PRESEARCH REPORT

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CO_2

Environmental data collection of new slag materials

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beyond the obvious

Report's title

Environmental data collection of new slag materials

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Summary

The Fossil-Free Steel (FFS) initiative, which is supported by Business Finland, leads the way in shifting towards carbon-neutral steel manufacturing through the utilisation of environmentally friendly power and hydrogen. In line with Finland's objective to achieve carbon neutrality by 2035 and the European Union's goal of producing steel without fossil fuels by 2050, FFS plays a crucial role in decreasing CO_2 emissions.

This report explores the environmental data for new electric arc furnace slag (EAFS) from fossil-free steelmaking combining direct reduced iron and electric arc furnace (DRI-EAF) with emphasis on EAFS applications. Consequently, this report examines data needs and gaps. The purpose of the report is also to evaluate the system boundaries and allocation methods employed in the LCA literature regarding EAFS applications. These examinations support later stage life cycle assessment (LCA) studies and understanding of environmental impacts of utilizing the new slags.

The primary findings from literature review highlight the prevalent utilization of EAFS as aggregates, underscoring the necessity to explore a variety of applications through LCA. Especially, using EAFS as cement substitutes could provide high positive environmental impacts. This report also recognizes the scarcity of LCA studies specifically focused on EAFS derived from DRI-EAF process.

The literature review reveals that employing EAFS provides reductions in greenhouse gas (GHG) emissions especially through avoided landfilling and raw material production. However, the high density and absorption rate of EAFS may lead to disadvantages as well. While the reviewed literature indicates that the burden from steelmaking is generally not allocated to EAFS in LCA studies, the report identifies a need for establishing more uniform and transparent approaches when defining the system boundary and allocation methods. Ultimately, this report offers comprehensive analysis of environmental impacts associated with employing EAFS and the transition from blast furnaces to fossil-free processes in the slag production.

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Contents

1 Introduction

Towards Fossil-free Steel (FFS) -project funded by Business Finland work for the transition from carbon intensive steelmaking. Utilization of ‘green’ electricity and hydrogen instead of fossil carbon in steelmaking provides opportunity for large-scale CO_2 emission mitigation. Due to the growing climate regulations, fossil-free steel will be in the interest of industries applying steel. FFS consortium promotes Finnish steel export and hydrogen economy, and at the same time contributes heavily to Finnish and EU climate targets, as steel industry is responsible for 7% of the total CO_2 emissions in Finland. A significant reduction of the emissions within the steel industry can contribute greatly to achieving the Finnish carbon-neutrality goal by 2035. The Finnish target is stricter than the EU-target: A Green Deal on Steel aims to reduce CO_2 emissions of the EU steel production by 30% by 2030 compared to the 2018 level and targets a fossil-free steel production in EU by 2050. FFS project will bring new research-based knowhow, process innovations, development of process practices and reassessment of circular economy that are required for realising fossil-free steel production. The transition to fossil-free steelmaking creates the need to find solutions for large-scale clean hydrogen production, storage and supply. In addition, the electrification of industrial kilns will be studied via development of new electricity assisted burners. Furthermore, investigation of fossil-free steelmaking residuals (slags, sludges, dusts) and their utilization methods will be leveraged.

This report focusses on environmental data collection of FFS project slag materials and their potential applications. New slag materials data collection supports later stage Life cycle assessment (LCA) studies for various end-uses. Data collection includes for example greenhouse gas (GHG) emissions and material and energy streams. In addition, this report explores the system boundaries and allocation methods applied in the relevant LCA studies.

Goal is to understand the availability of data and collect data to support new slag materials environmental life cycle assessment studies, and to understand the data needs and current data gabs for slag-based materials. This will support the understanding of the environmental impacts of the new slags and give guidelines for slag-based materials development from sustainability perspective. Ultimately, the goal is to evaluate the impact of a shift in slag production from blast furnace to the process combining direct reduced iron and electric arc furnace (DRI-EAF), and associated impacts on slag utilization.

2 Background

Chapter 2.1 describes the method for assessing environmental impacts and general allocation principles of steel co-product called slag. Next, Chapter 2.2 examines typical process steps for EAF slag production with its use cases and characteristics.

2.1 Life cycle assessment and allocation methods

Life cycle assessment (LCA) is a standardized method used to analyse different environmental impacts during the whole life cycle of a product, or a service. Principles and guidelines for LCA studies are given in the ISO 14040/14044 standards [1,2]. According to the standards, LCA studies consist of four steps:

1. Goal and scope definition
2. Life cycle inventory (LCI) analysis
3. Life cycle impact assessment (LCIA)
4. Interpretation

The first step, goal and scope definition, serves two main purposes. It describes the purpose of the study and defines the system boundary. This boundary outlines the stages of the life cycle involved in the LCA study, such as cradle to gate or cradle to grave. Additionally, the functional unit acting as a reference is determined in the first step. LCI phase includes gathering of input and output data for each unit process inside the system boundary. The data can include, energy and raw material inputs, products, waste, emissions and other environmental aspects. In the LCIA step, the collected data is associated with environmental impacts such as climate change and resource depletion. The significance of the environmental impacts is also evaluated. The last step, interpretation, includes discussion of the results, drawing conclusions and giving recommendations.

Often processes are multifunctional which means that they yield multiple products simultaneously. Consequently, environmental impacts need to be distributed to the products. Guidelines for solving this allocation problem are provided in several sources. These include the ISO 14044 standard and the ILCD handbook [3]. Additionally, sector-specific guides, particularly for steel industry co-products like slag-based items, offer guidance. Standards and product-category rules (PCRs), when available, also contribute valuable information. Steelmaking processes are an example of a multifunctional process, since in addition to steel, slag is also produced among other co-products in these processes. The final report of The Net-Zero Steel Pathway Methodology Project (NZSPMP) [4], gives recommendation how to account for the environmental burden reductions arising from employing the steelmaking by-products, such as slag, in applications. The report recommends employing system expansion as one method. This approach considers the avoided environmental impacts resulting from substituting a raw material with a steelmaking by-product. The ISO 20915:2018 standard [5] also highlights this as the primary method in the case of steelmaking LCA. Alternatively, the steelmaking burden could be divided in another way. It might be allocated to slag, using physical criteria like mass or commercial value. According to the NZSPMP report [4], the latter option is usually seen as less favorable. Regarding the steel sector decarbonisation approach (SDA), the NZSPMP report also suggests dividing emissions among different sectors within a designated budget for the steel industry based on the GHG value of co-products in addition to the system expansion and allocation.

2.2 Typical process steps generating EAF slag

Iron and steel slag are classified according to which type of furnace generates them as shown in Figure 1. The type of process used to produce the crude steel influences the properties, composition, and mineralogy of the slags. Cooling conditions and post-processing play significant roles in defining the characteristics of slag and its utilization [6]. In the production of steel from iron ore, iron is traditionally separated in a blast furnace (BF), producing blast furnace slag (BFS). The molten iron is then transformed into crude steel in a basic oxygen furnace (BOF), the process of which results in BOF slag (BOFS). Another two-step process is used to produce steel from scrap metal or from DRI/sponge iron, with the first stage generating electric arc furnace slag (EAFS) and the final refinement stage producing ladle furnace slag (LFS) [7].

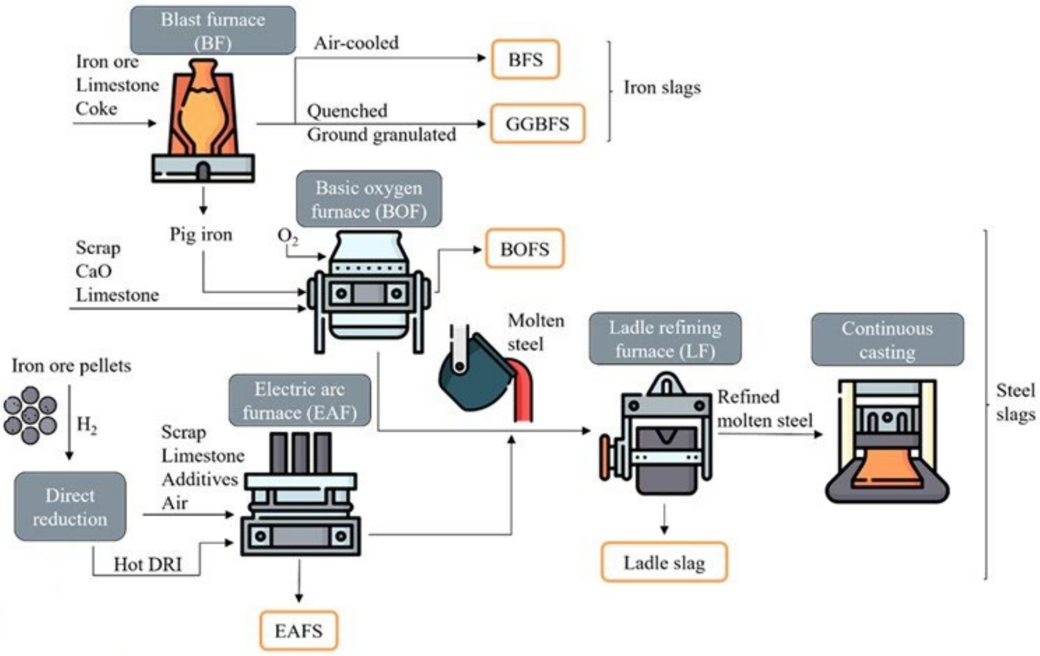

Figure 1 Iron and steel production processes and types of slags generated. Focus of this report is on EAFS using iron sponge/DRI as raw materials.

2.2.1 Production of EAF slag

The EAF process involves the melting and purification of metal scraps or DRI/iron sponge using electricity as an energy source, rather than combustion of carbon based fuels. Scrap steel is collected, classified, and sorted based on size and composition before being charged into an electric arc vessel. The advantages of scrap based steel production is that it is based on a secondary raw material/end of life materials, and therefore also lower CO_2-eq compared to traditional primary/ore-based steel. The DRI process involves heating iron ore below its melting point using hydrogen as a reducing gas, typically generated from natural gas or coal. However, in the case of fossil-free steel, hydrogen as reducing gas is needed to be also fossil-free. This process results in a product that is 90 to 95% metallised and can be used in electric arc furnaces for steelmaking. DRI offers several advantages, including a consistent and predictable composition of steel, ease of handling in comparison to scrap steel, and even the slag generated in the EAF when charged with DRI exhibits a more uniform composition.

EAFS is a by-product of the steel production from sponge iron or recycled steel obtained in an electric arc furnace (Figure 2). The production of EAFS include the following steps:

1. Along with steel scrap or sponge iron, the vessel is filled with limestone, dolomite, bauxite and other fluxing/slag forming agents [8].
2. The three graphite electrodes are lower into the material and as the electric current passes through them an arc is generated, providing the high heat needed for melting the materials, reaching temperatures of 1550 °C [8].
3. Oxygen is blown into the vessel and impurities such as silicon, manganese, and carbon are oxidised and combined with limestone [9].
4. Slag is formed, floating above the molten steel. This is collected from the charged door, while the molten steel is poured out.

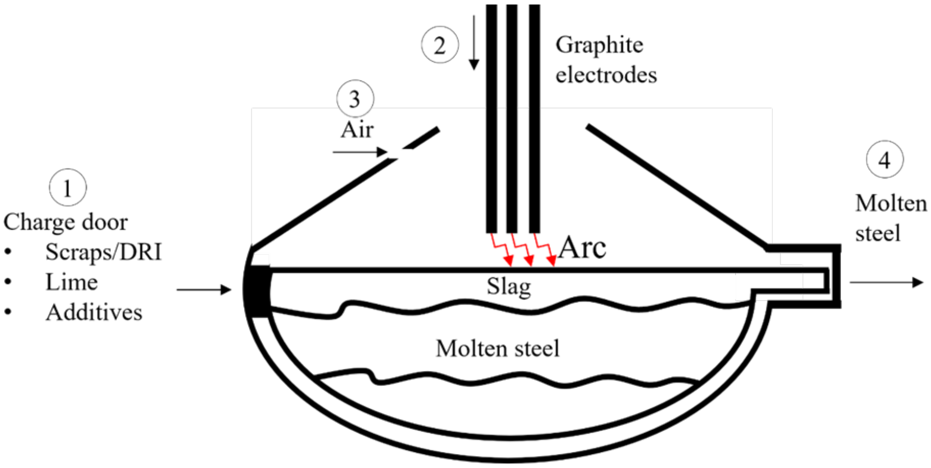

Figure 2 Schematic of an electric arc furnace.

5. Solidification of slags can example follow four pathways: a) air-cooled and weathered in slag pits under atmospheric conditions; b) steam hydration using hot water of the cooling circuits of the plant to accelerate conversion of lime; c) addition of silica to the molten slag to form stable calcium silicates as gehlenite; d) controlled formation of hydraulic phases [10].
6. The resulting solidified EAFS is then crushed and screened to produce a range of sizes suitable for various applications.
7. Metal can be recovered by magnetic separation or leaching. Valuable elements such as titanium, nickel, vanadium, iron could also be contained in EAFS in such case the development of suitable extraction methods must be considered [11,12].

2.2.2 Potential of EAF slag for different applications

EAFS potential for applications is depending on several aspects such as

1. **Cementitious activity.** To be a beneficial supplementary cementitious material (SCM), steel slag must exhibit at least one of the following characteristics:
   - a significant content of hydraulic phases such as alite (C_3S), belite (C_2S) or aluminoferrite (C_4AF)
   - pozzolanic reactivity, usually displayed as amorphous phase (like fly ash, metakaolin, or ground granulated blast-furnace slag)

   If any of these phases are not present and no additional treatment takes place than the recommended usage is as an aggregate. EAFS pozzolanic reactivity has been shown to be quite slow [13]. To potentially increase the cementitious activity, certain treatments can be considered. However, it is important to note that these treatments may lead to higher environmental impacts associated with EAF:
   a. Re-melting and rapid quenching [14]
   b. Carbonation activation [15]
   c. Chemical activation (for example with NaOH, acetic acid [16,17], Na_2SO_4, H_2SO_4 [18], or H_3PO_4 [19])
   d. Mechanical activation (for example grinding [20])
   e. Thermal excitation [21,22]

2. **Presence of expansive phases**. Volume instability is a major issue in the usage of steel slags in construction and it is associated with the presence of free lime (f-CaO) and MgO (f-MgO). These phases when hydrated generated volumetric expansions and can lead to structural collapse. Treatments listed below can lead to stabilisation of slags:

   a. Weathering: this is usually required prior utilisation as an initial preventive technique. CaO is converted to $Ca(OH)_2$ and $CaCO_3$. [23–25]. However, this can be slow and inefficient [10].
   b. Accelerated carbonation: CaO is converted to micro crystalline $CaCO_3$ which forms a protective layer [26].
   c. Silica addition to the liquid slag: highly stable gehlenite matrix (C_2AS) is formed [27].
   d. Chemical treatment: as acetic acid [17] phosphoric acid [19] addition will reduce-CaO concentration and increase the reactivity.

   Once the slag is stabilised, it is possible to utilise it as an aggregate. However, chemical composition, and heavy metals leaching may become as limiting factor for slag use as aggregate, described as following:

3. **Heavy metals leaching.** This represents a major environmental limitation. The most common heavy metals found in steel slags are Cr, V, Mo, and Ba. Also In these cases, stabilisation is required. Most of the treatment techniques acting on volume stabilisation should also reduce the leaching.
   a. Accelerated carbonation aids in preventing leaching by enhancing the stability of heavy metals within the slag [28].
   b. Controlled crystallisation (during the cooling of slag) promotes the formation of stable or very low solubility phases (for example solid spinel phases) in which heavy metals as Cr are strongly bounded [29,30].
   c. Silica addition to form gehlenite matrix [27].
   d. Immobilisation/encapsulation (when the heavy metals content is too high or too toxic) in alkali-activated materials or other techniques [31].

2.2.3 Potential use cases and their process routes

There are multiple potential use cases for EAFS. These include the following ones:

1. **As an aggregate (coarse and fine):**
   a. In roads and pavements [32–35] and microsurfacing [36]
   b. Buildings and infrastructures [37–40]
   c. Special application concretes (high strength [41], refractory [42,43], self-compacting)
2. **As supplementary cementitious material (SCM) - blended with cement:**
   a. In concrete [44]
   b. As filler material [13,45]
   c. For soil/subgrade stabilisation [46,47]
3. **As raw material (feedstock) for clinker production** [48,49]
4. **In other applications:**
   a. Absorbent in water treatment [10,50,51]
   b. Soil amendment [52,53]

Figure 3 illustrates the potential applications and their process routes. Treating EAFS starts with the metal recovery after which different treatments can be applied based on the desired application. Producing aggregates for varying use cases may require weathering, accelerated carbonation, silica addition or controlled crystallisation. These same treatments may be necessary to use EAFS as an adsorbent for wastewater treatment and as a soil amendment fertilizer. Generating supplementary cementitious material, instead, can demand mechanical and chemical treatments, rapid water quenching, and accelerated carbonation, as discussed in the previous subchapter.

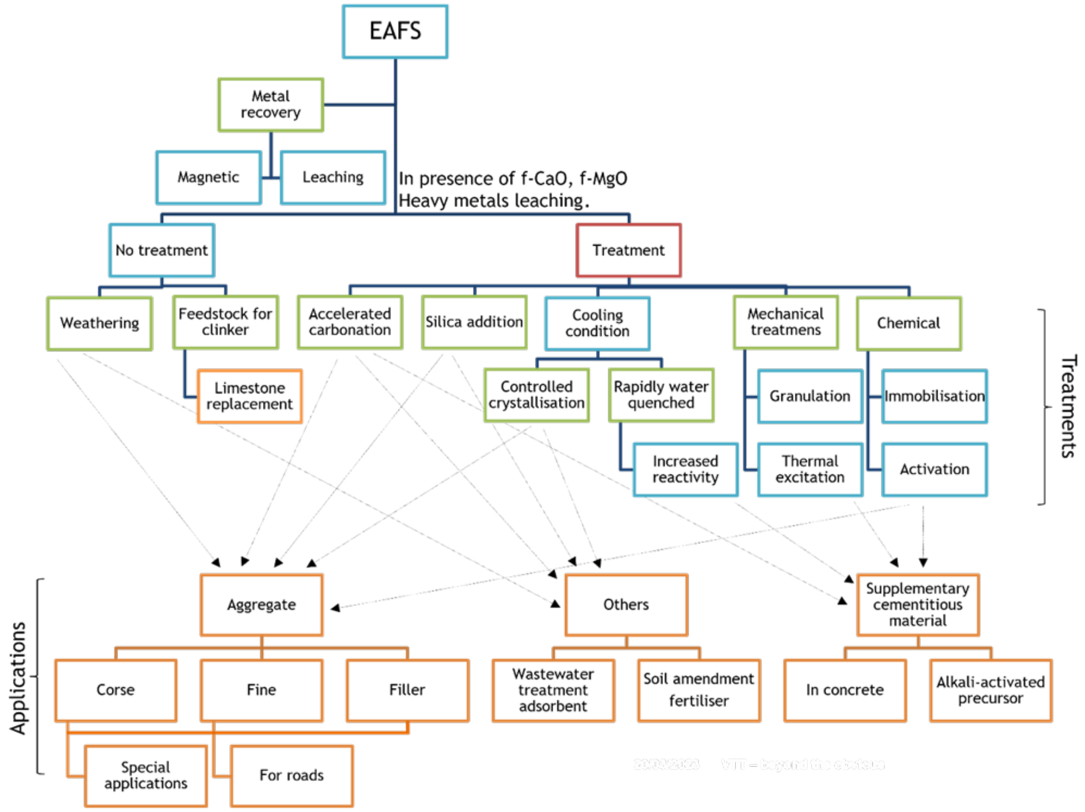

Figure 3 Process routes for different EAFS applications including aggregates and supplementary cementitious material among other applications. These routes incorporate typically EAFS treatments which can be, for example, granulation, chemical activation or accelerated carbonation depending on the application.

2.2.4 General characteristics of EAF slag

Chemical and mineralogical qualities of EAFS are affected by several factors, including the composition of the raw materials used in the steelmaking process, the additives and fluxes supplied, the targeted steel grade, furnace conditions, and cooling rate. However, some common and generic traits can be identified, which are summarized in Table 1.

Slag is often a black, rough irregular rock with densities ranging from 3 to 3.9 g/cm^3, which is greater than natural aggregates on average. EAFS also has high abrasion and corrosion resistance. CaO, Fe_2O_3, FeO, SiO_2, and Al_2O_3 make up most of the composition, with tiny amounts of MnO, MgO, P_2O_5, and possibly traces of Cr or other heavy metals. Calcium silicates, aluminosilicates, aluminoferriters, and RO phases (solid solution of CaO, MgO, SiO_2, and MnO) are organised in complexes. CaO content ranges from 40 to 55%, with SiO_2 content ranging from 12 to 28%. The Fe content varies more substantially.

Table 1 General characteristics and corresponding application for steel slags. Adapted from [54].

General characteristics	Suitable application
Hardness, wear and abrasion resistance, adhesive, rough	Aggregates for concrete, road, hydraulic construction and specific application
Porosity, high surface area, alkalinity	Wastewater treatment, absorbent
Metallic Fe, Fe components, FeO_x, other metals	Iron reclamation metal extraction
CaO, MgO, FeO, MgO, MnO	Fluxing agent
Hydraulic/cementitious phases C_3S, C_2S, C_4AF	Supplementary cementitious material
CaO, MgO components	CO_2 capture and flue gas desulfurization
FeO, CaO, $SiO\text{-}_2$ components	Feedstock for clinker production
Fertiliser component (P_2O_5, CaO, MgO, SiO_2, Fe oxides and other micronutrients)	Fertiliser and soil amendment

3 Methods for environmental slag data collection

This chapter describes the methods used to collect environmental data for EAFS and its potential applications. The data collection is based on a literature review of the hydrogen-based DRI-EAF process and the end products of EAFS presented in Chapter 3.1. The next subchapter, Chapter 3.2, summarises the reviewed literature while Chapter 3.3 explores the finding of the literature review.

3.1 Slag data collection

Different data requirements, including factors such as age and technology, can be applied in LCA studies, as outlined in ISO 14044:2006 [2]. This environmental data collection primarily focuses on the slag from hydrogen-based DRI-EAF process. Additionally, data pertaining to slag from the scrap-based EAF process has been included in the data collection process.

The environmental data requirements are determined by the system boundary, which outlines the process steps. Each sub-process necessitates data on the INPUT side, including raw material inputs, fuels, electricity, heat demand, and the need for other consumables. On the OUTPUT side, sub-processes involve data on products, by-products, and emissions to water, air, and solid waste. Figure 4 illustrates the data needs for EAFS. There were no specific age or geographical requirements defined.

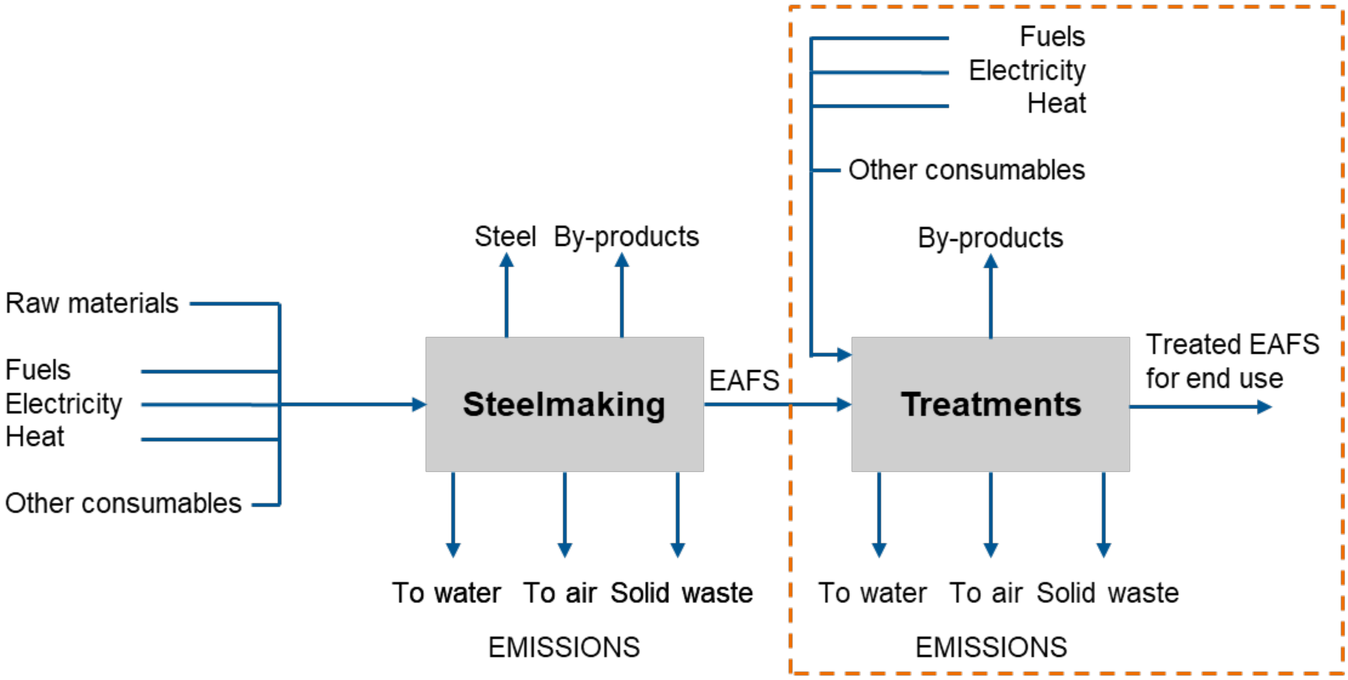

Figure 4 Simplified illustration of the data requirements.

The data collection was started by conducting a literature review of the steelmaking process, hydrogen-based DRI-EAF, using Scopus. The search string was chosen to: (LCA OR "life cycle" OR "life-cycle" OR "environmental impacts" OR "carbon footprint") AND ((DRI OR "direct reduced" OR "direct reduction") AND hydrogen) OR HDRI OR "H-DR" OR "H-DRI"). This search led to 43 results. Additional literature was gathered from the findings of the literature review. Next, the literature review regarding the end products was performed using Scopus. The search string was selected to: ("EAF slag" OR "electric arc furnace slag" OR EAFS OR "EAF steel slag") AND (LCA OR "life cycle" OR "life-cycle" OR environmental OR sustainability). The number of results obtained with the search string was 276. Additionally, the same search string was used to conduct a literature review using EBSCO which led to 27 results. All the results were screened, and duplicates with the literature not considering LCA or environmental impacts of the steelmaking process or EAFS were excluded. Additionally, only literature available in English and accessible sources were considered.

3.2 Environmental studies reviewed

A total of 22 studies were included in the literature review regarding the environmental studies of EAFS applications. These studies are summarised in Table 2. Most of the studies (20) applied EAFS as aggregates, while only one employed EAFS as a geopolymer binder, and another study use it as a precursor in alkali activated concrete. It is worth noting that the EAFS utilized in these studies is assumed to originate from scrap-based EAF steelmaking process instead of DRI-EAF process, as the latter was not discussed or mentioned in the studies.

Table 2 Characteristics of the EAFS application environmental studies.

Study	Year	Country	Focus	EAFS application	Use case	Burden allocated to EAFS
[55]	2023	Switzerland	Mechanical performance and LCA	Aggregates	Semi-dense asphalt	No
[56]	2023	Italy	Mechanical performance and LCA	Aggregates	Porous asphalt	Unclear
[57]	2022	Singapore	Carbon footprint	Aggregates	Asphalt	No
[58]	2022	Vietnam	Leaching	Aggregates	Road construction	n.a.
[59]	2022	Slovenia	Mechanical performance and LCA	Aggregates	Mass concrete	No
[60]	2021	Spain	Characterisation and LCA	Aggregates	Bituminous mixtures	No
[61]	2021	Iran	Mechanical performance and environmental analysis	Aggregates	Alkali-activated slag (GGBFS) concrete	Unclear
[62]	2021	Greece	LCA	Aggregates	Warm mix asphalt	Unclear
[63]	2021	Portugal	Sustainability assessment	Precursor	Alkali-activated concrete	No
[64]	2020	Thailand	Economic feasibility and LCA	Binder	Geopolymer	No
[65]	2020	Spain/USA	LCA	Aggregates	Asphalt	No
[66]	2020	Italy	Mechanical performance and LCA	Aggregates	Hot mix asphalt	No

Continued on next page

Table 2 Characteristics of the EAFS application environmental studies. (Continued)

Study	Year	Country	Focus	EAFS application	Use case	Burden allocated to EAFS
[67]	2020	Spain	Mechanical and economic feasibility, and LCA	Aggregates	Porous asphalt	Unclear
[68]	2020	Spain	Particle packing models (PPMs), LCA and economic assessment	Aggregates	Railway concrete	No
[69]	2018	Republic of Korea	Simplified LCA	Aggregates	Concrete	No
[70]	2017	Greece	LCA and economic assessment	Aggregates	Industrial concrete pavements, heavyweight concrete and pervious concrete paving blocks	No
[71]	2017	Greece	Mechanical performance, LCA and economic assessment	Aggregates	Industrial concrete pavements, heavyweight concrete and concrete paving blocks	No
[72]	2017	Brazil	LCA	Aggregates	Concrete paving blocks	No
[73]	2016	Spain	LCA and field tests	Aggregates	Railway track bed	Unclear
[74]	2016	Spain	LCA	Aggregates	Bituminous mixture	No
[75]	2014	Italy	LCA	Aggregates	Concrete	No
[76]	2011	Slovenia	Leaching	Aggregates	Asphalt	n.a.

In addition to the EAFS application studies, environmental studies regarding the hydrogen-based DRI-EAF process were also screened. Only a total of 5 studies were found and included in this review. Table 3 presents these studies.

Table 3 Characteristics of the steelmaking environmental studies.

Study	Year	Country	Focus	Steelmaking process	Burden allocated to EAFS
[77]	2023	China	LCA	DRI-EAF, BF-BOF, scrap-based EAF	No
[78]	2023	Germany	LCA	DRI-EAF	No
[79]	2023	Switzerland/Brazil	LCA	DRI-EAF, BF-BOF	No
[80]	2022	China	Thermodynamic performance and LCA	DRI-EAF	No
[81]	2022	Germany	LCA	DRI-EAF	No

3.3 Slag environmental data

This chapter presents the findings of the literature review. Chapters 3.4.1 and 3.4.2 summarize the literature on EAFS applications and steelmaking, respectively, while Chapter 3.4.3 investigates the system boundary and allocation methods applied in the studies. Chapter 3.4.4 provides the material and energy data, and environmental impacts analysed in the reviewed literature. Next, leaching data is provided in Chapter 3.4.5 for EAFS and its end products.

3.3.1 EAF slag applications literature

This section summarizes the main findings of the literature review on the environmental impacts of using EAFS in various applications, such as asphalt, concrete, and geopolymer. The literature applied different impact categories to assess the benefits and drawbacks of EAFS utilization.

Several studies in the literature investigated the environmental impacts of employing EAFS as aggregates in bituminous mixtures. Esther et al. [65] conducted a study of environmental impacts of using EAFS as coarse aggregates in asphalt mixtures. The bitumen production accounted up to 79% of the total impact in damage to resource availability (RA). In contrast, the production of asphalt mixtures notably contributed to the impacts on human health (HH) and ecosystem diversity (ED), with the environmental impacts being significantly influenced by the slag's absorption rate. Namely a higher rate results in increased bitumen content and aggregate moisture.

In the study conducted by Mikhailenko et al. [55], EAFS was employed as a substitute for sandstone aggregates in semi-dense asphalt used in the wearing course, replacing 13% of the total aggregate volume. The use of EAFS led to a 40% and 90% reduction in GHG emissions and ecological scarcity eco-points, respectively, compared to the reference mixture with sandstone aggregates. These reductions were primarily due to avoiding EAFS landfilling, which requires cement (in Switzerland). However, the use of EAFS aggregates did not result in a reduction of the non-renewable cumulative energy demand (CED) due to the increased bitumen content necessitated by higher water absorption. The requirement related to bitumen content corresponds to the claim by Esther et al. [65].

Loi et al. [57] also focused on asphalt wearing course and analysed the carbon footprint of locally produced EAFS aggregates used for the course. Based on the results, EAFS aggregates had a 29% lower carbon footprint than natural granite aggregates, with diesel for EAFS handling being responsible for about half of the CO_2 emissions. The total CO_2 equivalent emissions were 11.01 kg for ton of EAFS aggregates. The difference in the carbon footprints was mainly due to the significant emissions related to transporting granite. The study also remarked that employing EAFS diminishes the need of landfill disposal and resource depletion.

Ferreira et al. [74] studied the influence of avoided landfill and raw material consumption, in the study related to a similar application. The results indicated that the environmental impacts were reduced in all the considered impact categories due to the avoided landfill and raw material consumption. Additionally, the total impacts were mainly reduced except for abiotic depletion, ozone layer depletion and photochemical oxidation because of higher bitumen content when compared to a traditional mixture. The relative contribution of bitumen was between 40 and 90% of total impact in all the categories considered. Bitumen also had the highest energy demand.

Bonoli et al. [66] studied the incorporation of EAFS and reclaimed asphalt pavement in hot mix asphalt for both the wearing and binder courses. They observed decreases of 39% and 38% in the global warming potential (GWP) for the wearing and binder courses, respectively. Total impacts were also significantly reduced in all the other analysed impact categories. The environmental benefits were attributed to the reduced demand for fresh bitumen and natural aggregates, resulting in avoided impacts.

Terrones-Saeta et al. [60] focused on the environmental impacts of processing EAFS to be employed as aggregates in bituminous mixtures. The results showed that the total CO_2 equivalent emissions were 4.2 kg for 1 ton of EAFS aggregates, resulting in a 30% reduction compared to those of natural siliceous aggregates. This was primarily attributed to the absence of upstream emissions related to the extraction and landscape alteration. However, the slightly more complex processing of EAFS and higher density led to higher CO_2 emissions associated with the aggregate processing and transport stages, respectively. Despite this, the EAFS processing exhibited lower emissions across all assessed impact categories when compared to natural aggregates, with the most significant reductions observed in acidification emissions, followed by freshwater aquatic ecotoxicity and human toxicity.

Georgiou et al. [62] analysed the environmental impacts of warm mix asphalt containing EAFS and reclaimed asphalt, comparing it to traditional hot mix asphalt. Utilizing only the slag maintained CO_2 emissions on the same level while offering benefits in some categories, such as PM10, but increased SO_2, CO, and hazardous waste (HWG) burdens due to the high density of the slag. Material production and transportation were the main contributors. Shorter delivery distance of the EAFS aggregates was also found to enhance environmental benefits. Using reclaimed asphalt and increasing its content enhanced benefits across all considered impact categories and reduced CO_2 emissions by up to 33% due to reduced material transport, and the use of virgin aggregates and bitumen. However, the warm mix technology had no significant effect on the environmental benefits.

A similar application was also studied by Rodríguez-Fernández et al. [67], focusing on porous asphalt mixtures where natural aggregates were replaced with EAFS and reclaimed asphalt pavement. Additionally, a nano-modified binder and warm mix asphalt technology were applied. The results were compared to hot mix asphalt containing traditional bitumen and EAFS and reclaimed asphalt pavement as aggregates. The decrease in manufacturing temperature due to the warm mix asphalt technology reduced the impacts in resource availability, human health, and ecosystem diversity by 1.0%, 2.9%, and 3.3%, respectively, when only the wearing courses without service life extension were considered. This result aligns with the findings of Georgiou et al. [62]. Regarding the whole pavement, applying warm mix asphalt technology provides environmental benefits in all the three impact categories even if the service life is slightly (1.4%) reduced. On the other hand, applying nanotechnology also necessitated an extension of service life to achieve environmental benefits. However, based on calculated service lives, at least 12% reductions in the impacts can be achieved with the nano-modified binder.

The use of EAFS aggregates in porous asphalt mixtures has also been studied by De Pascale et al. [56]. The utilization of the slag led to an 8% reduction in the global warming impact, and similar benefits were observed across all the other environmental impact categories analysed. Burdens were further reduced (up to 25%) with the addition of reclaimed asphalt pavement. The additional benefits were associated to the reduced demand for bitumen. Namely, bitumen production and transportation of raw materials emerged as major contributors to the environmental impacts while the slag had negligible contribution. Based on normalization, human carcinogenic toxicity related to transportation, and thus also the human health category, had the greatest impact.

Employing EAFS aggregates in concrete has also been addressed in several studies. Kvočka et al. [59] examined the environmental impacts of mass concrete with EAFS aggregates partially substituting natural ones. Cement emerged as the major contributor to the impacts, accounting for 30–95% of the impacts across most of the categories. Additionally, metal recovery and transportation also had significant contributions (up to 10–20%). The EAFS based concrete had lower or similar impacts compared to that of the concrete with only natural aggregates. Reductions were observed especially in freshwater aquatic ecotoxicity potential (FAETP), ozone depletion potential (ODP), and terrestrial ecotoxicity potential (TETP) impact categories mainly due to the avoided pig iron production and landfilling with the aggregate type having less influence.

García-Cortés [68] also investigated the impacts of employing EAFS as coarse aggregates in concrete. The GWP of processing one ton of EAFS aggregates was determined to be 4.22 kg CO2-eq with transportation to the treatment plant included, and 2.43 kg CO_2-eq without it. Hence, the environmental impacts were lower than those of natural aggregates only when the transportation was excluded. However, the impacts of EAFS based concrete were similar or lower than that of concrete with only natural aggregates when the compressive strength was included in the analysis. Cement was revealed to have the most significant impact on all relevant impact categories while the primary contribution of EAFS aggregates was identified in the emission of particulate matter (PM), constituting 20% of the total impact. Considering the avoided landfilling also resulted in negative impacts across all relevant impact categories, mirroring observations made with asphalt mixtures [74].

Anastasiou et al. [70] and Liapis et al. [71] studied, instead, different concrete applications utilizing EAFS aggregates. These applications included industrial pavements, heavyweight concrete and pervious concrete paving blocks. Compared to the global warming impacts of traditional concretes with natural aggregates, the impact decreased by 14% for pervious paving blocks and by 44% for heavyweight concrete, respectively. Meanwhile, for industrial pavements, the impact remained similar. Material production, primary cement, was found to be the main source of the CO_2 emissions in all the cases. Hence, potential emission reductions were identified through adjustments in cement content.

Evangelista et al. [72] analysed the environmental impacts of using EAFS as coarse aggregates in concrete paving blocks, substituting 50% of the natural aggregates. Regarding the treatments for EAFS, metal recovery accounted for 84% of the negative impacts present in all the considered categories due to avoided pig iron production. The avoided impacts associated to the landfilling were not as significant due to the classification of EAFS waste as non-hazardous. In paving block production, cement production was identified as the main contributor to all environmental impacts, expect to terrestrial ecotoxicity which was mostly contributed by natural aggregates. The utilization of EAFS led to a reduction of 52% in the total impacts compared to the traditional concrete with natural aggregates. Additionally, the use of EAFS was found to be environmentally beneficial regardless of long transport distances.

Faleschini et al. [75] examined applying EAFS as medium and coarse aggregates in concrete. The climate change impact for processing one ton of EAFS aggregates amounted to 3.09 kg CO_2-eq., demonstrating a 63% reduction compared to the processing of natural aggregates. Overall, emissions from EAFS treatments across various categories were found to be 39–97% lower compared to that of natural aggregates. However, compared to traditional concrete with only natural aggregates, concrete based on EAFS had a greater impact on climate change (2.92%) and eutrophication (4.71%). The increased emissions were due to the need for more cement, attributed to a smaller maximum aggregate diameter, with cement being the primary contributor to emissions. However, the impact on acidification was reduced by 1.62%. The authors suggested considering the mechanical properties of concrete when determining the functional unit, as these properties can be enhanced by utilizing slag aggregates.

The use of EAFS in railway application has also been explored. Lee et al. [69] investigated the greenhouse gas emissions of railway concrete sleepers made with alternative materials, including EAFS and ground granulated blast furnace (GGBF) slag. The utilization of the slags reduced the GWP of a sleeper by 11.1 kg CO_2-equivalent, compared to a traditional one. This reduction was mainly due to the fact 23% less cement was required in the concrete mixture. Additionally, Morata et al. [73] analysed the environmental impacts of SFS-Rail which is a new aggregate made of EAFS for railway subballast and subgrade layers.

The results showed significant environmental benefits for the subballast layer utilizing SFS-Rail, including a 45% reduction in GWP and even a 193% reduction in human toxicity potential compared to the layer with only natural aggregates. The reductions in acidification and eutrophication potentials were 44% and 9%, respectively. Mention was made that using SFS-Rail offers even greater benefits when the valorisation plant is near the construction site. This proximity reduces the environmental impact of road transport, which significantly affects global warming, acidification, and eutrophication potentials. SFS-Rail was also found to enable thinner sub-layers, reducing the need for natural aggregates and transportation and thus lowering environmental impacts.

In addition to the environmental impacts of bituminous mixtures, concrete and railway applications, the impacts of alkali activated materials employing EAFS has been analysed. However, only a few studies were found. Amani et al. [61] investigated the CO_2 emissions of utilizing EAFS as fine and coarse aggregates in alkali activated slag concrete with low fineness GGBF slag. Based on the results, the equivalent CO_2 emissions were roughly 50% lower for the alkali activated concrete compared to Ordinary Portland cement concrete (OPCC). The use of EAFS as coarse aggregates instead of coarse natural aggregates provided a slight further reduction on the emissions with the most significant impact on the reduction stemming from the use of GGBF slag. Contrary, the use of EAFS as fine aggregates led to an increase in the emissions compared to that of alkali activated concrete utilizing only natural aggregates. The emissions for both the fine and coarse EAFS aggregates were mentioned to be 3.09 kg CO_2-eq/t.

Hafez et al. [63] focused on alkali-activated concrete employing EAFS as a precursor with fly ash. Hence, unlike in the studies addressed above, EAFS was not employed as aggregates. The environmental impacts of the concrete were studied using a concrete sustainability assessment framework, called ECO_2, which combines environmental and economic impacts. Replacing fly ash with EAFS resulted in a more environmentally friendly binder as the GWP of EAFS (3.11 kg CO_2-eq /t) was significantly lower along with other impacts compared to fly ash. Environmental impacts were also contributed to by sodium hydroxide and superplasticizer, while transportation had only a minimal influence. However, considering the durability of the concrete, mixtures incorporating EAFS demonstrated nearly a twofold increase in environmental impacts. The durability was affected by the lack of an ideal activator, sodium silicate, the addition of which on the other hand would have increased the impacts.

In addition, Apithanyasai et al. [64] examined the utilization of EAFS with fly ash as raw materials for binder in geopolymer bricks. Based on the LCA, alkaline solution and material preparation processes had the biggest contributions to the environmental impacts of the bricks. Geopolymer bricks were found to offer environmental benefits over traditional bricks, attributed to the absence of cement. This absence led to lower impacts, with a reduction in GWP by up to 99%. The contribution of EAFS to the impacts was not specified in the study.

As a summary, substitution of natural materials by EAFS has found following benefits:

- avoided landfill and raw material production;
- GHG emissions and ecological scarcity eco-points;
- shorter delivery distance of the EAFS;
- less cement was required in the concrete mixture;
- possible to use in alkali activated materials, also as a precursor and binder;
- replacing fly ash with EAFS in alkali-activated materials;
- potential metal recovery.

Considering the mechanical properties in functional unit may further improve the environmental benefits. Additionally, the identification of cement as the primary contributor to environmental consequences in concrete applications offers a potential for beneficial environmental outcomes via cement alternatives, which might be provided by EAFS. Prioritising research and development in this area can result in substantial breakthroughs in the manufacturing of sustainable concrete. However, shortcomings for slag use have been revealed as well. These included increased SO_2 and CO and hazardous waste burdens.

3.3.2 Steelmaking literature

The production of steel via hydrogen-based DRI-EAF has been examined in a few LCA studies. These studies have compared different steelmaking routes and evaluated the environmental impacts of hydrogen-based DRI-EAF under different scenarios.

Ren et al. [77] compared different steelmaking routes, including conventional routes, and hydrogen and fossil fuel based DRI-EAF routes. The study revealed that the hydrogen supply chain vigorously influences the emissions of the steelmaking process, indicating that the emission intensity of the supply chain should be under 200 g CO_2-eq/MJ to make hydrogen-based DRI-EAF equivalent to other routes. With pure hydrogen, the emission intensity of DRI-EAF totalled 950.4 kg CO_2-eq/t crude steel being 60% lower than that of conventional BF-BOF route.

Similarly, Graupner et al. [78] investigated the GHG emissions from the hydrogen-based DRI-EAF process, where hydrogen was produced via polymer electrolyte membrane (PEM) electrolysis. This study considered electricity from the German grid mix and onshore wind turbines as sources for the years 2025 to 2040. The results revealed a strong connection between greenhouse gas emissions and the electricity mix. Based on different scenarios, the production of one ton of crude steel could result in emissions ranging from 0.39 to 1.24 and 0.38 to 0.61 t CO_2-eq in 2040 when hydrogen is produced with electricity from grid mix and wind turbines, respectively. Employing natural gas for direct reduction (DR) was found to be environmentally feasible only in short term.

Suer et al. [81] also studied the anticipated carbon footprint for steel produced via hydrogen-based DRI-EAF. Projections for the year 2040 indicate a carbon footprint of 0.75 t CO_2-equivalent per ton of steel, based on the electricity mix in a European sustainable development scenario. This result agrees with Graupner et al. [78]. Suer et al. [81] also stated that the contribution of steel production was negligible, while the upstream processes, including iron ore pellets and hydrogen production, caused most of the emissions. Regarding the carbon footprint, the use of hydrogen instead of natural gas was predicted to be beneficial by 2030 which also supports the findings of Graupner et al. [78]. The energy requirement was found to be 4.9 kWh/kg steel with even 88% of the energy consumed in the electrolysis.

The type of hydrogen used for hydrogen-based DRI-EAF can also affect the carbon footprint of the steel production. Souza et al. [79] used LCA to compare the carbon footprints of steel produced via hydrogen-based DRI-EAF processes utilizing both 'blue' and 'green' hydrogen. The results revealed that considering upstream methane emissions is crucial when evaluating the carbon footprint. Considering the steelmaking with stoichiometric amount of blue hydrogen, the carbon footprint increased from 740 kg CO_2-eq/t liquid steel up to 1710 kg CO_2-eq/t liquid steel when the upstream methane emissions were included in the analysis. Instead, the carbon footprint of the steel produced utilizing green hydrogen remained under 600 kg CO_2-eq/t liquid steel in all cases. Additionally, the carbon footprint of this steel was not affected by the amount of hydrogen used in the reduction unlike that of steel produced using the blue hydrogen.

Li et al. [80] conducted LCA for hydrogen-based DRI-EAF process employing a shaft furnace in the reduction and coal gasification for hydrogen production. The LCA showed that the total environmental impact amounted to 2.25E-11 being 73% lower than that of BF-BOF process. Most environmental impacts stemmed from hydrogen production, EAF, and the heating process, collectively exceeding 90% of the total impacts. The CO_2 emissions and the energy consumption totalled 1079.56 kg and 9.08 GJ/t, respectively, for one ton of crude steel.

In conclusion, the LCA studies showed that hydrogen-based DRI-EAF can be a viable option for low-carbon steel production. However, the environmental performance of the process is significantly affected by the selection of the hydrogen source, the electricity mix, and the upstream processes. The studies revealed that the CO_2 emissions of hydrogen-based DRI-EAF can range significantly depending on these factors.

3.3.3 System boundary and allocation

The analysis of the system boundary mainly focused on the end products of EAFS. Consequently, it was of interest whether the slag contained allocated burden from the steelmaking in environmental impact assessments. Regarding the studies on the end products, in 15 studies no burden from steelmaking was allocated to EAFS while in five studies the allocation decision remained unclear. Figure 5 shows the typical system boundary used in the studies. A few inspections were also conducted from the raw material perspective, thereby involving the examination of the allocation in steelmaking LCAs. According to the literature review, none of the five LCA studies on hydrogen-based DRI-EAF assigned any burden to EAFS.

Steelmaking LCA guidelines on the other hand give alternatives how to allocate steel making process burden to the by-products such as EAF slag. The final report of The Net-Zero Steel Pathway Methodology Project (NZSPMP) [4] advocated accounting the environmental burden reductions arising from employing the by-products. For accounting reductions in LCA, the report recommended applying system expansion, wherein credits are awarded based on the avoided production resulting from the use of EAF slag. The report found that using the slag as aggregates avoids gravel production while adopting one ton of slag for fertilizer avoids 0.5 tons of lime production. Instead, employing the slag in cement and clinker production was stated to avoid one ton of Portland cement production. Alternatively, allocating burden from steelmaking to slag could be performed based on a physical criteria or commercial values.

Regarding the end product LCA studies, only Bonoli et al. [66] and Ferreira et al. [74] included the avoided production of natural aggregates in their assessment. Esther et al. [65] explored this option but decided not to adopt it, as explained below. However, the literature also considered other avoided processes. Avoided landfilling of the slag and pig iron production associated with the metal recovery were comprised in six and two environmental assessments, respectively.

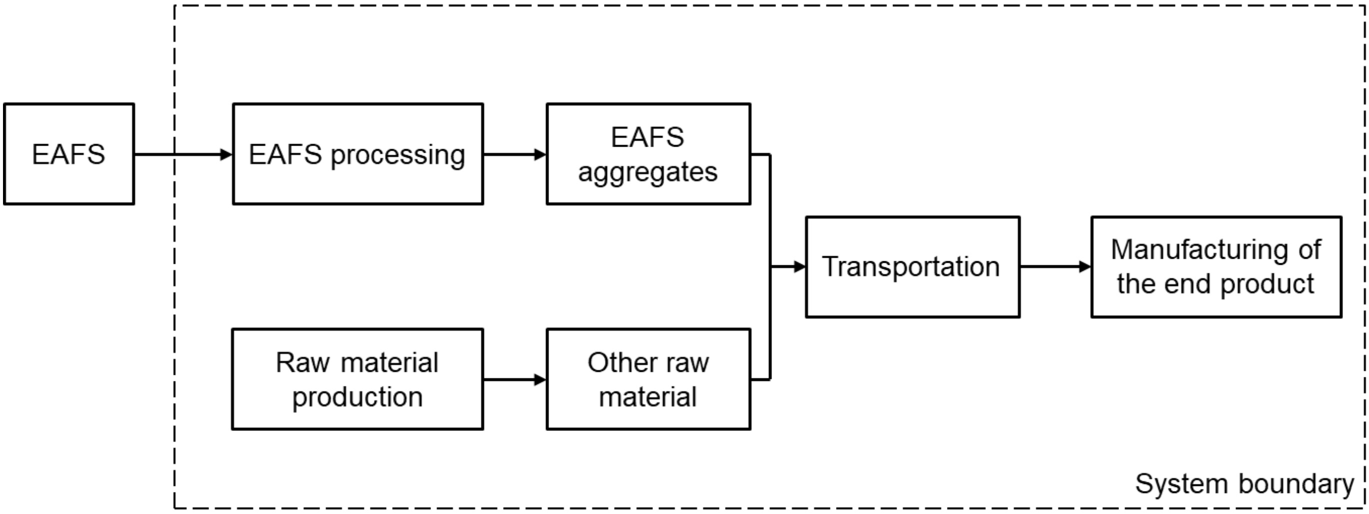

Figure 5 Typical system boundary in the LCA studies of the end products.

The literature discussed several reasons for not allocating the burden from the steelmaking to the EAFS. These will be explored next.

Esther et al. [65] examined four different allocation methods to determine the environmental impacts of EAFS used as aggregates in asphalt mixtures. In the first alternative, part of the impacts from steel production were allocated to the EAFS in addition to the impacts of slag treatment. This was performed combining the mass and economic values, resulting in a 0.23% attribution of the steel production impact. Instead, the second option considered only the impacts of the slag treatment, treating EAFS as a waste. In the third option, system expansion was used to also include the avoided impacts of not extracting natural aggregates. In the final option, 50/50 method was used to divide the avoided impacts and the impacts of the slag treatment between steel and the slag while considering the mass balance. Based on the results, the most beneficial and least favourable allocation methods varied between different impacts. However, the second allocation considering only the impacts from the slag treatment option always fell in the middle position compared to the other allocation methods. Additionally, this option was said to ensure the conservation of mass and avoid the challenges of distributing the credits. Hence, Esther et al. [65] selected the option considering only the impacts from the slag treatment for further examinations.

Loi et al. [57] also focused on asphalt mixtures and compared the environmental impacts of EAFS aggregates with those of naturally occurring materials. Allocating burden from steelmaking would have led to an unfair comparison between the environmental impacts of the materials, as the inherent embodied energy in natural materials cannot be quantified. Liapis et al. [71], instead, conducted a LCA study of different concrete products utilizing EAFS and opted not to allocate burden from the steelmaking process based on previous research [82]. This research has indicated that applying economic allocation for EAFS can lead to only minimal increase (up to 0.005%) in the total impacts of the life cycle. In addition, Evangelista et al. [72] stated that employing mass allocation would yield elevated emission values in comparison to those associated with natural aggregates due to the high emissions of steel. Burchart-Korol [83] applied the mass allocation considering scrap-based EAF steelmaking. As a result, 147 kg of CO_2-eq was allocated for EAFS in the production of one ton of cast steel, resulting in a CO_2-eq burden of 765 kg per ton of EAFS. As a comparison, Terrones-Saeta et al. [60] stated that CO_2-eq emissions for one ton of natural siliceous aggregates amounted to only 6.043 kg.

The NZSPMP report [4] guidelines were adhered to in hydrogen-based DRI-EAF LCA studies, unlike in the end product studies. Graupner et al. [78] and Suer et al. [81] both applied system expansion and considered credits for by-products, such as EAFS. However, the avoided productions were not described in these studies. Instead, Ren et al. [77] identified the avoided productions as cement, lime and natural aggregates productions since EAF slag was specified to be employed in cement and clinker production, fertilizers, and as aggregates, respectively.

This chapter examined the system boundary and allocation issues in the LCA studies of EAFS applications. Generally, these LCA studies did not allocate any burden from the steelmaking process to the EAFS, treating it as a waste or a free resource. The allocation of steelmaking environmental impacts to EAFS, may decrease the benefits of EAFS as substituting raw material compared to primary raw materials. This chapter also discussed the option of applying system expansion to account the environmental burden reductions associated with EAFS applications, as recommended by the guidelines. However, this method was not widely adopted in the EAFS application studies, contrary to the LCA studies regarding DRI-EAF steelmaking. Overall, there is a need for more consistent and transparent methods for defining the system boundary and allocation in LCA studies of EAFS applications.

3.3.4 Material streams, energy need and environmental impacts

This report focused on data collection regarding hydrogen-based DRI-EAF process and EAFS applications. This subchapter presents mainly the most reported data from the reviewed studies. Corresponding data with different units than in the summarizing Table 4, Table 5 and Table 6 were not included in the tables. Consequently, only part of the collected data from the reviewed literature is presented in this Chapter. The completeness and availability of the data varied significantly in the studies. As different system boundaries and allocation methods were applied in the studies, the data might not be comparable.

Table 4 shows the material flows in the steelmaking, EAFS treatments and in the manufacturing of different applications. The number of extracted metals had a substantial variation being 8–330 kg/t EAFS aggregates. The number of extracted metals can be crucial if avoided pig iron production is considered in LCA studies. Namely, the avoided production may bring benefits in several environmental impact categories as Chapter 3.4.1 revealed. Table 4 also indicates that up to 117 kg of EAFS is produced in the production of 1 ton of steel. The density and water absorption of EAFS were 3.0–3.9 g/cm^3 and 0.6–4.7%, respectively, according to several studies [55,56,59,61,65,67,71,72,75].

Table 4 Material streams regarding hydrogen based DRI-EAF process, EAFS treatments and the manufacturing of the end products.

Process	Input		Output		Study
DR	Iron pellets	0.45–1.5 t/t steel	DRI/sponge iron	306–911 kg/t steel	[78–81]
	Hydrogen	54–80 kg/t DRI			
EAF	DRI/sponge iron	306–911 kg/t steel	EAFS	71–117 kg/t steel	[78,80]
	Scrap	161–714 kg/t steel	Steel	1 t	
	Coal/coke	10–13.8 kg/t steel			
Treating EAFS into aggregates	Lubrication oil	0.02 kg/t EAFS aggregates	Metals	8–330 kg/t EAFS aggregates	[55,59,72,75]
	Water	0.25 m^3/ t EAFS aggregates			
Concrete production	EAFS aggregates	1183–2490 kg/m^3 concrete	Concrete	1 m^3	[59,68,70,75]
	Cement	260–370 kg/m^3 concrete			
	Plasticizer	0.9–7.5 kg/m^3 concrete			
	Natural aggregates	335–994 kg/m^3 concrete			
	Water	90–227 kg/m^3 concrete			

Continued on next page

Table 4 Material streams in hydrogen based DRI-EAF process, EAFS treatments and in the manufacturing of the end products. (Continued)

Process	**Input**		**Output**		**Study**
Alkali-activated concrete production	Fly ash	142–150 kg/m^3 concrete	Alkali-activated concrete	1 m^3	[63]
	EAFS	158–167 kg/m^3 concrete			
	Plasticizer	0–5 kg/m^3 concrete			
	Water	104–155 kg/m^3 concrete			
	NaOH	39–41 kg/m^3 concrete			
	Sand (0–1 mm)	251-265 kg/m^3 concrete			
	Sand (0–4 mm)	581-613 kg/m^3 concrete			
	Sand–Gravel (2–5.6 mm)	165-174 kg/m^3 concrete			
	Gravel (5.6–11.2 mm)	275-290 kg/m^3 concrete			
	Gravel (10–20 mm)	659-696 kg/m^3 concrete			
Bituminous mixtures production	EAFS	14–80 wt%			[55,56,65,67]
	Bitumen	3.3–6.89 wt%			
	Natural aggregates	2-76.4 wt%			
	Filler	2.4–6.7 wt%			
	Reclaimed asphalt pavement	14–33 wt%			

Table 5 shows the energy needs in steelmaking, EAFS treatments and in manufacturing of the end products. Most information was available on treating EAFS into aggregates. The electricity and diesel required for treating EAFS into aggregates were 0.5–22 kWh and 0.16–6.8 L per ton of EAFS aggregates. Table 5 also indicates the immense amount of electricity needed in hydrogen production, emphasizing the significance of green electricity.

Table 5 Energy needs in hydrogen-based DRI-EAF process, in EAFS treatments and in the manufacturing of the end products.

Process	Energy	Amount	Study
Hydrogen production by electrolysis	Electricity	4.2 MWh/t steel	[81]
DR	Electricity	5.9 kWh/t steel	[80]
	Natural gas	14.3 m^3/t steel	
EAF	Electricity	471–524 kWh/t steel	[78,80]
Treating EAFS into aggregates	Electricity	0.5–22 kWh/t EAFS aggregates	[55,59,68,72]
	Diesel	0.16–6.8 L/t EAFS aggregates	
Treating EAFS into precursor	Electricity	83 kWh/t EAFS	[63]
Concrete production	Electricity	6.2 kWh/m^3 concrete	[59]
Alkali-activated concrete production	Electricity	40 kWh/m^3 concrete	[63]
Bituminous mixtures production	Electricity	7.2–10.9 kWh/t mixture	[55,65]
	Diesel	6.5–9.8 MJ/t mixture	
	Natural gas	183.3–277.6 MJ/t mixture	

Environmental impacts of hydrogen-based DRI-EAF, EAFS treatments and manufacturing of the different end products were also collected from the reviewed literature. Table 6 presents some of the impacts covered in the literature. The table shows that only global warming potential was available for hydrogen based DRI-EAF process and alkali-activated concrete production.

Table 6 Environmental impacts of hydrogen-based DRI-EAF, in EAFS treatments and in manufacturing of the end products.

Process	Global warming CO_2-eq	Eutrophication PO_4-eq	Acidification SO_2-eq	Study
DRI-EAF including hydrogen production	0.24–2.28 t/t steel	–	–	[77–79,81]
Treating EAFS into aggregates	3.09–11.02 kg/t EAFS aggregates	0.0017–0.007 kg/t EAFS aggregates	0.019–0.020 kg/t EAFS aggregates	[57,60,68,75]
Treating EAFS into precursor	3.11 kg/t EAFS	0.009 kg/t EAFS	0.0 kg/t EAFS	[63]
Concrete production	185–503 kg/m^3 concrete	0.068 kg/m^3 concrete	0.45 kg/m^3 concrete	[68,70,75]
Alkali-activated concrete production	73.2–85.3 kg/m^3 concrete	–	–	[63]
Asphalt production	16.6 kg/m^2 asphalt	0.029 kg/m^2 asphalt	0.15 kg/m^2 asphalt	[74]

3.3.5 Leaching of metals and toxic substances

The collected standards related to leaching include the BS EN 12457-2 leaching test [84], the Toxic Characteristic Leaching Procedure (TLCP) method 1311 [85], and NEN 7345:1995 nl [86]. Literature on the leaching of elements from EAFS is reviewed in the following.

Nguyen et al. [58] studied the leaching of heavy metals from EAFS aggregates used in road construction. Two different standardized methods (US-EPA 1311 and JIS K 0058-1) were adopted and compared. Given the substantial impact of pH on leaching behaviour, it became evident that specific methods are better suited to certain conditions. Namely, JIS K 0058-1 was ideal to study the leachability in neutral conditions present in road construction. Additionally, the gentle agitation in this method prevented the reduction in particle size which also influences the leaching of metals. Leachates from JIS K 0058-1 method showed low metal concentrations, making EAFS safe for road construction after adjusting pH to neutral conditions.

Milačič et al. [76] performed leaching tests for EAFS and compact and ground asphalt in which natural aggregates were replaced by EAFS. In the tests both pure water and saltwater were used. Based on the results, the release of metals from asphalt mixtures was minimal. The study also revealed that chromium occurred primary in hexavalent form [Cr(VI)] in the leachates from the asphalt mixtures due to the alkalinity of the slag. However, the amounts of chromium were low, measuring less than 25 μgL^{-1} , which was notably less than the amounts in the leachates of EAFS. The presence of bitumen was found to decrease the occurrence of Cr(VI). Milačič et al. [76] also stated that its occurrence might be further reduced as the pH of the leachates could be somewhat decreased through carbonation over time. This, on the other hand, can lead to a higher release of vanadium.

Numeral other studies [64,65,72–75] also found that the leaching of metals and toxic substances from EAFS and EAFS based geopolymer and bituminous mixtures stayed below the limits set in different standards and does not cause a significant environmental risk. In bituminous mixtures, the bitumen prevents further leaching, according to Esther et al. [65] and Terrones-Saeta et al. [60]. However, normalization and weighting process can affect to the environmental impact of the leaching. Namely, Esther et al. [65] observed that the contribution of leaching from asphalt mixtures on the total impact was significant due to vanadium when the normalization and weighting process was applied.

As a conclusion, leaching tests for EAFS should consider the specific conditions of the application such as pH and agitation. EAFS has low leaching potential of heavy metals and toxic substances, especially when pH is adjusted to neutral conditions or when EAFS is mixed with bitumen.

4 Limitations

This report has some limitations that should be acknowledged. Firstly, the environmental data collection is based on a literature review that may not have covered all the relevant sources and studies. Therefore, some crucial information may have been inadvertently omitted. Secondly, the data collected from the literature may not be fully comparable or consistent due to differences in the system boundaries, allocation methods, slag treatments, and impact assessment methods used in the studies. For instance, some studies include the burden from steelmaking to the slag or consider the avoided impacts of landfilling and pig iron production while others do not.

Additionally, the environmental data collection is focused on the slag from hydrogen-based DRI-EAF process, which is a relatively new technology. Hence, the data availability and quality may be limited. Overall, the availability and completeness vary in the considered studies. Furthermore, the data pertaining to the EAFS from the scrap-based EAF process may not be representative or applicable for the EAFS from the DRI-EAF process, due to differences in the slag characteristics, for instance.

5 Conclusions

The main objective of this report was to gather and evaluate environmental data related to EAFS, a by-product of a steelmaking process, and its potential uses, as well as to identify data gaps and needs for LCA studies. The report concentrated on a novel process, hydrogen-based DRI-EAF, as the origin of EAFS. To accomplish the objective of the report, literature review was conducted.

EAFS was found to have various physical and chemical properties that influence its suitability for different applications. The slag may require treatments to enhance its cementitious activity, stabilize its volume, and reduce its heavy metal leaching. EAFS can be utilized in various applications, including asphalt, concrete, geopolymer, clinker production, wastewater treatment, and soil amendment. In reviewed studies, EAFS was utilized mostly as aggregates in bituminous mixtures and concrete applications. Only a few environmental impact assessments were conducted regarding other applications such as precursors in alkali activated materials.

The reviewed studies indicated that employing EAFS can provide environmental benefits in terms of reducing greenhouse gas emissions, energy consumption, resource depletion, and landfill disposal, compared to conventional materials. Cement was the main contributor to the environmental impacts in concrete applications therefore the cement substitutes may have the highest positive environmental impacts. However, the high density and absorption rate of the slag may negatively affect the environmental impacts due to various reasons including additional bitumen required in asphalt mixtures and increased emissions in processing and transports. In addition, EAFS was found to have low leaching potential of heavy metals and toxic substances especially in bituminous mixtures and at neutral pH. Consequently, the leaching tests should consider the specific conditions of the application. The literature review revealed that hydrogen-based DRI-EAF can significantly lower the emissions compared to conventional BF-BOF process. However, the environmental impacts depend on the source and production of hydrogen and the electricity mix indicating the significance of using green hydrogen and electricity. Additionally, only a few LCA studies focusing on hydrogen-based DRI-EAF were found in the literature review.

The system boundaries and allocation were also examined in this study based on literature review. The LCA literature regarding the applications of EAFS, was not found to generally allocate burden from steelmaking to EAFS, as it may decrease the benefits of the slag compared to conventional raw materials. As suggested in the guidelines, the literature regarding hydrogen-based DRI-EAF, instead, applied system expansion and included the credits based on avoided productions of conventional raw materials resulting from the slag utilization. This method was also adopted in a few LCA studies of EAFS applications. This report found a need for more consistent and transparent methods for defining the system boundary and allocation regarding EAFS applications. This would help to ensure that the data collected is accurate and comprehensive, and that the environmental impacts of new slag materials are fully understood.

More data collection should be conducted to support the LCA studies of EAFS and its end products, as LCAs on DRI-EAF based slags are scarce in the literature. Additionally, there is a need for the investigation of diverse applications through LCA, and the execution of customised environmental impact assessments. Due to the heterogeneity of EAFS, a nuanced comprehension is required; therefore, targeted research is essential to realise its complete potential in the field of sustainable materials. It is also suggested to consider mechanical properties to reduce the environmental impacts when determining the functional unit in LCA studies regarding EAFS applications.

6 Summary

The Fossil-Free Steel (FFS) initiative, which is supported by Business Finland, leads the way in shifting towards carbon-neutral steel manufacturing through the utilisation of environmentally friendly power and hydrogen. In line with Finland's objective to achieve carbon neutrality by 2035 and the European Union's goal of producing steel without fossil fuels by 2050, FFS plays a crucial role in decreasing CO_2 emissions.

This report explores the environmental data for new electric arc furnace slag (EAFS) from fossil-free steelmaking combining direct reduced iron and electric arc furnace (DRI-EAF) with emphasis on EAFS applications. Consequently, this report examines data needs and gaps. The purpose of the report is also to evaluate the system boundaries and allocation methods employed in the LCA literature regarding EAFS applications. These examinations support later stage life cycle assessment (LCA) studies and understanding of environmental impacts of utilizing the new slags.

The primary findings from literature review highlight the prevalent utilization of EAFS as aggregates, underscoring the necessity to explore a variety of applications through LCA. Especially, using EAFS as cement substitutes could provide high positive environmental impacts. This report also recognizes the scarcity of LCA studies specifically focused on EAFS derived from DRI-EAF process.

The literature review reveals that employing EAFS provides reductions in greenhouse gas (GHG) emissions especially through avoided landfilling and raw material production. However, the high density and absorption rate of EAFS may lead to disadvantages as well. While the reviewed literature indicates that the burden from steelmaking is generally not allocated to EAFS in LCA studies, the report identifies a need for establishing more uniform and transparent approaches when defining the system boundary and allocation methods. Ultimately, this report offers comprehensive analysis of environmental impacts associated with employing EAFS and the transition from blast furnaces to fossil-free processes in the slag production.

References

[1] ISO. ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework, 2006.
[2] ISO. ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines, 2006.
[3] European Commission. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance, 2010.
[4] The Net-Zero Steel Pathway Methodology Project - Final Report and Recommendations (Report No. RS-2021-01). ResponsibleSteel, 2021.
[5] ISO. ISO 20915:2018 Life cycle inventory calculation methodology for steel products, 2018.
[6] Durinck D, Engström F, Arnout S, Heulens J, Jones PT, Björkman B, Blanpain B, Wollants P. Hot stage processing of metallurgical slags. Resour Conserv Recycl 2008;52:1121–31. https://doi.org/10.1016/J.RESCONREC.2008.07.001.
[7] Yildirim IZ, Prezzi M. Chemical, mineralogical, and morphological properties of steel slag. Advances in Civil Engineering 2011. https://doi.org/10.1155/2011/463638.
[8] Karbowniczek M. Charge Materials. Electric Arc Furnace Steelmaking. 1st ed., CRC Press, 2021.
[9] Pellegrino C, Faleschini F, Meyer C. Recycled materials in concrete. Developments in the Formulation and Reinforcement of Concrete 2019:19–54. https://doi.org/10.1016/B978-0-08-102616-8.00002-2.
[10] Hosseini S, Soltani SM, Fennell PS, Choong TSY, Aroua MK. Production and applications of electric-arc-furnace slag as solid waste in environmental technologies: a review. Environmental Technology Reviews 2016;5:1–11. https://doi.org/10.1080/21622515.2016.1147615.
[11] Das P, Upadhyay S, Dubey S, Singh KK. Waste to wealth: Recovery of value-added products from steel slag. J Environ Chem Eng 2021;9:105640. https://doi.org/10.1016/J.JECE.2021.105640.
[12] Shen H, Forssberg E. An overview of recovery of metals from slags. Waste Management 2003;23:933–49. https://doi.org/10.1016/S0956-053X(02)00164-2.
[13] Rojas MF, Sánchez De Rojas MI. Chemical assessment of the electric arc furnace slag as construction material: Expansive compounds. Cem Concr Res 2004;34:1881–8. https://doi.org/10.1016/j.cemconres.2004.01.029.

[14] Muhmood L, Vitta S, Venkateswaran D. Cementitious and pozzolanic behavior of electric arc furnace steel slags. Cem Concr Res 2009;39:102–9. https://doi.org/10.1016/J.CEMCONRES.2008.11.002.

[15] Humbert PS, Castro-Gomes J. CO_2 activated steel slag-based materials: A review. J Clean Prod 2019;208:448–57. https://doi.org/10.1016/J.JCLEPRO.2018.10.058.

[16] Teir S, Eloneva S, Fogelholm CJ, Zevenhoven R. Dissolution of steelmaking slags in acetic acid for precipitated calcium carbonate production. Energy 2007;32:528–39. https://doi.org/10.1016/J.ENERGY.2006.06.023.

[17] Sukmak P, Sukmak G, De Silva P, Horpibulsuk S, Kassawat S, Suddeepong A. The potential of industrial waste: Electric arc furnace slag (EAF) as recycled road construction materials. Constr Build Mater 2023;368:130393. https://doi.org/10.1016/J.CONBUILDMAT.2023.130393.

[18] Dang YF, Li XG. Improvement of cementitous activation of composite powder made of steel slag and furnace slag with acid. China Powder Science and Technology 2006:16–8.

[19] Huo B, Li B, Huang S, Chen C, Zhang Y, Banthia N. Hydration and soundness properties of phosphoric acid modified steel slag powder. Constr Build Mater 2020;254:119319. https://doi.org/10.1016/J.CONBUILDMAT.2020.119319.

[20] Zhu X, Hou H, Huang X, Zhou M, Wang W. Enhance hydration properties of steel slag using grinding aids by mechanochemical effect. Constr Build Mater 2012;29:476–81. https://doi.org/10.1016/J.CONBUILDMAT.2011.10.064.

[21] Zhao Q, Stark J, Freyburg M, Zhou M. Steam and Autoclave Treatments on Structure Characteristics of Steel Slag. Adv Mat Res 2011;356–360:1919–27.

[22] Qian GR, Sun DD, Tay JH, Lai ZY. Hydrothermal reaction and autoclave stability of Mg bearing RO phase in steel slag. British Ceramic Transactions 2002;101:159–64.

[23] Frías Rojas M, Sánchez De Rojas MaI, Uría A. Study of the instability of black slags from electric arc furnace steel industry | Estudio de la inestabilidad en escorias negras de horno de arco eléctrico. Materiales de Construccion 2002:79–83.

[24] Juckes LM. The volume stability of modern steelmaking slags. Mineral Processing and Extractive Metallurgy 2003;112:177–97. https://doi.org/https://doi.org/10.1179/037195503225003708.

[25] Sivakumar R, Kumar N, Amarnath N. Studies on weathering of steel slag for volume stabilization and free lime reduction using pressurized steam injection – A possible way to recycle. 56th National Metallurgists' Day and the 72nd Annual Technical Meeting of the Indian Institute of Metals, 2018.

[26] Johnson DC, Macleod CL, Carey PJ, Hills CD. Solidification of stainless steel slag by accelerated carbonation. Environmental Technology 2003;24:671–8.

[27] Mombelli D, Mapelli C, Barella S, Gruttadauria A, Le Saout G, Garcia-Diaz E. The efficiency of quartz addition on electric arc furnace (EAF) carbon steel slag stability. J Hazard Mater 2014;279:586–96. https://doi.org/10.1016/J.JHAZMAT.2014.07.045.

[28] Zhang H, Wei C, Dong J. Inhibition Kinetics of Chromium Leaching by Calcite Coating on the Surface of Stainless Steel Slag via the Gas–Solid Accelerated Carbonation Process. Waste Biomass Valorization 2021;12:475–85. https://doi.org/10.1007/s12649-020-00988-5.

[29] Albertsson GJ, Teng L, Engström F, Seetharaman S. Effect of the heat treatment on the chromium partition in CaO-MgO-SiO_2-Cr_2O_3 synthetic slags. Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science 2013;44:1586–97. https://doi.org/10.1007/s11663-013-9939-0.

[30] Li W, Xue X. Effect of cooling regime on phase transformation and chromium enrichment in stainless-steel slag. Ironmaking and Steelmaking 2019;46:642–8. https://doi.org/10.1080/03019233.2018.1436890.

[31] Deja J. Immobilization of Cr^{6+}, Cd^{2+}, Zn^{2+} and Pb^{2+} in alkali-activated slag binders. Cem Concr Res 2002;32:1971–9. https://doi.org/10.1016/S0008-8846(02)00904-3.

[32] Pellegrino C, Faleschini F. Experimental behavior of reinforced concrete beams with electric arc furnace slag as recycled aggregate. ACI Mater J 2013;110:197–205.

[33] Pasetto M, Baldo N. Mix design and performance analysis of asphalt concretes with electric arc furnace slag. Constr Build Mater 2011;25:3458–68. https://doi.org/10.1016/J.CONBUILDMAT.2011.03.037.

[34] Fronek B, Bosela P, Delatte N. Steel Slag Aggregate Used in Portland Cement Concrete: U.S. and International Perspectives. Transportation Research Record: Journal of the Transportation Research Board 2012;2267:37–42.
[35] Oluwasola EA, Hainin MR, Aziz MMA. Comparative evaluation of dense-graded and gap-graded asphalt mix incorporating electric arc furnace steel slag and copper mine tailings. J Clean Prod 2016;122:315–25. https://doi.org/10.1016/j.jclepro.2016.02.051.
[36] Keymanesh MR, Ziari H, Zalnezhad H, Zalnezhad M. Mix design and performance evaluation of microsurfacing containing electric arc furnace (EAF) steel slag filler. Constr Build Mater 2021;269:121336. https://doi.org/10.1016/J.CONBUILDMAT.2020.121336.
[37] Rojas N, Bustamante M, Muñoz P, Godoy K, Letelier V. Study of properties and behavior of concrete containing EAF slag as coarse aggregate. Developments in the Built Environment 2023;14:100137. https://doi.org/10.1016/J.DIBE.2023.100137.
[38] Pellegrino C, Gaddo V. Mechanical and durability characteristics of concrete containing EAF slag as aggregate. Cem Concr Compos 2009;31:663–71. https://doi.org/10.1016/j.cemconcomp.2009.05.006.
[39] Sekaran A, Palaniswamy M, Balaraju S. A Study on Suitability of EAF Oxidizing Slag in Concrete: An Eco-Friendly and Sustainable Replacement for Natural Coarse Aggregate. Scientific World Journal 2015. https://doi.org/10.1155/2015/972567.
[40] Monosi S, Ruello ML, Sani D. Electric arc furnace slag as natural aggregate replacement in concrete production. Cem Concr Compos 2016;66:66–72. https://doi.org/10.1016/j.cemconcomp.2015.10.004.
[41] Faleschini F, Fernández-Ruíz MA, Zanini MA, Brunelli K, Pellegrino C, Hernández-Montes E. High performance concrete with electric arc furnace slag as aggregate: Mechanical and durability properties. Constr Build Mater 2015;101:113–21. https://doi.org/10.1016/j.conbuildmat.2015.10.022.
[42] Ducman V, Mladenovič A. The potential use of steel slag in refractory concrete. Mater Charact 2011;62:716–23. https://doi.org/10.1016/J.MATCHAR.2011.04.016.
[43] Papachristoforou M, Anastasiou EK, Papayianni I. Durability of steel fiber reinforced concrete with coarse steel slag aggregates including performance at elevated temperatures. Constr Build Mater 2020;262:120569. https://doi.org/10.1016/J.CONBUILDMAT.2020.120569.
[44] Kourounis S, Tsivilis S, Tsakiridis PE, Papadimitriou GD, Tsibouki Z. Properties and hydration of blended cements with steelmaking slag. Cem Concr Res 2007;37:815–22. https://doi.org/10.1016/J.CEMCONRES.2007.03.008.
[45] Bignozzi MC, Sandrolini F, Andreola F, Barbieri L. Recycling electric arc furnace slag as unconventional component for building materials. Proceedings of the 2nd International Conference on Sustainable Construction Materials and Technologies, 2010:557–67.
[46] Yildirim IZ, Prezzi M. Subgrade stabilisation mixtures with EAF steel slag: an experimental study followed by field implementation. International Journal of Pavement Engineering 2022;23:1754–67.
[47] Lopes EC, da Silva TO, Pitanga HN, Pedroti LG, de Carvalho JMF, Nalon GH, de Lima GES, Rodrigues MHR. Application of electric arc furnace slag for stabilisation of different tropical soils. International Journal of Pavement Engineering 2022;23:5003–14. https://doi.org/10.1080/10298436.2021.1990289.
[48] Monshi A, Asgarani MK. Producing Portland cement from iron and steel slags and limestone. Cem Concr Res 1999;29:1373–7. https://doi.org/10.1016/S0008-8846(99)00028-9.
[49] Tsakiridis PE, Papadimitriou GD, Tsivilis S, Koroneos C. Utilization of steel slag for Portland cement clinker production. J Hazard Mater 2008;152:805–11. https://doi.org/10.1016/J.JHAZMAT.2007.07.093.
[50] Li H, Guo R, Chen Y, Yang G, Wu T. Utilization of steel slag as a highly efficient absorbent for SO_2 removal at coal-fired power stations. Environmental Advances 2022;9:100276. https://doi.org/10.1016/J.ENVADV.2022.100276.
[51] Chen J, Xing Y, Wang Y, Zhang W, Guo Z, Su W. Application of iron and steel slags in mitigating greenhouse gas emissions: A review. Science of The Total Environment 2022;844:157041. https://doi.org/10.1016/J.SCITOTENV.2022.157041.

[52] Das S, Kim GW, Hwang HY, Verma PP, Kim PJ. Cropping with slag to address soil, environment, and food security. Front Microbiol 2019;10. https://doi.org/10.3389/fmicb.2019.01320.

[53] Yang C-Y, Reijonen I, Yu H, Dharmarajan R, Seshadri B, Bolan NS. Back to Basic Slags as a Phosphorus Source and Liming Material. Soil Amendments for Sustainability. 1st ed., CRC Press, 2018:237–50.

[54] Yi H, Xu G, Cheng H, Wang J, Wan Y, Chen H. An Overview of Utilization of Steel Slag. Procedia Environ Sci 2012;16:791–801. https://doi.org/10.1016/J.PROENV.2012.10.108.

[55] Mikhailenko P, Piao Z, Poulikakos LD. Electric arc furnace slag as aggregates in semi-dense asphalt. Case Studies in Construction Materials 2023;18. https://doi.org/10.1016/j.cscm.2023.e02049.

[56] De Pascale B, Tataranni P, Lantieri C, Bonoli A, Vignali V. Mechanical performance and environmental assessment of porous asphalt mixtures produced with EAF steel slags and RAP aggregates. Constr Build Mater 2023;400:132889. https://doi.org/10.1016/J.CONBUILDMAT.2023.132889.

[57] Loi SS, Subramaniam SK, Xusheng H. Carbon Footprint Assessment of Steel Slag Asphalt Pavement in Singapore. vol. 193. 2022. https://doi.org/10.1007/978-3-030-87379-0_58.

[58] Nguyen LH, Nguyen TD, Tran TVN, Nguyen DL, Tran HS, Nguyen TL, Nguyen TH, Nguyen HG, Nguyen TP, Nguyen NT, Ta Y, Sato R. Steel slag quality control for road construction aggregates and its environmental impact: case study of Vietnamese steel industry—leaching of heavy metals from steel-making slag. Environmental Science and Pollution Research 2022;29:41983–91. https://doi.org/10.1007/s11356-021-16438-1.

[59] Kvočka D, Šušteršič J, Mauko Pranjić A, Mladenović A. Mass Concrete with EAF Steel Slag Aggregate: Workability, Strength, Temperature Rise, and Environmental Performance. Sustainability 2022;14. https://doi.org/10.3390/su142315502.

[60] Terrones-Saeta JM, Suárez-Macías J, Moreno-López ER, Corpas-Iglesias FA. Determination of the chemical, physical and mechanical characteristics of electric arc furnace slags and environmental evaluation of the process for their utilization as an aggregate in bituminous mixtures. Materials 2021;14:1–16. https://doi.org/10.3390/ma14040782.

[61] Amani A, Ramezanianpour AM, Palassi M. Investigation on the sustainable use of electric arc furnace slag aggregates in eco-friendly alkali-activated low fineness slag concrete as a green construction composite. J Clean Prod 2021;307. https://doi.org/10.1016/j.jclepro.2021.127257.

[62] Georgiou P, Loizos A. Environmental assessment of warm mix asphalt incorporating steel slag and high reclaimed asphalt for wearing courses: a case study. Road Materials and Pavement Design 2021;22:S662–71. https://doi.org/10.1080/14680629.2021.1906305.

[63] Hafez H, Kassim D, Kurda R, Silva RV, de Brito J. Assessing the sustainability potential of alkali-activated concrete from electric arc furnace slag using the ECO_2 framework. Constr Build Mater 2021;281. https://doi.org/10.1016/j.conbuildmat.2021.122559.

[64] Apithanyasai S, Supakata N, Papong S. The potential of industrial waste: using foundry sand with fly ash and electric arc furnace slag for geopolymer brick production. Heliyon 2020;6. https://doi.org/10.1016/j.heliyon.2020.e03697.

[65] Esther L-A, Pedro L-G, Irune I-V, Gerardo F. Comprehensive analysis of the environmental impact of electric arc furnace steel slag on asphalt mixtures. J Clean Prod 2020;275. https://doi.org/10.1016/j.jclepro.2020.123121.

[66] Bonoli A, Degli Esposti A, Magrini C. A Case Study of Industrial Symbiosis to Reduce GHG Emissions: Performance Analysis and LCA of Asphalt Concretes Made With RAP Aggregates and Steel Slags. Front Mater 2020;7. https://doi.org/10.3389/fmats.2020.572955.

[67] Rodríguez-Fernández I, Lizasoain-Arteaga E, Lastra-González P, Castro-Fresno D. Mechanical, environmental and economic feasibility of highly sustainable porous asphalt mixtures. Constr Build Mater 2020;251. https://doi.org/10.1016/j.conbuildmat.2020.118982.

[68] García-Cortés V. Sustainable limestone and EAF aggregate concretes through particle packing models (PPMs) and life cycle assessment (LCA). Doctoral thesis. University of the Basque Country, 2020.

[69] Lee C-K, Lee J-Y, Lee I-W, Kim Y-K. GHG mitigation of railway concrete products using eco-concrete and surface protection agent. Constr Build Mater 2018;186:1154–60. https://doi.org/10.1016/j.conbuildmat.2018.08.046.

[70] Anastasiou EK, Liapis A, Papachristoforou M. Life Cycle Assessment of Concrete Products for Special Applications Containing EAF Slag. Procedia Environ Sci 2017;38:469–76. https://doi.org/10.1016/J.PROENV.2017.03.138.

[71] Liapis A, Anastasiou EK, Papachristoforou M, Papayianni I. Feasibility Study and Criteria for EAF Slag Utilization in Concrete Products. Journal of Sustainable Metallurgy 2018;4:68–76. https://doi.org/10.1007/s40831-017-0152-2.

[72] Evangelista BL, Rosado LP, Penteado CSG. Life cycle assessment of concrete paving blocks using electric arc furnace slag as natural coarse aggregate substitute. J Clean Prod 2018;178:176–85. https://doi.org/10.1016/j.jclepro.2018.01.007.

[73] Morata M, Saborido C. Slag aggregates with enhanced performance for railway track bed layers. Proceedings of the 3rd International Conference on Railway Technology: Research, Development and Maintenance. Civil-Comp Press, 2016;110.

[74] Ferreira VJ, Sáez-De-Guinoa Vilaplana A, García-Armingol T, Aranda-Usón A, Lausín-González C, López-Sabirón AM, Ferreira G. Evaluation of the steel slag incorporation as coarse aggregate for road construction: Technical requirements and environmental impact assessment. J Clean Prod 2016;130:175–86. https://doi.org/10.1016/j.jclepro.2015.08.094.

[75] Faleschini F, De Marzi P, Pellegrino C. Recycled concrete containing EAF slag: Environmental assessment through LCA. European Journal of Environmental and Civil Engineering 2014;18:1009–24. https://doi.org/10.1080/19648189.2014.922505.

[76] Milačič R, Zuliani T, Oblak T, Mladenovič A, Ščančar J. Environmental impacts of asphalt mixes with electric arc furnace steel slag. J Environ Qual 2011;40:1153–61. https://doi.org/10.2134/jeq2010.0516.

[77] Ren L, Zhou S, Ou X. The carbon reduction potential of hydrogen in the low carbon transition of the iron and steel industry: The case of China. Renewable and Sustainable Energy Reviews 2023;171. https://doi.org/10.1016/j.rser.2022.113026.

[78] Graupner Y, Weckenborg C, Spengler TS. Low-carbon primary steelmaking using direct reduction and electric arc furnaces: Prospective environmental impact assessment. Proceedings of the 30th CIRP Life Cycle Engineering Conference. Procedia CIRP 2023;116:696–701. https://doi.org/10.1016/j.procir.2023.02.117.

[79] Souza AM, Ribeiro R V., Oliveira LD, Alves da Silva AP. How upstream methane emissions can impact cost and emissions of steelmaking routes? Journal of Materials Research and Technology 2023;24:7153–61. https://doi.org/10.1016/j.jmrt.2023.04.238.

[80] Li F, Chu M, Tang J, Liu Z, Guo J, Yan R, Liu P. Thermodynamic performance analysis and environmental impact assessment of an integrated system for hydrogen generation and steelmaking. Energy 2022;241. https://doi.org/10.1016/j.energy.2021.122922.

[81] Suer J, Traverso M, Jäger N. Carbon Footprint Assessment of Hydrogen and Steel. Energies 2022;15. https://doi.org/10.3390/en15249468.

[82] Anastasiou EK, Liapis A, Papayianni I. Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials. Resour Conserv Recycl 2015;101:1–8. https://doi.org/10.1016/j.resconrec.2015.05.009.

[83] Burchart-Korol D. Life cycle assessment of steel production in Poland: A case study. J Clean Prod 2013;54:235–43. https://doi.org/10.1016/j.jclepro.2013.04.031.

[84] Zandi M, Russell NV, Edyvean RGJ, Hand RJ, Ward P. Interpretation of standard leaching test BS EN 12457-2: is your sample hazardous or inert?. J Environ. Monit 2007;9:1426–1429. https://doi.org/10.1039/B712957B.

[85] United States Environmental Protection Agency (EPA). Method 1311: Toxicity Characteristic Leaching Procedure,1992.

[86] NEN. NEN 7345:1995 Leaching characteristics of solid earthy and stony building and waste materials - Leaching tests - Determination of the leaching of inorganic components from buildings and monolitic waste materials with the diffusion test, 1995.