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Life cycle assessment of a new pyrometallurgical approach for dezincing and valorisation of iron and steelmaking sludge in the UK

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ABSTRACT

A new pyrometallurgical route enables the removal of zinc (dezincing) from iron-rich sludges from iron and steelmaking processes, allowing their reintroduction into the steel production cycle as a sinter feedstock for the blast furnace. The new technology was introduced and the life cycle assessment (LCA) was carried out to evaluate the environmental impacts arising in the treatment of seven steelmaking sludges. The technology involves preparation and roasting of sludges in a top-blown rotary converter at 1200 °C for 60 min resulting in a high degree of dezincing and retention of iron oxide. The inventory for the LCA was collected in situ and scaled up to emulate industrial conditions. The impacts were calculated for eight categories of the CML impact assessment method. The assessment determined the main environmental hotspots and compared the dezincing of sludges with the disposal to the landfill. The dezincing route was presented for the process-only burdens scenario and the avoided-burdens scenario (incorporating credits for valorisation of the dezinced product). The findings suggest that the dezincing of sludges is beneficial in majority of the impact categories compared to the landfill. On average, the dezincing results in a 9% reduction in CO_2 emissions, or 25% reduction when avoided burdens credits are factored in. Several process design strategies are identified to further reduce the impacts of dezincing.

1. Introduction

Reducing the environmental impact of the steel industry is seen as a major challenge in moving towards more sustainable development. Production of steel is the second biggest source of industrially-generated greenhouse gas emissions globally and the need for new steel products is likely to remain high or further increase with the growth in population and affluence (Bruyninckx et al., 2024). In order to meet the climate targets set out by the industry and governments, a decoupling of high demand for steel from the greenhouse gas emissions is needed.

Among strategies aimed at reducing environmental emissions and establishing the circular economy in the steel sector, a valorisation of off-gas dusts and sludges from the iron and steelmaking processes has received a significant attention. This waste byproduct stream is mainly composed of iron oxide that can be recirculated back in the steel production process as an iron feedstock but first needs to be treated to remove the contaminants such as zinc, lead, cadmium and chlorides that would otherwise impede the steel production process or affect the quality of steel products. Among the impurities, the greatest concern is a presence of zinc and the step of zinc removal (dezincing) is necessary in order to reuse this material. The dezincing as a recycling strategy is specifically sought for the dusts and sludges with relatively low concentrations of zinc typically arising in the process of iron and primary steel production – the blast furnace (BF) and basic oxygen furnace (BOS) route, where this additional dezincing step could sufficiently remove the zinc to meet the small tolerances to zinc concentration in BF feed (0.2 kg per tonne of cast steel). This is in contrast to the steelmaking dusts with higher zinc concentrations (over 20%) from the electric arc furnace (EAF) operations, where the recycling strategy is geared towards the zinc extraction and recovery (Rütten, 2006). Removal of zinc from low zinc-bearing dusts and sludges prior to their reuse is necessary in order to prevent the formation of the zinc scaffolds on the BF walls. These deposits are created as the zinc vapor re-oxidizes and condensates on the refractory lining due to a lower boiling temperature of zinc (907 °C) compared to the operating temperature of the BF (the hearth temperature is 1450–1550 °C, whereas near the tuyeres area the temperature

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is > 2000 °C). Zinc scaffolds undermine the energetic efficiency of the process, obstruct the gas flow and burden descent, and reduce the lifetime of the refractory.

The valorisation of dusts and sludges have been recently considered in the context of steel industry in the UK as a solution to both legacy waste and the storage and disposal of waste from future steel production while reducing costs and environmental emissions through recovery of constituent materials and diversion from the landfill (Smith et al., 2021). With 20–30 kg of dusts and sludges generated for every tonne of produced steel, around 90,000 tonnes of this waste are generated annually in the UK, with 6.7 million tonnes estimated to be stockpiled across the country. Untreated, these low zinc-bearing sludges are subjected to landfilling, incurring environmental and financial costs. Landfilling generates direct emissions to the environment through leachate and airborne dust emissions, waste transportation, and landfill construction and management. Combined costs of transport and waste handling, landfill gate fees and the landfill tax incur the costs to the steel industry of approximately £200–300 per tonne of waste (WRAP, 2025; HMRC, 2026). To reduce costs and environmental emissions associated with landfilling of iron and steelmaking dusts and sludges, a cost-effective and environmentally-friendly recycling methods are needed.

Various technological approaches for dezincing of iron and steelmaking dusts and sludges exists but the evidence of their implementation is sporadic, and their effectiveness for dezincing of dusts and sludges arising in the UK steel operations is unknown. The dezincing has been achieved by both pyrometallurgical and hydrometallurgical approaches. The pyrometallurgical route is a dominant industrial practice with most notable examples of steel-mill dust and sludges dezincing operations in South Korea and Japan (Ibaraki and Oda, 2002; Ichikawa and Morishige, 2003; Oda et al., 2006). Pyrometallurgical approaches largely involve roasting the dust or sludge in a rotary kiln or a rotary hearth furnace (RHF) at temperatures above 1200 °C for 15 min or longer, to achieve high dezincing rates of 75–95% (She et al., 2011, 2014; Wang et al., 2011; Andersson et al., 2019; Liu et al., 2020; Xiao et al., 2024). Hydrometallurgical approaches involve zinc reduction in acidic or basic solutions at temperatures between 50 and 60 °C (Savinov et al., 2005; Trung et al., 2011; Vereš et al., 2011; Cantarino et al., 2012; Kul et al., 2023). Generally, better dezincing rates are achieved by pyrometallurgical approaches given that the portion of zinc in steelmaking dusts and sludges exists in a ferrite form that cannot be easily broken down at lower temperatures (Bokanyi et al., 2007). Despite numerous approaches for dezincing available, the industrial evidence of dezincing of dusts and sludges remains sporadic which infers the limitations of the current technological approaches and their widespread implementation. Moreover, an effective recycling approach needs to take in to consideration the unique composition and characteristics of the dusts and sludges that varies across steel producers and the waste source origins (Matsuura, 2025).

In this study, a new approach for dezincing of low zinc-bearing sludges originating from the UK steel industry is presented. A new pyrometallurgical approach, resembling process conditions observed in previous works, has been developed and optimized for the purposes of sludges generated in steelmaking operations in the UK. The new dezincing approach, developed at the Materials Processing Institute (MPI), entails the roasting of sludges in a top blown rotary converter (TBRC) at moderate temperatures and relatively short times to achieve a dezincing of sludges sourced from different steelmaking plants in the UK. The system enables excellent mixing of materials without the need of a prior agglomeration, offering a potentially more energy-efficient alternative to other pyrometallurgical approaches.

The new technology was introduced and evaluated for environmental performance using life cycle assessment (LCA) methodology. The LCA was employed to assess the impacts of the new dezincing process and determine if the dezincing in this manner could bring about the desired improvements in greenhouse gases and other pollutant reductions in comparison to the landfilling practice, as any viable recycling approach should strive to minimise environmental impacts. An early application of LCA during process development aims to inform the technology design at low readiness levels when significant flexibility to the technology application and design is high and early insights are deemed particularly effective in lowering environmental impacts of the prospective technology (Smith et al., 2019).

Development of technologies for dezincing of steelmaking dusts and sludges have been scarcely supported by LCA research. An environmental assessment has been predominantly carried out on EAF dust in a context of zinc recovery, e.g., (Viklund-White, 2000; Rinne et al., 2022), which has a limited value to inform the management of low zinc-bearing dusts and sludges destined for dezincing and iron recovery. Environmental impacts of low zinc-bearing dusts and sludges has been explored in the context of their conversion to direct reduced iron (DRI) and use as an iron feedstock in EAF and BF operations. Lee et al. (2025) assessed environmental impacts of the use of dust-derived DRI in EAF steel production in South Korea and observed 18% reduction of CO_2 emissions (Lee et al., 2025). Conversely, Liu et al. (2016) observed negligible effect on steel decarbonization in the context of DRI use in several Chinese plants (Liu et al., 2016). Presently, no product derivatives of dust from dezincing treatment have been evaluated in the context of the UK steel industry using a TBRC, or compared to the landfilling as a conventional disposal practice. The present study has been positioned to address this gap.

2. Methodology

2.1. Technology description

Dezincing treatment involves several processes for the preparation of sludges, and roasting in a top-blown rotary converter (TBRC) to vaporize the zinc oxide while striving to maximise the retention of the iron oxide in a dezinced product and improve the level of metallization. The TBRC has been successfully installed and commissioned during this project to undertake the dezincing trials at scale (1–10 kg). The TBRC has a nominal capacity of 30 L, an operating temperature of up to 1600 °C, a door mounted water-cooled oxy-natural gas burner rated at 120 kW, a 1–15 rpm rotating vessel, an off-gas thermal oxidiser, a bag filter, and induced draught fan.

In the initial tests, while evaluating the capabilities of the pilot TBRC, alumina crucibles were used to contain the samples. The rig's operational capacity was progressively increased in a staged approach, gradually transitioning to a direct loading of materials onto the TBRC refractories and fully utilising its capabilities. The images in Fig. 1 display the TBRC setup and the alumina crucibles used. A Process and Instrument Diagram of the TBRC system is described in Fig. 2.

Preparation of the sludge samples involved drying at 150 °C overnight for 15 h to remove the moisture (between 6.3 and 34.2%, by weight) and then ground to a particle size below 0.25 mm and mixed with carbon powder at a ratio of 10:1. The mixture was then fed into the TBRC furnace and heated by combustion of natural gas supported by infusion of pure oxygen gas. The gases were delivered by a nozzle directly to the treated material to raise and maintain the temperature of around 1200 °C. To support the burning, the oxygen was pumped at about twice the volume of natural gas. The material was heated for 60 min while the furnace was slowly rotated to achieve homogeneous heat distribution across the material. After the smelting treatment, the furnace was filled with argon gas to prevent re-oxidation of the vaporised material, primarily zinc oxide. As a result of this high-temperature treatment in the presence of carbon, a portion of the treated material, including most of the zinc, was vaporised and the iron oxide concentration in the remaining material generally increased and achieved a certain level of metallization that is advantageous to its potential future valorisation in the BF. The flows of materials and their compositions were measured before entering and leaving the roasting process using X-ray Fluorescence (XRF) spectrometry to determine the elemental

Fig. 1. Top Blown Rotary Converter (TBRC) and crucible used in the experiments.

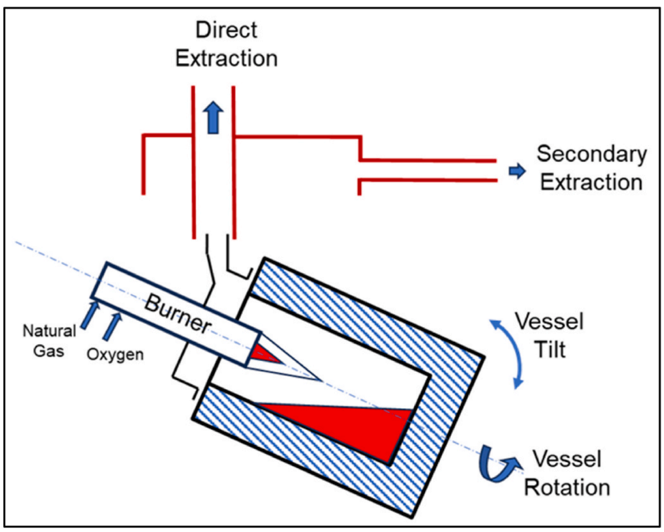

Fig. 2. A process and instrument diagram of the TBRC system.

composition of materials and X-ray Diffraction (XRD) spectroscopy to determine the crystalline composition of the iron-phase.

The process was applied to 11 dust and sludge samples in iron and steel production from different steel and ironmaking plants in the UK. Seven sludges achieved the levels of dezincing of a sufficient practical interest, and are focused on in this paper. In other instances, the rate of dezincing was low, or the zinc content in the dezinced product was still relatively high for this material to be suitable as a feedstock for the BF. For example, several EAF dusts arising as dropout box or primary off-gas dust with an initial zinc oxide concentration of 14% and 13% respectively, could achieve around 60% zinc removal, so the ZnO concentration in the dezinced product was still relatively high (around 5%). Considering low tolerances of 0.2 kg of zinc per tonne of crude steel, such material could only be used in a very small amount in the BF.

Table 1
Names and origins of sludge samples.

Acronym	Description of origin
medium-Zn BFES	Wastewater effluent sludge from BF operations.
low-Zn BFES	Wastewater effluent sludge from BF operations.
PMES	Wastewater effluent sludge from plate mill operations (descaling).
low-Zn BOSFS	Sludge from off-gas scrubbing in the BOS.
BFFS	Sludge from off-gas scrubbing in the BF.
high-Zn BOSFS	Sludge from off-gas scrubbing in the BOS.
EAFES	Suspended solids of EAF and mill dust removed during wastewater treatment.

The list and origins of the sludges covered by the scope of this LCA study, are given in Table 1. The first part of the acronyms refers to the source operations (BF, BOS, plate mill (PM), and EAF) and the second part refers to the nature of the sludge, as a wastewater effluent sludge (ES) or an off-gas filter sludge (FS). Most samples are roasted at 1200 °C for 60 min with a rotation speed of 2.91 RPM. These processing conditions were based on the results obtained in the experiments where the most promising results were achieved. The TBRC temperature was different for medium-Zn BFES (1350 °C), low-Zn BOSFS, and high-Zn BOSFS (1250 °C), and EAFES (1220 °C). The variation in the values was not deliberate and is due to limitations of the experimental setup as the TBRC equipment has no active feedback temperature control. Similarly, the deviation in the residence time was observed in the EAFES sample - which was treated for 55 min as the material was prematurely withdrawn from the furnace. The rotational speed was the same for all the tests except for medium-Zn BFES sample. The default speed of 2.91 RPM was chosen to reduce any loss of the material due to the particle size. However, the medium-Zn BFES sample was deliberately rotated at a higher speed (5.08 RPM) to ensure sufficient exposure of the material to the heat, and to maintain the movement of the material across the surface in the rotary converter. In practical terms, given these minor differences in processing conditions, it can be assumed that equal operational parameters of temperature, duration and rotation could be uniformly applied to all the sludges. However, to maintain the scientific rigour, the data inventory for the LCA was based on measured results.

2.2. Goal and scope

The analysis is carried out following recommendations outlined in ISO 14040 and 14044 standards for LCA studies (ISO-14040, 2006; ISO-14044, 2006). Accordingly, the assessment is carried out through four phases: goal and scope, life cycle inventory analysis, impact assessment, and interpretation. The first phase outlines the methodological choices underpinning the assessment, the second phase outlines the data, and the last two phases provide and interpret the final results of the environmental impact analysis.

2.2.1. Goal definition

The aim of this study is to investigate the environmental performance of a new pyrometallurgical route for recycling (dezincing and reuse) of iron and steelmaking sludges to identify impactful stages in the process, and realise potential environmental advantages of the new technology in comparison to the landfilling, as a main practice in the context of the current management and disposal of this waste. The findings are hoped to inform steelmaking industries about the environmental impact potential of processing this waste which is deemed useful in the context of sustainability, decarbonization, and circular economy efforts, and support further research in this area.

2.2.2. Function and functional unit

Consistent with the functional unit definition for waste treatment in LCA, the functional unit is defined as the treatment (dezincing or landfilling) of 1 kg of steelmaking sludge. This functional unit refers to the dry weight (a mass of the material achieved after the drying step) to enable consistent evaluation of the investigated sludges despite their different initial moisture concentrations.

2.2.3. System boundaries

The system boundary starts from the already collected sludges and includes all the preparation of this material and the final roasting process. The boundaries are extended also to include the substitution potential of the dezinced material to be reused as a feedstock in the BF sinter.

Data for LCA is collected from experiments and complemented from the literature and process engineering calculations. Background data related to the consumption of energy and materials in the process, and disposal of waste are considered for the geographical context of the UK. Impacts associated with the infrastructure, machinery, maintenance, and transportation are excluded from the analysis since those are not known and are generally negligible in the context of industrial activities (Frischknecht et al., 2007). However, due to the potentially corrosive effect of some metal oxides and compounds present in steelmaking sludges, the impact of infrastructure, such as periodic change of refractories, should be included in a more comprehensive analysis.

The impact assessment is carried out to identify the most impactful stages in the treatment process (environmental hotspots) and find out how the dezincing of sludges compares to the conventional disposal of this material to the landfill. Both the landfilling and dezincing serve as end-of-life management options where the landfilling represents a final sink to the material and the dezincing represents a transforming activity that generates an intermediate product. Essentially, the treatment of sludges should be considered environmentally viable if the associated impacts are similar to or lower than those arising during landfilling.

Impacts of dezincing are calculated for two scenarios: the process-only scenario, which takes into account only the impacts of the dezincing process, and the avoided-burden scenario which factors-in the benefits derived from the valorisation of the dezinced product. The dezinced product has a direct potential in substituting iron ore concentrate which is normally used as an iron oxide feedstock for BF sinter, so the dezinced material is credited for avoided environmental burdens of virgin iron oxide concentrate production. The substitution potential is calculated based on the iron oxide content in the dezinced product and that normally occurring in a virgin iron oxide concentrate.

The impact assessment is carried out using the CML method for the impact categories shown in Table 2. Modelling is carried out using SimaPro software v 9.6.0.1 and Ecoinvent v3.10 database (Frischknecht et al., 2007) consistent with the cutt-off system modeling of the attributional LCA approach.

Table 2
Environmental impact categories of the CML method used in this study.

Impact category	Unit	Description
Abiotic depletion	kg Sb eq	Quantifies the depletion of non-renewable mineral resources, including metals and rare earth elements considering their scarcity and the environmental impact of mining and processing activities.
Abiotic depletion (fossil fuels)	MJ	Evaluates the depletion of finite energy resources, such as coal, oil, and natural gas, based on their extraction rates and future availability
Global warming	kg CO2 eq	Refers to the radiative forcing effect of greenhouse gases in the atmosphere, that trap heat, leading to climate change and global temperature rise.
Fresh water aquatic ecotox.	kg 1,4-DB eq	Assesses the toxic effects of chemical emissions on freshwater ecosystems, which can harm aquatic organisms, while considering persistence and bioaccumulation of pollutants in water bodies and their disruptive effect on the food chain.
Terrestrial ecotoxicity	kg 1,4-DB eq	Assesses the toxic effects of chemical substances on soil and terrestrial organisms including contamination, bioaccumulation, and long-term impacts on biodiversity and soil fertility.
Photochemical oxidation	kg C2H4 eq	Refers to the formation of ground-level ozone (smog) through the reaction between volatile organic compounds (VOCs) and nitrogen oxides under sunlight, harmful to human health and vegetation.
Acidification	kg SO2 eq	Results from emissions of acidic substances, such as sulphur dioxide and nitrogen oxides, which lead to acid rain and the acidification of soils and water bodies affecting ecosystems and infrastructure.

2.3. Life cycle inventory

Experimental data and process engineering calculations are combined to complete the data inventory for LCA. Assessment-relevant inputs of materials and energy in the system and outputs of emissions are scaled-up to represent the industrial conditions, consistent with the assessment of emerging technologies in LCA (Cucurachi et al., 2018). This scaling-up largely concerns the consumption of energy, which is used more optimally in the large-scale continuous reactors in industry. The process flowchart is represented in Fig. 3.

Operational parameters and material flows are used as observed in the experiments. Energy use is estimated using process engineering calculations for the processes of drying, grinding, and roasting in TBRC. Energy for drying the samples is estimated based on the energy needed for evaporation considering specific heat capacity and evaporation temperature of the water, and 70 % drying efficiency, to provide an estimate of 3.372 MJ as the amount of energy needed to evaporate 1 kg of water (Mujumdar, 2006). Energy for heating in the TBRC was calculated based on the heating temperature and duration of the process using recommendations in the literature (Piccinno et al., 2016). The energy for roasting in the TBRC is calculated assuming a 5000 L reactor that has a capacity to treat 10 tonnes of material at an average density of iron oxide of 4000 kg/m3 (filled to one quarter of the reactor's capacity). The calculation takes into account energy needed to raise and maintain the temperature in the reactor and considers heat loss on the reactor surface, and the efficiency of the heating device. Depending on the temperature and residence time, it was calculated that 1.26–1.42 MJ is needed for roasting of 1 kg of the material entering the converter. Energy for rotation, enabled by an electromotor attached to the TBRC, is estimated to be 0.44 Wh and 0.76 Wh per 1 kg of material for 1 h at rates of 2.91 rpm and 5.08 rpm, respectively. This was estimated based on an existing industrial 1000 L TBRC operating at an estimated power consumption of 15 kVA at a maximum speed of 10 rpm. Energy for grinding was assumed to be 16 Wh per 1 kg of ground material as suggested in Piccinno et al. (2016). This is a conservative assumption as the grinding of dust mostly serves as a method of de-agglomeration of particles that are bonded in lumps during the drying rather than the grinding of solid ore.

The input quantities of sludge and carbon, and the outputs of dezinced product, are taken as observed in the experiments. The use of oxygen is adjusted to the calculated natural gas use at the same ratio as observed in the experiments (1:2.1). The use of argon is excluded from the projected industrial-scale model as this would be prohibitively expensive in commercial settings. An off-gas extraction using a fan or a vacuum pump would be a more likely way to prevent the re-oxidation. The consumption of natural gas for drying and the TBRC process, and accompanying emissions from the burning of natural gas, are represented by the integrated Ecoinvent datasets for heating using natural

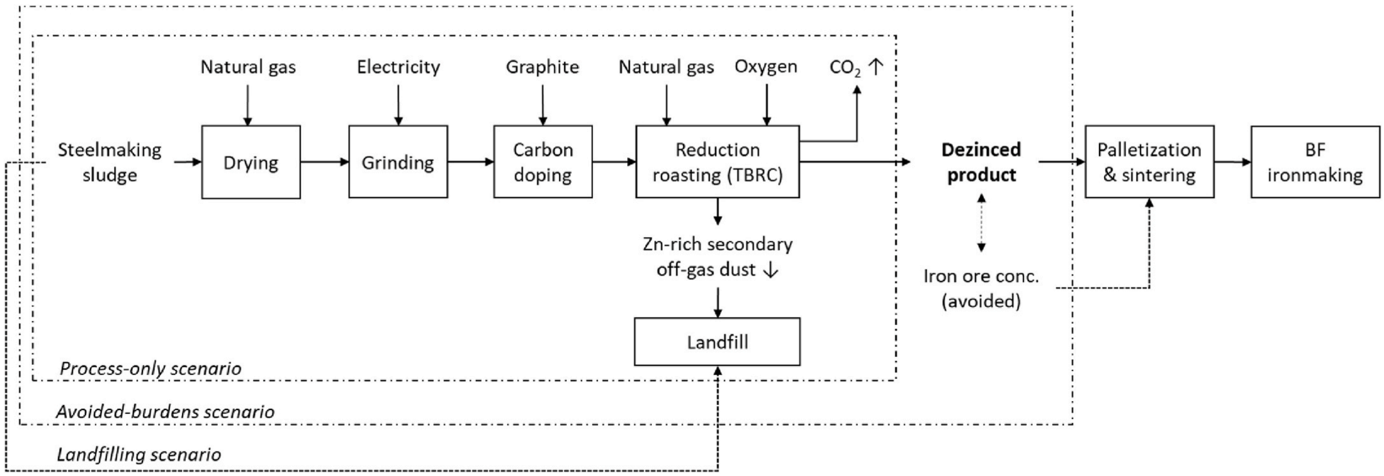

Fig. 3. Process flowchart of the dezincing of steelmaking sludges.

gas: natural gas, burned in a gas turbine {GB}. The use of carbon, oxygen and electricity was represented by the Ecoinvent processes: graphite {GLO}, oxygen, liquid {RER}, and electricity, medium voltage {GB}. Direct emissions of CO_2 from the burning of process carbon are accounted for separately. Impacts associated with the landfilling as a baseline scenario of the sludge disposal, and modelling of the disposal of secondary off-gas dust from the TBRC, are represented by the Ecoinvent dataset: treatment of electric arc furnace dust, residual material landfill {RoW}|. The mass of secondary off-gas dust is not experimentally observed. Instead, it is taken as the difference between the dried material input and the mass yield of the dezinced product, assuming that all the evaporated material is captured in the off-gas filter. The inventory of the dezincing process is given in Table 3. As per the functional unit, the inventories are normalised to 1 kg of dry sludge. Inputs for raw sludge correspond to the initial moisture levels of each sludge.

Avoided impacts of the iron ore concentrate were modelled using the Ecoinvent dataset 'iron ore concentrate {GLO}'. The mass of the avoided concentrate was based on the concentration of iron in the dezinced material derived from the XRF analysis. The substitution between iron ore concentrate ore and dezinced product is meaningful given that the virgin iron ore has a similar concentration of iron oxide in the forms of hematite and magnetite.

3. Results and discussion

3.1. Sludge and dezinced product composition

The concentrations of iron and zinc oxides in both the raw sludge and the dezinced product are shown in Table 4 andTable 5. XRF results of the dry raw sludge show the highest concentration of iron oxide (69–86%), followed by oxides of calcium (12%, on average), zinc and silica (5–6%, on average), and aluminium, magnesium and manganese (2–3%), with following oxides below 1% or in traces and not reported: SrO, Co_2O_3, Nb_2O_5, Br, Rb_2O, SnO_2, Bi_2O_3, NiO, CuO, ZrO_2, MoO_3, CdO, V_2O_5, BaO, Cr_2O_3, P_2O_5, and Cl. Results of XRD analysis are shown in Table 6.

Results from the XRD analysis show a predominant concentration of hematite (Fe_2O_3) and magnetite (Fe_3O_4), demonstrating the likely effectiveness of this material to be used as a fitting precursor and iron ore substitute as a feedstock for BF sinter.

Information from Table 4 andTable 5 was combined with the quantities of recovered dezinced product to derive the dezincing rates and the iron oxide recovery rates as shown in Table 7. The dezincing treatment results in 78 to 97% zinc removal and an average iron recovery rate of 82%.

The characterization results of XRF and XRD analysis were derived with several anomalies stemming from limitations of the experimental equipment and XRF and XRD measurements and in some cases, adjustments to data were made for the purposes of LCA. In one instance, the concentration of zinc for EAFES sludge appears to increase after XRD analysis (from 0.04% in raw sludge to 0.25% in the dezinced material), which is likely due to the zinc contamination from the refractory lining. Similar contamination pathway likely explains increase in concentrations of Al_2O_3 and SiO_2 in some of the samples. Moreover, a content of iron in dezinced material appears to be disproportionally high for the medium-Zn BFES and PMES samples (82% and 83%, respectively). This is attributed to a likely contamination of the samples from using the same crucible from dezincing of a sludge with the high iron concentration (likely low-Zn BFES) since the cost and time constraints prohibited changing the crucible after each test. For the purposes of LCA, it was necessary to address this exaggeration and balance skewed mass flows. Hence, the concentration of the iron oxide in dezinced material for medium-Zn BFES and PMES were adjusted to 73% and 74%,

Table 3
Inventory for the dezincing treatment of sludges.

Input	Unit	medium-Zn BFES	low-Zn BFES	PMES	low-Zn BOSFS	BFFS	high-Zn BOSFS	EAFES
Raw sludge	g	1390	1300	1518	1103	1264	1464	1144.6
Graphite	g	98.90	98.90	98.90	98.90	98.90	98.90	98.90
Drying	MJ	1.32	1.01	1.75	0.35	0.89	1.57	0.49
Grinding	Wh	16	16	16	16	16	16	16.00
Heating (TBRC)	MJ	1.66	1.47	1.47	1.53	1.47	1.53	1.27
Oxygen	kg	0.09	0.08	0.08	0.09	0.08	0.09	0.07
Rotation (TBRC)	Wh	0.76	0.44	0.44	0.44	0.44	0.44	0.44
Outputs								
Dezinced product	g	763.96	714.95	756.59	783.30	417.58	778.02	929.67
Off-gas dust	g	236.04	285.05	243.41	216.70	582.42	221.98	70.33
CO_2	g	0.36	0.36	0.36	0.36	0.36	0.36	0.36

Table 4
Composition of sludges before dezincing treatment (dry content).

Compound	Fe_2O_3	ZnO	CaO	SiO_2	Al_2O3	MnO	MgO	SO_3	PbO	TiO_2	K_2O	Na_2O
medium-Zn BFES	56.66%	4.95%	14.66%	8.66%	4.14%	2.99%	2.90%	2.36%	0.61%	0.28%	0.66%	0%
low-Zn BFES	73.49%	2.03%	10.03%	5.84%	2.78%	1.23%	1.67%	1.13%	0.36%	0.15%	0.45%	0.14%
PMES	57.31%	5.61%	15.25%	7.83%	3.81%	2.65%	2.79%	2.15%	0.82%	0.24%	0.66%	0%
low-Zn BOSFS	70.28%	0.82%	14.14%	2.76%	0.54%	5.96%	3.78%	0.65%	0.09%	0.09%	0.29%	0.17%
BFFS	66.35%	4.38%	6.29%	7.05%	3.55%	0.35%	1.25%	6.39%	0.48%	0.27%	1.59%	0.72%
high-Zn BOSFS	77.82%	8.41%	9.68%	1.16%	0.19%	0.84%	1.16%	0.21%	0.20%	0.04%	0.05%	0%
EAFES	96.59%	0.04%	0.21%	0.40%	0.15%	0.87%	0.05%	0.27%	0.00%	0.00%	0.01%	0.08%

Table 5
Composition of the dezinced product.

Compound	Fe_2O_3	ZnO	CaO	SiO_2	Al_2O3	MnO	MgO	SO_3	PbO	TiO_2	K_2O	Na_2O
medium-Zn BFES	82.4%[a]	0.17%	5.67%	6.06%	2.26%	1.21%	1.90%	0.00%	0.01%	0.08%	0%	0%
low-Zn BFES	69.2%	0.65%	12.03%	9.44%	3.76%	1.42%	3.09%	0.00%	0.00%	0.19%	0%	0%
PMES	82.9%[a]	0.88%	6.60%	4.77%	2.17%	1.14%	1.22%	0.00%	0.00%	0.09%	0%	0%
low-Zn BOSFS	86.01%	0.18%	7.20%	2.36%	0.63%	1.67%	1.76%	0.00%	0.00%	0.06%	0%	0%
BFFS	71.82%	0.49%	7.44%	11.53%	5.15%	0.37%	1.13%	0.00%	0.00%	0.27%	1.44%	0%
high-Zn BOSFS	86.17%	1.45%	8.57%	1.62%	0.20%	0.85%	0.89%	0.00%	0.00%	0.04%	0.01%	0%
EAFES	82.90%	0.25%	0.21%	0.45%	0.28%	1.28%	0.06%	0.00%	0.01%	0.00%	0.01%	0%

[a] Concentrations are adjusted in calculation of Fe_2O_3 yield to respect mass balance (73% for medium-Zn BFES and 74% for PMES). See below for further explanation.

Table 6
Iron-bearing phases in a dezinced product as determined by the XRD analysis.

Sample abv.	Fe_3O_4	Fe_2O_3	FeO	$ZnFe_2O_4$	Fe (metallic)
medium-Zn BFES	41.9%	55.5%	0.0%	0.0%	0.0%
low-Zn BFES	24.0%	64.6%	0.0%	0.0%	0.0%
PMES	–	–	–	–	–
low-Zn BOSFS	45.4%	54.4%	0.0%	0.0%	0.0%
BFFS	38.2%	54.4%	0.9%	0.0%	0.0%
high-Zn BOSFS	43.3%	55.1%	0.0%	0.0%	0.0%
EAFES	34.4%	64.6%	0.0%	0.0%	0.0%

Table 7
Dezincing, material recovery and iron-oxide recovery rates of sludge samples.

Sample	Dezinced product (kg)	ZnO removal (%)	Fe_2O_3 recovery rate (%)
medium-Zn BFES	0.764	96.6%	99.8%
low-Zn BFES	0.715	68.0%	67.3%
PMES	0.757	84.4%	99.7%
low-Zn BOSFS	0.783	78.1%	95.9%
BFFS	0.418	88.8%	48.1%
high-Zn BOSFS	0.778	82.8%	86.2%
EAFES	0.930	–	79.8%

respectively. This assumption stipulates that all the iron oxide traverses to the dezinced product.

3.2. Life cycle impact assessment and interpretation

3.2.1. Impact assessment and contribution analysis of dezincing

Environmental impact assessment results of the dezincing of sludges are shown in Tables 8 and 9, and contributions of impacts arising from each of the process stages of the dezincing are shown in Table 10 and presented graphically in Fig. 4. Average values are also shown as an indication of an average technology performance, and for the convenience of discussing impact assessment results. Impacts of dezincing shown in the process-only scenario are similar for most sludges given that the dezincing process is applied uniformly across samples with small differences in operating parameters. Variabilities in impacts among sludges mostly stem from different energy uses in the drying stage, given different initial moisture concentrations of sludge samples, and the amount of generated off-gas dust. This is consistent with the overall observation that the largest share of environmental impacts is associated with the processes of drying and smelting in TBRC (heating and use of oxygen) and disposal of off-gas dust. Given the use of natural gas for drying and roasting in TBRC, these trends are particularly visible in the impact categories of global warming, abiotic resource depletion (fossil fuels), and acidification, as these categories are commonly affected by the extraction and use of fossil fuels. Impacts associated with the landfilling of the off-gas dust from the TBRC process dominate the impact categories of abiotic depletion, human toxicity and freshwater ecotoxicity. On average, the use of oxygen contributes to about 10–20% of process-related burdens with higher burdens in the categories of photochemical oxidation, acidification and abiotic depletion. Carbon doping (material use and direct CO_2 emissions from combustion)

Table 8
Impact assessment results of dezincing of 1 kg of sludge.

	Abiotic depletion	Abiotic depletion (fossil f.)	Global warming	Human toxicity	Fresh water ecotox.	Terrest. eco-toxicity	Photo-chemical oxidation	Acidific-ation
	kg Sb eq	MJ	kg CO2 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg C2H4 eq	kg SO2 eq
medium-Zn BFES	3.84E-07	4.06E+00	3.47E-01	1.14E+00	1.77E+00	2.86E-03	2.64E-05	6.54E-04
low-Zn BFES	4.12E-07	3.60E+00	3.30E-01	1.30E+00	2.13E+00	2.99E-03	2.59E-05	6.37E-04
PMES	3.85E-07	4.32E+00	3.63E-01	1.17E+00	1.83E+00	2.93E-03	2.67E-05	6.66E-04
low-Zn BOSFS	3.43E-07	2.81E+00	2.67E-01	1.01E+00	1.63E+00	2.42E-03	2.19E-05	5.31E-04
BFFS	6.87E-07	4.07E+00	4.29E-01	2.45E+00	4.30E+00	4.80E-03	3.60E-05	8.80E-04
high-Zn BOSFS	3.66E-07	4.15E+00	3.48E-01	1.08E+00	1.67E+00	2.78E-03	2.58E-05	6.43E-04
EAFES	2.06E-07	2.62E+00	2.20E-01	4.43E-01	5.55E-01	1.52E-03	1.68E-05	4.10E-04
Average	**3.98E-07**	**3.66E+00**	**3.29E-01**	**1.23E+00**	**1.98E+00**	**2.90E-03**	**2.56E-05**	**6.32E-04**

Table 9
Impact assessment results of dezincing of 1 kg of sludge in the avoided-burdens scenario.

	Abiotic depletion	Abiotic depletion (fossil f.)	Global warming	Human toxicity	Fresh water ecotox.	Terrest. eco-toxicity	Photo-chemical oxidation	Acidific-ation
	kg Sb eq	MJ	kg CO2 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg C2H4 eq	kg SO2 eq
medium-Zn BFES	2.62E-07	3.34E+00	2.88E-01	9.30E-01	1.74E+00	1.40E-03	1.02E-06	−1.05E-04
low-Zn BFES	3.06E-07	2.98E+00	2.78E-01	1.12E+00	2.10E+00	1.71E-03	3.66E-06	−2.76E-05
PMES	2.62E-07	3.60E+00	3.03E-01	9.60E-01	1.80E+00	1.46E-03	1.01E-06	−1.01E-04
low-Zn BOSFS	1.97E-07	1.96E+00	1.97E-01	7.65E-01	1.59E+00	6.73E-04	−8.40E-06	−3.74E-04
BFFS	6.22E-07	3.69E+00	3.97E-01	2.34E+00	4.29E+00	4.02E-03	2.25E-05	4.77E-04
high-Zn BOSFS	2.22E-07	3.30E+00	2.78E-01	8.38E-01	1.64E+00	1.05E-03	−4.33E-06	−2.58E-04
EAFES	3.95E-08	1.64E+00	1.40E-01	1.62E-01	5.15E-01	−4.70E-04	−1.78E-05	−6.25E-04
Average	**2.73E-07**	**2.93E+00**	**2.69E-01**	**1.02E+00**	**1.95E+00**	**1.41E-03**	**−3.31E-07**	**−1.45E-04**

Table 10
Contribution analysis of different process stages in dezincing treatment of sludges showing percentage range and average values.

		Abiotic depletion	Abiotic depletion (fossil fuels)	Global warming	Human toxicity	Fresh water aquatic ecotox.	Terrest. Ecotox-icity	Photo-chemical oxidation	Acidif-ication
Carbon use	range	5–10%	2–3%	10–20%	1–6%	0–1%	3–10%	5–11%	5–10%
	avg.	**5.9%**	**2.4%**	**13.6%**	**2.5%**	**0.3%**	**6.0%**	**7.4%**	**6.8%**
Drying	range	2–7%	14–41%	8–31%	1–6%	<1%	4–16%	5–20%	6–23%
	avg.	**4.3%**	**29.9%**	**20.2%**	**4.1%**	**0.3%**	**10.2%**	**12.5%**	**14.5%**
Grinding	range	2–6%	1–2%	1–2%	0–2%	<1%	1–3%	1–3%	1–2%
	avg.	**3.3%**	**1.7%**	**1.3%**	**0.7%**	**0.1%**	**2.0%**	**1.9%**	**1.4%**
Heating (TBRC)	range	3–10%	32–53%	19–38%	2–12%	0–1%	7–23%	11–23%	13–27%
	avg.	**5.6%**	**40.1%**	**26.7%**	**5.6%**	**0.4%**	**13.5%**	**16.3%**	**19.0%**
Oxygen	range	12–39%	9–15%	8–15%	3–14%	1–5%	8–26%	18–39%	16–35%
	avg.	**22.9%**	**11.6%**	**10.8%**	**6.5%**	**1.8%**	**15.4%**	**27.4%**	**24.6%**
Rotation (TBRC)	range	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
	avg.	**0.1%**	**0.1%**	**0.0%**	**0.0%**	**0.0%**	**0.1%**	**0.1%**	**0.0%**
Off-gas dust landfill	range	32–79%	5–29%	11–49%	62–92%	93–99%	29–75%	15–57%	15–56%
	avg.	**58.0%**	**14.2%**	**27.4%**	**80.7%**	**97.0%**	**52.9%**	**34.3%**	**33.6%**

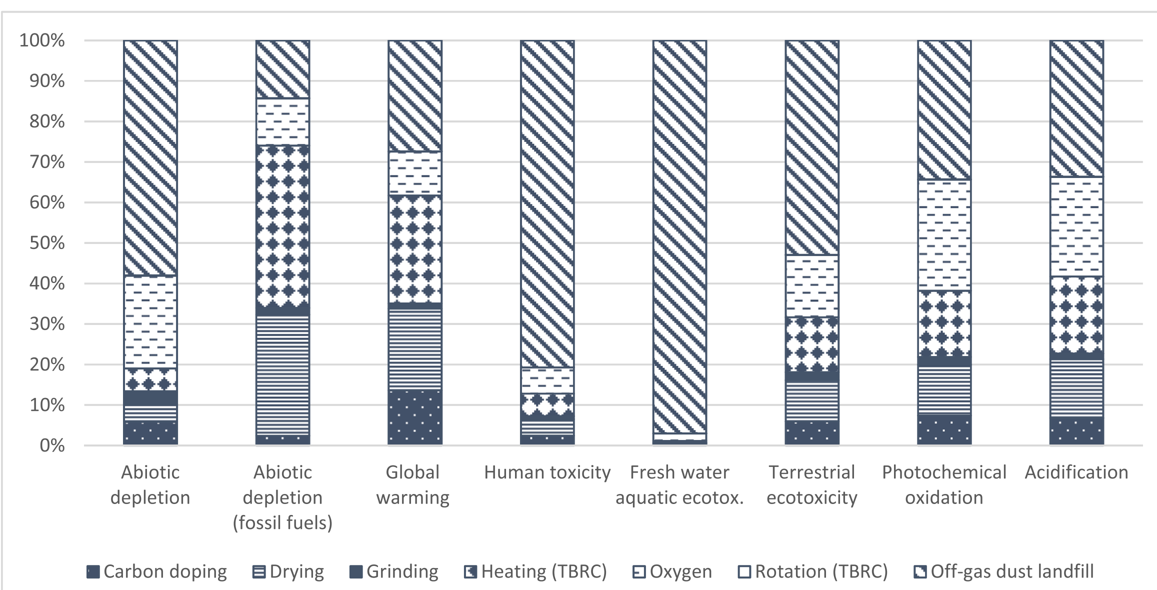

Fig. 4. Average contribution of different processes stages in dezincing of sludges.

contributes significantly to the global warming category (13.6% to process burdens) with a smaller contribution across other impact categories. Electricity use for grinding and rotation have negligible share of impacts. In the avoided-burdens scenario, impacts associated with the dezincing vary more widely among samples as benefits for avoided iron ore concentrate production are credited to the system, and given that the quantities of recovered iron vary among the sludge samples. On average, credits from avoided production offset the impacts of dezincing by around 20–30% for most of the impact categories. In the categories of photochemical oxidation and acidification the net impact reductions are observed, i.e., the net benefits of utilising this material as a substitute to the iron ore concentrate exceed the impacts arising in the dezincing treatment. During the iron ore mining, acidifying emissions arise due to the release of sulphur dioxide and sulfuric acid from oxidation and leaching of exposed sulphur-containing minerals, emissions of nitrogen oxide from the use of heavy machinery, and the use of nitrate-based explosives in mining. Smaller relative benefits are observed in the

human toxicity and freshwater ecotoxicity categories that are similar in

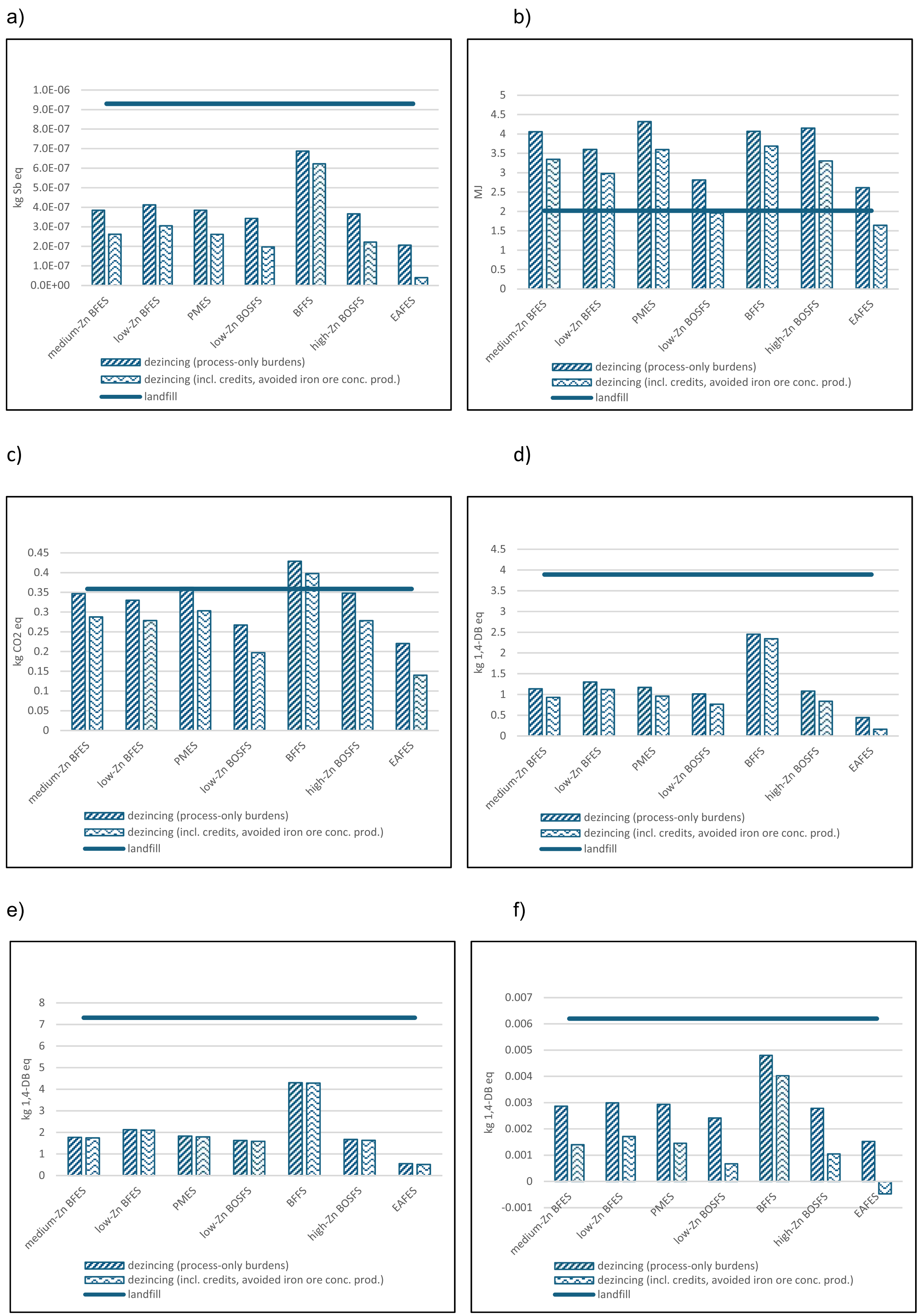

Fig. 5. (a–h). Comparison between dezincing and landfill: a) abiotic depletion category (kg Sb eq.), b) abiotic depletion (fossil fuels) category (MJ), c) global warming potential (kg CO_2 eq.), d) human toxicity potential (kg 1,4-DB eq), e) freshwater ecotoxicity potential (kg 1,4-DB eq), f) terrestrial ecotoxicity potential (kg 1,4-DB eq), g) photochemical oxidation potential (kg C_2H_4 eq.), and h) acidification potential (kg SO_2 eq.).

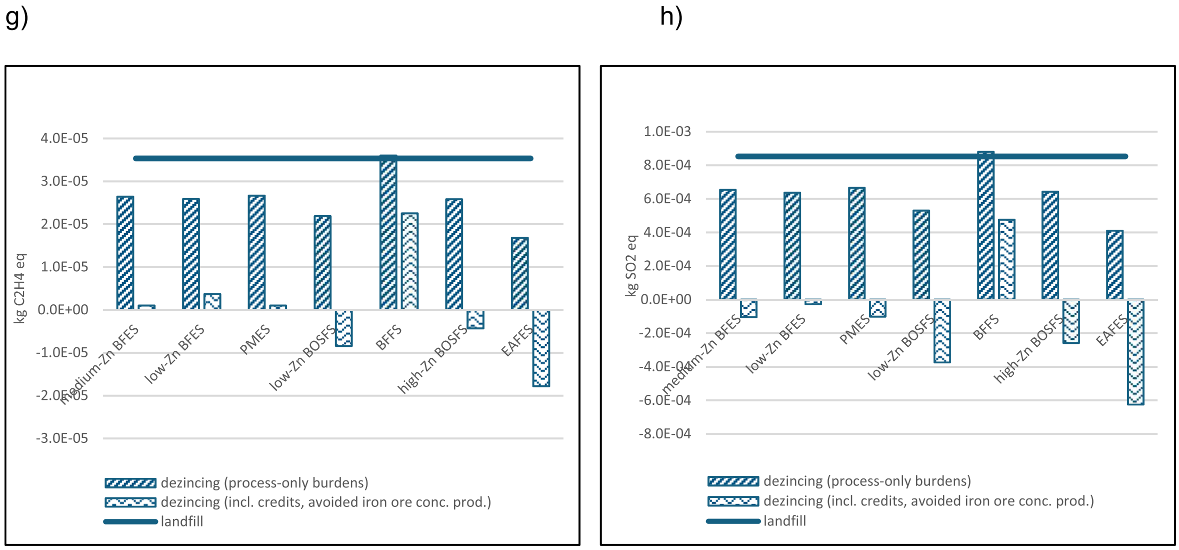

Fig. 5. (*continued*).

both the process-only and the avoided-burdens scenarios inferring that these categories are likely not significantly affected during the iron ore production. In terms of greenhouse gas emissions, indicated as CO_2 equivalents in the global warming category, a dezincing of 1kg of sludge emits an average of 0.33 kg of CO_2 eq., or 0.27 kg when the credits for the avoided production are factored in.

Dezincing of low-Zn BOSFS and EAFES sludges generates lowest impacts among sludges owing to their high material recovery (78.3% and 93%), high iron-oxide recovery (96% and 80%), and high concentration of iron oxide in the raw material (70.2% and 96.6%, in dry content), all contributing to a high iron-oxide recovery rate per 1 kg of dezinced product (0.72 and 0.83 kg). In contrast, the high impacts of dezincing of BFFS, relative to other sludges, mostly stem from the low material recovery rates (42%), low iron recovery rates (48.1%), and low concentrations of iron-oxide in the raw sludge (66.4%), which all contribute to higher projected quantities of waste off-gas dust sent to the landfill, and lower avoided burden credits. Impacts of high-Zn BOSFS are 20–40% higher than low-Zn BOSFS, almost exclusively due to higher moisture content in the raw sludge (9.4% in comparison to 31.7%), highlighting the effect of moisture on the overall impact of dezincing.

3.2.2. Comparison with landfill

Fig. 5(a–h) show comparison between landfilling and dezincing of seven sludges for the process-only and avoided-burdens scenarios. Overall, the dezincing appears to have lower impacts than landfilling in both of the dezincing scenarios. Steering material away from the landfill and putting it through the dezincing treatment generates less impacts for most of the sludges and across most of the impact categories except for the abiotic resource depletion (fossil fuels) category. The dezincing of BFFS is equal or worse than landfilling in four out of eight impact categories, in the process-only scenario. However, when accounting for the credits of avoided production, the dezincing generates higher impacts only in the global warming and abiotic depletion (fossil fuels) categories. Dezincing of most sludges can be accomplished at below 0.35 CO_2 eq, as emitted by landfilling, with an on average 15% impact reduction in the GWP category for the process-only scenario, and 22% for the avoided burden scenario. Dezincing have significantly lower impacts in the human toxicity and ecotoxicity categories investigated, representing a 2–3 fold reduction for all sludges.

3.2.3. Environmental trade-offs and design improvement opportunities

The results of environmental assessment show that the dezincing of sludges could be a meaningful strategy to reduce environmental impacts given lower emissions than landfilling in most impact categories. However, environmental impacts still occur and future design iteration should strive to minimise them. Primarily, further optimization of energy use for drying the sludge, residence time in the TBRC, and reduction in the use of carbon are possible and could further lower the impacts. Energy for drying could be lowered by controlling the water content during the sludge management and storage, or reducing the moisture levels by alternative low-energy means prior to the dezincing treatment. Reducing the residence time in TBRC could be possible without impeding the performance as some of previous studies show that high dezincing rates of 90–95% could be achieved at similar temperatures already after 30 min (She et al., 2011; Hai-hua, 2012). Similarly, while use of carbon is necessary to obtain good dezincing rates (Kurka et al., 2021), a further reduction from 10% could be possible. Wang et al. (2011) reported that 6% addition of carbon in the process of dezincing of steelmaking dusts led to the most optimal dezincing (99%) and iron recovery rates (96%) (Wang et al., 2011).

A possibility to substitute oxygen with air was also briefly explored but this strategy would likely result in shifting environmental burdens among impact categories and these trade-offs would need to be clearly understood before any recommendations were made. The substitution of oxygen with air would result in a reduction of impacts in the categories of abiotic depletion, photochemical oxidant depletion, and terrestrial ecotoxicity but the reduced efficiency of the combustion could result in increase of acidifying NO_x emissions. In addition, the oxy-fuel combustion enables more complete burning and higher carbon dioxide concentration in output gases, which might create opportunities for carbon capture and utilisation.

The impact of dezincing can also be influenced by further processing of the off-gas dust generated in the dezincing process to recover zinc metal. This recovery process has not been investigated in the scope of the current work. However, the off-gas dust from dezincing of sludges may contain up to 33% of zinc oxide and the additional step of zinc recovery could have an added economic and environmental benefits, including reduction of carbon emissions. Primary zinc production has been reported to generate around 2.6 kg CO_2-eq. per 1 kg of produced zinc (Van Genderen et al., 2016), and the zinc production from the steelmaking sludge and dusts was reported in a range value of 0.7–5.5 kg CO_2 eq. indicating potentially lower emissions of zinc derived through this secondary route (Ekman Nilsson et al., 2017). An observation that the zinc recovery from waste could have lower carbon emissions than the primary zinc production was also supported elsewhere (Salmi and Wierink, 2011; Rinne et al., 2022). However, other works suggest higher impacts in the global warming category (Viklund-White, 2000; Muica et al., 2021) and show that the zinc recovery is often associated with environmental trade-offs. In any case, the zinc extraction from off-gas dusts with higher zinc concentration are likely to be more favourable for further processing due to higher potential zinc recovery yield. In the context of this work, these include off-gas dusts from dezincing of medium-Zn BFES (up to 20.4% ZnO), PMES (up to 20.3% ZnO), and high-Zn BOSFS (up to 32.8% ZnO).

Achieving lower impacts of dezincing also stipulates that the dezincing process should be designed to achieve a dezincing with minimal loses of iron-oxide. The iron recovery rates affect both the quantities of displaced iron ore concentrate, and the quantities of secondary off-gas dust emitted. Lowering off-gas dust through better iron recovery will positively affect all the impact categories, and especially the ecotoxicity and human toxicity categories where the disposal of off-gas dust constitutes up to 97% of impact burdens. Moreover, avoided production burdens assigned to the iron recovery offset the impacts of dezincing by on average 20–30% across categories, making the dezincing decisively better decarbonization option than landfilling for most sludges.

The results of this LCA have to be interpreted in view of the scope of this assessment, modelling and data assumptions. The study is exploratory in nature and is meant to provide initial insight into the environmental performance of this technology while seeking to identify opportunities for future process design optimisation. The utility of this study could be improved using a measured data validated in a more optimised and scaled-up system and by addressing several data gaps discussed earlier. In addition, the scope could be extended beyond the environmental assessment, to also consider an economic feasibility of dezincing against sludge disposal to the landfill, and circularity and resource criticality in light on possible advantages and trade-offs of the dezincing to resource use and waste diversion (Young et al., 2010; Gemechu et al., 2017; Glogic et al., 2021).

4. Conclusion

A new pyrometallurgical route for dezincing and conversion of iron-rich waste sludges has been introduced and analysed for its environmental performance using the LCA method. The pyrometallurgical route achieves good dezincing and iron-recovery rates and can be applied to a variety of low zinc-bearing sludges arising in the iron and steelmaking processes. Analysis with LCA was able to identify the opportunities for impact mitigation of the dezincing process, and highlight the environmental benefits of the dezincing route in comparison to the disposal of this material to the landfill. Overall, a dezincing of sludges reduces environmental impacts in comparison to their landfilling in majority of investigated impact categories while further impact mitigation strategies could drive impact reduction further. Reducing the use of energy and reagents in the sludge preparation and roasting, and downstream capture and recovery of zinc from the TBRC off-gas dust, could potentially lead to further impact reductions. A low-impact dezincing technology should aim for high iron recovery rates which offset virgin ore concentrate production and reduce the volume of off-gas dust. Further research is encouraged to validate technical information and assumptions underpinning this assessment.

CRediT authorship contribution statement

Edis Glogic: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Hichem Hakka:** Data curation, Investigation, Project administration. **Kehinde Makinde:** Data curation, Investigation, Writing – review & editing. **Lucy Smith:** Funding acquisition, Project administration, Writing – review & editing. **Ji Fuzhong:** Data curation, Investigation, Writing – review & editing. **Stuart Higson:** Data curation, Investigation. **Richard Thackray:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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