The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-023-02274-7

LCA FOR MANUFACTURING AND NANOTECHNOLOGY

Attribution of Global Warming Potential impacts in a multifunctional metals industry system using different system expansion and allocation methodologies

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Received: 21 April 2023 / Accepted: 20 December 2023

Abstract

Purpose In order to reach a more circular economy, materials previously classified as waste can be upgraded and turned into valuable co-products, with associated environmental benefits. The generation of co-products raises many questions around the multifunctionality issue from a life cycle perspective. This article explores the attribution of Global Warming Potential (GWP) impacts for an ironmaking process, HIsarna, which additionally produces two co-products: zinc-rich process dust and slag, suitable for the zinc and cement sectors, respectively.

Methods A wide range of LCA allocation methodologies are applied to attribute impacts between the main product, hot metal, and the two co-products. These include system expansion, physical allocation, economic allocation and zero burden allocation. Each method attributes a different GWP to each co-product. Additionally, different perspectives are explored to consider the most suitable methods according to the co-product user and the co-product producer. For instance, it might be in the co-product user's interest that the co-product GWP was minimised, and lower than other material inputs performing a similar function. Conversely, the co-product producer may be incentivised to lower its primary product's GWP by attributing the greatest possible burden to the co-products.

Results and discussion The GWP impacts for zinc-rich process dust range from 0 to 3.71 kg CO_2 eq. per kg. At the higher end, the GWP of zinc-rich dust would be higher than that of primary zinc concentrate. A similarly wide range is applicable for slag, 0 to 1.27 kg CO_2 eq. per kg. This impacts the final GWP applied to HIsarna hot metal, which has an initial GWP of 1.72 kg CO_2 eq. per kg but could decrease to 1.17 kg CO_2 eq. per kg depending on the allocation methods employed. This would be a substantial reduction of over 30%, larger than many decarbonisation options that are predicted to provide. This scenario would also heavily burden the co-products and could be in conflict with interests of a co-product user seeking to utilise low emissions feedstocks as part of a decarbonisation strategy.

Conclusions The reduction in GWP impact attributed to hot metal with the different approaches highlights the relevance of harmonizing the allocation methods used for co-products. The appropriateness of each of the approaches for attributing GWP impacts has been explored, offering insights as to how the benefits of such systems could be assessed and attributed in the future as circularity strategies and valuable co-products become more prevalent.

Keywords Life cycle assessment · Multifunctionality · Multi-functionality · Steel · Co-products · Allocation · System expansion · Circular economy · Zinc

1 Introduction

The design and manufacture of goods according to circular economy principles would avoid generating waste in the first place and lead to "closing the loop" by recirculating products and materials so they can become new materials. This could contribute to the supply security of materials, such as metals, in the foreseeable future. Materials previously

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Communicated by Andrea J Russell-Vaccari.

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considered wastes can be upgraded and turned into valuable co-products, with associated environmental benefits. Recycling waste materials generates new products and this raises many questions around the multifunctionality issue from a life cycle perspective.

Steel is well placed to be part of the circular economy. Steel is reusable and recyclable, the recycling technologies are proven and well established. Due to the value of steel scrap, it is widely recovered currently. Although figures differ, the overall steel recycling rate in the USA was 71% in 2019, with higher rates depending on the sectors (AISI and SMA 2021). The recycling rate for structural steel in the USA is 97%, and 96% from the automotive sector. Similar values are observed in Europe (Tata Steel 2022; EuRIC AISBL 2022; APEAL 2023). Slag, the main co-product of steelmaking, can be used to make cement, where it can reduce the CO_2 emissions by 50% (UKCSMA 2023). It is also used in road-making and as a fertilizer. Other co-products include dust and sludge, which are rich in iron and other metals and can be recycled back through the process (ArcelorMittal, 2022). The steelmaking process can be adjusted to maximise recovery of metals in the process dust, such as zinc, so it can become a secondary input in the production of zinc.

The recovery of zinc is a key issue. China is the largest producer of zinc globally, accounting for 32% of the zinc mine production in 2022 (ILZSG 2022). Australia is another major zinc supplier, accounting for 11% of the global zinc mine production (TDi and RMI 2022; USGS 2023). While there are enough extractable resources to ensure the long-term availability of zinc, there may be a short-term supply risk due to very limited exploration efforts in recent years. Zinc prices can be volatile and heavily depend on events in China. For instance, concerns over Chinese refined zinc output were one factor that contributed to prices reaching a multi-year high in June 2021 (Luke Nickels 2021). Similarly, prices rose over 2020 as lockdowns in various countries slowed production. In addition, the World Bank indicates that the growth of zinc mines and refineries in China is at risk due to safety and environmental concerns, suggesting that supplies may struggle to keep pace with increased demands (World Bank Group 2021). At national and regional level, critical or strategical raw materials and their availability from local sources for green transition technologies move into focus. Increasing zinc recycling is a meaningful and increasingly important additional source in supplying future zinc demand at global, regional and national level (Grund et al. 2019). On average, 13% of all refined special high grade (SHG) zinc produced in 2019 came from secondary sources, mostly from zinc-rich steel mill dusts (IZA 2022a). An additional 6 million tonnes of zinc were recycled by remelting zinc from zinc metal scrap and zinc containing industrial residues (Rostek et al. 2022). Zinc produced from secondary materials has a lower environmental impact in terms of land-use, water consumption and resource depletion. Remelting zinc metal scrap has a much lower carbon footprint than primary zinc produced from ore. However, the recycling of zinc from its main use — galvanized steel — increases the Global Warming Potential of the product (SHG zinc) (IZA 2022a).

When recycling galvanised steel, the scrap is usually remelted in electric arc furnaces (EAF) for steel recovery. In this process, zinc is found in the flue dust, the so-called EAF dust is too low in zinc concentration for direct use as a raw material for zinc production. The availability of zinc-free scrap is decreasing; as a result, the zinc content of dusts and sludges is increasing (Ma 2016; Stewart et al. 2022). A consequence is that larger amounts of these residues must be sent to landfill. The tightening of legislation around landfilling of these materials makes landfilling less attractive and potentially impossible in the future (Jalkanen et al. 2005). EAF dust, rich in iron, zinc, and other metals, is classified as hazardous waste in Europe and the USA. Landfilling of EAF dust is strictly regulated (Suetens et al. 2014), and alternative uses would be beneficial to the steel and the zinc smelting industries. The standard method for enriching zinc in EAF dust and thus making it a suitable raw material for primary zinc production is the Waelz process. It is considered the best available technology for recycling EAF dust (Grudinsky et al. 2019; Genderen et al. 2021). However, the final product has a relatively high content of impurities, such as halides (e.g., chlorides and fluorides) which are removed in an additional washing step (Antrekowitsch et al. 2015). Another limitation is the loss of iron to the slag during recovery (Lin et al. 2017). To increase profitability of the Waelz process, the minimum zinc content of the feed materials (mainly EAF dust) should be above 15%, limiting the feedstocks that can be input into the kiln. Other low zinc containing dusts arise in today’s steel production, such as basic oxygen steelmaking dust. Mostly the zinc concentration in these dusts is too low to allow for a financially viable zinc recycling.

The HIsarna process is an innovative smelting reduction technology developed by Tata Steel as a low carbon smelting reduction technology (ULCOS 2010). Innovative smelting reduction technologies have been identified as (near-) zero-emissions technologies when combined with Carbon Capture Storage and Utilisation (CCUS) (MPP 2021). It is an alternative to the blast furnace process and removes several pre-processing steps, such as sintering and pelletising (Fig. 1). As the process gases from HIsarna are more suited for CCUS applications, this technology can be an important option for near-zero emissions steelmaking. In the HIsarna process, the injected iron ore melts and is converted into liquid hot metal. Hot metal can be used as an input in Basic Oxygen Steelmaking (BOS) to produce crude steel. The main product from HIsarna is hot metal; however, slag is also produced alongside it. Additionally, zinc-bearing

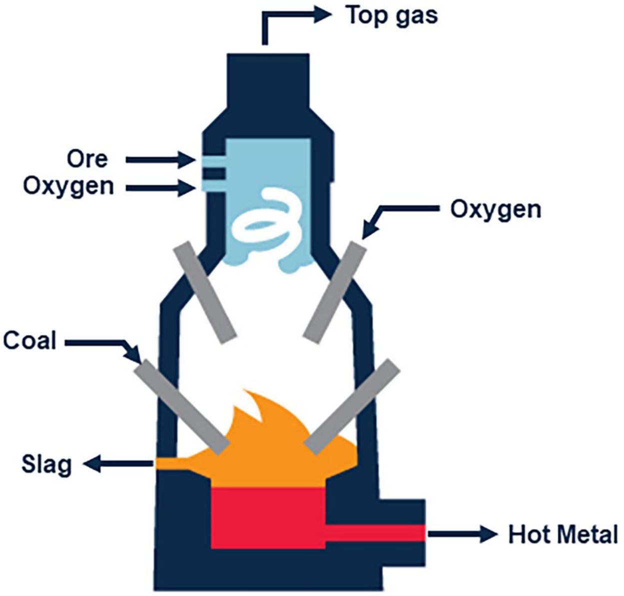

Fig. 1 The HIsarna plant consists of a cyclone converter furnace (upper part) and a HIsmelt vessel (lower part)

residues can be injected into the HIsarna reactor. The zinc evaporates and is removed with the exhaust gas. HIsarna is a promising alternative for the treatment of zinc-bearing residues as it allows for the recovery of zinc from both high and low zinc residues, as well as galvanised zinc-coated steel, and the recovery of iron from those inputs into hot metal. However, this configuration makes the HIsarna process multifunctional. Understanding the environmental impacts of the hot metal, slag and zinc-rich dust in this multifunctional system is not straightforward.

This study builds on the findings of the ReclaMet project (EIT RawMaterials 2018), a project that explored the recovery of zinc and iron from zinc-containing residues with HIsarna. Earlier tests indicated the possibility of concentrating zinc into the HIsarna process dust (Kerry et al. 2022). This recycling promotes a more circular economy and closes the waste material loops from the zinc and automotive industries (Kerry et al. 2022). The flow of products and secondary materials can be seen in Fig. 2. Slag is also produced as a co-product from HIsarna and can be used as an input in the cement and concrete industry. Currently, no co-products or waste streams from the cement industry have been tested in HIsarna and this represents an open material loop.

Many institutions have created emissions trajectories and climate mitigation targets for each sector to reach net zero. This includes the steel sector (ArcelorMittal et al. 2021). When considering the different co-products in a system, understanding their GWP impact becomes key to ensuring that the current and future sectoral emission targets are accurate. Additionally, it supports monitoring and setting realistic science-based targets (SBTs). Life Cycle Assessment (LCA) has become the most commonly used method for assessing the environmental impact of a product or process. The

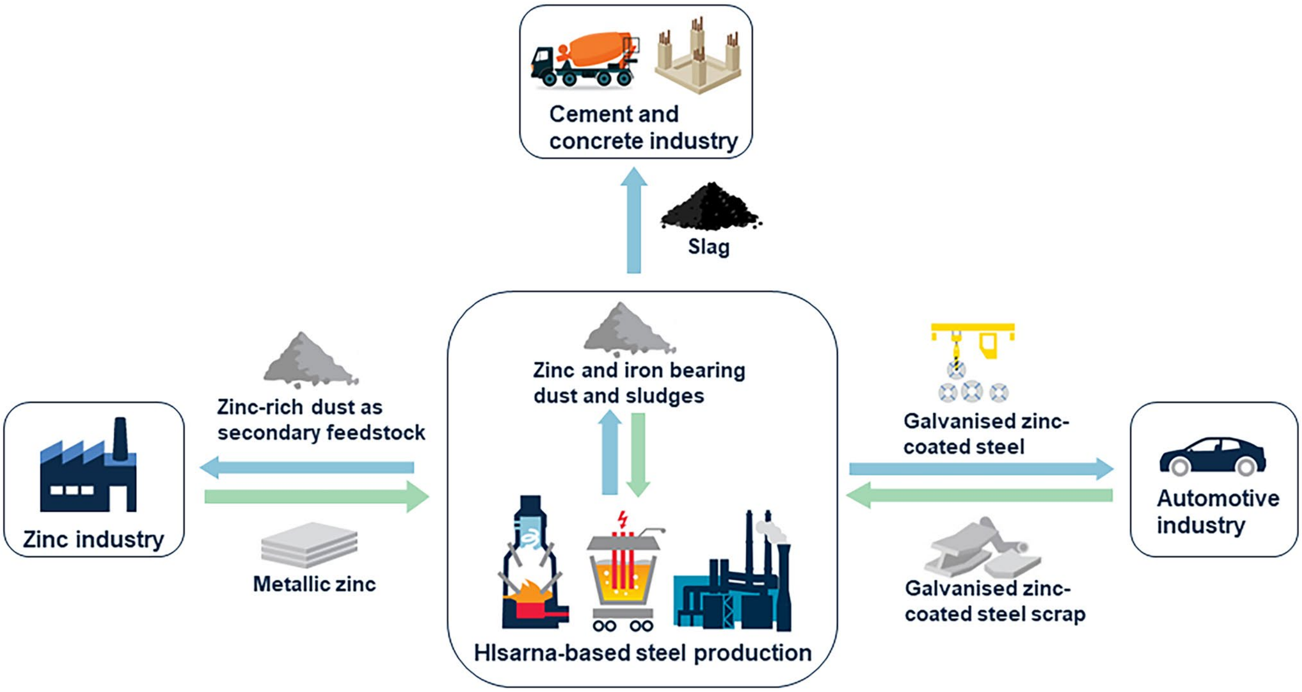

Fig. 2 HIsarna and the circular economy

allocation method used to share emissions between the product and co-products may have a significant impact on their respective GWP. Depending on the method used to attribute emissions to the co-product, the co-product GWP impact may be different, which could affect the GWP impact of the main product (e.g., hot metal). While many published LCAs focus on systems with one product, other studies fail to address this multifunctionality issue (Cherubini et al. 2018). This provides an incomplete picture of the system, and the full picture including the different co-products has to be considered. This paper will assess the effect of several allocation and system expansion methods on the Global Warming Potential (GWP) of the multifunctional HIsarna process by assessing the issue of two co-products, zinc-rich process dust and HIsarna slag. This supports a more complete and accurate picture of the GWP impacts of various industries, by understanding the GWP of each co-product. The addressed audience of the paper is the steel industry, zinc industry, and LCA practitioners interested in the broader discussion concerning the attribution of environmental impacts in multifunctional and multi-sectoral systems.

2 Methodology

Different LCA allocation methods exist to address the issue of multifunctionality. To deal with multifunctionality, the ISO 14044 recommends the following hierarchy (ISO 2006a, b): (1) Subdivision, (2) System expansion, (3) Allocation (physical relationship) and (4) Allocation (by other relationships). A summary of the main methods relevant to this study is shown in Table 1, with their strengths and limitations. Aside from this hierarchy, there is little guidance for LCA practitioners to deal with the issue of multifunctionality. Some authors have published recommendations for dealing with co-products from specific sectors such as the metals industry (Santero and Hendry 2016) and zinc in particular (IZA 2022b), with variations of the hierarchy provided by the ISO standard. Other authors have developed an allocation method decision tree to aid in the decision of allocation method depending on the goal of the study (Ijassi et al. 2021). However, these publications focus on one co-product at a time, without considering the interactions between co-products and the need for a consistent approach across the full system. This general lack of guidance leads to inconsistencies and different approaches for similar multifunctionality problems in LCA, producing divergent results. Furthermore, justifications for the choice of approach are not commonly provided (Kyttä et al. 2022). This issue is further complicated as the ISO standard makes no distinction between different modelling approaches such as attributional and consequential LCA (Pelletier et al. 2015).

The choice of allocation method can create significant uncertainty on the results of LCA studies (Cherubini et al. 2018). This uncertainty can mislead decision-makers in comparing scenarios (Geisler et al. 2005). An uncertainty analysis is not always included in LCA studies. It would support the interpretation of LCA results, and it could verify that the results for each scenario are different (Huijbregts et al. 2001). Other authors have previously studied the uncertainty due to allocation methods (Mendoza Beltran et al. 2016, 2018; AzariJafari et al. 2018; Cherubini et al. 2018). A sensitivity analysis should be performed for multifunctional systems to assess the uncertainty created by the different allocation methods. This study is the first in which the choice of allocation method has been evaluated for HIsarna and its application for zinc recovery, enabling the assessment of uncertainty when different allocation methods are used.

One of the key issues from an LCA perspective is that the production of hot metal, slag and zinc-rich dust cannot be divided into sub-processes. The main product and co-products are produced simultaneously. For this reason, subdivision has not been considered any further in this study (Step 1:1 of the allocation procedure in ISO 14044:2006). The current worldsteel methodology on Life Cycle Inventory Methodology (Worldsteel Association 2017) proposes using system expansion to deal with multifunctional systems. This method "expands" the system boundaries beyond the steelmaking process to incorporate those processes avoided due to the production of co-products in the multifunctional system. Other standards, e.g. ISO 20915, provide more specific substitution options for different co-products.

The function of the system is defined as the production of 1 kg of hot metal from HIsarna. For this study, GWP (over 100 years) has been assessed. The CML2001 (Aug. 2016) method is used to assess the GWP impacts of the inventory data, as a means to explore the issues of attribution in multifunctional systems CML was developed at Leiden University and followed guidelines established by ISO 14044 (2006b) and by the International Life Cycle Data System (ILCD), developed by the European Commission Joint Research Centre (2011). The LCA is a cradle-to-gate study, including in the system boundary the raw material inputs into the HIsarna process and the zinc-rich feedstocks up until the production of the hot metal, slag, and zinc-rich process dust from HIsarna. The system boundary is depicted in Fig. 3.

2.1 Co-products under study

2.1.1 Zinc-rich process dust

In order to assess the recovery of zinc in HIsarna process dust, EAF dust has been considered as an input. The zinc content in EAF dust depends on the composition of scrap used in specific furnaces. It can vary from 2 to 43 wt%

Table 1 Summary of advantages and limitations of each attribution method

Attribution method	Definition	Strengths	Limitations
Subdivision	It disaggregates a process into smaller units	• It is the preferred solution to deal with multifunctionality in the ISO standards (ISO 2006b)	• The production of co-products tends to be simultaneous, and subdivision is not always possible
System expansion / substitution	It assesses the avoided burden (substitution) or expands the system boundaries and functional unit to reflect both functions (system expansion)	• It is the second option in the ISO standards • It encourages an understanding of what processes the co-product is replacing/substituting • It avoids arbitrary decisions about allocation factors (Kyttä et al. 2022)	• Every co-product may have different uses; therefore, different avoided burdens may be applicable, making it more challenging to implement. Choosing the most representative use comes down to the LCA practitioner • Some argue that for attributional LCA, only physical burdens should be considered and not avoided burdens that don't occur (Brander and Wylie 2011). This approach may lead to misleading negative LCA results • Others argue that more clarity is needed to distinguish substitution from system expansion and whether their use is appropriate for attributional LCAs (Brander and Wylie 2011; Pelletier et al. 2015)
Physical allocation	Physical properties of the different flows are used to allocate the environmental impacts of the process. For example, volume, mass, energy, or exergy are usually used for physical allocation	• It is the third option for dealing with multifunctionality according to the standard • It provides an easy and straightforward connection between the different products • This approach is preferred when the economic values between co-products are similar	• Some authors contest that more clarity is needed to define "physical relationship" as this might include causal or other physical relationships (Ekvall and Finnveden 2001; Guinée et al. 2004) • "Arbitrary physical relationships (i.e., mass, volume, or energy content) should be avoided as they don't capture the changes in the system when products or functions change" (Guinée 2001) • For some systems, it may not be possible to identify a representative physical criterion for attributes such as taste or comfort (Ardente and Cellura 2012) • It might attribute significant burdens to low-value co-products
Economic allocation	The environmental impact is divided according to the economic value of the co-products	• The economic incentive usually drives the production of the main product and co-products. This approach would partition the environmental impacts according to their degree of responsibility (Weinzettel et al. 2012). Most widely used approaches for multifunctionality (Beccali et al. 2010; van der Voet et al. 2010) • Prices are helpful proxies for value or other attributes (e.g., artistic) not represented by physical qualities (Ardente and Cellura 2012) • It solves the issue of attributing large burdens to low-value co-products	• It is subject to uncertainty as prices may not be publicly available for some products (i.e., if a market does not exist for intermediate products) and are subject to market volatility. Prices are affected by monopolies or oligopolies or where there are government interventions (Guinée et al. 2004) • A low-cost co-product might be regarded as less environmentally harmful and may indicate that utilising or recycling materials would not be beneficial from an environmental perspective (Pelletier and Tyedmers 2011; Weinzettel et al. 2012) • The economic value might not reflect the actual value to society

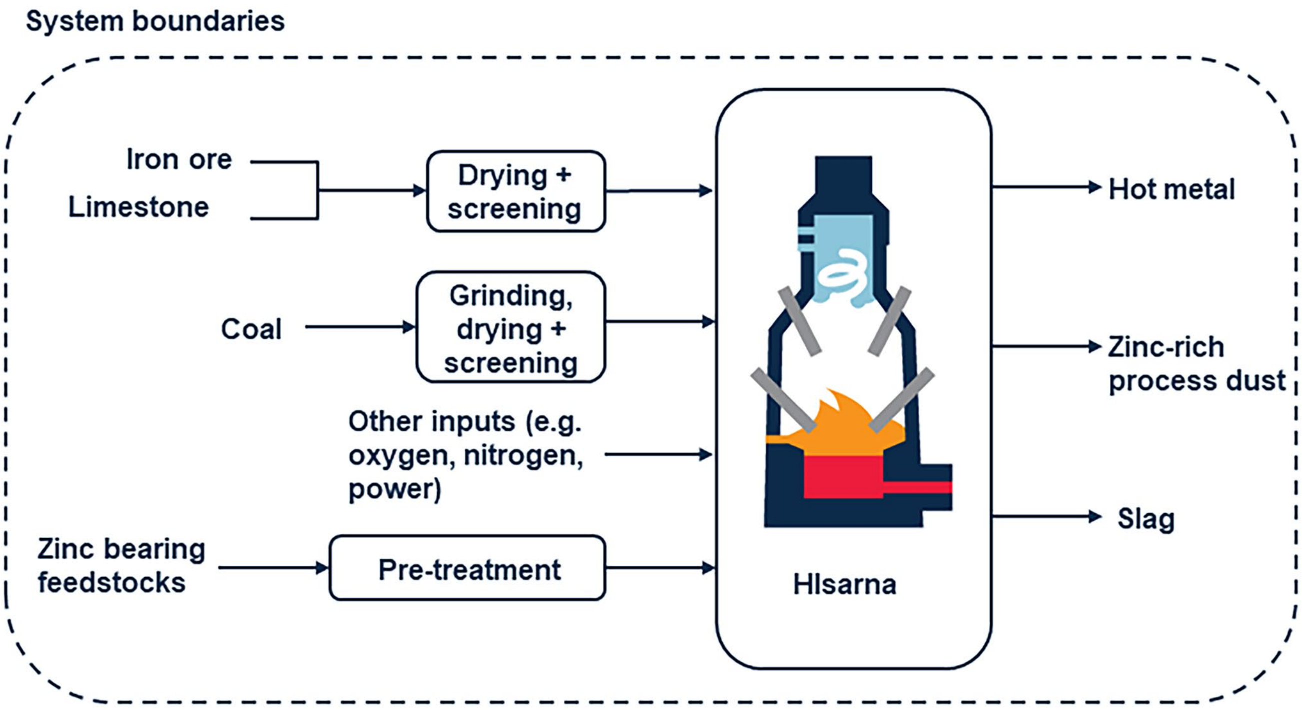

Fig. 3 System boundaries for the LCA

(Abdel-Latif 2002; Doronin and Svyazhin 2011; Lin et al. 2017; Genderen et al. 2021). For this study, EAF dust with a zinc concentration of 20 wt% is assumed. When the zinc-rich residues are input into HIsarna, the zinc is vaporised, and the zinc concentration in the HIsarna off-gas can be significantly increased. The concentration of zinc in the process dust is 69 wt% zinc oxide (56 wt% zinc) in this study, similar to that of Waelz kiln oxide. On the other hand, the primary zinc ores contain 5–15 wt% of zinc (IZA 2022a) which is concentrated in the beneficiation process to primary zinc concentrate containing 53–55 wt% zinc. The difference in concentration with the primary zinc ore illustrates the high potential of the zinc-rich dust in being used as secondary raw material for zinc production.

2.1.2 Slag

The second co-product of the HIsarna process is slag, which has similarities to blast furnace slag. There have been several studies considering the allocation methods for blast furnace slag (Lee and Park 2005; Chen et al. 2010; Crossin 2015; Li et al. 2016). Traditionally, blast furnace slag has been used by the cement and concrete industry. It can be used as a substitute for Portland cement clinker in cement production. This replacement reduces the need for clinker from limestone in the cement sector and reduces the sector's emissions. It is also used as a direct replacement of Portland cement in ready mixed concrete. HIsarna slag is considered functionally equivalent to blast furnace slag for this study.

2.2 LCA data and model

Process data from a HIsarna full-scale model simulation has been used in this study to assess the operation of full-scale HIsarna when recovering zinc from zinc-rich reverts. This process model was developed in-house by Tata Steel Netherlands to assess the technical and economic feasibility of full scale HIsarna. It considers the chemical reactions and kinetics inside the furnace to calculate accurately the mass and energy balances of the process. As the process model contains commercially sensitive information, a summary only of the input and output data is shown in Table 2. These foreground inventory data have been input into a GaBi model to assess the GWP of HIsarna as referred to 1 kg of hot metal, using GaBi 10.6 (2022) and Ecoinvent 3.8 inventory data. The datasets used in the model are shown in Table 3. The list of allocation methods and details about the assumptions are included in Table 4.

3 Results and discussion

The GWP of HIsarna hot metal with the HIsarna full scale model data is 1.72 kg CO2 eq./kg hot metal. This is the impact of baseline HIsarna, when no zinc-rich feedstocks

Table 2 Summary of the main input and output data from the HIsarna full scale model

Main inputs		Main outputs	
Iron ore	271 tonne/h	Slag	56 tonne/h
Coal	118 tonne/h	Hot Metal	180 tonne/h
Limestone	12 tonne/h	Zinc-rich process dust	7 tonne/h (69% wt ZnO)
Oxygen	133 kNm^3/h	Flue gas	337 tonne/h
Nitrogen	6 kNm^3/h		
Net power export	62 MWh		
Zinc-rich reverts:			
EAF dust	6 tonne/h		

are added and zinc is not recovered in the dust. In baseline HIsarna, some co-products/by-products receive a system expansion GWP credit according to common practice. The co-products/by-products that receive a credit are gypsum, beach iron and slag. These co-products and their credits are reflected in Table 3. Different allocation methods were considered for zinc-rich process dust and slag. The GWP results for each co-product, according to each allocation method are shown in Table 4.

3.1 Attribution of GWP impacts with one co-product: zinc-rich process dust

The results for each multifunctionality approach are represented in Fig. 4 when considering only one co-product, zinc-rich dust. The Y-axis shows the GWP impact of the zinc-rich dust according to the different approaches. The range of GWP impact on zinc-rich process dust with the methods explored starts at 0 and increases to 3.71 kg CO_2 eq./kg zinc-rich dust. The X-axis shows the GWP impact of hot metal. When HIsarna zinc-rich dust is not attributed a burden or impact, all the emissions stay with the main product, the hot metal. In this case, the GWP of the hot metal remains 1.72 kg CO_2 eq. per kg. As a higher GWP impact is attributed to the zinc-rich dust, the GWP impact of hot metal is reduced to 1.57 kg CO_2 eq. per kg. The reduction in GWP of hot metal is relatively small with any approach due to the difference in hot metal and zinc-rich dust outputs, with a maximum reduction in the GWP of hot metal of 8%. Although the economic allocation shown here has illustrative figures, this approach burdens the zinc-rich dust the most. Mass allocation gives the zinc-rich dust a GWP impact of 1.65 kg CO_2 eq./kg dust, which falls in the middle of the range. Functionally, Waelz kiln oxide would be the most similar to HIsarna zinc-rich dust, based on a 69 wt%

Table 3 Summary of datasets used

Item	Dataset	Year	Source
Datasets used for HIsarna LCA model			
Electricity	NL: Electricity grid mix	2017	GaBi
Iron ore	GLO: Iron ore mining and processing – region variable	2018	GaBi
Limestone	DE: Limestone (CaCO3, washed)	2020	GaBi
Compressed air	EU-28: Compressed air, 10 bar, low efficiency	2017	GaBi
Coal	EU-28: Hard coal mix	2017	GaBi
Nitrogen	NL: nitrogen (gaseous)	2020	GaBi
Quicklime	NL: lime (CaO, quicklime, lumpy)	2020	GaBi
Oxygen	NL: oxygen (gaseous)	2020	GaBi
Gypsum (Credit used for gypsum)	EU-28: Gypsum (CaSO4 alpha hemihydrate from FGD gypsum) (EN15804 A1-A3)	2020	GaBi
Slag (Credit used for slag)	EU-28: Cement (CEM I 42.5) (burden free binders) (EN15804 A1-A3)	2020	GaBi
Sludge bleed to disposal	EU-28: Hazardous waste (statistical average) (C rich, worst case scenario incl. landfill)	2020	GaBi
Beach iron (Credit used for beach iron)	GLO: Hot metal 2018 – 1 kg weighted average v3 18–12-13 worldsteel [2018]	2018	Worldsteel
Waste water treatment	EU-28: Municipal waste water treatment (sludge treatment mix)	2020	GaBi
Datasets used for upstream impacts of zinc-rich reverts			
Special high-grade zinc	GLO: special high-grade zinc IZA	2018	GaBi
Datasets used for the Waelz kiln model (not listed before)			
Coke	NL: PET coke at refinery TS	2014	GaBi
Silica	DE: Silica sand (flour) ts	2019	GaBi
Lime	EU-27: Hydrated lime	2015	GaBi

Table 4 Attribution methods assessed for zinc-rich process dust and slag

	Attribution method for zinc-rich dust	GWP (kg CO_2 eq./kg zinc-rich dust)	Reference	Attribution method for slag	GWP (kg CO_2 eq./kg slag)	Reference
System expansion	A. Product replaced: Primary zinc concentrate Primary zinc concentrate is produced from zinc ore and used as an input for the zinc smelting process (van Genderen et al. 2016; Nilsson et al. 2017). The concentration of zinc is approximately 55% for primary zinc concentrate (IZA 2022a) and 56% for HIsarna zinc-rich dust. As the concentration of metallic zinc is very similar, primary zinc concentrate is considered an appropriate proxy for the GWP of HIsarna zinc-rich dust	0.44	Ecoinvent dataset for “Zinc concentrate”	A. Product replaced: Silicate fertiliser slag can be used as a fertiliser, providing SiO_2 and acidic soil improvement (Lee and Park 2005)	0.155	(Lee and Park 2005)
	B. Product replaced: Waelz kiln oxide This is a secondary zinc source in the zinc smelting process The Waelz kiln process concentrates the ZnO in EAF dust to a suitable level for input into the zinc smelting process (Muica et al. 2021). The main product is Waelz kiln oxide, with a very similar ZnO concentration (71% ZnO (Ruetten and Crittendon 2006)) as HIsarna zinc-rich dust (69% ZnO). This product is considered a good substitution for calculating the impact of HIsarna process dust as a secondary zinc source	2.74	In-house model results for Waelz kiln oxide based on data from Ruetten et al. (2006)	B. Product replaced: Cement clinker slag could be used in the cement manufacturing industry, reducing the clinker used for the cement product. Currently, more than 90% of Granulated Blast Furnace Slag (GBFS) is used as raw materials for Portland cement and slag cement (Lee and Park 2005), and it is assumed that HIsarna slag would have similar uses	0.875	(Lee and Park 2005)

Table 4 (continued)

	Attribution method for zinc-rich dust	GWP (kg CO_2 eq./kg zinc-rich dust)	Reference	Attribution method for slag	GWP (kg CO_2 eq./kg slag)	Reference
	C. Product replaced: Special high-grade zinc in a 2:1 mass ratio Following the standard BS ISO (2018). This method assumes that 2 kg of zinc-rich dust would displace 1 kg of special high-grade zinc for the purposes of calculating the GWP This method uses the most reliable datasets from the International Zinc Association, published by van Genderen et al. (2016). The authors acknowledge that zinc-rich dust is not functionally equivalent to high-grade zinc, even at 50%, however this allocation method is outlined in the standard and included here for consistency	1.31	High-grade zinc from primary zinc sources (Van Genderen et al. 2016)	C. Product replaced: Portland cement GBFS is used as raw material for slag powder, which reduces the amount of Portland cement, which is used as a raw material for ready-mixed concrete. In this case, GBFS would replace Portland cement, and HIsarna slag is assumed to have similar uses as GBFS	0.871	(Lee and Park 2005)
Mass allocation	The attribution of impacts is based on the relative amount of zinc-rich dust recovered from HIsarna compared to the amount of Hot Metal produced. This study attempts to assess the GWP of the co-products, so the mass of the co-products is used and not their metal content, e.g., iron or zinc, for consistency in the results with the other attribution methods	1.65 (for 1 co-product), 1.27 (for 2 co-products)		The attribution of impacts is based on the amount of slag produced compared to the amount of Hot Metal	1.27	

Table 4 (continued)

	Attribution method for zinc-rich dust	GWP (kg CO_2 eq./kg zinc-rich dust)	Reference	Attribution method for slag	GWP (kg CO_2 eq./kg slag)	Reference
Economic allocation	Option a. Assumes a net zinc dust price of 600 €/t and 424 €/t for hot metal The zinc dust price is based on LME prices. The net zinc dust price is derived from the LME price, assuming a treatment charge of 250 €/t is added to the net zinc price and assuming only 85% of the ZnO concentration in zinc-rich dust would be valued due to possible losses in the processing steps. Although a higher percentage of ZnO is likely to be recovered, 85% was used a conservative estimation LME price = (Net zinc dust price + Treatment charge) / (% ZnO * 85%) The hot metal price was obtained from the International Steel Statistics Bureau	2.30	London Metal Exchange (2022)	Option a. 25.6 €/t slag, 424 €/t hot metal and 600 €/t zinc-rich dust The assumption for slag price is based on the 2020 slag price from the US Geological Survey (2020)	0.097	US Geological Survey (2020)
	Option b. Assumes a net zinc dust price of 800 €/t and 424 €/t for hot metal	3.02	Same as option a	Option b. 41.8 €/t slag, 424 €/t hot metal and 600 €/t zinc-rich dust The assumption for slag price is based on 2021 prices from ISSB	0.156	(ISSB 2022)
	Option c. Assumes a net zinc dust price of 1000 €/t and 424 €/t for hot metal	3.71	Same as option a	-	-	

Table 4 (continued)

	Attribution method for zinc-rich dust	**GWP (kg CO_2 eq./kg zinc-rich dust)**	**Reference**	**Attribution method for slag**	**GWP (kg CO_2 eq./kg slag)**	**Reference**
Burden-free co-product	This approach is considered in this study, although it is not part of the methodologies included in the ISO standards. With this approach, the zinc-rich dust would carry no burden or environmental impact. This approach would make the zinc-rich dust a more attractive co-product for the co-product user if low carbon feedstocks were part of their decarbonisation strategy. On the other hand, this can impact the co-product producer (HIsarna), who retains all the emissions from the process	0		A zero-allocation approach was also considered for slag	0	

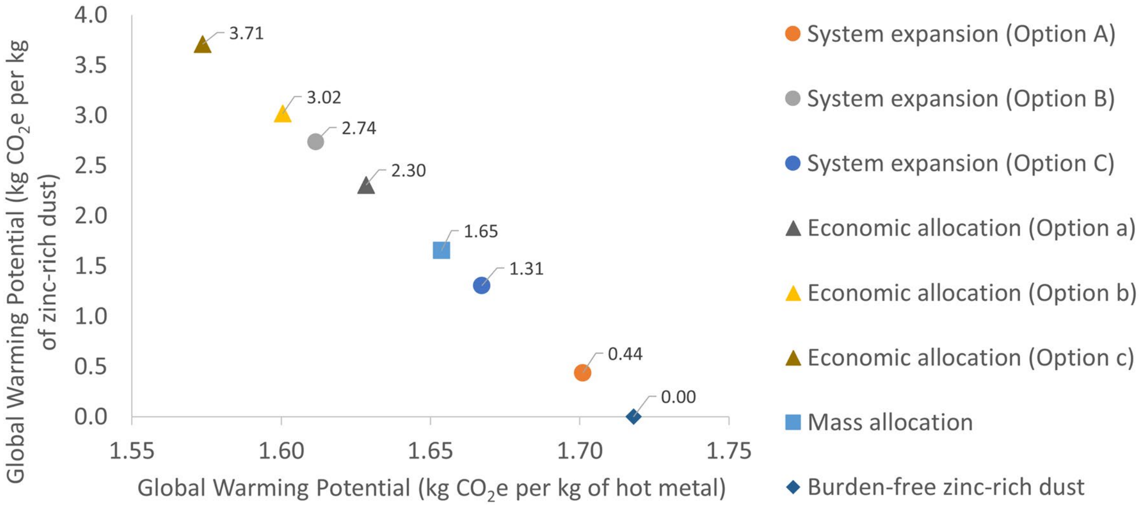

Fig. 4 GWP results of different allocation methodologies for solving multifunctionality issues applied to zinc-rich dust

ZnO (56 wt% zinc) content and the input point in the zinc smelting process. With this system expansion approach, the zinc-rich dust would have a GWP impact of 2.74 kg CO_2 eq./kg dust, in the middle of the range.

These results show that attributing a GWP impact to the zinc-rich dust affects the GWP impact of the hot metal. Because the zinc-rich dust output considered in this study is relatively small compared to the mass of hot metal, the GWP reduction for hot metal is small. However, the range of GWP impacts considered for the zinc-rich dust is significant. Applying a higher environmental impact to the co-product would directly influence the assessed GWP impacts of zinc smelting products using the dust as a feedstock.

3.2 Attribution of GWP impacts with two co-products

The results were then expanded to consider the influence of including a second co-product in the model. In this case, the GWP impact of slag with the methods considered ranges from 0 to 1.27 kg CO_2 eq./kg slag. The GWP impact on the main product, hot metal, and the two co-products is shown in Fig. 5. These results illustrate how the attribution of impacts to the different co-products affects the impact attributed to hot metal.

In the field of LCA, there is a tendency towards standardisation and harmonization. Any guidelines developed regarding circular economy and co-products may advise using the same methodology for all co-products from a single process. In alignment with this philosophy, only the combinations of GWP impacts calculated with the same method for both co-products have been plotted in Fig. 5, these combinations are shown with the markers on the graph. With mass allocation (white triangle), the GWP impact is divided between the hot metal, slag and zinc-rich dust according to their mass outputs, with the same GWP of 1.27 kg CO_2 eq. per kg attributed to each kg of material output from the process. With this allocation method, the GWP impact of zinc-rich dust would be higher than that of primary zinc concentrate (0.44 kg CO_2 e/kg) but lower than that of the secondary zinc source, Waelz kiln oxide (2.74 kg CO_2 e/kg). However, the GWP attributed to slag would be the highest from the options considered. From the hot metal perspective, applying mass allocation would reduce the assessed GWP, reflecting the changes in the process needed to recover zinc in the dust.

When the highest GWP impact is attributed to the zinc-rich dust (with economic allocation, option c, an impact of 3.71 kg CO_2 eq. per kg dust) and to slag (with mass allocation, an impact of 1.27 kg CO_2 eq. per kg slag), the GWP impact attributed to the hot metal would be reduced significantly, to 1.17 kg CO_2 eq. per kg hot metal. This is a substantial reduction in assessed emissions of over 30%, in context a reduction larger than many steel decarbonisation options are predicted to provide. According to the IEA, the largest cumulative emission reductions in the iron and steel sector during 2020–2050 are delivered by material efficiency, technology performance improvements and CCUS (40%, 21% and 16%, respectively) (IEA 2020). These are followed by fuel switching to hydrogen, bioenergy, and other fuel shifts (8%, 6% and 5% respectively). The scale of this impact on assessed GWP for the hot metal highlights the importance of improving material efficiency across sectors, as considered here for closed-loop recycling between the steel, automotive, and zinc industries, and open-loop recycling with the cement and concrete industry. The variability of attributed GWP due to the selected allocation method highlights the need for consistent reporting of the GWP of a process's main product and its co-products, and the transparent use of allocation methods within LCA studies.

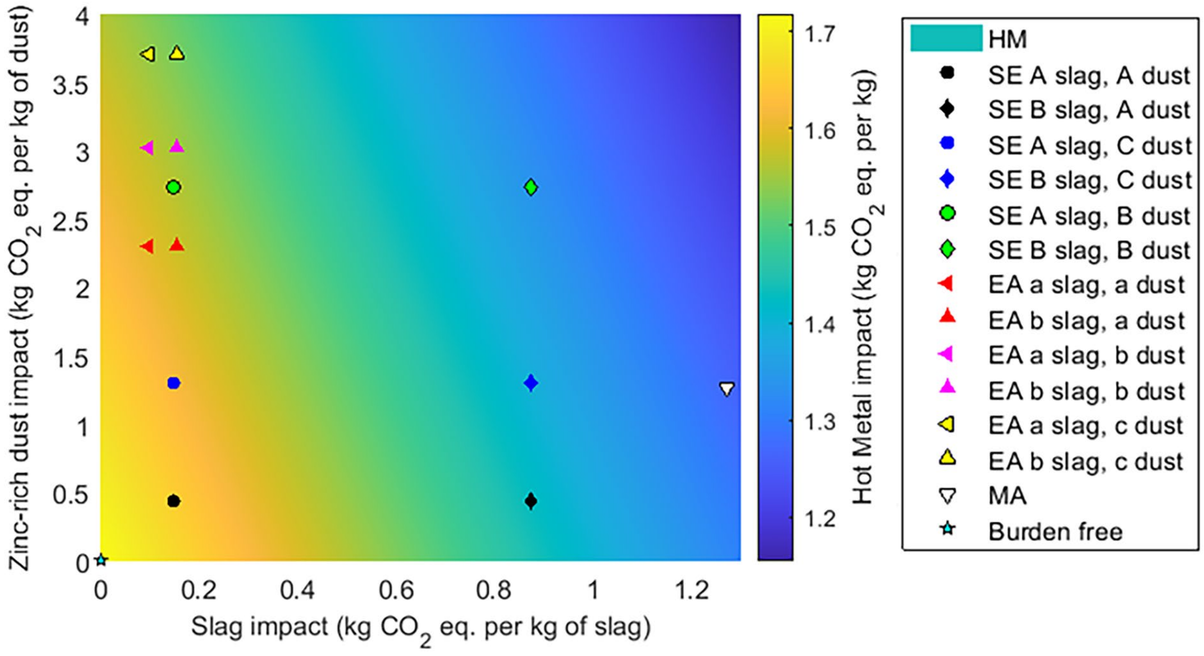

Fig. 5 Allocation of GWP impacts with two co-products, utilising the same method for both co-products. The acronyms used in the legend are HM for hot metal, SE for system expansion, EA for economic allocation and MA for mass allocation. The letters A–C and a-c reflect the different allocation methods chosen for each co-product, as shown in Table 4.The system expansion values for slag for option B and C as very similar, 0.875 and 0.871 kg CO_2 eq./kg slag respectively, so only the returns for option B are shown to avoid an overlap of the markers

In sectoral level reporting, the emissions of certain co-products are reported within the steel sector, while others are reported in the co-product user sector. This highlights the need to agree on the emissions associated with a co-product, especially those crossing the sectoral boundaries. This is the case for zinc-rich dust and slag. Both sectors, those of the co-product users and the co-product producer, should agree on the methodology used to burden co-products. This is relevant for both product and organizational LCA, as the burden attributed to the co-product will affect the main product's GWP in product LCA, and the upstream scope 3 emissions of the co-product user in organizational LCA. It is vital that the reporting of emissions is accurate from both sides.

Although the ISO 14044 standard provides a hierarchy of allocation methods, the standard still leaves many decisions to the LCA practitioner. The issue of inconsistent allocation methods for the same co-product highlights this issue. The LCA methodological preferences might differ between the co-product users and the co-product producer. To aid this discussion, different perspectives have been considered. They include the co-product producer (e.g., steelmaker) and the co-product users (e.g., cement and concrete industry, zinc smelting industry). A summary of these perspectives for different co-products is shown in Table 5.

As there is an increasing number of cases in which the utilisation of co-products may be regarded as an important lever for environmental or resource use improvement, including as part of a more circular economy or as alternative low carbon emission feedstocks into downstream or cross-sectoral processes, it becomes increasingly important to attribute an appropriate burden to each co-product in such cases. While co-product utilisation facilitating a circular economy and the recovery of waste materials would be beneficial for resource depletion, in cases where co-product utilisation is focused on decarbonisation strategies, there is a clear incentive that the GWP burden attributed to the co-product should be lower than alternative (e.g. primary) feedstocks. If the burdens associated with the co-products are higher than those of the alternatives, the co-product could be seen as undesirable in the market, and the use of these co-products may be disincentivised, at the potential detriment to other circular economy focused benefits. For example, in the case of zinc, this value could be the GWP impact of primary zinc concentrate for zinc-rich dust (0.44 kg CO_2 eq. per kg of zinc-rich dust). However, such a unique substitution value is not obvious for slag, as its applications are multiple.

In line with this notion, a co-product user would be incentivised if a low environmental (GWP) footprint were assigned to the co-product. A possible upper limit would be the environmental (GWP) footprint of current feedstocks being used. For similar reasons, the

Table 5 Industry perspectives for each co-product

Perspective	Input/output co-product	Predominant approach
Steelmaker	Slag	There is general agreement within the steel sector on using system expansion for accounting for the slag emissions according to the application of slag (World Steel Association 2017). This attributes emissions to the slag similar to clinker. However, the approach from the cement industry differs
	Zinc-rich dust	The ISO 20915 standard includes zinc-rich dust as a co-product and recommends using a hybrid system expansion method where 1 kg of zinc-rich dust substitutes 0.5 kg of special high-grade zinc to calculate the zinc-rich dust GWP impact However, this attributes a relatively high impact to the dust, much higher than the GWP of the zinc concentrate being used now. This approach is unlikely to be used by the zinc smelting industry
Cement and concrete industry	Slag	Economic allocation is used by the concrete and cement industry, which represents the main destination for slag, resulting in a very low GWP impact on slag compared to materials it substitutes. Additionally, it is still the case that slag is considered a burden-free input for ETS purposes. While this approach helps cement products present a lower product GWP profile (reflected and captured in their Environmental Product Declarations) it fails to recognise the value and economic savings provided when using slag instead of clinker (Competition and Markets Authority 2014) and contrasts with the approach taken by the steel industry
Mining industry	Metallic zinc	For base metals, such as zinc, the recommended approach by Santero et al. (2016) is to use mass allocation when base metals are mined together. This allows for geographic and temporal consistency. The market value of many base metals is similar, so this is considered an appropriate methodology over economic allocation
Zinc smelting industry	Zinc-rich dust	No recommended methodology was found for zinc-rich dust when used as an input to the zinc smelting process. The International Zinc Association recommends using subdivision, system expansion and mass allocation for valuable products from metallurgical mining and refining (IZA 2022b). However, there is no mention of how to approach the issue for secondary materials. If the attributed GWP burden of zinc-rich dust is higher than other sources, this may not be desirable for producers. Under the assumptions in this study, economic allocation would attribute a relatively large burden to the zinc-rich dust

co-product producer would likely be incentivised to lower its main product's environmental footprint by assigning a higher GWP to the co-products. This tension is of importance as no methodological choice or combination explored would likely be considered favourable by all stakeholders. The decision of allocation approach would become less connected to a particular methodology and more centred on a discussion and agreement between all involved parties.

Given the variety of predominant approaches shown in Table 5, if no agreement between stakeholders is reached, this would potentially lead to a mismatch in accounting for the benefit of the use of co-products between the co-product user and producer. A new allocation method could be a hybrid between two existing methods. For example, for energy products with little or no mass, and mass products carrying no energy, a novel hybrid mass-energy allocation method has already been developed (Njakou Djomo et al. 2017). However, these hybrid approaches are likely to have a limited scope in application. On the other hand, existing methods have the potential to solve the multi-functionality issue if applied consistently across sectors. The results in this paper emphasise the need for continued discussion between co-product users and producers to find common ground when attributing environmental impacts to co-products.

4 Conclusions

This study has evaluated the effect of different allocation methods on the GHG emissions attributed to hot metal and two co-products (zinc-rich dust and slag) within the steel industry. This case study reflects a common challenge in LCA, where there is a need to ensure consistency of allocation approaches but also to retain relevance for each product system in all circumstances. In the current analysis, GHG emissions of the main hot metal product were found to vary from 1.72 to 1.17 kg CO_2 eq. per kg hot metal depending on the allocation method employed. This represents a substantial reduction of over 30%, a reduction larger than many decarbonisation options are predicted to provide. Each method attributes each co-product a different GWP value. The GWP impacts for zinc-rich process dust range from 0 to 3.71 kg CO_2 eq. per kg zinc-rich dust. A similarly wide range is applicable for slag, 0 to 1.27 kg CO_2 eq. per kg slag. This highlights the relevance of harmonizing the allocation methods for co-products. Several allocation combinations have been explored; however, no allocation method or combination of methods was identified as likely to be preferable for all stakeholders. No combination was highlighted as a good compromise for both the co-product producer and co-product users.

The relation between the GWP attributed to the main product and two co-products has been explored. No single methodology recognizes the complexities of both co-products, and the attribution of impacts from the steel production process may require approaches unique to each co-product. At present, there are inconsistencies in how impacts are attributed to the same co-product between the participating industries, which risks underreporting of the overall impact of associated production processes. Engagement of stakeholders, alongside consideration of additional allocation options, existing or hybrid, is needed to create a standardized allocation approach with consensus of the involved industries and credible to external stakeholders.

Governments, regulators and society have made increasing efforts in recognising the importance of lifecycle-based assessments. This has highlighted the need for a consistent approach regarding the attribution of impacts. In this study, the same allocation methods have been applied to both co-products. Further research is suggested to explore other methods, existing or hybrid, that might be suitable for multifunctional systems involving co-products and that could identify the preferred option for future guidance.

Funding This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation, as part of the ReclaMet project, contract 17209.

This work was also supported by the EPSRC [grant number EP/S022996/1] as part of the Centre for Doctoral Training in Resilient Decarbonised Fuel Energy Systems.

Data availability The data that support the findings of this study are not publicly available.

References

Abdel-Latif MA (2002) Fundamentals of zinc recovery from metallurgical wastes in the enviroplas process. Miner Eng 15:945–952. https://doi.org/10.1016/S0892-6875(02)00133-4

AISI and SMA (2021) Determination of steel recycling rates in the United States

Antrekowitsch J, Rösler G, Steinacker S (2015) State of the art in steel mill dust recycling. Chem Ing Tech 87:1498–1503. https://doi.org/10.1002/CITE.201500073

APEAL (2023) APEAL Steel for packaging statistics. https://www.apeal.org/statistics/. Accessed 10 Jul 2023

ArcelorMittal By-products, scrap and the circular economy. https://corporate.arcelormittal.com/sustainability/by-products-scrap-and-the-circular-economy. Accessed 15 Jul 2022

ArcelorMittal, BlueScope, GFG Alliance et al (2021) The net-zero steel pathway methodology project | Final report and recommendations

Ardente F, Cellura M (2012) Economic allocation in life cycle assessment. J Ind Ecol 16:387–398. https://doi.org/10.1111/J.1530-9290.2011.00434.X

AzariJafari H, Yahia A, Amor B (2018) Assessing the individual and combined effects of uncertainty and variability sources in comparative LCA of pavements. Int J LCA 23:1888–1902. https://doi.org/10.1007/S11367-017-1400-1

Beccali M, Cellura M, Iudicello M, Mistretta M (2010) Life cycle assessment of Italian citrus-based products. Sensitivity analysis and improvement scenarios. J Environ Manage 91:1415–1428. https://doi.org/10.1016/j.jenvman.2010.02.028

Brander M, Wylie C (2011) The use of substitution in attributional life cycle assessment. GHG Measure Manage 1:161–166. https://doi.org/10.1080/20430779.2011.637670

BS ISO (2018) BS ISO 20915:2018 Life cycle inventory calculation methodology for steel products

Chen C, Habert G, Bouzidi Y et al (2010) LCA allocation procedure used as an incitative method for waste recycling: an application to mineral additions in concrete. Resour Conserv Recycl 54:1231–1240. https://doi.org/10.1016/J.RESCONREC.2010.04.001

Cherubini E, Franco D, Zanghelini GM, Soares SR (2018) Uncertainty in LCA case study due to allocation approaches and life cycle impact assessment methods. Int J LCA 23:2055–2070. https://doi.org/10.1007/S11367-017-1432-6/FIGURES/5

Competition and Markets Authority (2014) Aggregates, cement and ready-mix concrete market investigation. Final report

Crossin E (2015) The greenhouse gas implications of using ground granulated blast furnace slag as a cement substitute. J Clean Prod 95:101–108. https://doi.org/10.1016/J.JCLEPRO.2015.02.082

Doronin IE, Svyazhin AG (2011) Commercial methods of recycling dust from steelmaking. Metallurgist 54:673–681. https://doi.org/10.1007/S11015-011-9356-Z

EIT RawMaterials (2018) ReclaMet. https://eitrawmaterials.eu/project/reclamet/. Accessed 24 Jun 2021

Ekvall T, Finnveden G (2001) Allocation in ISO 14041 - a critical review. J Clean Prod 9:197–208. https://doi.org/10.1016/S0959-6526(00)00052-4

EuRIC AISBL (2022) Metal Recycling Factsheet

European Commission Joint Research Centre (2011) International reference life cycle data system (ILCD) handbook general guide for life cycle assessment: provisions and action steps. Publications Office

Geisler G, Hellweg S, Hungerbühler K (2005) Uncertainty analysis in Life Cycle Assessment (LCA): case study on plant-protection products and implications for decision making. Int J LCA 10:184–192. https://doi.org/10.1065/LCA2004.09.178

Genderen E, Grund S, van Leeuwen M et al (2021) Increasing the circularity of zinc – pathways to closing the loop

Grudinsky PI, Zinoveev DV, Dyubanov VG, Kozlov PA (2019) State of the art and prospect for recycling of Waelz slag from electric arc furnace dust processing. Inorg Mater Appl Res 10:1220–1226. https://doi.org/10.1134/S2075113319050071

Grund S, van Genderen E, van Leeuwen M (2019) Circular economy - recycling at all costs? Zinc: unleashing valuable resources. Proceedings of the 10th European Metallurgical Conference. EMC 3:1181–1193

Guinée J (2001) Handbook on life cycle assessment — operational guide to the ISO standards. Editorial in Int J LCA 6:255–255. https://doi.org/10.1007/bf02978784

Guinée JB, Heijungs R, Huppes G (2004) Economic allocation: examples and derived decision tree. Int J LCA 9:23–33. https://doi.org/10.1007/BF02978533

Huijbregts MAJ, Norris G, Bretz R et al (2001) Framework for modelling data uncertainty in life cycle inventories. Int J LCA 6:127–132. https://doi.org/10.1007/BF02978728

IEA (2020) Iron and steel technology roadmap towards more sustainable steelmaking Part of the Energy Technology Perspectives series

Ijassi W, Ben Rejeb H, Zwolinski P (2021) Environmental impact evaluation of co-products: decision-aid tool for allocation in LCA. Int J Life Cycle Assess 26:2199–2214. https://doi.org/10.1007/S11367-021-01984-0

ILZSG (2022) Zinc outlook for 2022 and 2023

ISO (2006a) Environmental management - life cycle assessment - requirements and guidelines (ISO 14044:2006)

ISO (2006b) ISO 14044:2006. Preview Environmental management - life cycle assessment - requirements and guidelines

ISSB (2022) Steel industry import prices

IZA (2022a) Zinc environmental profile - 2022 update

IZA (2022b) Carbon footprint technical guidance on carbon footprint calculation for special high-grade zinc

Jalkanen H, Oghbasilasie H, Raipala K (2005) Recycling of steelmaking dusts: the Radust concept. J Min Metall B 41:1–16. https://doi.org/10.2298/JMMB0501001J

Kerry T, Peters A, Georgakopoulos E et al (2022) Zinc vaporization and self-reduction behavior of industrial waste residues for recycling to the HIsarna furnace. J Sustain Metall 1–15. https://doi.org/10.1007/S40831-021-00440-5/FIGURES/17

Kyttä V, Roitto M, Astaptsev A et al (2022) Review and expert survey of allocation methods used in life cycle assessment of milk and beef. Int J LCA 27:191–204. https://doi.org/10.1007/S11367-021-02019-4/FIGURES/9

Lee KM, Park PJ (2005) Estimation of the environmental credit for the recycling of granulated blast furnace slag based on LCA. Resour Conserv Recycl 44:139–151. https://doi.org/10.1016/J.RESCONREC.2004.11.004

Li Y, Liu Y, Gong X et al (2016) Environmental impact analysis of blast furnace slag applied to ordinary Portland cement production. J Clean Prod 120:221–230. https://doi.org/10.1016/J.JCLEPRO.2015.12.071

Lin X, Peng Z, Yan J et al (2017) Pyrometallurgical recycling of electric arc furnace dust. J Clean Prod 149:1079–1100. https://doi.org/10.1016/J.JCLEPRO.2017.02.128

London Metal Exchange (2022) LME Zinc. https://www.lme.com/en/Metals/Non-ferrous/LME-Zinc#Trading+day+summary. Accessed 13 Apr 2022

Luke Nickels (2021) Zinc CBS June 2021 — Supply concerns add to price volatility in June. In: S&P Global Market Intelligence. https://www.spglobal.com/marketintelligence/en/news-insights/blog/zinc-cbs-june-2021-supply-concerns-add-to-price-volatility-in-june. Accessed 29 Mar 2022

Ma N (2016) Recycling of basic oxygen furnace steelmaking dust by in-process separation of zinc from the dust. J Clean Prod 112:4497–4504. https://doi.org/10.1016/j.jclepro.2015.07.009

Mendoza Beltran A, Chiantore M, Pecorino D et al (2018) Accounting for inventory data and methodological choice uncertainty in a comparative life cycle assessment: the case of integrated multi-trophic aquaculture in an offshore Mediterranean enterprise. Int J LCA 23:1063–1077. https://doi.org/10.1007/s11367-017-1363-2

Mendoza Beltran A, Heijungs R, Guinée J, Tukker A (2016) A pseudo-statistical approach to treat choice uncertainty: the example of partitioning allocation methods. Int J LCA 21:252–264. https://doi.org/10.1007/S11367-015-0994-4/FIGURES/5

MPP (2021) Net zero steel - sector transition strategy

Muica VT, Ozunu A, Török Z (2021) Comparative life cycle impact assessment between the productions of zinc from conventional concentrates versus Waelz oxides obtained from slags. Sustainability (switzerland) 13:1–17. https://doi.org/10.3390/su13020580

Nilsson AE, Aragonés MM, Torralvo FA et al (2017) A review of the carbon footprint of Cu and Zn production from primary and secondary sources. Minerals 7:168

Njakou Djomo S, Knudsen MT, Parajuli R et al (2017) Solving the multifunctionality dilemma in biorefineries with a novel hybrid mass–energy allocation method. GCB Bioenergy 9:1674–1686. https://doi.org/10.1111/gcbb.12461

Pelletier N, Ardente F, Brandão M et al (2015) Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: is increased consistency possible? Int J LCA 20:74–86. https://doi.org/10.1007/S11367-014-0812-4/TABLES/1

Pelletier N, Tyedmers P (2011) An ecological economic critique of the use of market information in life cycle assessment research. J Ind Ecol 15:342–354. https://doi.org/10.1111/J.1530-9290.2011.00337.X

Rostek L, Tercero Espinoza LA, Goldmann D, Loibl A (2022) A dynamic material flow analysis of the global anthropogenic zinc cycle: providing a quantitative basis for circularity discussions. Resour Conserv Recycl 180. https://doi.org/10.1016/j.resconrec.2022.106154

Ruetten J, Crittendon R (2006) GSD's state of the art Waelz process

Santero N, Hendry J (2016) Harmonization of LCA methodologies for the metal and mining industry. Int J LCA. https://doi.org/10.1007/s11367-015-1022-4

Stewart DJC, Scrimshire A, Thomson D et al (2022) The chemical suitability for recycling of zinc contaminated steelmaking by-product dusts: the case of the UK steel plant. RCR Advances 14. https://doi.org/10.1016/j.rcradv.2022.200073

Suetens T, Klaassen B, van Acker K, Blanpain B (2014) Comparison of electric arc furnace dust treatment technologies using exergy efficiency. J Clean Prod 65:152–167. https://doi.org/10.1016/J.JCLEPRO.2013.09.053

Tata Steel Circular economy . In: 2022. https://www.tatasteeleurope.com/sustainability/circular-economy. Accessed 15 Jul 2022

TDi, RMI (2022) Material insights. https://www.material-insights.org/. Accessed 29 Mar 2022

UKCSMA (2023) Effectiveness of GGBS in reducing the embodied carbon dioxide of concrete. https://ukcsma.co.uk/sustainability/. Accessed 10 Jul 2023

ULCOS (2010) Ultra-low CO_2 steelmaking. https://cordis.europa.eu/project/id/515960/es. Accessed 16 Aug 2021

US Geological Survey (2020) Mineral Commodity Summaries: Iron and Steel Slag

USGS (2023) Mineral commodity summaries 2023

van der Voet E, Lifset RJ, Luo L (2010) Life-cycle assessment of biofuels, convergence and divergence. Biofuels 1:435–449. https://doi.org/10.4155/BFS.10.19/SUPPL_FILE/TBFU_A_10815805_SM0001.DOC

van Genderen E, Wildnauer M, Santero N, Sidi N (2016) A global life cycle assessment for primary zinc production. Int J LCA 21:1580–1593. https://doi.org/10.1007/s11367-016-1131-8

Weinzettel J, Pelletier N, Tyedmers P (2012) Understanding who is responsible for pollution: what only the market can tell us—comment on "an ecological economic critique of the use of market information in life cycle assessment research." J Ind Ecol 16:455–456. https://doi.org/10.1111/J.1530-9290.2012.00460.X

World Bank Group (2021) Commodity markets outlook
Worldsteel Association (2017) Life cycle inventory methodology report for steel products

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