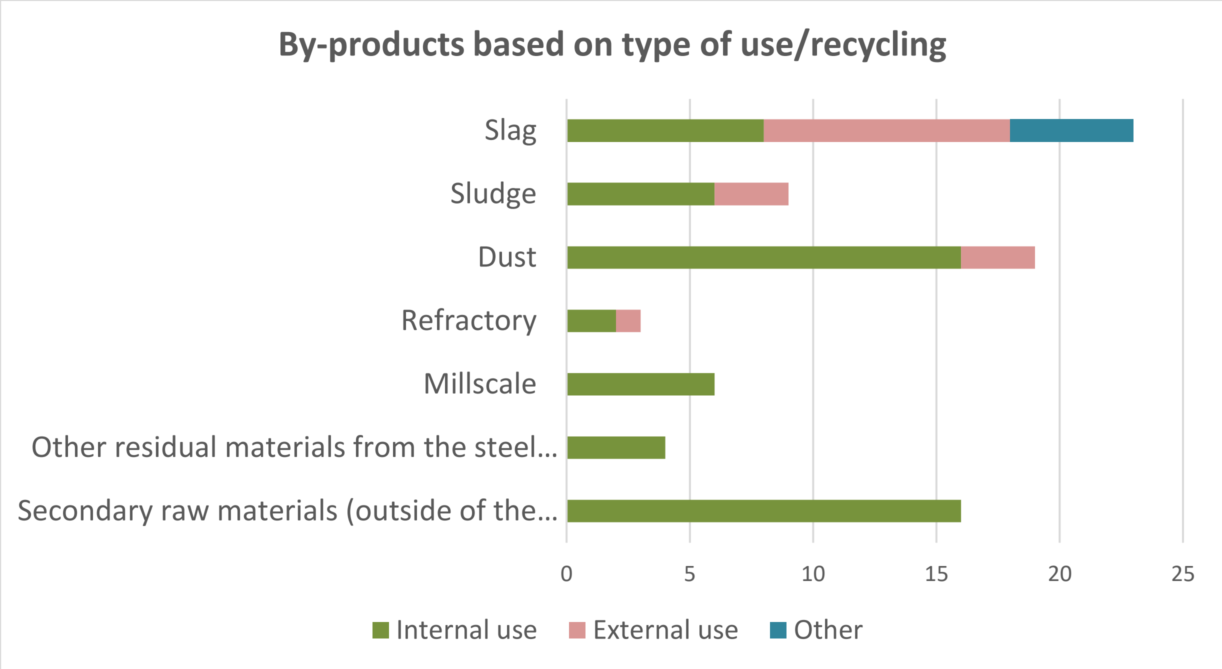


Figure 14 Research trends of the By-products based on type of use/recycling from EU research projects since 2020

The number of slag research topics within the evaluated research projects is by far the highest, in line with the amount of slag, and for this research topic the highest number of external and other uses was investigated. This correlates also with trend in the industrial utilisation. With regard to the amount of sludge and dust, the number of research topics is high which obviously meets the need. The topics for dust and sludge are oriented towards internal utilisation. The research topics of mill scale are fully geared towards internal use. Also, the number of research topics about secondary raw materials from outside the steel works is high even though no scrap recycling topics are included.

In the following, technological trends sorted by kind of residue/by-product are described more detailed, classified by substances and based on the evaluated EU research projects. As far as possible, a follow-up of the derived trends was carried out and is integrated. Further information regarding follow ups can be found in Appendix 10.

4.1.1 Slag

From the evaluated EU projects 18 deal with slag. From these, 8 deal with slag internal use/recycling, 10 deal with slag external use and 5 projects deal with slag analysis. Some projects deal with different aspects within the same project (**Figure 15)**.

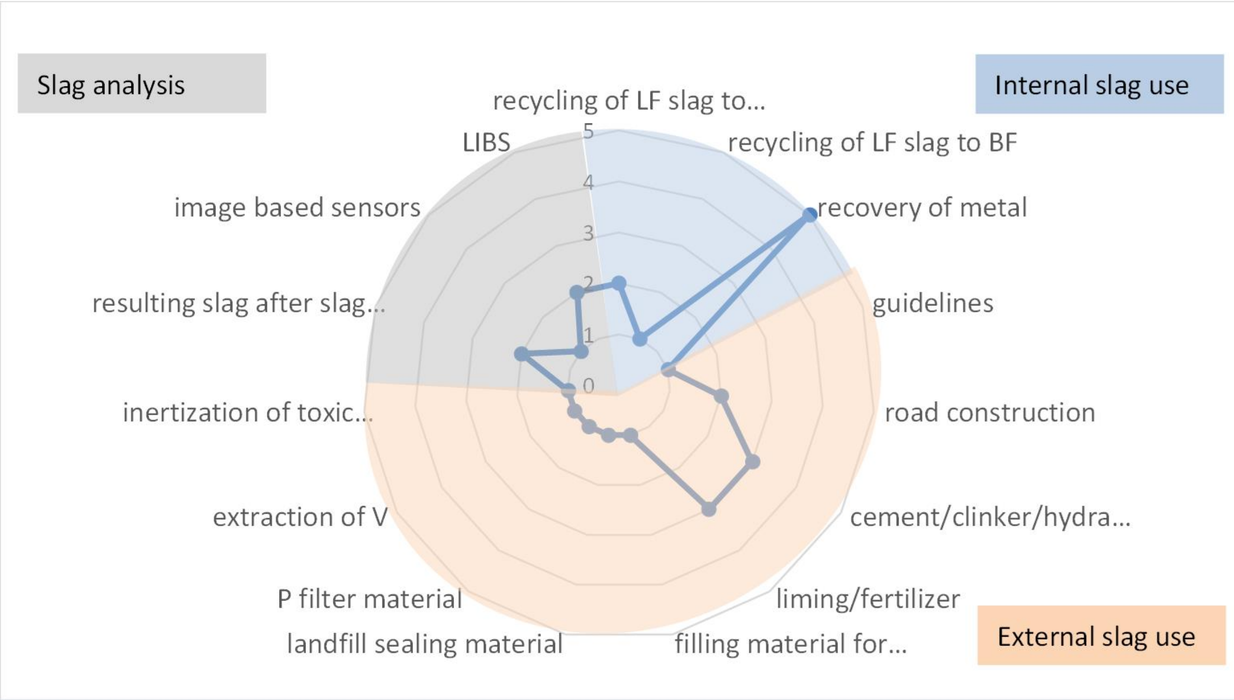


Figure 15. Subcategories of projects dealing with slag

<u>Internal metallurgical slag use/recycling</u>

With respect to slag use/recycling the projects were dealing with:

- LF slag recycled as replacement for lime in EAF [P9, P29]
    - This includes liquid and solid addition of LF slag to the EAF which was successfully tested in ECSC 7210-PR/203 [P9] in industrial setting, however it was steelwork specific, and logistics of the steelwork limited the success of this approach to only one steelwork while in the other steelwork dry LF slag was used in pelletized mixtures.
    - In the EIRES [P29] project simulation of LF slag as a replacement for lime and dolime in EAF showed that the practice might increase overall electricity use slightly.
- LF slag recycled in BF as slag former in the REFFIPLANT [P27] project which showed only minor cost savings but showed potential to reduce landfilling.
- Recover metal from BOF or recover metal from EAF slag [P2, P18, P19, P27, P30, P40]
    - The IPBM [P2] project developed tests in laboratory and then with a DC-furnace to recover metal and V from BOF and EAF slag and other by-products. The stand-alone alternative gives the possibilities to optimise slag, metal and inertisation of products to market demands without limitations to treatments within a steel plant. However, the process was expensive due to the cost of electricity and low value of recovered products.
    - The URIOM [P18] project conducted modelling of processing of oxidic residues (spray roasting residue and a high-Cr EAF slag from stainless steelmaking) by a coupled process of cupola furnace and inductively heated coke bed reactor. The

needed electric energy consumption of the coupled process to recycle EAF slag in the modelling was high.

- The EPOSS [P19] project investigated the increase of energy efficiency and productivity during EAF high alloyed stainless steelmaking by development of innovative slag conditioning techniques for slag foaming and adjusted use of all available energy sources. Different process variants of slag conditioning have been investigated at the electric arc furnaces of three stainless- and special steel producers such as slag foaming and improved chromium control in the slag, a slag conditioning technique based on CaC_2 mix injection, adjusted addition of FeSi and injection of carbon/oxygen or adjusted supply of chemical energy to the EAF (and Cr recovery) by injection of aluminium granules. The process was successful in decreasing the amount of Cr going into the slag, but no electrical power savings were observed.
- The REFFIPLANT [P27] project conducted laboratory tests and simulation tests to optimize the pelletisation of BOF slag fractions to have good separation for internal recycling (e.g. to produce pellets for the sinter plant), resulting in cost savings, reduction of disposed slag, maximization of products quality, reduction of use of iron ore pellets. This recycling of the pellets was not tested in the sinter plant.
- The PSP-BOF [P30] project conducted laboratory and industrial tests to try to separate Fe-rich fraction of the BOF slag through different cooling procedures and physical/magnetic separation. The idea was to use the Fe-rich fraction for internal recycling and Fe-poor fraction as slag fertilizer. While the processes showed some potential it was not successful during the project to recycle the entire BOF slag.
- The FP4-BRPR970446 [P40] project treated BOF and EAF slag in a reduction furnace (DC-furnace) using anthracite coal and plant tests to recover Cr and Ni. The Cr-recovery exceeded 90% and for Ni was close to 100%. The resulting slag could be modified to meet the requirements of ballast material by air cooling; water granulated slag has a latent hydraulic effect and is comparable with blast furnace cement.

External slag use

The projects were dealing with

- guidelines how to increase EAF slag use were described in SLACON [P28] project. Different laboratory and industrial scale tests were made to solve problems at 3 different steelworks resulting from the environmental behaviour of EAF slag based on the local regulations. For example: to decrease Ba addition sand was recommended, to decrease V addition sand or LF slag was recommended, to decrease Cr addition aluminium oxide was recommended and to decease free lime adjustment LF addition or storage/watering was recommended. In addition, a filter system was designed and investigated in large scale tests that can absorb and remove at the same time F, Mo and V from the slag cooling water.
- Potential effects of BF, GBF, BOF and EAF slags use in road construction were evaluated in ECSC 7210-PR/195 [P10] on groundwater. Laboratory and pilot lysimeter tests were done to try to simulate the effects the use of slags might have in road construction. While a recommendation was given for use of these slags in road construction precautions were recommended (e.g., setting up a cover represented by an asphalt-fines matrix or concrete surface on road, reducing lateral infiltration towards the subgrade (boarder effect)).

- BOF, EAF and LF slags as cement/clinker/hydraulic binder [P2, P30, P40, P43]. Three of the RFCS projects investigated slag after metal separation (and therefore changing the original slag characteristics) and one project developed a model. In this respect none of the projects investigated BOF, EAF and LF slag directly after production for possible use in cement.
    - The IPBM [P2] project BOF and EAF slag were recycled for metal in a DC-furnace, the resulting slag was investigated for use as clinker material and hydraulic binder successfully, except from BOF slags high in V.
    - The PSP-BOF [P30] project investigated Fe-poor fraction of BOF slag after magnetic separation, however due to wet process that was used the resulting slag did not meet the requirements for clinker.
    - The FP4-BRPR970446 [P40] project treated BOF and EAF slag in a reduction furnace (DC-furnace) to recover metal, the resulting slag treated with glass cullet in lean concrete has been tested on a laboratory scale, however the results showed the slag did not meet the requirements in 4 out of 5 samples due to volume stability.
    - The FISSAC [P43] project tried to establish a sound valorisation scheme for EAF and LF slag similar to BF slag incorporation into cement by creating a model that can take into consideration environmental, economic and social situations of different products.
- BF, BOF, LF and basic slags as fertilizer/liming material [P12, P26, P30].
    - The ECSC 7210-PR/267 [P12] project and follow up SLAGFERTILISER [P26] project investigated currently produced slag as fertiliser (BF, BOF, LF and basic slag), the effects on harvest yield of crops and hay, and the influence of Cr and V on the soil, plants, and crops. The projects investigated short term effects in field trials as well as long term effects on field trials that have been fertilized with slag for 60 years.
    - The PSP-BOF [P30] project treated BOF slag in laboratory melting tests with sewage sludge to create a P rich fertilizer where the P is bioavailable to plants. The resulting slag was tested in pot trials and performed as well as currently available on the market P fertilizers.
- In the FP4-BRPR970446 [P40] project the GBF slag was tested in laboratory and semi-technical trials as filling material for mining shafts by analysis of the compressive strength and leachability. After 1 year of testing the results were not successful.
- The 7215-PP/028 [P7] project tested BF, EAF and LF slags as landfill sealing material on inhouse landfill. After 15 months of testing, the alternative sealings with a silica gel amended EAF-slag system (using ProfilArbed materials) or a sealing from complete substitution through a mixture of LF slag – BF sludge 1:1 showed comparable, and in relation to the standard GCL-Bentonite Mat reference, significantly better sealing efficiency compared with the sealing materials available on the market.
- BOF and EAF slags were used as P filter material in SLASORB [P21] project to remove P from municipal wastewater treatment plants. The project showed that slag can be used as P remover in filters, however filters may vary based on parameters included in the design and operation of the system (e.g., batch load, downflow, residence time, etc…), the temperature and wastewater composition. There needs to be additional studies to determine the optimal conditions for using slag P filter. In addition, the release of heavy metals from slag into the wastewater treatment plant needs to be kept in mind to ensure quality of the water.

- The PSP-BOF [P30] project investigated the market potential of recycling Fe-poor fraction (after separation of BOF slag into Fe-rich and Fe-poor fractions after cooling and physical/magnetic separation) for extraction of V from the resulting BOF slag.
- The IPBM [P2] project investigated the inertization of toxic wastes by vitrification with liquid BOF and EAF slags. Laboratory scale tests were conducted prior to pilot scale test in an induction furnace and showed the possibility of inertization of toxic wastes.

Other/Slag analysis

With respect to slag analysis the projects were dealing with:

- EAF slag quality after optimisation of slag foaming [P8, P19].
  - The ECSC 7215-PP/026 [P8] project investigated pneumatic injection of dust from stainless steelmaking (dust alone or co-injecting it with carbon, FeSi or coke) into EAF with or without decreasing slag foaming in EAF while maintaining slag properties. Chemical and mineral properties of the EAF slag before and after treatment were analysed to control its quality. The quality of the resulting slag was similar to the slag without recycling of dust, small decrease of Cr in the slag was seen, but the concentration was still significant.
  - The EPOSS [P19] project investigated different process variants of slag conditioning at EAF of three stainless- and special steel producers: for slag foaming and improved chromium control in the slag, a slag conditioning technique based on CaC_2 mix injection; adjusted addition of FeSi and injection of carbon/oxygen and adjusted supply of chemical energy to the EAF (and Cr recovery) by injection of aluminium granules. The resulting slag was analysed for quality control.
- The OPTDESLAG [P24] project investigated image-based sensors to optimise BOF and EAF slag amounts during tapping.
- Laser based analytical tool (LIBS) for BOF, EAF and LF slags composition in liquid state was investigated in two projects: [P11, P26].
  - The INQUISSS [P11] project worked on detection of Fe, Ca, Si, Al, Mg, Cr and Mn by LIBS system. The developed LIBS-method can be used in steelmaking plants in order to control the slag composition online, although the environment is rough. The developed system could be used in processes where there is a homogeneous liquid slag of low viscosity, such as continuously melting of DRI, control of foaming slag in an EAF, metallurgical work in a vacuum tank.
  - The SLAGFERTILISER [P26] project used LIBS system to determine which slag can be used as fertilizer.

4.1.2 Dust/Sludge

In this subchapter the valorisation of projects dealing with sludge and dust is summarized.

Sludge

From the evaluated EU projects 9 deal with pre-treatment and utilisation of sludge from blast furnace and BOF. From these, 6 deal with internal use/recycling of sludge by briquette production [P5, P14, P17, P20, P27, P30] and 3 deal with external use of sludge [P2, P7, P40]. Some projects deal with different aspects within the same project [P5, P14, P17, P20, P27, P30] **(Figure 16**).

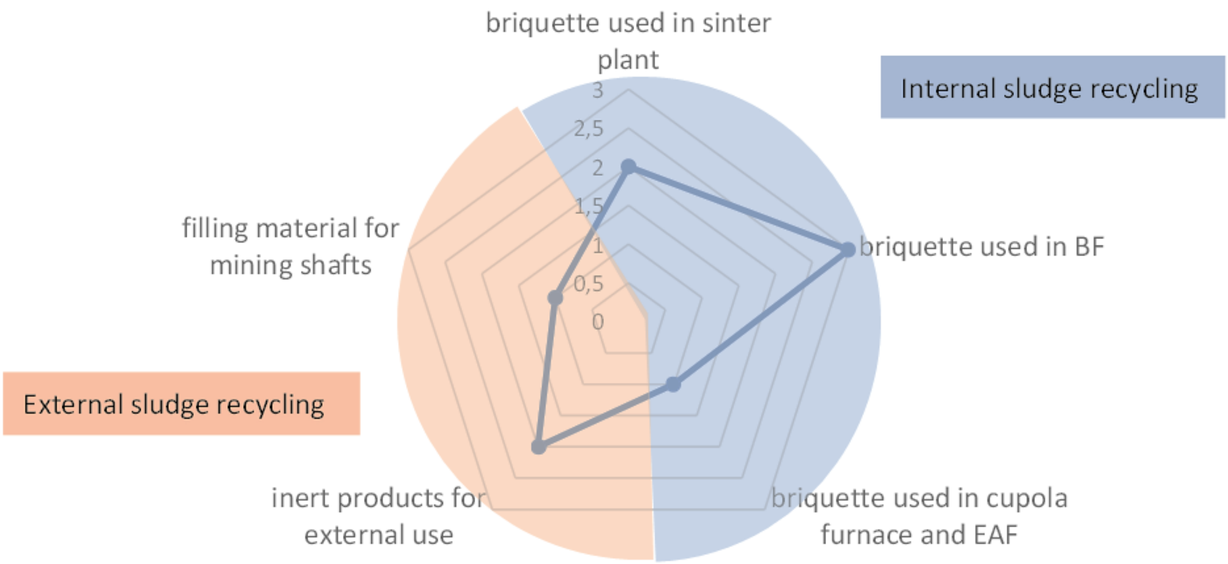


Figure 16. Subcategories of projects dealing with sludge

<u>Internal sludge use/recycling</u>

The internal utilisation of sludge from BF/BOF route

- Within the EU projects [P5] and [P14] BF- and BOF sludge were briquetted as one compound of a matrix of residual oxide materials with cement as binder and were charged to a shaft furnace. Also tests with self-reducing briquettes from mill sludge with low zinc content were successfully carried out at the blast furnace. The aim was to show an alternative recycling route for residuals which usually are recycled in the sinter plant.
  In follow ups until today investigations on optimising the briquette mixture with low zinc content and binder are proceeded. Improved briquette quality in terms of reduced disintegration of the charged briquettes and limited dust generation were produced and are a standard compound of BF burden.
- Within project ACASOS [P17] the utilization of carbon rich BF-sludge as substitute for coke-breeze and for ore fines in sinter plants was investigated. Different agglomeration and granulation processes were evaluated for the BF sludge as component in order to influence the process efficiency when adding sludge. Also, at this topic the investigations are carried on until today to valorise BF sludge and reduce landfilling.
- In the project FLEXINJECT [P20] BF sludge was injected in the blast furnace as one compound of a residual mixture. Segregation effects during the injection of BF sludge at the BF injection show the need for further research into appropriate preparation. The investigation on injection of residuals in the BF ware continued in [P27- see “dust”].

- In the project REFFIPLANT [P27] also coarse BOF sludge was briquetted as minor component and charged to the BF to avoid landfilling. Recycling BOF fine sludge into the BF led to cost savings and to reduced need for iron ore pellet and limestone input. The Zn-input to BF sludge increased and the landfill could be reduced. The conclusion was drawn that for each plant a specific investigation needs to be made with boundaries and restrictions that apply for that plant in that specific region.

External sludge use

- By vitrification of sludge and other wastes, such as spent refractory and zinc containing dust, using steel slags, products marketable for glass and ceramic industries as well as for potential use in civil engineering construction was obtained [P2].
- Mixture of LF slag and BF sludge used successfully as landfill sealing material showed comparable or better results than material currently available on the market for in top capping systems of statically stable industrial mono-landfills [P7]. Investigations into long-term rooting problems and efficiency of physiological boundaries are proposed as well as investigations into long-term soil-forming processes (shrinkage or mineral new phase formations) and into the influence of vegetation and evapotranspiration development.

- Mixture of BF sludge and residues was used as filling material for mining shafts but did not show potential in laboratory investigations [P40].

Dust

From the evaluated EU projects 18 deal with dust. From these, 16 deal with internal use/recycling of BF, BOF, EAF, sinter plant dust and 3 deal with external use of dust. One project deals with different aspects within the same project (**Figure 17**).

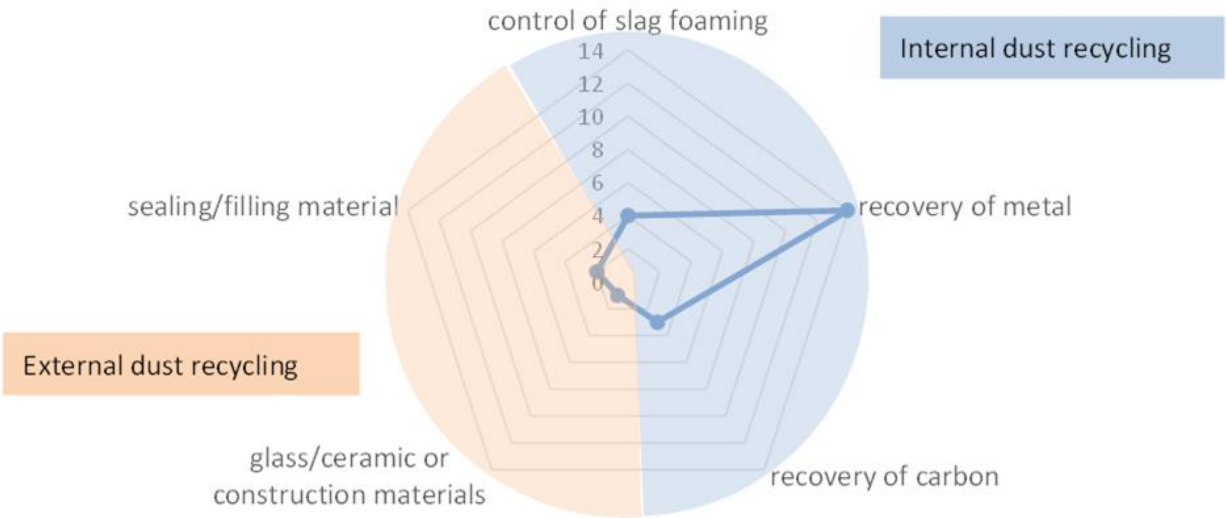


Figure 17. Subcategories of projects dealing with dust

Internal use/recycling of dust

With respect to internal use/recycling of dust the projects were dealing with

- EAF dust to control slag foaming [P1, P6, P8, P38].

- Recovery of valuable metals from dust (mainly Zn but also Pb and other heavy metals) and internal recycling of Fe. These topics were evaluated in the EU research projects [P1, P2, P3, P4, P5, P6, P8, P13, P14, P18, P27, P38, P40, P42]; the following main aspects have been explored:

  Pyrometallurgy

  BF dust and coarse BOF dust are returned directly to sintering in the raw material because they contain a high proportion of iron and carbon. The BF and BOF dusts are used to produce briquettes as well as self-reducing briquettes in mixture with different residuals and binders ([P5], [P14], [P27]). Investigations on this topic are ongoing.
  Also, the injection of BF dust with high carbon iron content to the BF as well as to EAF were investigated ([P20], [P27]) and is reported to be industrially utilized.
  Recycling of BOF dust into BOF showed no negative results on the resulting BOF slag. The Zn was concentrated in the BOF dust over time resulting in easier recycling [P40].

  Pyrometallurgical processes for production of a high-grade zinc oxide product (including also other volatile non-ferrous metals) intended for external zinc (and non-ferrous metal) extraction, while the contained Fe is recovered in the metal bath of the furnaces was studied in [P2]. Further, the recovery of alloying metals like chromium and nickel from fine-grained residues was investigated.
  Trends concerning necessary future research for the pyrometallurgical processes were mentioned in the projects:

  - Further improvement of the zinc yield
  - Scale-up of the combined pyro/hydrometallurgical process for full recovery of zinc containing EAF dusts to industrial level
  - Optimization of EAF and BOF dust treatments as mixing with coal for recovery of zinc in pyrometallurgical processes (e.g. DC furnace, BOF)
  - Gas reforming of Zn-containing process-gas from Zn recycling reactors to produce hydrogen

  Hydrometallurgy

  Hydrometallurgical processes: Chemical treatments aimed at the leaching, purification and separation of ferrous and non-ferrous metals contained in the EAF and BOF dusts. Two different hydro processes have been explored, namely one based on leaching of EAF dust by ammonium chloride [P1], the other by sulphuric leaching [P6] and [P13].

  Future research topics for the hydrometallurgical processes which were mentioned regarding the sulphuric acid leaching process [62] are:

  - The operation of hydro-metallurgical plant in continuous mode in order to evaluate the effect of possible accumulation phenomena [P6]. This has been investigated by the following FULLREC2 project [P13].
  - Use of improved anodes at zinc electrowinning stage (e.g. Ti instead of Pb) in order to minimise the impurities level in the solution.
  - Also, application of double solution purification treatment (e.g. to decrease Ni content) [P13].

The recovery of metals contained in the EAF dust is the main topic investigated by the evaluated projects. The main related problems have been the separation of Fe and Zn, the enrichment of ZnO in the dust fraction (useful for both internal recycling e.g. by hydrometallurgy and external recycling e.g. by Waelz), the recycling of Fe in the steelmaking cycle, the recycling of other valuable metals on the basis of the different treatments done (e.g. Pb, Cd in the residues of leaching treatments). These aspects are also included in recent presentations at metallurgical conferences and other literature that can be considered as indicative for the trends concerning the recycling of EAF dust. Some relevant examples are included in what follows.

Pyrometallurgy: recent works

New two-step pyrometallurgic processes are under investigation with the aim to achieve a very pure zinc oxide product minimising common volatile impurities like Pb, chlorides and fluorides. These components are usually contained in the crude zinc oxide of 1-step pyrometallurgic processes and avoid the direct use of the zinc oxide in the hydrometallurgical zinc production process without a further pretreatment step for purification. An example for this is the 2-step dust recycling ("2sDR"-process), which involves a calcination step for removal of Pb and halides and a reduction step, where a pure zinc oxide and a liquid iron for use in steelmaking are produced [1].

Improved briquetting processes for recycling of EAF dusts and other residues into the EAF are still of actual interest. This for instance involves the EAF dust recycling by self-reducing briquettes, which was reported to be investigated for free lime containing EAF dust from high alloyed steelmaking [63]. These briquettes are used for ferroalloy production in an EAF. Main point of the investigation is to prevent swelling and disintegration of the briquettes and thus ensure the required stability during recycling. A similar approach has also been considered by producing briquettes with different mixes including EAF dust, scale, sludge, and slags to be processed in a dedicated plasma reactor working under reducing conditions [64]. The process has been verified to allow the recovery of valuable metals producing ferroalloys (usable for steelmaking refinement process), a stable and environmentally inert slag (usable as a replacement of natural aggregate materials in the construction industry), and Zn rich dust (60-70% ZnO; usable for zinc recovery with high yields).

Further, a binder-free compaction process for EAF by-products recycling has been investigated [65]. This makes use of further EAF residues like sludge, slag and used refractories.

The use of microwave heating for the reduction process of EAF dust is another possibility which stimulated a growing interest in the recent years. The EAF dusts are indeed good microwave absorption materials. Such aspects together with the peculiarities of volumetric and selective heating of microwave lead towards a high thermal efficiency of the system. The use of microwave heating applied to briquettes of biochar and EAF dust has been evaluated as a valuable and efficient way for achieving the reduction of metal oxides in dust with a high percentage of dezincification (>92%) [66].

Hydrometallurgy: recent works

Also, hydrometallurgical recycling processes are still under investigation with the aim to achieve a very pure zinc metal product from zinc containing EAF dust. An example is the EZINEX® process, for which the results of demo plant trials are reported [67]. This process has the advantage, that the galvanising unit of a steel plant can directly be fed with the zinc metal, while galvanizing dross can also be processed back to EZINEX®, which enables a closed-loop internal zinc recycling.

- Recovery of carbon in dust [P17, P20, P23].
  The utilization of the carbon content of BF dust as well as of pre-treated BF sludge as carbon replacement for carbon breeze in the sinter mixture was investigated evaluating also different agglomeration processes, mixing process at the granulation processes at the sinter plant and type of binder. Also, the injection of carbon bearing dust and sludge in BF were investigated.

  Trends regarding the recovery of carbon in dust were mentioned in the projects:

  - Evaluation of the agglomeration of carbon containing residues like BF dust with the aim of an industrial application
  - Further investigation for industrial implementation regarding process control and adjustment were recommended

External use/recycling of dust

With respect to external use/recycling of dust the projects were dealing with using dust as sealing materials for landfills [P7], inertization of toxic-noxious metals by vitrifying wastes, for example zinc containing dust, by using slags, resulting in products marketable for glass and ceramic industries [P2] and filling material for mining shafts [P40].

Future research would be devoted to optimised restoration layers upon a compacted landfill body of typical in-house mono-deposits of the iron and steel industries and further to the test of other material compositions concerning mining shaft refilling mixtures.

4.1.3 Millscale

From the evaluated projects 6 deal with recycling of mill scale to recover metal [P2, P5, P14, P18, P27, P29]. Different recovery furnaces were used: 1 project deal with metal recovery in a standalone vessel (DC furnace) [P2], 2 of the projects deal with metal recovery in BF [P14, P27] and 3 of the projects deal with metal recovery in EAF [P5, P18, P29]. The trends derived from the assessed EU projects are summarized below.

DC furnace

One of the projects dealt with metal recovery in a standalone vessel, the so called in-plant by-product melting process (IPBM). In the DC furnace with hollow electrodes a mixture of mill scale, BOF- and BF-dust and BOF slag was treated and over 95% of the iron was recovered [P2].

The objective of this pilot and demonstration project was to develop a flexible process outside the main metallurgical line allowing the total transformation of steel slags and in plant by-products into value-added products by recovering metal ready for reuse in the steel production. The technical ability and flexibility of the process for total transformation of V-rich and normal BOF slag (together with other by-products e. g. BF and BOF sludge) into value-added products was investigated. An efficient reductant for the new process was identified. The IPBM process was proven to be an excellent tool for treatment of fine-grained by-products generated within steel plants including steel slags of smaller size. EAF-dust from both carbon- and stainless steelmaking, BOF-dust, BF-dust and mill scale from an integrated steel plant have been successfully treated.

The project has been followed by a number of big public projects on recovery of V from BOF-slag and numerous contract projects on V-extraction. The project consortium also continued with an EU project for slag reduction of stainless-steel slag and waste.

Blast furnace

Sinter plant recycling materials like for example mill scale and BF dust were used in high iron-content briquettes for direct BF charging [P14]. In [P27], through pilot scale and simulation tests, the oily mill scale, after removing oil, was treated to be reused in sinter plant in order to improve its recovery in BF.

[P14] was focused on the investigation of briquetting of sinter plant recycling materials like BF dusts or mill scale and the utilisation of these briquettes as additional charging material for ironmaking in the blast furnace. For briquetting, a vibration densification was selected which is used for the well-known concrete brickmaking. The production of cold bonded briquettes and their use as an additive raw material for the blast furnace was found to be an alternative way to relieve the sinter plants. This is because, the use of recycling materials in sinter plants is limited due to productivity drop, sinter quality as well as emissions.

The investigations on optimising the briquette mix recipes were conducted at SSAB to improve briquette quality in terms of reduced disintegration of the charged briquettes and limited dust generation. Over the course of the following years briquettes became a standard compound of the BF burden.

The main objective of [P27] concerning mill scale was to increase its internal reuse after oil removal in an integrated steelwork. Therefore, simulations for de-oiling of mill scale were carried out. Using an Aspen Plus simulation a high oil removal rate (of about 80-90%) and an oil content in the treated mill scale suitable for reuse in sinter production was indicated.

Electric arc furnace

Mill scale is used to manufacture briquettes that are self-reducing and suitable for direct use in an EAF process [P5]. Alternative binder materials were also tested [P18]. In [P29] the rolling mill scale has been tested in EAF to replace scrap. Through modelling and simulation, it has been shown that the introduction of scale in the furnace does not result in increasing by-products and waste generation, as all the introduced mill scale can be reduced to iron.

The objectives of [P5] were to develop technologies to manufacture self-reducing briquettes out of waste iron oxides and to recycle them in existing melting facilities like an electric arc furnace or a cupola furnace. These by-products, like oily mill scale, oily mill sludge and zinc bearing BF dust/sludge from gas cleaning, are not all recyclable in the conventional blast furnace route, due to their high oil and zinc contents. The briquettes also need to have sufficient strength for handling and storage.

It was shown that it is possible to recycle mill scale and EAF by-products conditioned in self-reducing briquettes in an electric arc furnace. The iron of the by-product was almost completely reduced and zinc completely removed. The charging of the new briquettes has shown no significant influence on the EAF performances concerning the productivity, the energy consumption, or the liquid steel and slag chemical composition, if the quantity charged was less or equal to 2 tons of briquettes per melt. Hence, other process parameters have proven to be a greater influence on EAF performance than the quantity of charged briquettes.

[P18] focused on the upgrading and internal utilization of residual iron oxide materials for hot metal production. Therefore, a new briquetting technology using vegetable-based binders was developed and tested. The produced briquettes were directly recycled to an electric arc furnace. The experiments conducted both in a Vacuum Induction Melting (VIM) furnace and in pilot plant scale, regarding the analysis of the briquettes melting behaviour, have also shown an iron recovery rate higher than 90 %.

The objective of [P29] concerning the reuse of rolling mill scale was to charge it directly to an EAF as scrap substitute. For the evaluation of this recycling concept, the EAF process with mill scale charging has been simulated. The model simulations have shown that the introduction of mill scale in the furnace does not affect changes in by-products and waste generation, as all the mill scale is expected to be reduced to iron. The authors concluded that the increase of energy consumption is not negative, as the global environmental evaluation shows that the efficiency in material reuse is very high and balances out the increase in energy consumption.

4.1.4 Refractory

From the evaluated projects, 3 deal with the possible use of spent refractory materials from steelmaking production. These projects [P2, P9, P18] faced both the possibility of internal and external recycling of the spent refractories as follows:

<u>Internal use/recycling</u>

- Use of the spent refractories in mixtures with other steel by-products forming briquettes to be treated with the aim of metal recovery. This possibility is investigated as an option in [P18] but not applied
- Use in mixtures with LF slags as EAF slag formers giving encouraging results both in terms of resulting slag characteristics and energy consumption [P9]
- Use of spent magnesite-based refractories as a suitable substitute for olivine and soft-burnt dolomite in integrated steelmaking plants including sinter plant, blast furnace, and LD-converter [P9]

External use/recycling

- Inertization of spent noxious refractory linings containing Cr^{6+} by melting them with steel slags together with other steel by-products such as dusts and sludges [P2]. The process converts wastes containing toxic and noxious matters into inert products that can be used for glass and ceramic industries.

The evaluated projects included possible ways of spent refractory recycling that became more and more important in the last years. This action will require a cultural change that has to be considered from all stakeholders [68]. The open-loop way of spent refractory recycling, explored with project [P9] and [P2], has been largely used with good results in internal recycling as slag conditioners in the steel industry [23], [32] or for external recycling as roadbed aggregates [69]. Such way of recycling continued having a relevant importance being the undoubtable benefits in terms of reduction or even complete avoidance of landfilling, energy savings, longer refractory lifetime (e.g. decrease of refractory dissolution rate), and saving in slag formers/fluxes [22].

On the other hand, the closed-loop way of spent refractory recycling can be considered as an option that can give higher economic values. The advantages in this case are related to both the avoidance of virgin materials usage with subsequent energy and associated greenhouse gas emission savings (e.g. the production of MgO from raw magnesite is a particularly energy intensive process) and the obtainment of materials (the produced new refractories) having high commercial value [22]. The closed-loop implies higher difficulties that requires in particular the improvement of online analysing methods, of sorting and related separation of the different fractions of spent materials [27].

One example moving in the direction of the enhancement of closed-loop way of refractory recycling is given by Sidenor with its integrated and systematic management of all the refractory wastes at its Basauri plant. The company started working on the idea some years ago and then the acquired practices on the subject allowed to do the 5REFRACT project (approved within the framework of the EU LIFE program) [70]. The concept is that to the 4R paradigm consisting in reduce/reuse/remanufacture/recycle was added also the fifth R that is re-educate. This last aspect is important as the whole process requires a real change of stakeholder's mentality to be successful; for example, one of the typical opinions to overcome is that of refractory producers feeling about the perceived lower quality and related higher risk of recycled materials that should consequently be significantly cheaper than the products made using virgin materials. The partnership included in 5REFRACT is formed by various entities such as the R&D unit of Sidenor, different companies producing refractories, stakeholders from iron and steel sector, universities, public bodies and clusters in order to guarantee not only the solution of technical problems but also to have the possibility to do a correct exploitation of the results such as the satisfactory outcomes achieved with isostatic tubes and tundish mixes in the tilting area [68].

4.1.5 Secondary raw material

From the evaluated projects 16 deal with secondary raw materials from outside the steelworks that is used inside the steel works. From these, 3 project is about the use of external residual material as binders, 2 projects deal with metal recovery, 7 project is about using the external residual material as sources of carbon and 4 projects are uncategorized. Some projects deal with different aspects within the same project. At least half of the studied projects have been followed up with continued research. Several of the continuation projects aimed to raise the TRL of the technology, some of them also reached industrial implementation.

Used as binders

The projects where external residual material is used as binders all deals with different types of residual material from different industries. Molasses [P5], different types of waste material from e.g., forestry, agriculture and waste plastics [P32] were all used as binders in briquette making. Fayalite slag from a copper smelter was tested used in the preparation of hydraulic binders in the IPBM process [P2]. The IPBM process has been further investigated in several continuation project, both on research level and industrial. Whether or not the use of fayalite slag is studied further is unknown since several of the follow up projects have been confidential.

Metal recovery

In one project cinder was used as a compound of briquettes together with BF dusts/sludge, BOF dust, and mill scale for Fe recovery in the blast furnace [P14]. By using waste plastics as energy source, scrap was treated in order to recover zinc [P25].

Carbon source

Several different alternative carbon sources have been studied and used in various parts of the steel production cycle. Project GREENEAF [P22] and the continuation project GREENEAF2 [P31] studied the EAF use of charcoal and syngas produced by pyrolysis of biomass. These projects demonstrated the feasibility of the use of biomass/biochar as substitute of fossil coal in a relevant industrial level (3 different industrial EAF) both for charging and injection purposes. The use of torrefied biomass for producing biochar is beneficial to optimize the operating conditions hence to achieve a stability and reliability of the process [P31]. Three projects deal with carbon from waste plastics [P16, P20, P32]. [P32] also dealt with numerous other waste materials e.g., from forestry, agriculture and coke making as sources of carbon and use as binders in briquette making. Biological carbon sources as nut shells and olive pits, anthracite and pet coke are agglomerated and tested as a carbon source in sinter plants [P17] and pet coke, charcoal, lignite coke are briquetted and tested as coke substitute in BF [P23].

In the project FLEXINJECT [P20] automotive shredder residue (ASR) was tested together with other alternative carbon materials (ACM) such as BF sludge and dust as a replacement of coke and coal for injection into BF. This method has been further developed in IMPCO and is further developed in DuMiCo, Spareribs, Bio4BF, etc. Measurements have been performed for several weeks on industrial scale at SSAB in Oxelösund, Sweden.

The research in GREENEAF and GREENEAF2 have been followed up in industry tests with charging (more than 700 heats) and injection. Ferriere Nord (Italy) is participating in a SPIRE project (RETROFEED). In this project, the injection of biochar by devoted injection system will be done. Due to the number of heats, the TRL will be 7. In case of satisfactory results, the system will be used on a permanent basis for steel production. This gave the possibility to have a further increase of the TRL up to its maximum stage. The SHOCOM project [P16] also had a follow-up project. It was a laboratory investigation about efficient utilization of waste plastics as raw material for metallic iron and syngas production by combining heat treatment pulverization and direct reduction.

Uncategorized

> The projects that cannot be categorized in the previous categories of secondary raw material from outside of the steelworks are about slag foaming using aluminium granules [P19], using sewage sludge ash to enrich P-rich BOF slag, to be used as fertilizer [P30], using quartz sand to treat liquid slag from carbon and low alloy steelmaking [P40] and injecting Rutil (TiO_2) into the BF for hearth protection [P15], which has also been followed up with hearth protection mainly in China.

4.1.6 Modelling/simulation for by-products reuse and recycling

Some of the evaluated projects deal with different aspects and, in addition, apply advanced modelling and simulation tools to improve the recovery and recycling of by-products. These tools can be considered transversal applications across the past EU research projects analysed in the REUSteel project.

In [P10] modelling, laboratory tests and in-situ investigations were used to assess the environmental impact of slags (EAF, BOF, GBF and BF) or slag mixtures used in road construction. However, after various simulations, it seemed very difficult to propose complete methodological guidelines concerning appropriate use of iron and steelmaking slags in road techniques with respect to the quality of underground water.

In [P11] the LIBS-method was used for online control slag composition in a harsh environment. Mathematical modelling was applied to interpret results and to support LIBS measurement sequences. In particular, the modelling work aimed at identifying effects of influencing parameters, such as sample temperature, exchange of elements between metals/slag interface and measured free slag surface, chemical slag composition, and viscosity.

In [P16] lab tests and modelling were used for evaluating the charcoal top charging influence of thermal reserve zone. In addition, modelling was conducted on the CO_2 mitigation and cost scenarios for the described scenarios. Based on model calculation and lab tests the utilisation of charcoal as well as CO_2 neutral plastic waste led to a CO_2 mitigation.
Also, a comparison of the CO_2 mitigation of different steel production routes was carried out The various routes proposed in the project have shown various potentials in term of CO2 mitigation. Charcoal and Plastics can be applied relatively easily, if local conditions allow it, like the availability of charcoal, the sustainable way of producing this charcoal, or the C-neutral classification of plastics wastes.
In [P18] process data (electric and thermal energy consumption, coke consumption) for the recovery of Cr from high-Cr EAF slag was used. The project concerned modelling of the treatment of high-Cr EAF slag from stainless steelmaking by a coupled process of cupola furnace and inductively heated coke bed reactor.

In [P22] a theoretical evaluation was carried out by means of computational fluid dynamics (CFD) simulation concerning the use of syngas in partial substitution of natural gas and related effect on the EAF process.

In [P24] image-based sensors were used to optimise slag raking, resulting in slightly reduced hot metal loss. This part concerned the analysis of EAF slag or BOF slag after installation of image-based sensors and analysis tools, monitoring the deslagging process to optimize the amount of slag tapped and increase the metal production. The EAF online monitoring and control of the deslagging process were successful in optimizing the slag amount and on average steel losses were reduced by 29%. On the other hand, the BOF process was less successful with respect to reducing steel losses and with only about 4% reduction.

In [P25] a model for de-zincing and reuse of scrap steel using pyrolysis of plastics, and one model for the same purpose using gasification of plastics were developed. The models are based on LCA of the modelled process section.

In [P27] advanced flow sheeting models were exploited to assess the viability of process integration solutions. The project included the production of Fe-rich pellets, following reMIND simulations, to be used in sinter plant. The optimization of internal use of BOF slag, with reduction of iron ore use, disposed slag, costs and improvement of product quality, was achieved. In addition, through pilot scale and simulation tests, oily mill scale, after oil removal, was treated to be reused in sinter plant to improve its recovery in BF.

In [P29], advanced modelling and environmental impact monitoring through KPIs were coupled. Through simulations, lime and dolomite replacement was shown to be possible only with LF slag in EAF, while the use of EAF slag increases the energy consumption. In addition, the rolling mill scale was tested in EAF to replace scrap. Model simulation showed that the introduction of scale in the furnace does not result in increased by-products and waste generation, as all the introduced mill scale can be reduced to iron.

In [P30] computational fluid dynamics (CFD) modelling of a pot/ladle design was made and flow sheet modelling was carried out to evaluate the recycling process.

In [P43] new symbiosis models were successfully applied to different case studies involving use of EAF and LF slags in concrete and cement production. In addition, new business models, taking into account technical, environmental and socio-economic aspects, were developed.

4.2 Questionnaire

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. The questionnaire was introduced at the REUSteel webinars, as well as distributed through ESTEP and European research institutes active in the steel sector. The participating experts were given the option to vote for any number of given topics concerning any number of by-products and residuals. Additionally, each participant was given the opportunity to make remarks in an open text. The by-products and residuals, as well as the research topics, were categorized in the same way as the reviewed EU-research projects. During the REUSteel symposium at the 5th ESTAD conference, a Menti survey was also used to identify important topics for the future.

By-product and residual categories:

- BF-slag
- BOF-slag
- EAF-slag
- LF-slag
- BF-dust
- BOF-dust
- EAF-dust

Given research topics:

- Internal recycling
- Valorisation outside the steel production cycle
- Extraction of valuable material from waste and wastewater
- Elimination of harmful elements

- LF-dust
- Sinter Plant dust
- Coke dust
- BF-sludge
- BOF-sludge
- EAF-sludge
- Mill sludge
- Mill scale
- Oily mill scale
- Refractory
- Other residues from inside the steel works
- Sec. raw material from outside the steel works
- Minimisation of waste generation and landfill
- Process integration solutions for by-products management
- Modelling and simulation

In the scope of the questionnaire was also surveyed which type of organisation and which business area the participants belonged to (**Figure 18**). In total 66 experts answered the questionnaire. Almost all the participants either work for a large enterprise (50 %) or at a research institute (41 %). The majority of the participants work in the iron and steel sector (77 %). The remaining fraction of the participants is distributed among the cement, chemical, base metals, ceramics, waste management, and renewable energy sector.

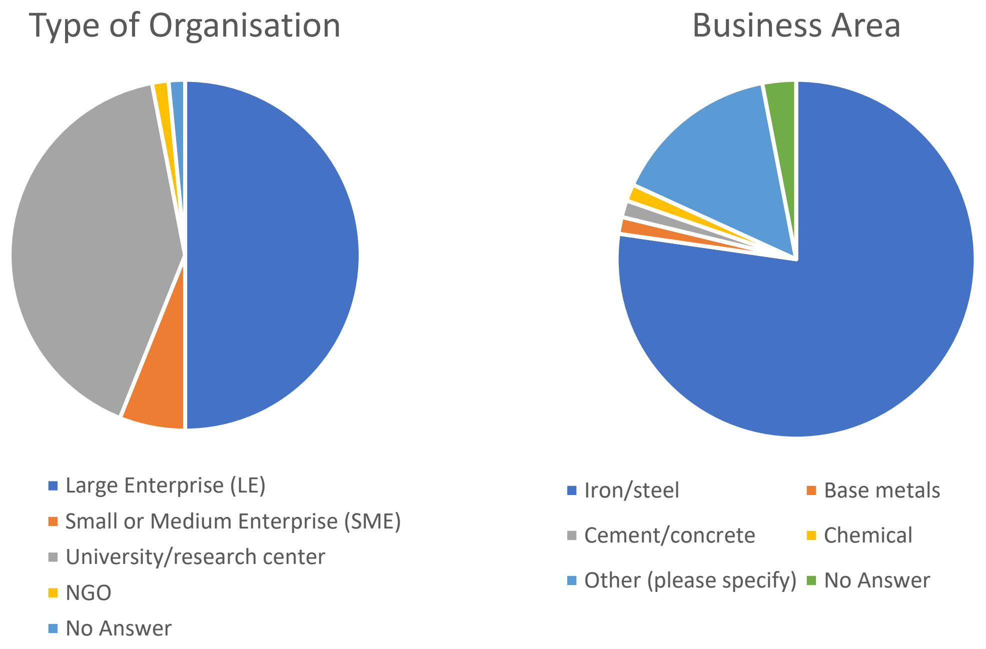


Figure 18. Affiliation of questionnaires participants.

4.2.1 Overview

In **Figure 19** an overview for which type of by-product/residual the participants see the need for research is given. All steel making slag (BOF, EAF, LF) is of interest. Furthermore, all EAF related topics are a major concern, as of every slag, dust and sludge type, in the EAF category the most feedback was received, making EAF-slag the category in which the greatest need for research is seen by the participants. Apart from the mentioned categories, Refractory and Oily Mill Scale stand out. In the following Chapters the feedback to given research topics for the individual types of by-products/residuals is listed in detail.

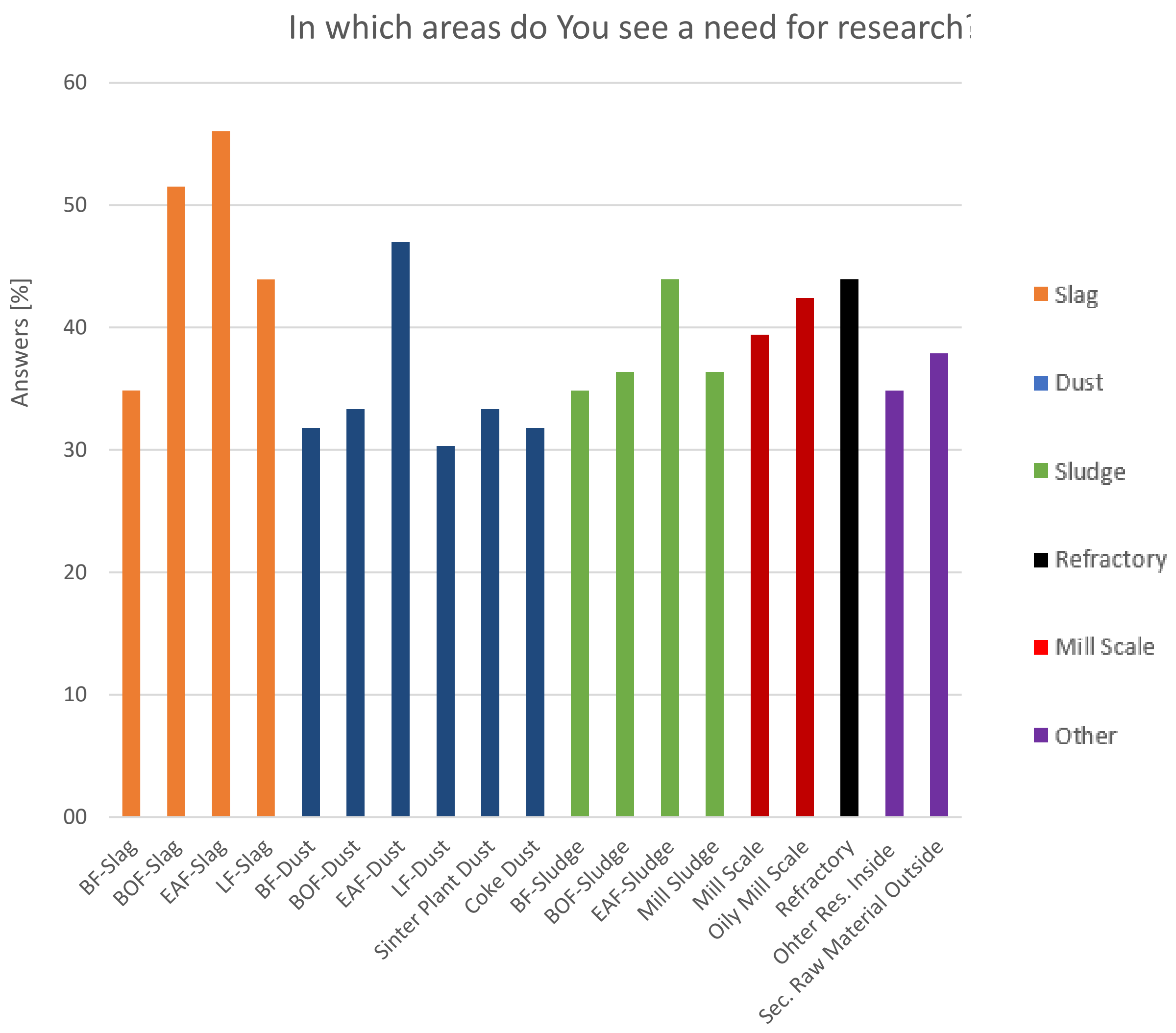


Figure 19. Overview research needs for by products/residuals in general.

4.2.2 Slag

In **Figure 20** the research needs for slag with respect to the given topics are listed according to the participants' vote. In all topics the least research need is seen for BF-slag. The largest interest remains in the valorization outside of the steel production cycle (21 %), as is the case for all slag types listed here. For BOF-slag, minimization of waste generation (20 %) and internal recycling (18 %) are deemed important as well, apart from external valorization (26 %). For EAF-slag, which is the type of by-product whose external valorization (36 %) the participants see as the overall most important topic, the research into process integration solutions (27 %) and the minimization of waste generation (26 %) are also of great interest. For LF-slag internal recycling (24 %) is viewed as very pressing and this is also the type of by-product experts for which modeling and simulation tools (18 %) are the most asked for.

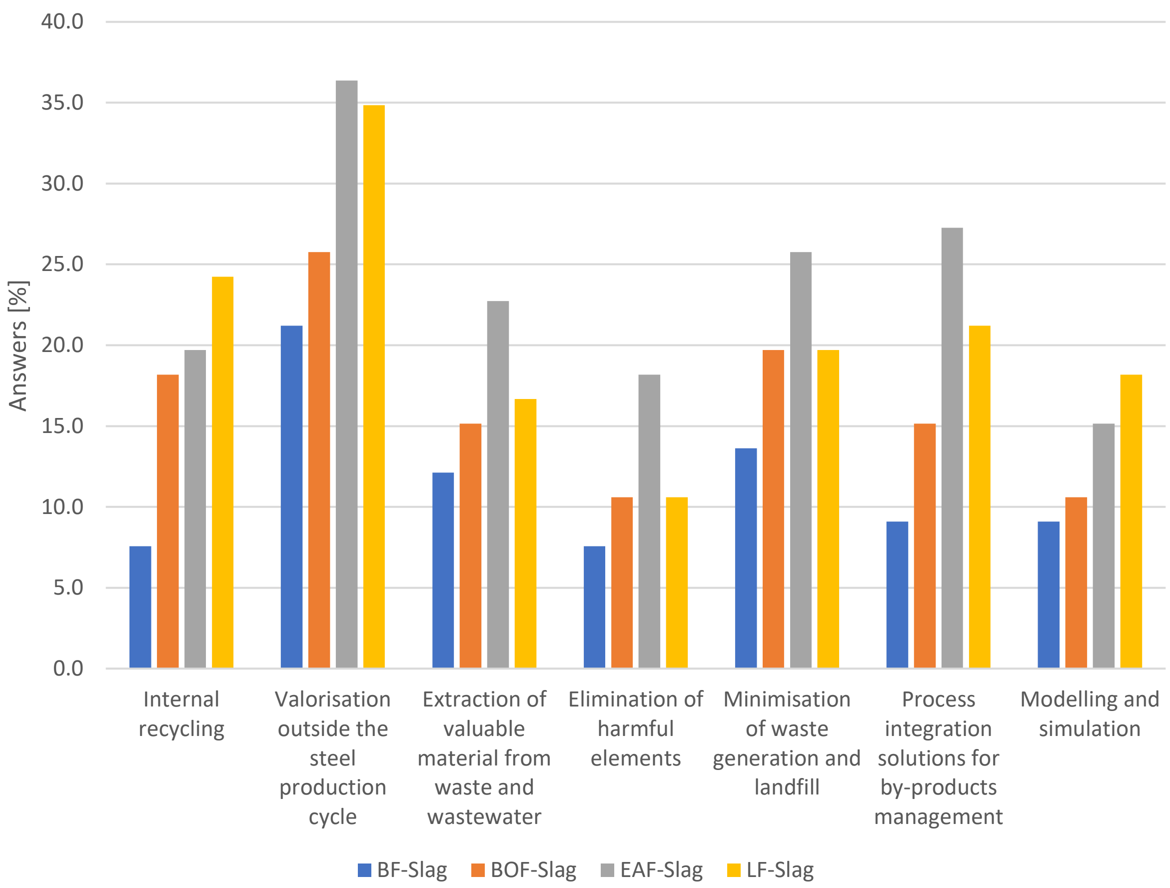


Figure 20. Research needs for slag derived from REUSteel-questionnaire

4.2.3 Dust

In **Figure 21** the research needs for dust with respect to the given topics are listed according to the participants' vote. For BF-dust internal recycling (23 %) is deemed most important, followed by the elimination of harmful elements (15 %). For BOF-dust the distribution is essentially the same with 26 % and 18 % of votes respectively. For EAF-dust internal recycling, extraction of valuable materials and the elimination of harmful elements are voted as equally important with 26 %, closely followed by the minimization of waste generation (24 %). Again, the largest interest is shown for EAF related topics concerning the recycling of dust. For LF-dust internal recycling (18 %) is voted as most important as well, however for the other topics almost the same interest is displayed. For sinter plant dust the elimination of harmful elements (18 %) is voted the most pressing closely followed by internal recycling again (17 %). For coke dust the distribution of votes is similar to that of BF and BOF-dust, with internal recycling (21 %) voted as most important research need, followed by the elimination of harmful elements (14 %).

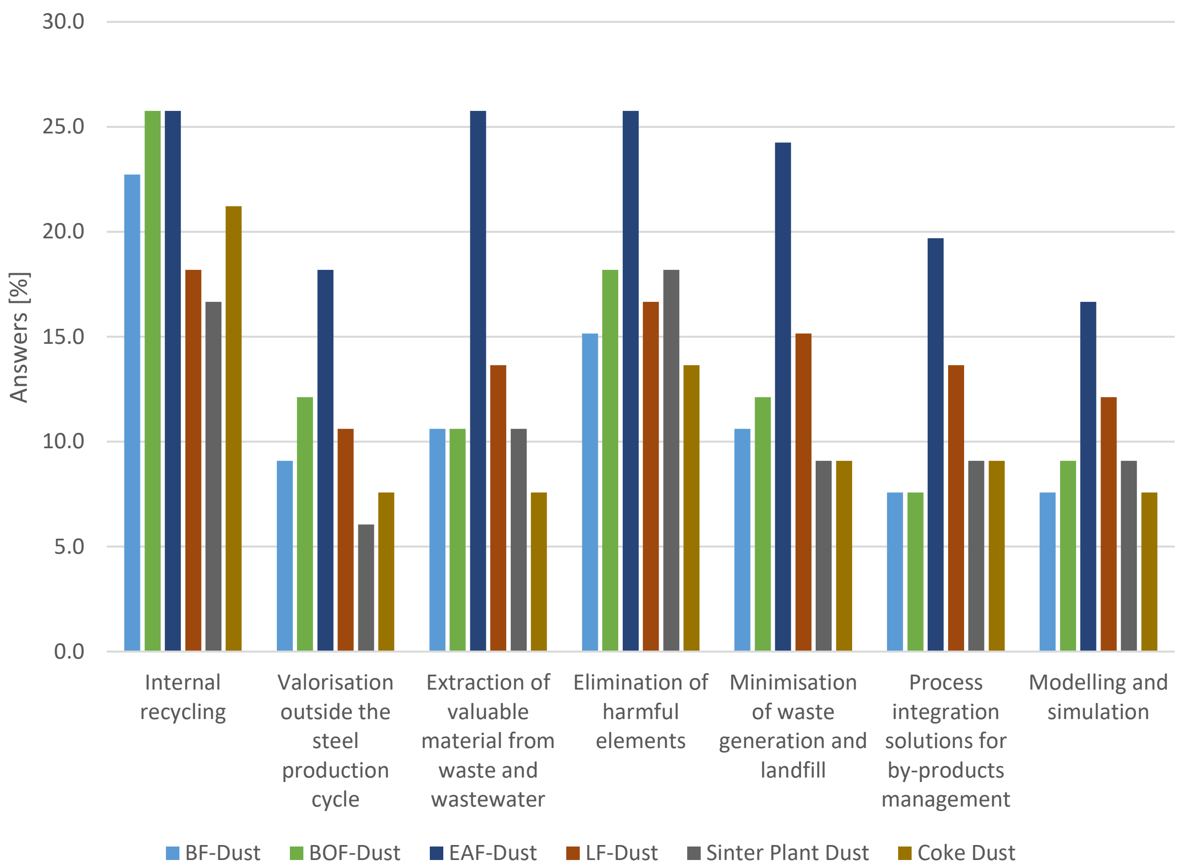


Figure 21. Research needs for Dust derived from REUSteel - questionnaire

4.2.4 Sludge

In **Figure 22** the research needs for sludge with respect to the given topics are listed according to the participants' vote. For BF-sludge the minimization of waste generation (23 %) is voted as most important research need, closely followed by the internal recycling (21 %). The reverse is true for BOF-sludge, thus for internal recycling (23 %) the greatest research need is seen, followed by the minimization of waste generation (18 %). For EAF-sludge the most important topic is the minimization of waste generation (27 %). Apart from this the need for research into internal recycling and elimination of harmful elements (both 21 %), as well as process integration solutions (20 %) is deemed as important. For mill sludge focus should be again on internal recycling and minimization of waste generation (both 20 %).

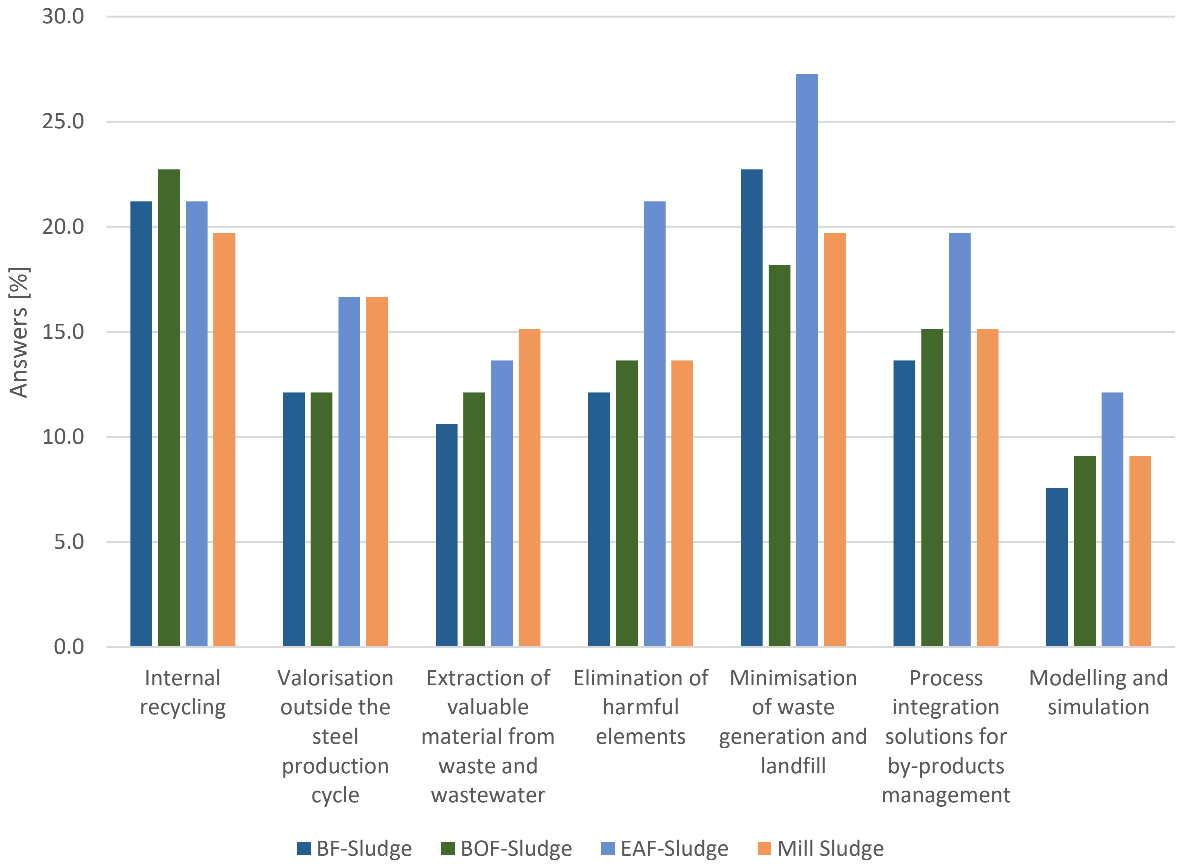


Figure 22. Research needs for Sludge derived from REUSteel – questionnaire.

4.2.5 Mill Scale

In **Figure 23** the research needs for mill scale with respect to the given topics are listed according to the participants' vote. For mill scale the participants see the greatest research need in the topic of internal recycling (23 %) and external valorization (20%). Considerable interest is also expressed for research in the topics of extraction of valuable material (18 %) and process integration solutions (17 %). For oily mill scale, according to the participants, the focus should be only on the internal recycling (24 %).

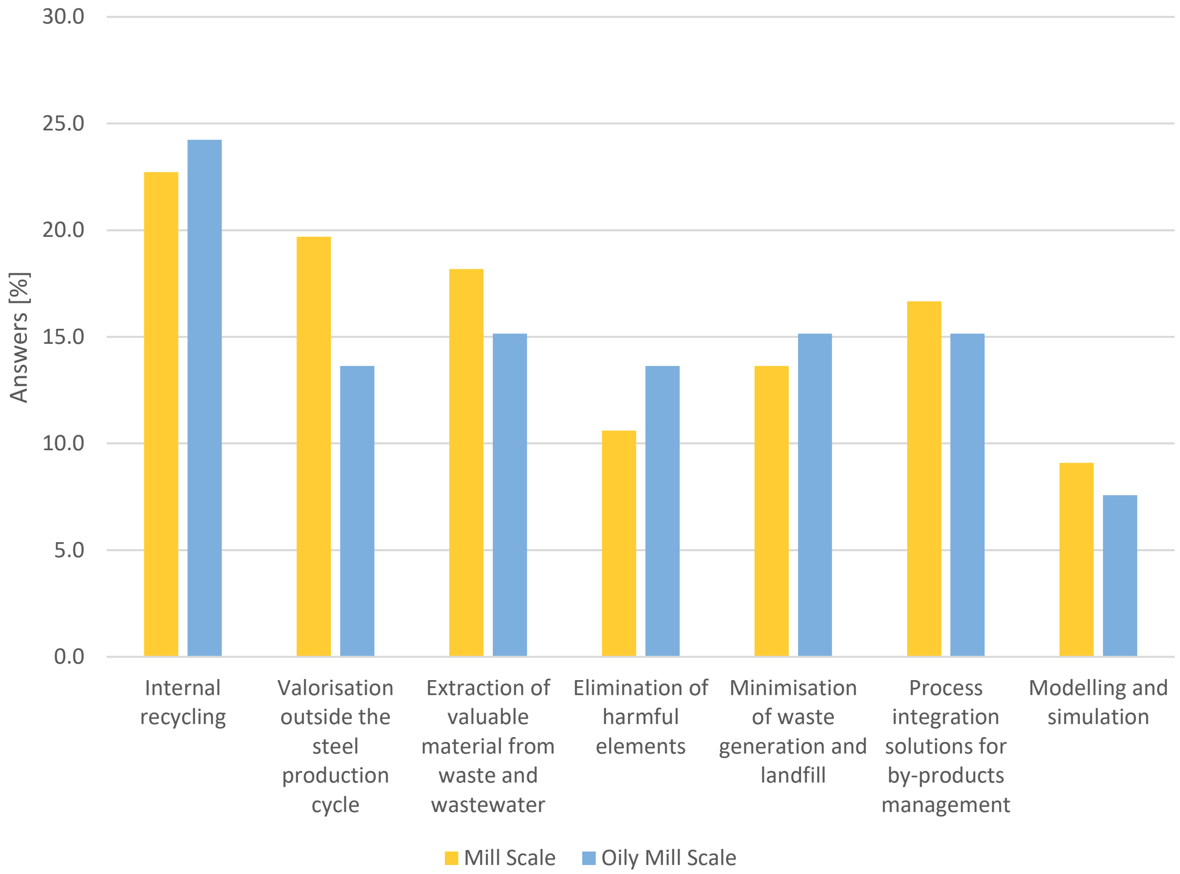


Figure 23. Research needs for Mill Scale derived from REUSteel – questionnaire.

4.2.6 Refractory, other residuals from inside the steel works and secondary raw materials from outside

In **Figure 24** the research needs for refractory, other residuals from inside the steel works and secondary raw materials from outside with respect to the given topics are listed according to the participants' vote. According to this, for refractory the emphasis should be on internal recycling (24 %), followed by external valorization (21 %). For other residuals from inside the steelworks the greatest need is seen for research into the internal recycling and minimization of waste generation (both 21 %) in the first place. The participants were given the opportunity to specify what other residuals from inside the steel works the research should be focused on. The mentioned residuals are listed in **Table 7**. There was a lot of feedback given concerning process gases and waste heat, which were not the main focus of REUSteel, but seem to be a major topic for the participants. For secondary raw material from outside the steelworks participants would like to see research on the topic of internal recycling (30 %) the most. The mentioned types of secondary raw materials are also listed in **Table 7**. The most mentioned byproducts were biomass, polymeric residues, and slags/residues from other metal industries. This and the listing of ash from waste incineration show a trend that industry collaboration is needed.

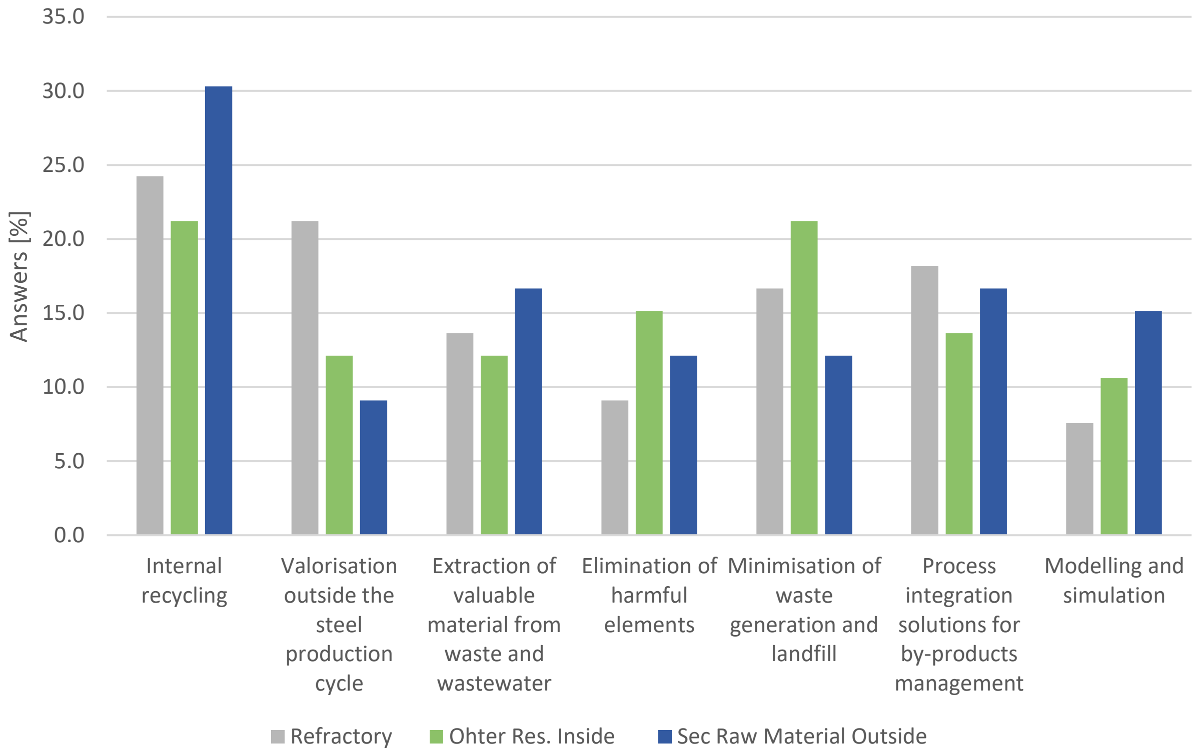


Figure 24. Research needs for refractory, other residues from inside and secondary raw material from outside the steelworks derived from REUSteel.

Table 7 Other residuals from inside and secondary raw material from outside the steelworks

<table>
<tr><th>Other Residuals from Inside:</th><th>Secondary Raw Material from Outside:</th></tr>
<tr><td>
• Exhaust/process off-gases
• Residual heat
• Pickle sludge
• Residue high in V and/or Ni and/or Mo content.
• Secondary dusts
• Residues from scrap management
</td><td>
• Biogenic residues/ biomass
• Ferro alloy industry-based residues
• Polymer residues
• Tyres
• Zinc containing residue
• Mine tailings
• Waste incineration bottom ash
• Bauxit residue
• Copper slag
• Char coal
• Low volatile carbon materials
• Jarosite
• Pulp and paper sludge
• Water treatment sludge
</td></tr>
</table>

4.2.7 Additional comments

At the end of the survey and during the webinar the participants were given the opportunity to make additional comments. This was used to express that legislative issues are a big concern when it comes to recycling and reuse. They also mentioned that they see an overall need for research due to the change of by-products and residuals due to the decarburization of the steel industry. Some also asked for an even more holistic approach, which also take the unused excess energy streams into account, as well as an increased collaboration between the industrial sectors e.g., to use slags in a broader range of construction material. However, the de-oiling of mill scale was specifically mentioned in this chapter again, emphasizing its importance. An overview of the content from the comments made is listed below:

- Legislative issues
- Influence of decarburization on recycling processes/composition and properties of the next generation steel making residue
- Utilisation of waste heat, e.g. for drying of sludges and that way enabling use of sludges
- De-oiling mill scale
- Alternative reducing agents facilitates the co-utilisation of secondary resources
- Reusage of landfilled fine-grained fractions
- CO_2 reduction by coproduct recycling
- Microwave treatment
- Geopolymers for slag valorization/carbonation for the production of green construction materials
- Conditioning of EAF, BOS, LF slags for use as supplementary cementitious material
- Integration of non-technological issues/integrating technological development in a broader social innovation process
- Smart tools for online characterization of residual material will allow maximizing valorization

5 Research needs - Roadmap

The roadmap, which is focused on the industrial research needs for the next 10 years is based on the current industrial utilisation, the challenges based on the targets of the circular economy and the prevention of emission, the trends derived from the reviewed EU projects and the results of the questionnaire. Additional interviews and surveys of specialists from industry and research institutes were conducted on the basis of a categorisation drawn up in Appendix 11 to take current topics into account.

The course of the roadmap for by products and residues is strongly influenced by the proposed roadmap for CO_2 mitigation. Nevertheless, efforts must be continued to optimise internal recycling or external valorisation of residues and by-products, reduce harmful elements and recover valuable components from residues in an economic and energetic way, and reduce landfilling [104].

In the short-term range existing integrated steel mills (e.g. **Figure 25**), which cannot be replaced by new low-CO_2 process routes, will continue to operate on carbon basis. The challenge is to implement process-integrated solutions that enable an economic low-carbon production of steel with appropriate quality at stable and secure operating processes. Possible solutions which could be applied are for example

- the use of hydrogen rich auxiliary reduction gases (CnHm) injected via the tuyere,
- the charging of scrap via the burden and
- the utilisation of biogenic/alternate carbon sources which can partly replace fossil carbon resources.

This will also influence the amount of content of the residues as well as the by-products and require a revision of known recycling routes

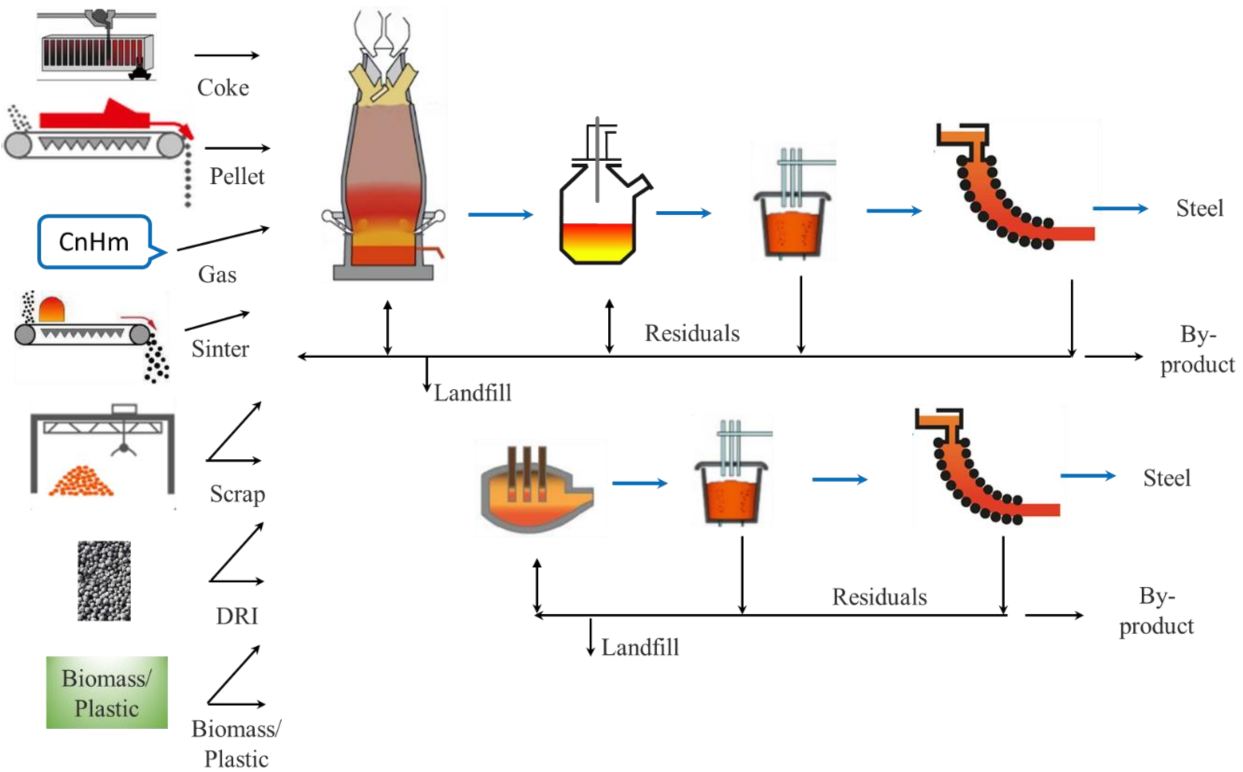


Figure 25. Optimised production routes – Short-term

New direct reduction processes producing natural-gas or hydrogen based DRI and the subsequent melting in the electric furnaces are planned and will be started to set in operation within the next 10 years. Although numerous natural gas-based direct reduction processes are already in operation worldwide, the operational behaviour and range of possible feedstocks as well as the by-products and residues generated by these processes are not fully known.

Additionally, the development of alternative smelting reduction processes as “iron bath smelting reduction” (IBRSR) and Hydrogen-Plasma smelting and also iron ore electrolysis, which can be operated on a CO_2 lean process mode, are in progress and can be an alternative for the steel production.

In **Figure 26** mid- and long-term production routes are shown.

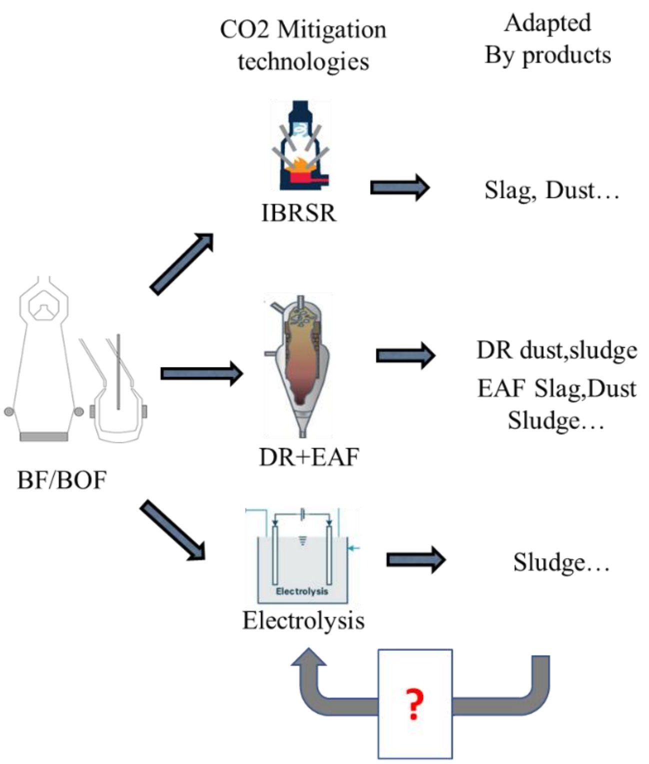


Figure 26. Alternative production routes - Mid-term and Long-term [104]

A shift in iron and steel production towards alternative CO2 lean production routes will lead to residues and by-products with changed properties. The sintering plants that enable internal recovery and recycling of residues will probably be replaced or modified in the long term. So ways have to be developed for the internal utilization based on existing knowledge and available processes. Also, investigation is necessary to meet the requirements for an external valorization of by-products.

Due to the diversity of existing and new process combinations described above, the prediction of relevant research needs is very broad and contains a large number of possible options.

In the following, the derived research needs are presented according to the categories already introduced, i.e. slag, dust/sludge, mill scale, refractory and secondary raw materials. In addition, a chapter on "Modelling/Simulation for By-Products" contains a general research need that can be applied to all categories. In addition, a further breakdown into process routes and internal and external utilisation was introduced.

5.1 Slag

The short-term research needs for the steel industry with respect to slag are twofold: on the one hand, currently produced slag needs to be recycled/used and on the other hand the steelworks have to prepare for the next generation of steel production with reduced CO_2 footprint and with this any changes to the slag have to be investigated. Up to now the RFCS projects dealt with needs associated with currently produced slag. BOF slag is currently one of the main topics. In the future EAF will be used more and EAF slag production will increase, while the amount of BOF slag produced will decrease. In addition, research needs will include all processes without carbon-based metal reduction.

Some of the most mentioned needs for example were metal recovery from the slag. This interest is also reflected in previous RFCS projects (this topic was investigated the most), but since this is still one of the most mentioned need for the near future it shows that the topic is difficult and a final solution that fits each steelwork has not yet been achieved. Due to the increasing production of EAF slag with higher iron content, compared to BOF slag, this topic will be even more important in the future. In particular, due to the increasing costs for hot metal production from iron ore, metal recovery by reduction from EAF slag could be ecological and also economically feasible.

There is a general need for further research to currently produced slag to be utilization by different steelworks who are struggling to find specific solutions for different reasons such as economical, regulatory, physical, or because of the environmental properties of the slag.

Future research activities should also focus on a system solution rather than just solve a single problem. For example, one should aim at both zero waste and low CO_2/or high CO_2 credits, to some extent comparable with the research done in the IPBM project. Suggested research activities are 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.

Based on interviews with relevant stakeholders in the steel sector and literature review the specific short-term needs of the steel industry given in Chapter 5.1.1–5.1.3 were identified. (see Appendix 11 and 12)

5.1.1 BF/BOF route

Currently the produced BF and BOF slags are mostly used externally in cement and road construction. The slags have to be prepared either in the liquid or solid phase or both to meet the chemical and physical requirements. Some countries or specific steelworks have better solutions for their BF or BOF slags while others are still struggling to find appropriate solutions other than landfilling. With the prospect of decarbonization some of the BF or BOF will not exist in the future. In the meantime, solutions for recycling of BF and BOF slag must be researched to reduce the amount that will be landfilled in the next years before the transition takes place. In addition, the lack of these slags in industries that are currently incorporating them will leave a void and provide an opportunity for the new slags. As an example, the demand for BF slag as granulated material for cement industry is increasing. Therefore, the remaining BOF slags could be an appropriate material to substitute this lack of BF slag, but a treatment is necessary to meet the requirements of the cement industry.

The following are examples of research needs for internal and external utilization of the BF and BOF slags to increase the recycling amount.

Internal utilisation

- Recovery of Fe metal, e.g. Fe from BOF slag as scrap substitute for e.g. 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
- Further efforts on hot slag reduction aiming for P-recovery/V/Fe and a slag product for the cement industry with high potential for energy and CO2-saving.
- Changing BOF slag properties to resemble granulated BF slag
- Road construction, e.g. ensuring volume stability by using in bound and unbound layers
- Extraction of valuable material (P-recovery; fertilizer), e.g. investigations are needed for slag utilization as liming/fertilizer material in areas without historical precedent and in areas with historical precedent to evaluate long term impact that slag has on soil and plant health.
- Improving the quality (environment, physical properties…) to better meet utilization requirements of slag for specific applications.
- Investigation of processes for crystallization to minimize the leaching of certain elements of interest to reduce the amount of slag that is landfilled
- Industrial plant installation to produce material for building industry

Other

- Industrial plant installations for heat recovery from slag

5.1.2 EAF route

Currently the produced EAF slag is used externally mostly in road construction and to a lesser extent in other applications. Same as the BF and BOF slags, the EAF slag has to be prepared either in the liquid or solid phase or both to meet the chemical and physical requirements for specific applications. Some countries or specific steelworks have better solutions for their EAF slag while others are still struggling to find appropriate solutions other than landfilling. With the prospect of decarbonization even more EAF slag will be produced in the future with a slightly different chemical composition, while the currently produced EAF slag still needs to be recycled to avoid landfilling and to substitute virgin materials.

The following are examples of research needs for internal and external utilization of the EAF slag to increase the recycling amount.

Internal slag utilisation

- Recovery of Fe and other metals from slag

    - Fe recovery without carbon-based reduction or with biogenic carbon
    - For EAF slag from stainless steel, this should have high economic potential as this slag contains high heavy metals which could be recovered, and it needs to be stabilized anyway.
    - Recovery of Fe for internal utilization e.g., recycling in the EAF
- Recovery of non-Fe-metal, e.g., hot slag reduction aiming at Ni/Cr/Fe/Mn (stainless slag) or P-recovery/V/Fe/Mn (C-steel) and a slag product for the cement industry with high potential for energy and CO_2-saving. Coprocessing with other production residues like millscale/EAF dust etc. Ref to IPBM process.
- 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 (latent) hydraulic properties for substituting Portland cement and reducing CO_2 emissions in cement industry
- Research of slag during transitions to H_2 ironmaking
- Road construction, e.g. improving environmental properties by decreasing leaching of specific elements
- Improving the quality (environment, physical properties…) to better meet utilization requirements
- Investigation of slag as liming/fertilizer material, especially long-term effects on soil and plants

5.1.3 Decarbonisation

Currently produced slag is mostly used in external applications with some exceptions (see Chapter 2.2). This means that over the years the slag has been adjusted (in liquid and dry form) to fit different requirements based on the chemical or physical properties required for given application and country. With any changes to the current production process the real chemical composition and the properties of the new slag are unknown.

In the near future, with the foreseen change in the steel industry to decarbonise, a new slag will be produced. One of the first research needs for any new technologies with respect to slag will be characterisation of this resulting slag to evaluate the chemical, environmental or physical properties. From there the slag's characteristics will fit into an existing utilization route or more research will have to be done to try to adjust it (in liquid or solid form) to meet the requirements or new utilization paths will have to be investigated.

Mainly a DRI based EAF slag will be produced in the future, but also a slag from the SAF; a similar technique but due to the reducing conditions a completely other type of slag will be produced. Because of the high demand from the cement industry for by-products with (latent) hydraulic properties, in particular due to the decreasing amounts of granulated blast furnace slag, there will be a strong need for metallurgical treatment of these new slags to meet this demand. If an economic and ecological solution can be shown to substitute granulated blast furnace slag by DRI based EAF or SAF slag, the CO_2 reducing potential of using a by-product from steel industry for the cement industry can be maintained. This interdisciplinary approach will be a benefit for the EU industry with respect to sustainable economy.

The following are examples of research needs for utilization of the slag from decarbonisation routs to increase the recycling amount.

- Research of slag from all processes without carbon-based metal reduction, depending on the direction different steelworks will take.
    - As an example, slag resulting from a DRI shaft, when operated with low grade ore will result in higher gangue and slag quantities which will be difficult to handle in a BOF or EAF but will have to be resolved.
    - After the new produced DRI slag from low grade ore will be used in a BOF or EAF; the slag from this smelter (e.g., concept of a submerged arc furnace) should be modified and/or treated to produce a similar material to granulated blast furnace slag which can be used as a secondary additive for cement production to reduce CO_2 emissions
- Improving environmental compatibility of "new" EAF slags for different applications, like road construction or concrete aggregate

5.2 Dust and sludge

The research needs for the dust and sludge recycling must be divided into the short-term research needs for the steel industry and into the next generation of steel production with reduced CO2 footprint and with this any changes to the dust and sludge which have to be investigated.

The review of the European research projects as well as the questionnaire have shown the trend on the internal recycling of dust and sludge with the aim to utilise the high iron and carbon contents. The interviews with relevant stakeholders and a literature review revealed the interest to continue research trends which were identified on a short-term view. Nevertheless, also new needs were proposed.

Also, at the recycling of dust and sludge research is needed to develop and implement new measurement methods as well as new methods for data collection, analysis and use to support the operator and improve the processes.

5.2.1 BF/BOF route

The evaluation of the EU research projects by REUSteel revealed, that the internal recycling of dust and sludge in the sinter plant, BF and BOF via the addition into processes after upgrading processes is already in progress and is already utilized. Nevertheless, from the survey it emerged that the BF- and BOF dust and sludge internal recycling is deemed important, followed by the elimination of harmful elements.

Internal utilisation

The improvement of the utilisation of sinter, BF and BOF dust and sludge with low zinc content to recover Fe-metal as well as valuable oxidic and carbon components into the sintering raw mixture is still a challenge. Due to the different chemical compositions and the morphological surface properties, as well as the wide range particle size and form, the granulation process as well as the utilisation of binder needs to be optimized and adapted to the local boundary conditions.

Coarse dust has a high iron percentage which is attractive to be used as raw materials for previous processes of the steel mill such as sintering and blast furnace or BOF.

The briquetting process of residues is in industrial application and briquettes are charged as burden in industrial scale to the BF, shaft furnaces as well as to the BOF. The briquetting process itself and the briquetting mixture to incorporate a variety of different Fe-containing residues and reactive carbon containing sources as well as suitable binders for improved hot strength must be optimized due to the plant specific boundary condition. The use of biogenic CO_2-neutral alternative carbon carriers to produce self-reducing briquettes and pellets is still a future topic and a way to reduce the CO2 emission as well as to optimize the BF process.

Research still needed at the injection of residues from BF and BOF for iron and oxide recovery and the injection of alternate carbon sources into the tuyeres of the BF. Working focus are still the suitable preparation of the residues for the conveying and injection as well as the chemical and thermal utilisation within the tuyere and the raceway and within the furnace.

A main focus must still be the internal utilisation of the fine fractions of the dust and the sludge, which containing high fraction of iron and also carbon but also valuable fraction as zinc and interfering components such as phosphorus, alkalis in the form of oxides or chlorides.

The recycling of dust into BOF or secondary metallurgy has also to be carried on as the generation of self-reducing pellets to partially replace the scrap charged in BOF converter or addition of alternative additives for metal treatment.

External utilisation

The recycling via external upgrading processes for separating valuable components from the fine fractions and the recycling of the processed iron- and oxide-rich fractions has to be continued.

One main issue is the zinc content of the fine dust fractions and the sludges which restricts recycling of valuable compounds and lead to landfilling. Development work has to be started or continued applying mechanical and thermal treatment as well as pyro- and hydrometallurgical processes to remove zinc and producing a valuable zinc product and iron rich fraction for recycling. Methods for separation of zinc rich dust from zinc poor dust already when the dust is generated would lower the amount of dust that has to be treated, thus enhancing efficient recyclability.

The improvement of hydrometallurgical, dry and hydro-mechanical magnetic as well as thermal separation processes is essential to considerably reduce the heavy metals, alkalis and chlorides content of residuals from sinter plant, BF and BOF off gas cleaning, assuming the industrial and economic feasibility of the processes.

5.2.2 EAF route

The following aspects and related technological issues can be highlighted in this regard:

Pyrometallurgical processes

- Optimization of separation of iron from other (high volatile) oxides. The use of dedicated furnaces operating in reducing conditions is recommended for this purpose. These furnaces can be installed in steel mill and managed directly by steel dedicated personnel.

- The use of briquettes and/or pellets including EAF dust and other fine steel by-products is a preferable option with an increasing interest as demonstrated by recent projects.
- Self-reducing briquettes using carbon from alternative sources (e.g. biochar) must be preferred. The use of innovative technologies for facilitating the reduction process of reducible oxides (e.g. FeO), hence the separation of the different fractions for the selective recovery of valuable metals must be considered (see also point 5).
- A good optimization of the synergy between the procedures listed in points 1 and 2 gives the possibility to obtain 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. This last operation can be done either externally (e.g. by Waelz) or internally (e.g. in case of implementation of a hydrometallurgical plant).
- Innovative technologies allowing to increase the efficiency of the pyro process must be considered of priority interest. Microwave heating looks very promising for this aim.
- The use of devoted reducing furnaces for pyrometallurgical processes operating in parallel with EAF can be considered as a valid option to be implemented for serving single steel mills.

Hydrometallurgical processes

- Among the different leaching solutions, the one based on ammonium chloride proposed by Ezinex® seems to be the "more mature" and practically ready for stable industrial implementation.
- The best option is to have an integrated pyro/hydro metallurgical process that gives the possibility of obtaining the best in terms of pre-selection of the different fractions, hence on the yield of obtained product (metallic zinc having high purity as main objective).
- The recovery of the residues from the different stages of the hydro process, containing these residues Pb, Ni, Cd, Cu, Al, Si as oxides or as different species according to the different leaching methods (e.g. sulphates) must be considered also involving external recycling treatments.
- Possible new options facilitating the leaching process must be considered. One innovative way is the ultrasound assisted sulphuric leaching that allows to maintain the process efficiency in terms of dissolution of franklinite but at lower acid concentration.
- The implementation of hydrometallurgical plants serving a single steel mill (or a very limited number of steel mills located in favourable positions in terms of distance) that manage directly the plant is a favourable option.

As concluding remark, an integrated pyro/hydro metallurgical process (with related plants installed in the steel mill) can be considered as a valuable option for a full recovery of EAF dust and, in case of other steel by-products (see the points 2, 3, and 4). The best solution is to have devoted pyro/hydro plants working in parallel with EAF. This solution is suitable to be implemented and serving a single steel mill.

A hydrometallurgical or a combined process with zinc electrowinning at final stage has the advantage that the zinc product (here: zinc metal) can be reintroduced into galvanising plants within the steel industry, instead of being processed externally for primary zinc production. This would contribute to an enhanced circular economy within the steel sector.

Other

External utilisation of EAF dust usually takes place in large, centralised plants (e.g. Waelz process) aiming in production of an enriched zinc oxide to be further used as raw material in zinc metallurgy. The use of dust enriched in Zn, also after Fe separation as feed material for Waelz treatment needs to be investigated to increase the efficiency of this process.

The development of new pyrometallurgical processes using devoted furnaces as melt bath injection process, the RecoDust process or 2sDR process as well as existing processes as the OxyCup and the DK process should be continued to proper operating ways for such tasks.

In future, iron recovery from the EAF dust will be increasingly important for achieving a zero-waste strategy. On the one hand this could promote large scale recycling technologies like the rotary hearth furnace (RHF) or the multiple hearth furnace (MHF), which in contrast to the Waelz process are capable for iron recovery in the form of DRI. On the other hand, research could be needed concerning iron recovery from Waelz slag.

Also, the use of carbon-based processes, that are suitable to be combined with CCU/CCS technologies for avoiding CO_2 emissions and suitable for zinc separation (e.g. HiSarna/Reclamet process) must be investigated.

5.2.3 Decarbonisation

Research needs for the utilisation of residues at the decarbonisation of integrated steel mills comprises investigation on pre-treatment and the utilisation of changed BF dust and sludge when

- at the partial replacement of fossil coal and coke by climate neutral pre-treated biomass and plastic wastes
- at the partial replacement of iron oxides in the burden by suitable scrap as secondary raw material.
- at the injection of hydrogen rich reduction gases or alternative carbon sources via tuyeres in the BF.

The (hydrogen based) DR/EAF route is expected to evolve in the future and to replace BF/BOF plants. Future recycling topics for this evolving process route are expected to focus on the *internal utilisation* of dust or sludge from the direct reduction plant respectively of the dust from the EAF.

- One main focus will be the recovery of the contained iron. Usually, an appropriate agglomeration (pelletisation, briquetting) needs to be applied for recycling of these fine-grained residues into the DR-plant (shaft furnace) or the EAF.
- Some important aspects concerning the recycling of DR-plant dust/sludge to the same plant by a suitable briquetting technology have already been reported [1]. This involves the test of new organic or inorganic binder systems in order to optimise the size of briquettes, the thermal stability and reducibility and further the selection of an appropriate continuous agglomeration device like a roller press.
- The shift to the DR/EAF route would result in the newly upcoming DR-plant dust and in an increased amount of produced EAF dust. However, this EAF dust is expected to be low

in zinc, so that a recycling back to the DR-plant or the EAF could be an option. In contrast to this the scrap based EAF route, which would produce a higher zinc containing EAF dust as previously discussed, is not expected to change significantly, since scrap availability will also be limited in future.

The need for CO_2 mitigation would also affect the dust recycling processes directly. To face this challenge for the utilisation of residues, the following aspects are expected to gain importance:

- Electrically operated processes (e.g. electric furnaces like EAF, SAF, plasma furnace, or hydrometallurgical electrowinning) would be advantageous to mostly C-based processes, since they are nearly carbon neutral, when operated with 100% "green" electricity.

5.3 Mill scale

Internal utilization

The evaluation of the REUSteel-questionnaire underlined that the iron and steel industry see the greatest need for research in the topic of internal recycling of mill scale. 23% of the participants pointed out that this topic is quite important for their company and that further R&D is needed. Other topics of considerable interest for the participating companies were the extraction of valuable materials from the mill scale (18%) and to find process integration solutions (17%).

An important topic for future R&D is to develop CO_2 neutral solutions for internal utilization of mill scale and other waste iron oxides. The charging of self-reducing briquettes out of waste oxides (e.g. oily mill scale, oily mill sludge) into e. g. the blast furnace and EAF has already been investigated in the past and is already operational practice in some steel works. Future R&D has to focus on advanced compacting and processing technologies and processes using CO_2 neutral carbon material (e. g. biomass) in order to support the transformation process to a CO_2 neutral European steel industry.

Furthermore, the existing routes for internal utilization of mill scale and other waste iron oxides has to be adapted for hydrogen steelmaking processes.

Established R&D topics from the past have to be continued. A main focus should be the de-oiling of mill scale for further internal utilization as one of those topics. Generally, the presence of disturbing components in mill scale and in other waste iron oxides result in a limitation of metallurgical reuse of those materials. Therefore, the removal of disturbing components e. g. by hydrometallurgical treatment followed by material preparation for dosing in metallurgical units is another R&D topic for the future.

External utilization

In the past several applications for external utilization of mill scale have been developed. Such examples are the utilization of mill scale in the production of refractory, as flux material or in the cement industry for manufacturing of cement clinker. The latter involves mixing it with feedstock materials before the introduction of the raw material into the heated rotary kiln. Technological options for the external utilization are important in order to have a wide range of alternatives and possibilities for using mill scale. Therefore, the development of new, advanced applications for the external utilization of mill scale is still an important topic for future R&D.

The evaluation of the REUSteel-questionnaire pointed out very clearly that the external valorisation of the mill scale (20%) is a really important topic for R&D in the iron and steel industry.

Change/ adaptation due to decarbonisation

In the next decades alternative reduction technologies, for example hydrogen based direct reduction, will successively replace the conventional, carbon-based blast furnace. This transition process has no direct effect on the amount of mill scale in an integrated steel work. Rolling processes will still be operated in a carbon neutral steel production. However, the internal utilization routes will change due to technological shift by CO_2 mitigation. Hydrogen based direct reduction technology is ready to use and can step-by-step replace the carbon-based blast furnace technology in the existing integrated steel works. With ongoing transition processes the required capacity of the traditional sinter process will decrease successively and therewith also the capacity for internal utilization of mill scale in sinter plants. A huge R&D demand is given to develop new internal utilization routes for mill scale. Some examples of future topics for R&D are given below:

- Concepts for the transformation of internal utilization routes for mill scale and other waste iron oxides from carbon based to hydrogen based integrated steelworks have to be developed. This would involve the processing of these residues in the DR plant (shaft furnace) or in the electric furnace for DRI melting (EAF or SAF), both with different requirements concerning the pre-treatment of the residues.
- The potential for internal utilization of mill scale in a hydrogen based integrated steel work has to be estimated and evaluated.
- Advanced material preparation processes for internal utilization of mill scale e. g. in DR/EAF plants must be developed.
- Limitations for metallurgical reuse in hydrogen-based steel production due to presence of disturbing components have to be defined.
- Advanced processing routes for the mill scale to meet the requirements of the new carbon free metallurgical technologies have to be developed.

5.4 Refractory

The way of refractory recycling following the open-loop, namely the use of slag conditioners/slag-formers in the main steelmaking processes (EAF, converter, ladle furnace) is expected to maintain its primary role in reuse of this kind of residues. The individual process steps for reprocessing must be optimised in order to meet the quality requirements.

In the future the recycling via closed-loop, i.e., reuse of spent refractories for the production of new ones, is expected to have a growth of interest, especially considering the possible abatement of CO_2 emissions related with the processes needed for obtaining the basic material components from raw materials (e.g. MgO from raw $MgCO_3$).

The following aspects and related technological issues can be highlighted in this context:

Open-loop recycling (particularly suitable for internal recycling)

- Development/refining of the processes for selection of spent materials has a relevant importance allowing a proper selection driving the choice of the most adequate mixtures to be used in the different cases. Proper grinding/sieving and sorting of the spent material are areas of action for these aims.

- Laboratory activities for evaluating the behaviour in dissolution of the mixtures including common slag formers and fractions from spent refractories. The evaluation should be related with dissolution kinetic to evaluate the optimal mixtures to be used in relation to the industrial process with the support of theoretical models (see also point 3).
- Development/refinement of theoretical models able to calculate aspects related with both kinetics and thermodynamics of the mixtures including spent refractories when used under the operational conditions. The use of such models should be aimed to the selection of proper mixes that ensure slag formation in due time and with proper fluidity.
- Possible reuse of selected fractions of spent refractories outside the steel making (external recycling). In this context, cement and ceramic industries could be considered as the “natural candidates” of interest.

Closed-loop recycling (suitable for both internal and external recycling)

- Further refinement/optimization of automatic systems for identification of different classes of spent materials aiming at an efficient and objective sorting. In this context, methods based on cameras/laser systems (such as LIBS) can be considered as of interest.
- Development/refinement of intelligent software systems to be coupled with the optical devices mentioned in point 1. The application of Artificial Intelligence, Machine Learning and other concepts such as Big Data and Edge Computing is expected to be mandatory and fruitful for the success in such task.
- Optimization of the methods for purification of the materials obtained from the spent refractory as to achieve a purity level comparable with that of the correspondent virgin materials is another mandatory aspect to consider.
- Demonstrative projects involving the use of refractories produced from recycled refractories that highlight adequate performance of such materials in real operating conditions could be considered as a mandatory step to overcome the inescapable mistrust still present in stakeholders and refractory producers.

The possible use of spent refractories from steelmaking for producing new refractories for external industries could be an additional point of interest.

5.4.1 Decarbonization

Aspects involving the chemistry of refractory materials and related use can be considered in the context of a progressive decarbonization of the steel industry.

In general, refractories contribute to the overall CO_2 emission of steel production. This contribution can be considered as small, being equal to approximately 3% of the total, but in the optic of the challenging 2050 objective of the European Steel Industry it started to be considered by the users and the producers. The CO_2 emission from refractories is due to the presence of carbon (both graphite and pyrolytic carbon are used for such purpose) used in the composition of such materials to improve their resistance against thermal shock [71]. This aspect is then particularly important in refractories used for processes involving fast temperature changes such as magnesia carbon bricks used in converters, EAF, ladles. Another aspect that is related to the carbon contained in the refractory materials is the thermal conductivity[72] of the material itself. Logically, better insulation properties of the material will also have an impact on the energy saving, hence on reduced amount of CO_2 emissions (particularly important in countries where the electricity is mainly produced by conventional sources). Some activities aimed at the decrease of carbon in the refractory materials already started; these includes studies on the use of nano-carbon [73] that allows to produce refractories such as MgO-C having adequate characteristics but containing around the half of the total carbon in the conventional ones.

In this optic research needs in the field of refractory for steelmaking are:

- Study and development of refractory materials with reduced carbon or even down to carbon free content having structures and microstructures adequate for the steelmaking processes.
- In parallel with the previous point, individuation of adequate materials to be used in substitution of species such as graphite, pet-coke, tar-pitch, petroleum pitch currently used in the material manufacture.
- Studies at laboratory and pilot scale for the needed refining of the new materials chemical composition focusing the attention on the possible impact of their use also in relation to the quality of the steel (e.g. because of the local interaction between refractory component and steel)
- Studies at laboratory and pilot scale to individuate the possible refinements in terms of chemical composition for using them the new materials in process conditions involving the use of hydrogen (this last also related to the general trend towards decarbonization) and then to evaluate their effective performances and related adequateness.
- In addition to the development of new refractory materials, the introduction of the new process routes also requires the adaptation of the processing methods for recycling refractory materials.

Such context can be considered as perfectly integrated in the closed-loop recycling of spent refractories above discussed. In particular, the improvements of the sorting methods of selection of the different components of spent materials would be beneficial to facilitate their use in the new developed refractories.

5.5 Secondary raw material

Based on the answers given in the questionnaire (see Chapter 4.2) there is an interest and need for research on the topic of recycling of secondary raw material from other industries within the steel making cycle. In the questionnaire, biomass, polymeric residues, and slags/residues from other metal industries were the materials mostly mentioned. Other residues that were mentioned were for example ash from waste incineration processes and waste tires.

There are several reasons for the increasing interest of research about utilization and the use of secondary raw material from outside the steelwork. Material containing carbon is of interest in order to reduce the use of virgin fossil carbon, i.e., to reduce the fossil footprint of the steel making process. All alternative carbon-bearing materials have obvious differences in comparison to fossil carbon sources in terms of volatile matters, density, and different chemical interaction with iron oxide rich slags. Other aspects to be considered involve the required pre-treatment according to the possible ways of use; agglomeration/densification forming briquettes in case of charging together with scrap, obtaining grains of suitable size proper for injection.

A smarter carbon usage is the first step of the complicated process leading towards a progressive decarbonization. This started with the use of biomass and biochar as substitute of fossil coal for steelmaking operations (e.g. in EAF) but can be considered still in progress for the next years. In particular, a significant experience has been gained regarding the management of biomass/biochar for proper charging operations but there is still space for the optimization of injection systems and operations for these specific materials, especially considering their use as foaming agents as this is not yet fully optimized. Furthermore, the use of waste plastics (non-recyclable fractions) is expected to grow in importance. Further refinements of the systems for optimizing the yield of such materials in relation with its s thermal properties and with the needs of steelmaking plants operations are expected as necessary. The pilot/demonstration of integrated technologies, e.g., pyrolysis/torrefaction of biomass with utilization of waste heat from steel production followed by the industrialization of biochar onsite production can be considered as relevant actions leading the research in the medium/long-term period (for the next ten years or so). This is also noted in a recent review study on use of alternative carbon sources in EAF steelmaking [74] where Echterhof concluded that while a lot of research has already been done on use of alternative carbon sources in EAF, there is still a large potential which would benefit from further research in this area. The review identified some topics that need further research for a successful implementation of alternative carbon sources in EAF steelmaking such as:

- use of real plastic material waste streams, e.g., ASR, which are more complex than separated plastic wastes that have been widely studied,
- integration of biomass treatment and upgrading with EAF processes, e.g., using waste heat from the EAF process for biomass processes,
- charging and EAF operation when materials with high volatile matter content are being used (to ensure that the alternative carbon is used as an energy source in an efficient way and does not cause operational issues),
- increasing the amount of polymers blended with fossil coke for injection carbon.

The use of lime containing residues can also reduce the overall fossil footprint as well as the requirement of energy and the environmental impacts due to mining when the need for primary lime decreases. Further research is needed both to confirm the technical possibilities in a larger scale and to study for example the overall environmental performance (LCA) and the energy aspects of using these types of residues [37]. As concluded in the questionnaire (see Chapter 4.2) further research is also desirable regarding how to utilize residues from other metal industries. Such residual materials can for example contribute with valuable metals and there is also a mutual desire to decrease the residue material and waste in order to reach a sustainable future.

5.6 Modelling/simulation for by products

Examples of application of advanced simulation tools for improving the environmental footprint of the steel production processes are provided in different EU-funded projects. For instance, in the project entitled “Efficient use of resources in steel plants through Process Integration” (ReffiPlant), the exploitation of advanced flow sheeting models was carried out (using Aspen Plus® modelling and simulation tool) to evaluate the viability of Process Integration solutions, aiming to improve by-products handling and water efficiency in integrated steelworks [75]–[77]. In another RFCS project entitled “*Cyanide Monitoring and Treatment under Dynamic Process Conditions” (DynCyanide)*, the Aspen Plus® modelling and simulation were tuned through Genetic Algorithms through the exploitation of experimental data in order to test and validate a preliminary innovative treatment for blast furnace (BF) gas washing waters [78]. In addition, coupling advanced modelling with the monitoring of the environmental impact by means of Key Performance Indicators (KPI) was carried out within the EU-funded project entitled *“Environmental impact evaluation and effective management of resources in the EAF* *steelmaking" (EIRES)*. In this context, the developed tools allow evaluating different scenarios and operating conditions to promote the increase of internal slag reuse [79].

The research advances of the last decade highlighted that, to improve the recovering and recycling of by-products, it is fundamental to constantly monitor and control production processes by exploiting suitable sensing tools and advanced information processing techniques also based on Artificial Intelligence (AI), Machine Learning (ML) or on hybrid solutions, coupling these advanced techniques with physic-based modelling.

Modelling and simulation tools along with monitoring tools based on data analytics and physical and soft sensors can be the basis for the construction of digital twins supporting process advanced real-time control and optimal resource management (material and energy inputs). Process data and information collected by physical sensors can be exploited through modelling and simulation tools to achieve further information on processes that cannot be directly assessed inline and in real time by sensors. This information includes both status of processes (e.g. energetic status and efficiency of energy inputs, meltdown status of charged materials, performance of metallurgical reactions, etc.) and status of some by-products (e.g. slag temperature and composition). Modelling tools can be based on analytical calculations, by using energy and material balances and thermodynamic calculations, and on ML and Deep Learning (DL) techniques.

The combination of these approaches is often the most suitable modelling approach. In recent years a growing consensus is observed toward solutions to complex science and engineering problems which are able to integrate traditional physics-based modelling approaches with state-of-the-art ML techniques [80]. This emerging field, also referred to as *physics-guided ML*, *physics-informed ML*, or *physics-aware AI*, actually covers many scientific disciplines and includes those approaches where the application of AI and ML is integrated and somehow guided by scientific knowledge. These inter-disciplinary approaches are receiving increasing attention especially for environmental and engineering systems, where scientific knowledge is available as mechanistic models, theories, and laws but AI can indeed empower extraction of further knowledge from data as well as computational efficiency and optimization capabilities. The exploitation of this kind of approaches for improving material reuse and recycling must be enforced in the short-medium term.

Materials characterization is indeed a further open point for future research, and concerns both raw materials and by-products. Having a precise knowledge of the chemical composition and properties of the materials which are input to the process is challenging especially when such properties are variable by nature, such as in the case of scrap fed to the EAF, whose feature have an obvious effect on steel but also on slag. On the other hand, an accurate characterization of by-products while they are produced or once they are produced enables their future optimal valorisation in a Circular Economy perspective. The ongoing iSlag project started facing this issue for slag produced in the electric steel route, but further research is needed concerning all the other by-products. AI and ML approaches can strongly support material characterization, while advanced process modelling, control and optimization tools can allow adapting both single processes and the whole production chain, management and logistic for optimal residues valorisation and waste and costs minimization, while preserving (and even improving) steel products quality [81].

Modelling, simulation, and optimization approaches can help both finding the best route for by-products reuse (e.g. secondary products for external or internal reuse) and achieving information on their treatments (e.g. magnetic separation). For instance, they can support selection and validation of potential solutions to overcome technical, economical, and environmental issues affecting the recycling rate of by-products and the assessment of the possible advantages [76].

Furthermore, tools can be realised to be used by plant managers and operators supporting field tests aimed at improving by-products management. For instance, combining by-products, and waste management simulations and optimization, can allow identifying the most suitable procedures for their potential internal or external recovery as well as maximizing by-products reuse to improve their recycling rate. This approach can provide significant potentials to be applied not only in the steel sector but also to other sectors for investigating material and energy efficiency, to improve the recycling rates of different by-products.

Control and optimization problems targeting an improved management of resources, such as material and energy can be faced through different approaches, such as Model Predictive Control (MPC), Economic Model Predictive Control (EMPC) or bio-inspired optimization methodologies. Furthermore, implementing advanced AI and ML-based techniques can help to enforce the role in decision-making of operators.

Such optimization tools are often coupled to the ever-increasing deployment of Cyber-Physical Systems, Internet of Things (IoT), Big-Data Technologies and edge Computing, which is observed in the steel sector for improving flexibility and reliability of the processes and for the quality control of products. These technologies, which rely on a network of sensors collecting data and tools for interpreting them, can be applied not only to monitor and assess the environmental impact of the production processes, but also to control production and auxiliary processes. In addition, such tools, coupled to advanced modelling and simulation approaches, can support both control tasks and scenario analyses to assess environmental benefits and the technical and economic feasibility of process modifications and new operating practices.

Some technical actions in the field of sensoring and control are also proposed for the short, medium and long terms. In particular, for enhancing the management and optimisation of resources, environmental impact, quality and productivity, the application in the short term of innovative multi-criterial optimisation tools targeting different impacts (e.g. environmental footprint, productivity, costs, quality). In the medium term, combining optimization tools with model-based real-time control, can allow immediate reaction to changing process conditions and enhanced flexibility with respect to variable external factors (e.g. raw material prices, market demand for by products). In the long term, industrial application and demonstration of through-process real-time optimization can be achieved.

Such as previously stated, collected data can be exploited to assess the viability of novel processes by developing relevant models, to test them and related new operating practices, in order to decrease the importance of secondary working operations by providing ready-to-sell resources, according to market requirements. Different modelling tools can be exploited after being tuned through process data, by enforcing resource and energy efficiency [82]–[85]. These modelling tools can also be embedded into processes digital twins and advanced monitoring systems to improve energy and resource efficiency at plant level [86], [87].

To sum up, modelling and simulation show a relevant potential to support improvements of material and energy efficiency contributing to environmental and economical sustainability of the steel sector and enabling and enforcing the cooperation with other industrial sectors. This can pave the way for a better implementation of the Industrial Symbiosis and Circular Economy concepts across different industrial sectors and the establishment of a network facilitating the exchange of by-products and unrecovered energy. This will result in a reduction of landfilled material and CO_2 emissions, by increasing natural resources preservation and revenues generation.

6 Target audience and dissemination of the Roadmap

The EU steel sector and the ESTEP Community is the main envisaged target audience for this document, which should help companies and research organisation in identifying the most urgent and demanding research directions for the incoming years. In particular, the document can support steel companies and companies providing services to the steel industry (e.g. Original Equipment Manufacturers, Providers of services in the field of by-products treatment and valorisation) in selecting their investments in the field of research and development related to the topic of reuse and recycling of by-products from the steel production cycle. Moreover, the document can also help public organisations and policy makers in identifying the research topics that can demand public support (e.g. funding and facilitations for research activities). Finally, as the Roadmap also analyses the challenges related to regulations (see Section 3), it can be of help for policy makers in trying to implement actions, which overcome regulatory gaps and lack of homogeneity among EU countries, which is a relevant factor hampering the general uptake of novel technological solutions targeting improved recycling and valorization of by-products as well as the practical implementation of Circular Economy and Industrial Symbiosis solutions.

The present Roadmap was the last product of the REUSteel project, therefore it was finalised at the very end of the project. Its full content was preliminary presented and discussed within the ESTEP Circular Economy Focus Group meeting, which took place on January 2022. In that occasion, the request was issued by the audience to share the document, once approved and finalised, within the ESTEP community. Such dissemination within the ESTEP community will obviously be done after the approval of the final version of Deliverable 5.1. Moreover, the Roadmap will be downloadable from the web site of the project in the section devoted to Public Deliverables as well as from partner web pages devoted to the project REUSteel after the project is finished (https://www.reusteel.eu/deliverables.html; http://www.bfi-blogs.de/reusteel/).

As far as the dissemination within the scientific and technical community is concerned, part of the contents of the Roadmap were included in some of the presentations held during the last months of the project. For instance, parts of these content were included in the presentation given at the International Meeting RawMat 2021, which was held in Bergamo on December 1-2, 2021. On that occasion, the Consortium was invited by the organising committee to submit a paper for possible publication in the Journal “La Metallurgia Italiana”, edited by the Italian Association of Metallurgy (AIM) and indexed on SCOPUS, ISI-WOS and other scientific databases. The paper, which is entitled “Economia Circolare e Simbiosi Industriale in una recente analisi dei progetti europei rilevanti relativi all'industria siderurgica” and is authored by V. Colla, T.A. Branca, A. Morillon, D. Algermissen, H. Granbom, S. Rosendahl, U. Martini, R. Pietruck, D. Snaet, was submitted at the end of March 2022 and has been accepted for publication in the issue of May 2022 (Vol 5, 2022, pp. 8-15) of the Journal. The article will be open access after a delay period of about 3 months.

Indeed, the Roadmap could not be disseminated “as such” within the duration of the project, as it was finalised after the formal project conclusion. Therefore, the Consortium agreed on developing the dissemination of the Roadmap contents beyond the project conclusion. The following activities are in progress:

- Preparation of a paper to be submitted to the Open Access International Journal Metals, (indexed on SCOPUS, ISI-WOS and other scientific databases, ranked Q1), within the Special Issue entitled “Reuse and Recycling of By-Products in the Steel Sector”, for which V. Colla and T.A. Branca act as Guest Editors. The deadline for Submission is 30.11.2022.
- Presentation given by A. Morillon (FEHS) and V. Colla (SSSA) at the Euroslag 2022 Conference entitled “The transformation of the steel industry and its effects on the slag value chain” (www.euroslag2022.com), which will be held in Cologne on October 4-7, 2022.
- Part of the content of presentation given by V. Colla (SSSA) as invited speaker at the 8th International Slag Valorisation Symposium, which will be held in Belgium on April 18-20, 2023 (https://slag-valorisation-symposium.eu/).

The Consortium is fully committed to seek further opportunities for disseminating the Roadmap in other events in and possibly also outside Europe.

7 Literature

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8 List of Tables

9 List of Figures

List of symbols, indices, acronyms and abbreviations

Acronym	Name
AAC	Aerated Autoclaved Concrete
BET	Brunauer Emmett Teller
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CE	Circular Economy
DRI	Direct Reduction Iron Furnace
EAF	Electric Arc Furnace
ECSC	European Coal and Steel Community
ESTEP	European Steel Technology Platform
EZINEX	Engitec Zinc Extraction
FP	Framework Programme
GBF	Granulated Blast Furnace (referring to slag)
HRM	Hot Rolling Mill
IS	Industrial Symbiosis
IBRSR	Iron bath smelting reduction
LCA	Life Cycle Assessment
LD converter	Linz-Donawitz also known as BOF
LF	Ladle Furnace
LIBS	Laser-Induced Breakdown Spectroscopy
RFCS	Research Fund for Coal and Steel
SFA	Submerged arc furnace
SRA	Strategic Research Agenda
TRZ	Thermal Reserve Zone (temperature)

10 Appendix Table of studied projects

Table 8 The studied projects and their associated project numbers

Project number	Project identification	Title
[P1]	7215-AA/403	Economic advantages of integrated processing of steelworks EAF wastes, mainly containing Zn, Pb, Cd, FeOx, Zn ferrite and others, with total recovery
[P2]	IPBM	The in-plant by-product melting (IPBM) process
[P3]	TREATDUST	Development of technologies for treatment of dusts and sludges containing zinc and lead to improve their recycle reuse
[P4]	7215-AA/803	Improved cleaning of waste gases and recycling of BOF dusts
[P5]	7210-PR/005	Briquetting of self-reducing blendings of waste iron oxide mixtures
[P6]	7215-PP/012	High purity zinc and ferroalloys recovery from EAF dusts through a combined pyro-hydrometallurgical treatment
[P7]	7215-PP/028	Innovative use of iron and steel making by-products for the sealing and securing of steel industry deposits
[P8]	7215-PP/026	Foaming of slag and recycling of steel dust by injection into the electric arc furnace
[P9]	7210-PR/203	Efficient utilisation of raw materials used in secondary steelmaking as flux in steelmaking furnace
[P10]	7210-PR/195	Characterization, modelling & validation of the impact of iron and steelmaking slags used in road construction on groundwater
[P11]	7210-PR/271	In situ, quick sensing system for measurements of process-critical components in steelmaking slags
[P12]	7210-PR/267	Sustainable agriculture using blast furnace and steel slags as liming agents
[P13]	FULL-REC 2	Hydrometallurgical continuous treatment of ZnO enriched powders for metal zinc production
[P14]	7210-PR/326	Alternative Processing of Sinter Plant Recycling Materials
[P15]	7210-PR/327	Hearth protection in BF operation by injection of TiO2-materials
[P16]	SHOCOM	Short term CO2 mitigation for steelmaking
[P17]	ACASOS	Alternate carbon sources for sintering of iron ore
[P18]	URIOM	Upgrading and Utilisation of Residual Iron Oxide Materials for hot metal production
[P19]	EPOSS	Energy and productivity optimised EAF stainless steel making by adjusted slag foaming and chemical energy supply
[P20]	FLEXINJECT	Flexible injection of alternative carbon material into the blast furnace
[P21]	SLASORB	Using slag as sorbent to remove phosphorus from wastewater

[P22]	GreenEAF	Sustainable Electric steel production
[P23]	INNOCARB	Innovative carbon products for substituting coke on BF operation
[P24]	OPTDESLAG	Increased yield and enhanced steel quality by improved deslagging and slag conditioning
[P25]	PROTECT	Processes and technologies for environmentally friendly recovery and treatment of scrap
[P26]	SLAGFERTILISER	Impact of long-term application of blast furnace and steel slags as liming materials on soil fertility, crop yields and plant health
[P27]	REFFIPLANT	Efficient use of resources in steel plants through process integration
[P28]	SLACON	Control of slag quality for utilisation in the construction industry
[P29]	EIRES	Environmental impact evaluation and effective management of resources in the EAF steelmaking
[P30]	PSP-BOF	Removal of Phosphorous from BOF Slag
[P31]	GREENEAF2	Biochar for a sustainable EAF steel production
[P32]	ALTERAMA	Developing uses of alternative raw materials in cokemaking
[P33]	RIMFOAM	Recycling of industrial and municipal waste as slag foaming agent in EAF
[P34]	ACTISLAG	New Activation Routes for Early Strength Development of Granulated Blast Furnace Slag
[P35]	FINES2EAF	Cement-free brick production technology for the use of primary and secondary raw material fines in EAF steelmaking
[P36]	ECOSLAG	Eco-friendly steelmaking slag solidification with energy recovery to produce a high quality slag product for a sustainable recycling
[P37]	Slagreus	Reuse of slags from integrated steelmaking
[P38]	FP3-BRE20116	Recycling of zinc and lead containing dusts from the electric arc furnace
[P39]	FP4-INCO	A new treatment process to recover magnetite, zinc and lead from iron and steel making dusts and sludges
[P40]	FP4-BRPR970446	Treatment of liquid steel slag with sand and oxygen in order to improve their volume stability and their environmental behaviour
[P41]	REZIN	Elimination of zinc ferrite
[P42]	REDILP	Recycling of EAF dust by an integrated leach-grinding process
[P43]	FISSAC	Fostering industrial symbiosis for a sustainable resource intensive industry across the extended construction value chain
[P44]	CHROMIC	efficient mineral processing and Hydrometallurgical RecOvery of by-product Metals from low-grade metal containing secondary raw materials
[P45]	RESLAG	Turning waste from steel industry into a valuable low cost feedstock for energy intensive industry

11 Appendix - Current state of EU research projects

Slag

Table 9 Internal slag use/recycling

Project	Titel	Year	TRL project	Continuation (Y/unknown)	Comment
Recycling of LF slag to EAF					
[P9]	LF	2003	6-8	Y	Continuation of the project in ECOSLAG project: recharging of LF slag into the EAF process as lime substitute.
[P29]	LF	2016	7	Y	Continuation of the project in ECOSLAG project: recharging of LF slag into the EAF process as lime substitute
Recycling of LF slag to BF					
[P27]	LF	2015	5	unknown	
Recovery of metal					
[P2]	BOF, EAF	1998	7	Y	Several continuation project, some on research level and some industrial. The ZEWA (zero waste) process is one of the continuations from P2.
[P18]	EAF	2010	4-5	unknown	
[P19]	EAF	2010	9 (for Al-injection)	unkonwn	
[P27]	BOF	2015	7	unknown	Modelling: Fe-rich pellets
[P30]	BOF	2016	6	Y	Slagreus – Reuse of Slag from Integrated Steelmaking, A project about heat recovery from slag also has its origin in PSP-BOF.

Table 10 External slag use

Project	Titel	Year	TRL project	Continuation (Y/unknown)	Comment
Guidelines					
[P28]	EAF	2015	5	Y	EAF slag is continuously being researched to improve its quality and increase utilization at different steelworks.
Road construction					
[P10]	EAF, BOF, GBF and BF	2003	4	Y	In the literature some studies investigated slags' effects on the groundwater. However, no RFCS study was done about this since this project.
[P40]	BOF and EAF	2020	4-9	unknown	
Cement/Clinker/Hydraulic binders					
[P2]	BOF, EAF	1998	7	Y	Several continuation project, some on research level and some industrial. The ZEWA (zero waste) process is one of the continuations from P2.
[P30]	BOF	2016	6	Y	Slagreus – Reuse of Slag from Integrated Steelmaking, A project about heat recovery from slag also has its origin in PSP-BOF.
[P43]	EAF, LF slag	2020	7	Y	The industrial production and real scale demonstration on different case studies will be done. Concerning the cement-based product eco-design the industrial application was already done.
Liming/fertilizer					
[P12]	BF, BOF, LF and basic slag	2004	6	Y	SLAGFERILZIER project was a continuation of research on effects of slag in long term soil studies. In addition, research is continuously conducted on small scale aspects of this projects ((e.g. suitability of different slags to be used as fertilizers).
[P26]	BOF, LF and basic slag	2011	6	Y	Research is continuously conducted on small scale aspects of this project (e.g. suitability of different slags to be used as

					fertilizers). However, since this project no long term research has been done on the effects of slag in soil in RFCS.
[P30]	BOF	2016	6	Y	Slagreus – Reuse of Slag from Integrated Steelmaking, A project about heat recovery from slag also has its origin in PSP-BOF.
Filling material for mining shafts					
[P40]	BF	2020	1	unknown	
Landfill sealing material					
[P7]	BOF, EAF, LF	2002	7	Y	A mixture of EAF or LF slag with BF sludge was comparable to materials available on the market. Other studies than RFCS have reported on using slag as sealing material this technology shows potential.
P filter material					
[P21]	BOF and EAF	2012	5	Y	Research on using slag as a filter material is being investigated in other studies, but not RFCS
Extraction of Vanadium					
[P30]	BOF	2016	6	Y	
Inertization of toxic wastes					
[P2]	BOF and EAF	1998	7	Y	Several continuation project, some on research level and some industrial.

Table 11 Slag analysis

Project	Title	Year	TRL project	Continuation (Y/unknown)	Comment
Resulting slag after slag foaming optimization					
[P8]	EAF	2002	8	Y	EPOSS project investigated further the idea of slag foaming. In addition, SLACON project also investigated this aspect. Slag forming is an important issue at the steelworks and different studies are being conducted.
[P19]	EAF	2010	9	unkown	
Image based sensors					
[P24]	EAF, BOF	2013	8	Y	RFCS project: Improving steelmaking processes by enhancing thermal state ladle management (LADTHERM)
LIBS					
[P11]	EAF, BOF, LF	2004	6	Y	The developed LIBS-method in INQUISSS project for controlling the slag composition online will be further exploited in the iSlag project to identify the most suitable recycling paths
[P26]	BOF	2015	6	Y	LIBS is investigated in different studies. iSLAG is further investigating different aspects of LIBS.

Sludge

Table 12 Internal sludge use/recycling

Project	Type of sludge	Year	TRL project	Continuation (Y/unknown)	Comment
Briquette production for recycling					
[P5]	Mill scale, BF, BOF	2000	5	Y	Industrial application at BF using dust, sludge and slag, Optimization of Binder for Improving Strength and Shatter Index of Briquettes for BOF Dust using Design of Experiments [88]
[P14]	BF sludge	2005	5	Y	Follow up: Upgrading of Blast Furnace Sludge and Recycling of the Low-Zinc Fraction via Cold-bonded Briquettes [89]
[P17]	BF	2013	5-6	Y	Follow up: Study on applicability of biomass in iron ore sintering process [90]
[P20]	BF	2011	7-9	Y	Follow up: Injection of BOF Dust Into the Blast Furance Through Tuyere [91]
[P27]	BOF	2015	5	Y	Closing the Loop – Processing of Waste By-Product from Aluminum Recycling into Useful Product for the Steel Industry [92]

Table 13 External sludge use/recycling

Project	Type of sludge	Year	TRL project	Continuation (Y/N, unknown)	Comment
Inert products for external use					
[P2] IBPM	BF	1998	7	Y	Several continuation project, some on research level and some industrial. The ZEWA (zero waste) process is one of the continuations from P2. Sludge require drying and microgranulation.
[P7]	BF	2002	7	unknown	.
Filling material for mining shafts					
[P40]	BF	2020	1	unknown	

Dust

Table 14 Internal dust use/recycling

Project	Type of sludge	Year	TRL project	Continuation (Y/unknown)	Comment
Control of slag foaming					
[P6]	EAF dust	2001	5	Y	Selective Zinc Removal from Electric Arc Furnace (EAF) Dust by Using Microwave Heating [93]
[P8]	EAF dust	2002	8	Y	At USI slag foaming is now applied to all heats made in the EAF n°1 with recycled dust, except those with strong residual constrains (2002)
[P38]	EAF dust	2017	6	Y	Selective Zinc Removal from Electric Arc Furnace (EAF) Dust by Using Microwave Heating [93]
Recovery of metal					
[P1]	EAF dust	1998	7	unknown	
[P2]	BOF, BF, EAF-dust stainless EAF-dust C-steel	1998	7	Y	Valorization of Slags Produced by Smelting of Metallurgical Dusts and Lateritic Ore Fines in Manufacturing of Slag Cements [94]
[P3]	EAF, BOF dust	1999	4	Y	The results achieved have been used for following European research projects 7215-PP/012and FULL-REC 2 in the context of metal recovery from EAF dust via pyro-hydro process. Other results defined optimal conditions for dust pre-treatment in order to enhance the metal recovery via Waelz process.
[P4]	EAF dust	1999	4	unknown	
[P5]	EAF dust, BF dust	2000	5	Y	Mill scale and flue dust briquettes as alternative burden to low height blast furnaces [95]
[P6]	EAF dust	2001	5	Y Continued by [P 13]	*Proposed follow-up:* Implementation of the hydro-metallurgical plant in order to operate in continuous mode, thus allowing to evaluate the effect of possible accumulation phenomena

[P8]	EAF dust	2002	8	Y	*Environmental evaluation:* While the slag that resulted from the process had some Cr reduction their overall concentrations were still significant. => further decrease Cr content in slag
[P13]	EAF dust	2005	6-7	unknown	As in the project P6. The hydro process is operating in continuous manner. *Eventual follow-up & Interesting ideas that could be further investigated:* The purity of the metallic Zn obtained at cathodes (99.98%) has been little lower than the targeted one (>99.99%). This is due to the actual level of impurities in the solution. In particular, the substitution of Pb with Ti anodes will allow to limit the Pb content in the solution due to electrode dissolution. A further purity level could also be reached by a double purifying treatment in order to furtherly decrease Ni.
[P14]	BF and BOF dust	2005	5	Y	Optimization of Binder for Improving Strength and Shatter Index of Briquettes for BOF Dust using Design of Experiments. [88]
[P18]	EAF dust	2010	4-5	N	*Interesting ideas that could be further investigated:* Gas reforming of Zn-containing off-gas from Zn recycling reactors (ICBR reactor) with water vapour to produce ZnO as well as H_2.
[P27]	BF, BOF dust	2015	6	unknown	*Interesting ideas that could be further investigated:* Models of treatment units to be exploited in other case studies and to be transferred to other steelworks.
[P38]	EAF dust	1996	6	Y	Concepts taken up in various subsequent projects on dust recovery. Pyro-metallurgical concepts for treatment of EAF dust to enrich the Zn concentration. Useful for different post processing of dust powders aimed at valuable metal recovery including Waelz process and hydro processes.
[P40]	BOF dust	2020	1	unknown	*Eventual follow-up:* Improve the reduction step in the steel shop, further investigations of generated slag in real applications.
[P42]	EAF dust	2007	7	unknown	The commercialisation of the REDILP process is today not reachable because the technology is not sufficient economic. Nevertheless, if the commodity market is developing further in direction to higher prices of Zinc it could be possible that the developed REDILP-process will break the break-even point.

					Eventual follow-up: SME partners realised a network of companies for marketing and exploiting the developed system at European level (EAF dust recycling and activating leach grinding technology; REDILP).
Recovery of carbon					
[P17]	BF, BOF dust	2010	6	Y	EU research project: Improved sinter mix preparation while using challenging raw materials (IMSIMI)
[P20]	BF dust	2011	7-9	Y	Sludge as coal injection to BF. Further development in following research projects as well as measurements for several weeks on industrial scale.
[P23]	Coke dust from cokery	2013	6	Y	Alternative Carbon Sources for Reduction [96]

Table 15 External dust use

Project	Type of sludge	Year	TRL project	Continuation (Y/unknown)	Comment
Inert products for external use					
[P2]	EAF and sinter plant dust	1998	7	Y	Several continuation project, some on research level and some industrial. The ZEWA (zero waste) process is one of the continuations from P2. Mineral products can be used in cement production.
[P7]	various	2002	7	unknown	
Filling material for mining shafts					
[P40]	LF dust, casting bay dust, sinter plant dust	/	1	unknown	

Refractory

Table 16 Use of spent refractory

Project	Type of sludge	Year	TRL project	Continuation (Y/unknown)	Comment
[P18]	Refractory residues	2010	4-5	unknown	
Internal substitution for dolomite					
[P9]	EAF, BOF and secondary steelmaking	2003	6-8	unknown	
Inert products for external use					
[P2]	High silica refractory, Silicon-alumina refractory containing Cr VI	1998	7	Y	The ZEWA (zero waste) process is one of the continuations from P2. Mineral products can be used in cement production.

Millscale

Table 17 Internal mill scale use/recycling

Project	Type of sludge	Year	TRL project	Continuation (Y/unknown)	Comment
Metal recovery in standalone vessel					
[P2]	Mill scale	1998	7	Y	The project has been followed by a number of big public projects on recovery of V from BOF-slag and numerous contract projects on V-extraction. The project consortium also continued with an EU project for "Slag Reduction of Stainless Steel slag and Waste". The ZEWA (zero waste) process is one of the continuations from P2.
Metal recovery in BF					
[P14]	Mill scale	2005	5	Y	Follow up: Mill scale and flue dust briquettes as alternative burden to low height blast furnaces [95]
[P27]	Oily mill scale	2015	5	Y	Follow up: Production of cleaner mill scale by dynamic separation of the mill scale from the fast-moving flume water at a hot rolling mill. Journal of Cleaner Production. [97]
Metal recovery in EAF					
[P5]	Mill scale	2000	5	Y	Development and use of mill scale briquettes in BOF [98] Recycling of steel plant by-products by cold bonded briquetting [99]
[P29]	Mill scale	2016	7	unknown	

Secondary raw materials (outside the steelworks)

Table 18 Secondary raw materials from outside the steelworks used in the steelwork

Project	Type of residues	Year	TRL project	Continuation (Y/unknown)	Comment
Used as binders					
[P2]	Fayalite slag	1998	7	Y	Several continuation project, some on research level and some industrial.
[P5]	Molasse	2000	5	Y	Scale Recycling Through Self-Reducing Briquettes to Use in EAF. [100].
[P32]	Lignin, waste plastics, forestry by-products, sugar production by-products, coking plant by-products, brown coal, coal tar etc.	2017	4	unknown	No known means of contacting the project consortium.
Metal recovery					
[P25]	Waste plastics (low value, energy rich fractions)	2013	5-6	unknown	
Carbon source					
[P16]	Charcoal	2008	5	unknown	
	Waste Plastic	2008	5	Y	Waste Plastics Injection: Reaktion Kinetics and Effect on the Blast Furnace Process [48]
[P17]	Biological Carbon Sources, Carbon contain residues, Anthracite; Pet coke for sintering	2010	6	Y	Biomass for iron ore sintering [101]; Walnut Shells as a Potential Fuel for Iron Ore Sintering [102]

[P20]	Waste plastics, e.g. packaging, ASR	2011	7-9	Y	Sludge as coal injection to BF. Further development in following research projects as well as measurements for several weeks on industrial scale.
[P22]	Charcoal and syngas from biomass	2012	6	Y (P31)	Project P31 is the continuation of this project
[P23]	Pet Coke, Charcoal, Lignite coke, BF dust - briquettes for BF	2013	6	Y	Experiences of Bio-Coal Applications in the Blast Furnace Process—Opportunities and Limitations [43]
[P32]	Lignin, waste plastics, forestry by-products, sugar production by-products, coking plant by-products, brown coal, coal tar etc.	2017	4	unknown	.
[P31]	Charcoal Torrcoal biochar	2016	7 (for charging) 6 (for injection)	Y (see comments)	Industrial with charging (more than 700 heats) and injection Ferriere Nord (IT) is participating in a SPIRE project (RETROFEED). In this project, the injection of biochar by devoted injection system will be done. Due to the number of heats, the TRL will be 7 for the injection, too. In case of success, the system will be used in operation on a permanent basis.
Miscellaneous					
[P15]	Rutilit/TiO2	2005	8	Y	Titanium distribution between blast furnace slag and iron for blast furnace linings protection [103]

[P19]	Secondary Al granules	2010	9	unknown	
[P30]	Sewage sludge ash	2016	6	Y	Internal investigations of are being conducted, but no RFCS project has been done as a follow up.
[P40]	Glass cullet	2020	6	unknown	

12 Appendix Questionnaire

In which business area do you work? (Former D3)

- Iron/Steel
- Base Metals
- Cement/Concrete
- Chemical
- Pulp & Paper
- Forestry
- Other

This gives a good overview where the trends or challenges may come from and will allow the evaluation of the questionnaire with respect to business area.

Please qualify your organisation (Former D25)

- LE
- SME
- RTO
- Academia
- Other

Same as above with respect to the type of organisation.

Would you say that your business area is prepared to support the steel industry in the use of recycled material? (Former D7)

In combination with the other questions this could help to identify the areas with the greatest research need

In Your opinion, how great is the potential of recycled materials to replace primary materials in the steel industry? (Former D9)

- Less than 30%
- 30 to 70%
- More than 70%

Good to obtain a general impression. Though a larger number answer option might have been preferable. Discrepancy to reported data; World Steel.org reports 90% of by-products recycled.

In which areas do You see a need for research? (Former D26, 27 & 28)

In combination with questions 1 and 2 we could perform a detailed evaluation for which materials the participants see the greatest needs and then divide into the recycling uses they envision for the respective materials – all with respect to business area and organisational background. For example: participants from the steel industry see the greatest research need for EAF slag, especially in the area of external valorisation.

Type of By-product/residual	Slag Internal recycling	Slag 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 like metals, coal and lime	Elimination of harmful elements	Minimisation of waste generation and landfill	Process integration solutions for by-products management	Modelling and simulation
BF-Slag	☐	☐	☐	☐	☐	☐	☐	☐	☐
BOF-Slag	☐	☐	☐	☐	☐	☐	☐	☐	☐
EAF-Slag	☐	☐	☐	☐	☐	☐	☐	☐	☐
LF-Slag	☐	☐	☐	☐	☐	☐	☐	☐	☐
BF-Dust	☐	☐	☐	☐	☐	☐	☐	☐	☐
BOF-Dust	☐	☐	☐	☐	☐	☐	☐	☐	☐
EAF-Dust	☐	☐	☐	☐	☐	☐	☐	☐	☐
LF-Dust	☐	☐	☐	☐	☐	☐	☐	☐	☐
Sinter plant	☐	☐	☐	☐	☐	☐	☐	☐	☐

Coke-dust	☐	☐	☐	☐	☐	☐	☐	☐	☐
BF-Sludge	☐	☐	☐	☐	☐	☐	☒	☐	☐
BOF-Sludge	☐	☐	☐	☐	☐	☐	☐	☐	☐
EAF-Sludge	☐	☐	☐	☐	☐	☐	☐	☐	☐
Mill-Sludge	☐	☐	☐	☐	☐	☐	☐	☐	☐
Refractory	☐	☐	☐	☐	☐	☐	☐	☐	☐
Mill-scale	☐	☐	☐	☐	☐	☐	☐	☐	☐
Oily Mill sc.	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other res. Inside Steel Industry. Please specify below	☐	☐	☐	☐	☐	☐	☐	☐	☐
Secondary raw materials from outside the steel industry. Please specify below	☐	☐	☐	☐	☐	☐	☐	☐	☐

13 Appendix Interview with experts

RFCS-Reusteel	"Dissemination of the results of European research projects on the reuse and recycling of by-products in the steel sector"		
Please add:	route - untilisation - subcategory - residue -	15.11.2011	
Route	**Utilisation**	**Subcategory Utilisation**	**Please specify type of residue (slag, dust, slag, mill scale, etc.) and way of utilisation and short remarks regarding research needs for the near future (10 Years)**
From Sinter/BF/BOF/LD			Comment: No detailed answer possible due to ongoing research
BF	Internal utilisation	o *Recovery of C content*	
BOF		o *Recovery of Fe content*	
Hot rolling		o *Recovery of Fe content*	
	External utilisation		
		o *Use as Inert product*	
		o *Cement*	
		o *Road construction*	
		o *Hydraulic eng.*	
		o *Extraction of valuable materi*	
		o *Etc.*	
	Other		
		o *Minimisation of waste generc*	
		o *Modelling/Simulation (AI)*	*(example) AI in residue recycling (example)*
From EAF route			
	Internal utilisation		
		o *Use as Inert product*	
		o *Recovery of Fe metal*	
		o *Recovery of non-Fe-metal*	
		o *Recovery of oxides*	
		o *Recovery of carbon content*	
	External utilisation		
		o *Cement*	
		o *Road construction*	
		o *Hydraulic eng.*	
		o *Extraction of valuable materi*	
	Other		
		o *Minimisation of waste generc*	
		o *Modelling/Simulation*	
From Alternative routes(I			
	Internal utilisation		
	External utilisation		
	Other		