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LCA OF METALS AND METAL PRODUCTS: THEORY, METHOD AND PRACTICE

A global life cycle assessment for primary zinc production

Eric Van Genderen[1] · **Maggie Wildnauer**[2] · **Nick Santero**[2] · **Nadir Sidi**[2]

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Abstract

Purpose The purpose of this study was to update the average environmental impacts of global primary zinc production using a life cycle assessment (LCA) approach. This study represents the latest contribution from zinc producers, which historically established the first life cycle inventory for primary zinc production in 1998 (Western Europe) and the first global LCA-based cradle-to-gate study for zinc concentrate and special high-grade zinc (SHG; 99.99 %) in 2009. Improvements from the previous studies were realized through expanded geographical scope and range of production technologies.

Methods The product system under study (SHG zinc) was characterized by collecting primary data for the relevant production processes, including zinc ore mining and concentration, transportation of the zinc concentrate, and zinc concentrate smelting. This data was modeled in GaBi 6 and complemented with background data from the GaBi 2013 databases to create the cradle-to-gate LCA model. Allocation was used to distribute the inputs and outputs among the various co-products produced during the production process, with mass of metal content being the preferred allocation approach, when applicable.

Results and discussion In total, this global study includes primary data from 24 mines and 18 smelters, which cover 4.7×10^6 MT of zinc concentrate and 3.4×10^6 MT of SHG zinc, representing 36 and 27 % of global production, respectively. While the LCA model generated a full life cycle inventory, selected impact categories and indicators are reported in this article (global warming potential, acidification potential, eutrophication potential, photochemical ozone creation potential, ozone creation potential, and primary energy demand). The results show that SHG zinc has a primary energy demand of 37,500 MJ/t and a climate change impact of 2600 kg CO_2-eq./t. Across all impact categories and indicators reported here, around 65 % of the burden are associated with smelting, 30 % with mining and concentration, and 5 % with transportation of the concentrate. Sensitivity analyses were carried out for the allocation method (total mass versus mass of metal content) and transportation of zinc concentrate.

Conclusions This study generated updated LCA information for the global production of SHG zinc, in line with the metal industry's current harmonization efforts. Through the provision of unit process information for zinc concentrate and SHG zinc production, greater transparency is achieved. Technological and temporal representativeness was deemed to be high. Geographical representativeness, however, was found to be moderate to low. Future studies should focus on increasing company participation from underrepresented regions.

Keywords Life cycle assessment (LCA) · Primary zinc · Zinc concentrate · Zinc smelting

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✉ Eric Van Genderen
evangenderen@zinc.org

[1] Department of Environment and Sustainability, International Zinc Association, Durham, NC 27713, USA

[2] Thinkstep, Boston, MA 02109, USA

1 Introduction

Recognized in India as a metal in the fourteenth century, zinc and zinc oxides have been used for centuries for a variety of applications. Currently, over 13×10^6 MT of refined zinc are produced annually from ores, concentrates, and recycled materials (ILZSG 2016). The predominant application for zinc is in the galvanization process to protect steel by increasing the durability and lifetime of construction, transportation, and consumer products. In addition, applications for zinc include alloying with copper (brass) or aluminum (zinc die casting), rolled zinc sheet, and chemicals for use in rubber, fertilizers, and personal care products. Like other metals, zinc can be recycled indefinitely, without changing its physical properties or economic value.

Due to its many uses throughout society, demands for information concerning the environmental footprint of refined zinc metal have emerged from regulators, engineers, and downstream users of zinc and zinc-containing products. In the 1990s, the zinc industry published an eco-profile of primary zinc production, which analyzed the environmental burdens associated with primary zinc production in Western Europe for the year 1995. This publication was the first life cycle inventory (LCI) of primary zinc, and although it was not globally representative, the study provided an important profile of primary zinc production. Consequently, the first global life cycle assessment (LCA) was published in 2009 for primary zinc production (cradle-to-gate), which established an environmental profile for zinc that represented geographic differences in mining, smelting, energy use, and transportation.

The current study builds upon the initial LCA and provides an update for global production of special high-grade zinc (SHG; 99.99 % pure). The update combines data collected from the 2009 study (2005 reference year; mines and smelters that have not had significant changes in their processes) with new 2012 production data. In total, this LCA represents 4.7×10^6 MT of zinc concentrate and 3.4×10^6 MT of SHG zinc, respectively. To put this in context, 2012 production data worldwide is estimated to be 12.9×10^6 MT of zinc concentrate and 12.6×10^6 MT of SHG zinc (ILZSG 2016). It further incorporates general improvements that reflect current best practices for metal LCAs. The information provided by this LCA is intended to be used by zinc industry stakeholders and LCA practitioners to evaluate and improve environmental performance of zinc in end-use applications.

2 Goal and scope of the study

The purpose of this study is to update the average LCA of global primary zinc production. This LCA provides an up-to-date LCI and impact assessment of primary zinc production (ingot at refinery gate). Additionally, this study includes a "cradle-to-gate" inventory and impact assessment for zinc concentrate—the main upstream material used to produce primary zinc metal.

The product system under study is virgin special high-grade zinc. There are a variety of processes that must be undertaken to transform zinc ore into zinc metal (for more details, see Sects. 5 and 6), and each of these unit processes have been included as part of this study. The end result is an LCI for SHG zinc at the smelting facility with additional information for the aggregated processing of zinc ore into zinc concentrate (an intermediate product in the zinc production process).

2.1 Functional unit

The functional unit of this study is the production of 1 MT of SHG zinc with a purity of at least 99.99 % zinc. Additionally, results are presented for the production of 1 MT of the zinc concentrate, which is the purified ore at the gate of the mine/concentrator. Concentrate compositions for the mines included in this study range from roughly 50 to 60 % zinc; however, for the purposes of aggregating the zinc concentrate production, a production-weighted average concentrate was presented without making any adjustments to weigh the individual concentrates based upon their zinc concentration. The average zinc concentration in the concentrate was 59 %.

2.2 System boundaries

SHG zinc production from cradle-to-gate includes zinc ore mining, ore concentration, transportation of zinc concentrate, and zinc concentrate smelting. In order to collect information on each of these processes, companies involved in mining and concentration and zinc smelting were including in the data collection effort. The study is limited to the manufacturing stage of SHG zinc's life cycle and purposefully excludes its use and end-of-life. Since the study does not aim to draw any conclusions with regard to the use or end-of-life stages of the life cycle, or with regard to the total life cycle burden for any such application, a cradle-to-gate system boundary is appropriate with regards to the goal of the study.

2.3 Geographic coverage

This study is intended to be representative of global SHG zinc production. In total, this LCA includes primary data from 24 mines and 18 smelters, representing mining and smelting operations in Africa, Asia, Australia, Europe, and North America. Some site information collected from the previous (2009) study were combined with current data from new sites, which increases the overall representativeness compared to the previous study. Those sites included from the 2009 study did not undergo significant technological process changes;

thus, the primary data was deemed representative of current conditions for those sites. This assumption is discussed in more detail in subsequent sections.

2.4 Temporal coverage

This study is intended to be representative of zinc production during the year 2012. This study was undertaken as an update to the 2009 zinc LCA study. Of the final zinc concentrate presented in this study, 71 % (by mass) is based on primary data from 2005 to 2006; 29 % of the total zinc concentrate production are based on primary data from 2012. All background data—including electricity grid mixes, ancillary material impacts, and other associated data—are from the GaBi 2013 database. The final SHG zinc results presented consist of 73 % production from the 2005 and 2006 primary data and 27 % from the 2012 primary data. In total, this covers an annual production of 4.9×10^6 MT of zinc concentrate and 3.4×10^6 MT of SHG zinc. Within this time frame, the global production of refined zinc increased by 24 %, from 10.1 to 12.6×10^6 t. However, this increase was realized from the same infrastructure available in 2005/2006, As such, the current study simply added existing sites to the database that were also in operation during the previous LCA effort.

Additionally, in an effort to be consistent with the 2009 study, the 2009 unit processes have not been changed to reflect any updates in methodology, including the allocation methods. The exception is with respect to allocation of metal content (zinc) from the ore, which was adjusted in the 2009 study to improve mass balancing.

2.5 Allocation

Various co-products are produced throughout the zinc mining and smelting processes. Zinc ore is not mined as pure elemental zinc but rather is extracted along with other elements. As a result, the beneficiation of ore into concentrate and the smelting of concentrate into primary zinc metal produce additional, valuable products. In order to distribute the total energy and process material inputs as well as any emissions, wastes, and other flows between these co-products and the zinc-containing main product, it was necessary to apply allocation methods and system expansion within the study. Details about the allocation techniques can be found in the GaBi documentation (see PE 2012).

2.5.1 Allocation for zinc mining

The mines included in this study use a variety of ore grades, which commonly include copper and lead in addition to zinc. As the ore is processed, concentrates of some of these metals are produced in addition to the zinc concentrate. A list of the co-products produced in the concentration of zinc, as reported by the 2014 mine respondents, is included in Table 1. Also included are the general inputs to the mining process, as well as the allocation method used for the input and co-product flows.

In the 2009 study, mining and beneficiation co-products were allocated using the masses of the concentrates produced. For all process materials, water, energy, wastes, and emissions, these allocation methods have not been changed, as sufficient data was not available to make them consistent with the current best practice allocation approaches.

Within the 2012 production data, metal content and zinc content are used instead of mass for metal-containing co-products, as ISO 14044 prioritizes the use of "underlying physical relationships" between the co-products to determine allocation factors. Additionally, this co-product allocation approach is preferred for base metals (such as zinc), based on recommendations made in the *Harmonization of LCA methodologies for metals* (Santero and Hendry 2016), because it reflects the underlying principle that the metal content of the co-products is the useful product that creates a market for these materials. Zinc content allocation ensures that the final zinc-containing products have an accurate value for quantity of zinc extracted from the Earth's crust, which would enable proper reporting of environmental indicators related to resource extraction.

Finally, one producer of zinc concentrate also produced a significant portion of agricultural lime. As agricultural lime does not have a meaningful metal content, mass was chosen as the physical property for allocating the process materials, water, energy, and emissions for that producer. This site contributes to less than 2 % of the concentrate mix represented within the study, and therefore, changes in allocation of the agricultural lime have an insignificant influence on the final results.

2.5.2 Allocation for zinc smelting

Similar to zinc mining and beneficiation, zinc smelting results in the production of various, non-zinc co-products. The zinc concentrate sent to smelting facilities is typically between 50 and 60 % zinc but contains fractions of other metals and elements, such as sulfur. As the concentrate is processed into SHG zinc, these processes result in valuable co-products. A list of the major co-products produced during zinc smelting is provided in Table 1.

For all zinc-containing inputs, such as zinc concentrate, allocation for the new smelting data was calculated based upon the mass of zinc content, as discussed above. All other process materials and energy for the electrometallurgical smelting sites that reported data for this study were allocated based upon the mass of metal content of the co-products.

A significant co-product produced during zinc smelting is sulfuric acid. This is due to the large amount of sulfur that is

Table 1 Co-products of zinc mining and smelting

Process	Co-products	Inputs/outputs	Allocation method
Mining and benefaction	Zn, Pb, Cu concentrates	Zinc ore	Mass of zinc content
		Process materials, water, energy, wastes, emissions	Mass of metal content
	Agricultural lime	Zinc ore	Mass of zinc content
		Process materials, water, energy, wastes, emissions	Mass
Smelting	Special high-grade Zn, Cu cement, Cd, Co cement, Mn sludge, Zn alloys, Zn dross, Al dross	Zinc-containing materials	Mass of zinc content
		Process materials, water, energy, wastes, emissions	Mass of metal content
	Sulfuric acid	Not applicable	System expansion

driven from the ore during roasting, emitted as sulfur dioxide, and then processed into sulfuric acid for sale or use within the facility. Consistent with the 2009 study, this study uses system expansion to credit the production of sulfuric acid. This is the preferred approach provided in the *Harmonization of LCA methodologies for metals* for non-metal co-products within metal production systems, allowing for consistency with LCAs conducted on other metals (Santero and Hendry 2016). Only the portion of the acid not used within the smelting facility was credited. Aggregated processes for sulfuric acid production through the oxidation of sulfur and specific to the geographic location of the smelting facility were used whenever possible to calculate the system credit.

2.5.3 Recycling allocation

Some sites included in this study reported useful waste products designated for recycling. If specific materials were reported and known by the company to be recycled, a system expansion approach was used to credit the creation of the recyclable product. The *Harmonization of LCA methodologies for metals* article recommends the use of system expansion for co-products with alternative production routes, as is the case with steel and lubricants (Santero and Hendry 2016). End-of-life scrap is first balanced out with the manufacturing phase to account for any open scrap inputs into production. The appropriate share of the remaining net scrap is then sent to material recycling. The subsequent process steps are modeled using industry average inventories. The original burden of the primary material input is then allocated between first and second life cycle using the mass of recovered secondary material. For example, metal-grinding media are used as part of the beneficiation process for zinc concentrate production. Multiple manufacturers indicated that the metal-grinding media are recycled at the end-of-life, so credit was given for the recovered secondary material. If waste flows designated for recycling were not listed with specific products, the flows remained unconnected representing a cutoff approach.

2.6 Cutoff criteria

All reported data were incorporated and modeled using best available LCI data. Information for the inbound transportation of process materials to the mining and smelting sites was not comprehensively reported by all participating companies; however, in all cases, the missing transportation information was deemed insignificant due to the fact that the mass of the process materials represented less than 1 % of the mass of zinc-containing material being processed.

Additionally, there were a few materials reported that were not approximated due to uncertainty regarding their composition and their mass being less than 1 % of the mass of the zinc-containing material being processed. Examples include liquorice (a process material used for electrolysis) and promoter (a process material for the beneficiation of zinc ore).

2.7 Selection of Life cycle impact assessment methodology and types of impacts

In accordance with the recommendations of the *Harmonization of LCA methodologies for metals* (Santero and Hendry 2016), the set of impact assessment categories for this project include global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), and ozone depletion potential (ODP). In addition, the primary energy demand (PED) inventory metric was characterized. The CML impact assessment methodology framework (CML 2001–April 2013) was selected for this assessment.

Global warming potential and primary energy demand are presented because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be the most pressing environmental issues of our time. Eutrophication, acidification, and photochemical ozone creation potentials are presented because they are closely connected to air, soil, and water quality and capture the environmental burdens associated with commonly regulated emissions such as NO_x, SO_2, and VOC.

Ozone depletion potential was chosen because of its high political relevance, which eventually led to the worldwide ban of more active ozone-depleting substances; the phaseout of less active substances is due to be completed by 2030. Current exceptions to this ban include the application of ozone-depleting chemicals in nuclear fuel production. The indicator is therefore included for reasons of completeness.

Abiotic depletion potential (ADP) is excluded from this study due to the lack of robustness and accuracy of the metal and mining industry associates with the characterization factors used within the CML methodology (Drielsma et al. 2016). Toxicity, land use change, and water scarcity are also excluded, in line with the recommendations of the harmonization document that these impacts not be reported for metal LCAs (Santero and Hendry 2016). Finally, water consumption is excluded due to the lack of data provided on water outputs, as discussed in Sect. 4.5.

2.8 Interpretation to be used

The study does not apply normalization, and no grouping or further quantitative cross-category weighting has been applied. Instead, each impact is discussed in isolation, without reference to other impact categories.

2.9 Software and database

The LCA model was created using the GaBi 6 software system for life cycle engineering, developed by Thinkstep AG (formerly PE INTERNATIONAL AG). The GaBi 2013 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

3 Assumptions and limitations

One key limitation of this study is the temporal coverage discussed in Sect. 2.4. The key assumption is that the practices of the companies who reported data for the 2009 study, and did not provide updated information, have not significantly changed their processes and are therefore still representative of the year 2012. To confirm this assumption, all companies were polled and confirmed that the previous primary data was still representative. In addition, all upstream and downstream background data were updated.

In order to model the full cradle-to-gate production process for primary zinc, a key assumption is the combination of the zinc mining and concentration sites with the zinc-smelting sites. Zinc concentrate is sold as a commodity, so depending on market forces, a zinc smelter may process zinc concentrate from a variety of mines. How the supply chain is linked has an impact on transportation assumptions. In 2009, the assumption was made that smelting companies used concentrate produced at their own mines. In the event a smelting company reported data and did not own a mine, a global average of zinc concentrate was created using a weighted average of the "orphan" mining companies. Within the current study, all sites using a global average of zinc, both from 2009 to 2012, use a dataset that contains the production-weighted average of all concentrate-producing sites.

For this study, an attempt was made to more comprehensively understand the supply chain between mines and smelters. Companies who reported new data for this study were asked to disclose their sinks (for mines) and sources (for smelters) of their zinc concentrate. Then, using this primary information supplemented with online fact sheets published by the companies, the smelters and mines were linked in an effort to emulate actual transportation pathways. This information is potentially sensitive to company's operations, so for sites unwilling to provide raw material sourcing information, the approach of a global mix was implemented with production-weighted estimates for transportation distance based upon the top five mines by production which account for about 65 % of the global concentrate mix. The effect of the production-weighted distance is further examined below within a sensitivity analysis (Sect. 8.3.2).

A common limitation across all zinc-mining and zinc-smelting companies who reported data for this study was a lack of data surrounding water treatment and discharge. For many mines, water leaks into the site and must be collected. Some of this water is used for cooling machinery, but generally, much of it is sent to treatment or tailing ponds. Similarly, smelters use water for cooling and as a process material, but it was difficult to obtain information on the output of this water. As a result, a comprehensive water balance for zinc production could not be created and is not reported in this study. Process materials are inputs to the product itself and can be found in the composition of the output of a process, such as flotation chemicals and water, as opposed to ancillary materials that are required for production but do not end up in the final product, such as lubricants and grinding media.

Another limitation of the study is the lack of high global coverage and differential regional representation. As company participation is voluntary, higher representation from countries with significant SHG zinc production (such as China, India, and Brazil) was not possible. While broad technologies are similar across the globe, differences in environmental impacts can be expected based on, in particular, regional electricity grid mixes but also environmental legislation, specific local technologies, supply chains, transport distances and modes, and raw materials, among other variables.

4 Data collection and data sources

4.1 Data collection and quality assessment procedure

All primary data were collected using customized data collection templates, which were sent out by e-mail to the respective data providers in the participating companies. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, and benchmarking. Issues related to data gaps, outliers, or other inconsistencies were resolved through individual engagement with the participating companies.

4.2 Fuels, energy, raw materials, and processes—background data

National and regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2013 databases. Similarly, data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2013 databases.

4.3 Transportation

Average transportation distances and modes of transport are included for the transport of zinc concentrate for the new data. Additional transportation information was included, when reported by the manufacturer. Transportation distance and source assumptions from the 2009 study have not been changed. The transportation for concentrate from mines to smelters was partly unknown for the new data. For estimating transportation distance for the global average concentrate, a production-weighted mix of the distances between the port closest to the top five mines and the relevant smelter was used. For the transportation of the global average concentrate, only the ocean travel distance was estimated for the 2014 smelters, as the modes and distances of any land transportation were often not provided. The GaBi 2013 database was used to model transportation.

4.4 Emissions to air, water, and soil

All emissions reported by the producers for the manufacturing phase are taken into account in the study (data used for official reporting). All gate-to-gate emissions data were obtained from the producers, except in the case of some fuel combustion emissions, which were calculated using processes for combustion from the GaBi 2013 database; emissions for the on-site combustion of gasoline were taken from AP-42 emission data (USEPA 1995), as comparable data was not available from GaBi. Those emissions are only for the combustion of the fuel on-site; consequently, there is no double counting with the upstream greenhouse gas emissions (production of fuel or combustion of fuel to produce electricity for the grid mix). The energy supply emissions are provided by the GaBi LCI database.

Implementations of environmental controls affecting emissions are accounted for in the gate-to-gate data provided by participating sites; technologies for water, waste, or flue gas treatment were not modeled as separate processes. Different technologies employed will vary regionally depending on legislative requirements.

Data for all upstream materials, electricity, and energy carriers were obtained from the GaBi 6 database (2013). The emissions (CO_2, NO_x, etc.) due to the use of electricity are accounted for with the use of the database processes. Emissions associated with transportation were determined as described in the previous section. Energy use and the associated emissions were calculated using existing transportation models from the GaBi 2013 database.

Some sites did not report emissions to water; this oversight was considered to be a gap in available data. In order to fill the gap, an average emission-to-water profile was calculated based on available data from other sites and applied to those sites that did not report emissions to water. This data gap only affected a small percentage of the total zinc production, thus having only a minor impact on the results. Small changes were observed in the inventory results, as well as those impact categories (e.g., eutrophication) that rely on emissions to water.

Data on the interactions of on-site deposits of tailings or waste rock with air, water, or land, including evaporation or leachate, was not provided and therefore not included in the scope of the study.

4.5 Water usage

Data was collected on water usage but was not comprehensively reported by all sites. Although the withdrawal (input) of water from the ecosphere into the technosphere is well documented, the release (output) of water back from the technosphere into the ecosphere is not well tracked. Possible areas of release include freshwater sources (e.g., lakes), seawater, and evaporation to air. Due to this data gap, this study does not include reliable information for the net consumption (inputs minus outputs) of freshwater.

For SHG zinc, the total water withdrawals are approximately 8 m^3/kg of zinc.

5 Processes under study

5.1 Zinc concentrate production

Zinc concentrate production involves the following three major processes: mining, comminution, and floatation. Often, the last two processes are collectively called beneficiation. Information was collected from mining companies by individual unit processes or as an aggregated total, depending on the information available from the company. Figure 1 presents the main inputs and outputs associated with each step of the zinc concentrate production process. Unit process inputs and outputs associated with the average production of zinc concentrate can be found in the Electronic supplementary material (Tables S1 and S2).

5.1.1 Mining

The mining of zinc ore includes underground and open cast mining processes. Within the global zinc industry, about 80 % of zinc ore come from underground mines and 20 % from open pit mines. In the following sub-sections, the two average mining processes are described.

- Underground mining: Access is via vertical shafts or inclined roadways. There are usually two access routes (one for mining personnel and materials and one for the ore) for safety and for ease of ventilation (fresh air comes in one and is then exhausted out of the other). Once the correct depth has been reached, horizontal tunnels are driven to reach the ore deposit. These are often temporary so the support requirements are less substantial. Transport for personnel and materials can be by train, truck, or conveyor belts. The largest share of the consumed fuels is diesel followed by electricity. Other major inputs include explosives and water.
- Open pit mining: Hard-rock surface mining usually includes drilling, blasting, or a combination of both processes and then lifting of the broken ore either into trucks or onto conveyors for transportation to the processing plant. This lifting is usually by excavator (electric or hydraulic; with shovel or backhoe configuration) or front-end loader.

5.1.2 Beneficiation (comminution and flotation)

Zinc ore is milled to recover a fine concentrate by gravity and elutriation techniques. During this process, the ore is milled and mixed with water. The separation process of the metal is realized through the addition of various floatation chemicals.

5.2 SHG zinc production

There are two main processes used to produce SHG zinc from zinc concentrate and zinc containing wastes, electrometallurgical zinc smelting and pyro-metallurgical zinc smelting. Worldwide, electrometallurgical smelting produces over 95 % of refined zinc. For this study, information was collected from seven smelting sites, all of which use the electrometallurgical process. Information on pyro-metallurgical zinc smelting is also included, as one smelter from the 2009 study uses this process. Unit process inputs and outputs associated with the average production of SHG zinc from zinc concentrate can be found in the Electronic supplementary material (Tables S1 and S2).

5.2.1 Electrometallurgical zinc smelting

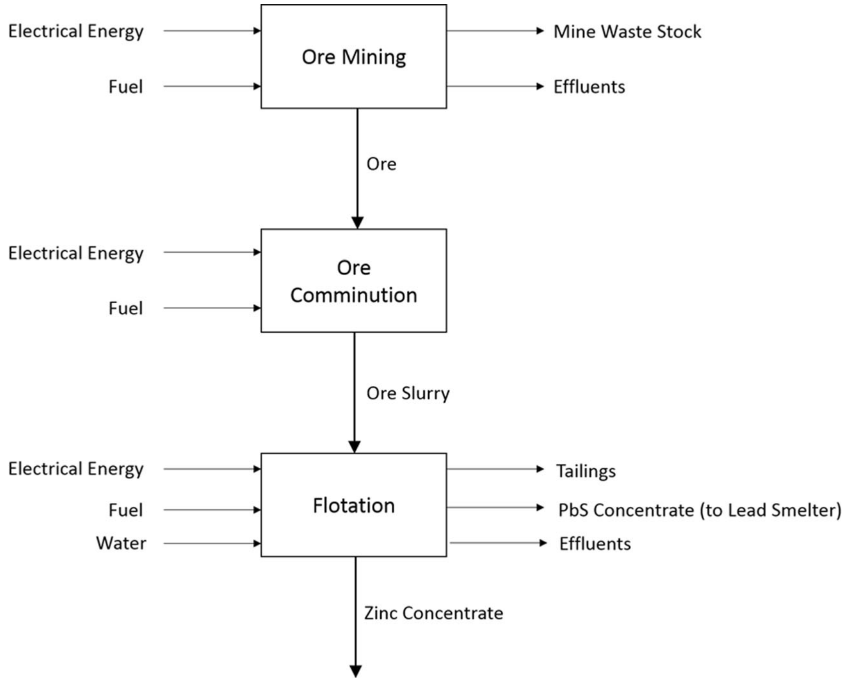
If provided by the manufacturer, information for zinc smelting was collected by unit process; otherwise, data was collection for the aggregated smelting process. The main unit processes for electrometallurgical zinc smelting are roasting, leaching, purification, electrolysis, and melting. Figure 2 provides an overview of the process routes and the most important inputs and outputs to the unit processes. In both electrometallurgical and pyro-metallurgical zinc production routes, the first step is to remove the sulfur from the concentrate. Roasting or sintering achieves this. The concentrate is heated in a furnace with operating temperature above 900 °C (exothermic, autogenous process) to convert the zinc sulfide to calcine (zinc oxide). Simultaneously, sulfur reacts with oxygen to produce sulfur dioxide, which is subsequently converted to sulfuric acid in acid plants, usually located with zinc-smelting facilities.

During the leaching process, the calcine is dissolved in dilute sulfuric acid solution (re-circulated back from the electrolysis cells) to produce aqueous zinc sulfate solution. The iron impurities dissolve as well and are precipitated out as jarosite or goethite in the presence of calcine and possibly ammonia. Jarosite and goethite are usually disposed of in tailing ponds. Adding zinc dust to the zinc sulfate solution facilitates purification. The purification of leachate leads to precipitation of cadmium, copper, and cobalt as metals. In electrolysis, the purified solution is electrolyzed between lead alloy anodes and aluminum cathodes. The high-purity zinc deposited on aluminum cathodes is stripped off, dried, melted, and cast into SHG zinc ingots (99.99 % zinc).

5.2.2 Pyro-metallurgical smelting

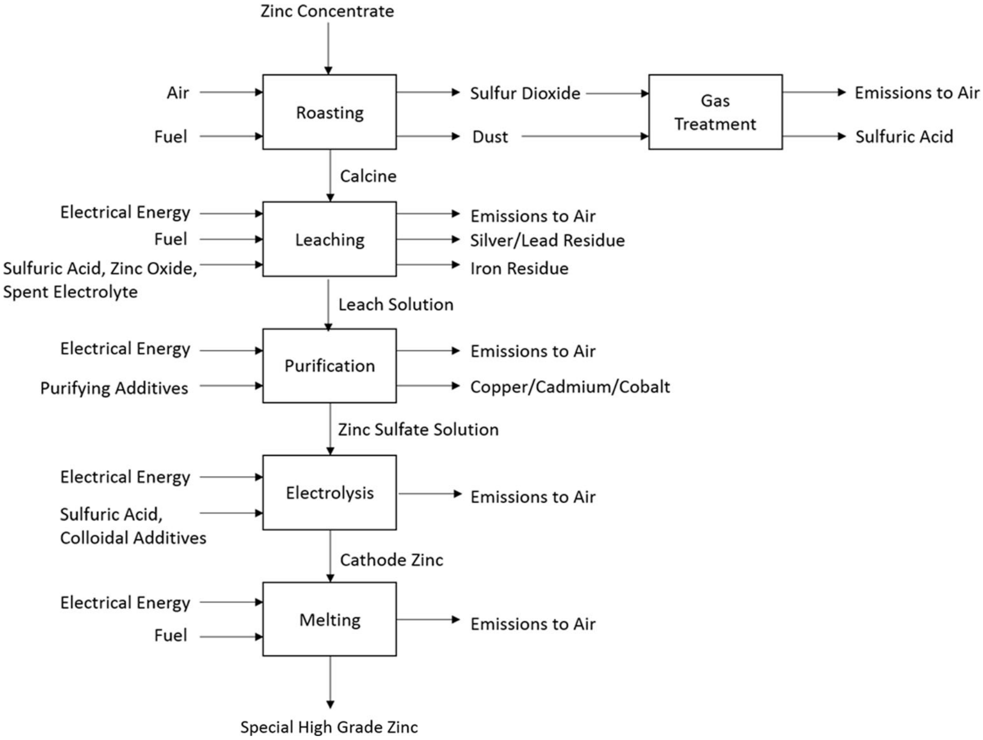
For pyro-metallurgical smelting sites, it was assumed that boundary conditions for the following unit processes were similar to the electrometallurgical system: sintering, imperial smelting furnace, and refining. Figure 3 provides an overview of the process routes and the most important inputs and outputs to the unit processes. The pyro-metallurgical smelting process is based on the reduction of zinc and lead oxides into metal with carbon in an imperial smelting furnace. The sinter, along with pre-heated coke, is charged from the top of the furnace and injected from below with pre-heated air. This ensures that temperature in the center of the furnace remains in the range of 1000–1500 °C. The coke is converted to carbon

Fig. 1 Flowchart of zinc concentrate production



monoxide, and zinc and lead oxides are reduced to metallic zinc and lead. The liquid lead bullion is collected at the bottom of the furnace along with other metal impurities (copper, silver, and gold). Zinc in vapor form is collected from the top of the furnace along with other gases. Zinc vapor is then condensed into liquid zinc. The lead and cadmium impurities in zinc bullion are removed through a distillation process. The imperial smelting process is an energy-intensive process and produces zinc of lower purity than the electrometallurgical process. The difference in purity between zinc generated from the pyro-metallurgical process (>98 %) and SHG was not considered in the current analysis due to its negligible

Fig. 2 Flowchart of SHG zinc production via electrometallurgical smelting



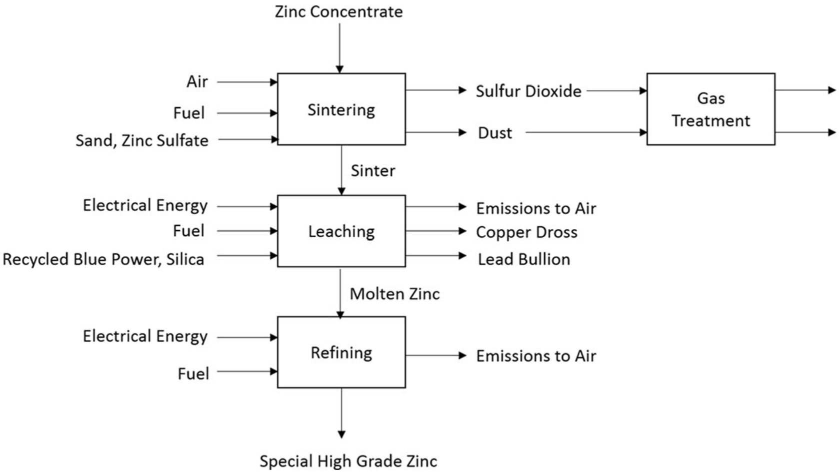


Fig. 3 Flowchart of SHG zinc production via pyro-metallurgical smelting

influence on study results. That is, refined zinc produced pyrometallurgically represents less than 2 % of the total dataset.

6 LCI results

The cradle-to-gate life cycle inventories for selected flows associated with zinc concentrate and SHG zinc production are presented in Table 2. The table includes results for energy and elemental zinc as inputs and emissions to air and freshwater as outputs. Although not shown here, the study produced a full inventory of inputs and outputs, with flows corresponding to the international life cycle data system (ILCD).

7 Life cycle impact assessment results

The results for zinc concentrate and SHG zinc production are presented in Table 3. Additionally, as the SHG zinc production includes the cradle-to-gate life cycle results, a more detailed breakdown is shown in Fig. 4 to provide the relative impact of smelting as compared to mining and intermediate concentrate transportation. It can be seen that smelting represents the majority of the burden, between 56 and 73 % depending on the impact category considered. Concentrate burdens range from 17 to 31 %. Finally, intermediate concentrate transport ranges from 4 to 15 %. Overall, the largest contributor to the environmental impacts of both concentrate and SHG zinc is electricity consumption. Within mining, the contribution of diesel combustion is also significant. The burden avoided by the co-product sulfuric acid could provide on the order of 10 % reductions to the smelting impact, depending on the category assessed.

Because a full inventory was developed as part of this study, practitioners with access to the dataset (via the GaBi databases) can generate a variety of other impact categories, per the needs of individual studies and purposes. Effort was taken to develop a full complement of flows in order to enable these other impact categories to be analyzed, such as those associated with resource depletion and toxicity.

8 Interpretation

8.1 Relevant findings

In general, the impacts due to mining and concentration are largely driven by the energy consumption due to these activities. The process materials are a minor aspect of mining and do not greatly affect the overall impacts associated with zinc concentrate production.

As with the zinc concentrate production, the SHG zinc production impacts are driven by energy consumption. The electricity source for the smelter and thus the country and grid mix specific to that region are key drivers of environmental performance for SHG zinc production.

Further breakdown of the results into contributions from specific processes was not possible due to the variability in the process-level data provided by each facility. Although each facility was modeled comprehensively, process steps and data availability of those process steps are not uniform. For example, some sites provided smelting information as one set of “black box” inputs and outputs, while other sites broke the smelting process into the separate unit processes of roasting, leaching, purification, electrolysis, and melting.

8.2 Data quality assessment

8.2.1 Precision and completeness

As the relevant foreground data is primary data or modeled based on primary information sources of the owner of the technology, no better precision was achievable within this project. Seasonal variations and variations across different

Table 2 Selected inventory results, per metric ton

Inventory measure	Value		Unit
	Concentrate	SHG zinc	
Energy			
Non-renewable energy resources	5,860	27,301	MJ (net cal. value)
Crude oil (resource)	1,855	−4,802[a]	MJ (net cal. value)
Hard coal (resource)	988	11,340	MJ (net cal. value)
Lignite (resource)	478	3,153	MJ (net cal. value)
Natural gas (resource)	2,152	11,076	MJ (net cal. value)
Peat (resource)	19	231	MJ (net cal. value)
Uranium (resource)	304	6,304	MJ (net cal. value)
Renewable energy resources	771	10,143	MJ (net cal. value)
Primary energy from geothermics	52	260	MJ (net cal. value)
Primary energy from hydro power	516	6,323	MJ (net cal. value)
Primary energy from solar energy	133	2,046	MJ (net cal. value)
Primary energy from wind power	70	1,515	MJ (net cal. value)
Elemental zinc	591	1,141	kg
Emissions to air			
Greenhouse gases			
Carbon dioxide (CO_2)	411	2,541	kg
Methane (CH_4)	0.620	3.61	kg
Nitrous Oxide (N_2O)	0.0139	0.0775	kg
Conventional air pollutants			
Oxides of sulfur (SO_x)	0.00180	0.0240	kg
Oxides of nitrogen (NO_x)	1.84	17.9	kg
Particulate matter (PM_{10})	0.962	1.66	kg
Carbon monoxide (CO)	0.496	1.47	kg
Metals			
Antimony	2.36E-04	9.21E-04	kg
Arsenic	0.00208	0.00687	kg
Cadmium	3.98E-04	0.00757	kg
Chromium	1.25E-04	5.56E-04	kg
Cobalt	5.20E-04	0.00175	kg
Copper	0.0392	0.128	kg
Iron	1.66E-04	3.97E-04	kg
Lead	0.0383	0.122	kg
Manganese	0.00474	0.0163	kg
Mercury	3.75E-05	0.00291	kg
Nickel	7.16E-04	0.00246	kg
Selenium	8.37E-05	4.99E-04	kg
Silver	9.64E-08	4.05E-06	kg
Thallium	5.82E-08	6.27E-08	kg
Tin	2.39E-05	2.34E-04	kg
Vanadium	0.00120	0.00513	kg
Zinc	0.0426	0.166	kg
Emissions to freshwater			
Biological oxygen demand (BOD)	0.00317	0.0140	kg
Chemical oxygen demand (COD)	0.243	1.91	kg
Ammonium/ammonia	0.00596	0.0925	kg
Nitrate	0.151	0.383	kg
Nitrogen	0.00919	0.0145	kg

Table 2 (continued)

Inventory measure	Value		Unit
	Concentrate	SHG zinc	
Phosphorus	0.00132	0.00332	kg
Metals			
Antimony	2.36E-04	9.21E-04	kg
Arsenic	0.00208	0.00687	kg
Cadmium	3.98E-04	0.00757	kg
Chromium	1.25E-04	5.56E-04	kg
Cobalt	5.20E-04	0.00175	kg
Copper	0.0392	0.128	kg
Iron	1.66E-04	3.97E-04	kg
Lead	0.0383	0.122	kg
Manganese	0.00474	0.0163	kg
Mercury	3.75E-05	0.00291	kg
Nickel	7.16E-04	0.00246	kg
Selenium	8.37E-05	4.99E-04	kg
Silver	9.64E-08	4.05E-06	kg
Thallium	5.82E-08	6.27E-08	kg
Tin	2.39E-05	2.34E-04	kg
Vanadium	0.00120	0.00513	kg
Zinc	0.0426	0.166	kg

[a] Net negative inventory results have occurred as a consequence of the system expansion approach applied to sulfuric acid and shall not be interpreted in a way that an increase in consumption of the products under study will lead to any "reversal" of environmental burden elsewhere

manufacturers were balanced out by using annual data and production-weighted averages. All background data are GaBi data with the documented precision.

Data was provided voluntarily by participating companies and not third-party verified. Data was requested for the process of mining, concentration, and the sub-processes within smelting; however, some sites were only able to provide smelting data as a single process. Each unit process was checked for mass balance and completeness of the emission inventory. Internal quality assurance was conducted on the completed model. One issue that was encountered in checking the mass balance of the data was a general inadequate tracking of the water usage for both mining and smelting sites. As a result, the water input or output was often not complete and could not be considered in the mass balance. Challenges with collecting the water data are discussed in Sect. 4.5. Similarly, during the calcination process of zinc sulfide ore, oxygen is absorbed by the process and undergoes a reaction with the sulfur to produce sulfuric acid. Although every attempt was made to estimate the oxygen consumption based upon stoichiometric analysis when it was not tracked by the smelter, the calcination process is also a source of potential mass

Table 3 Selected impact assessment results, per metric ton of zinc concentrate or SHG zinc[a]

Impact category (CML 2001–April 2013)	Zinc concentrate (59 % Zn)	Special high-grade zinc	Units
Global warming potential (GWP 100 years)	431	2660	kg CO_2-eq.
Acidification potential (AP)	4.40	17.5	kg SO_2-eq.
Eutrophication potential (EP)	0.287	2.55	kg PO_4^{3-}-eq.
Photochemical ozone creation potential (POCP)	0.255	0.932	kg C_2H_2-eq.
Ozone layer depletion potential (ODP, steady state)	2.69E-07	−8.30E-08[b]	kg R11-eq.

[a] Results conformant with ILCD requirements. Zinc concentrate results serve as an intermediate benchmark for the purposes of the study and will not be made available as a separate dataset; therefore, they do not conform with ILCD

[b] Net negative impact results have occurred due to the energy credit associated with waste incineration and should not be interpreted in a way that an increase in consumption of the products under study will lead to any "reversal" of environmental burden elsewhere

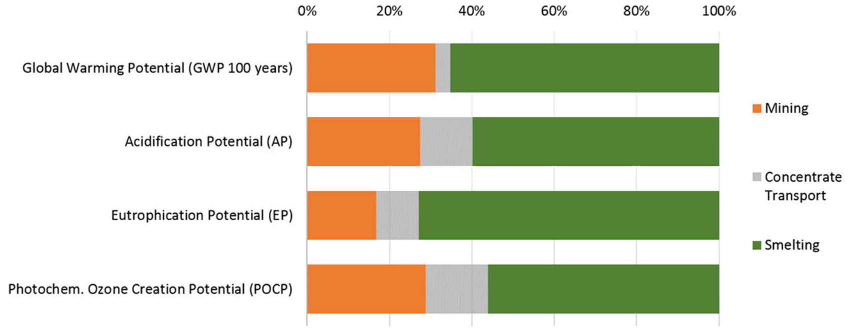


Fig. 4 Relative influence of life cycle stages on concentrate and special high-grade zinc production

imbalance. Finally, there was a data gap related to emissions to water for some sites; this data gap was filled using average data from other sites. No data were knowingly omitted except as mentioned in Sect. 2.6.

8.2.2 Methodology differences compared to the 2009 report

To ensure consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases. One issue of inconsistency is the allocation methods discussed for the new data. For the 2009 data, a mass allocation was universally applied except when co-products could be credited using system expansion. For the new data, allocation was mostly done using the mass of metal content except for isolated exceptions and zinc-containing products, as discussed in Sect. 2.5. The difference in allocation methodology represents an improvement on the field of LCA, and in general, the mass of metal content is close to the relative masses of the co-products.

8.2.3 Representativeness

All primary data collected for this study is representative of the year 2012. All secondary data come from the GaBi 6 2013 databases and are representative of the years 2006–2012. The data used from the 2009 study are representative of production in the years 2005 and 2006. It is assumed that the technology has not significantly changed since then. As the background data has been updated for the 2009 data, the temporal representativeness is considered to be high.

All primary and secondary data were collected specific to the countries/regions under study. Where country/region-specific secondary data were unavailable, proxy data were used. Table 4 presents the regional composition of global concentrate and refined zinc production compared to the regional composition of all sites participating in the current study. The deviation of this study's composition compared to the global production is presented in a third column, for both concentrate and SHG zinc. It is calculated as the absolute value of the difference in percentage points between the study and global compositions. A weighted average deviation is shown in the bottom row, calculated based on this study's regional composition. The deviations for the mine and smelter regional composition are 23 and 25 %, resulting in global representativeness values of 77 and 75 %, respectively. The study's global representativeness is therefore deemed to be moderate.

All primary and secondary data were modeled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used (see Sect. 3). In practice, mining and concentration methods for zinc are consistent in all regions. However, 90 % of zinc smelting is done using electrometallurgical techniques (Fig. 2); this same representation is reflected in the primary zinc LCI. As such, technological representativeness is considered to be high.

8.3 Sensitivity

8.3.1 Allocation method

As mentioned in Sect. 2.5, the 2009 study used mass allocation for many of their co-products. In contrast, the new data was allocated by metal content (where metal co-products were produced). This results in an inconsistency between the 2009 study data and the new primary data collected for this study; however, the quantitative difference between the allocation factors is ultimately less than 2 percentage points, which would have little effect on the final results. This can be seen in Table 5, which compares the allocation factors used to distribute the environmental burden between co-products, calculated for the two alternative allocation methods of metal and mass. Examples of selected mines and smelters and their associated co-products are presented. The final column shows the average difference in percentage points between the metal and mass allocation factors used to allocate burden for each co-product.

8.3.2 Global mix concentrate transport to smelter

As mentioned previously, one assumption made was the source of zinc concentrate for each smelter. For the new data, each company was asked to provide a source or sink to describe the flow of zinc concentrate through the value chain. For some smelting companies, the aggregated, production-weighted global mix was used as a proxy or to fill deficits in the zinc

Table 4 Comparison between relative contribution of each continent to global zinc supply (concentrate and refined metal production) and representation of each continent in the LCA (ILZSG 2016)

Continent	Regional share of global mine production (2012)	Share of regional mine production in 2014 dataset	Deviation	Regional share of global refined zinc production (2012)	Share of regional refined zinc production in 2014 dataset	Deviation
Africa	4 %	3 %	1 %	2 %	3 %	2 %
Asia	34 %	0 %	34 %	59 %	17 %	42 %
Australia	15 %	34 %	20 %	4 %	9 %	4 %
Europe	10 %	14 %	4 %	19 %	49 %	30 %
North America	17 %	49 %	31 %	11 %	23 %	12 %
South America	20 %	0 %	20 %	6 %	0 %	6 %
Weighted average deviation			23 %			25 %

concentrate imports reported. The global mix represents all available data for mining and concentration from the 2009 report and the new concentrate data and is consistent with the LCI and LCA reported for aggregated concentrate in this report. In order to model the global mix, a distance had to be assumed for the shipping of this concentrate to the new smelter respondents. In order to determine the distance, the top five producers of zinc concentrate were used to estimate the shipping distance between these producers and the receiving smelters. The top five producers of concentrate in the global mix represent 65 % of the concentrate production.

To determine the sensitivity of this calculated theoretical distance, a sensitivity analysis was performed using the 5th and 95th percentile values of all concentrate shipping distances reported. This impacted the results for the SHGZ as shown in Table 6.

8.4 Consistency

All assumption, methods, and data were found to be consistent with the goal and scope of the study. The use of primary data from a previous LCA is considered to be consistent with the 2012 primary data due to the lack of significant technological changes at those sites. The largest methodological inconsistency between the 2009 and 2012 study is the method of allocation, which was shown to have little impact on the final results. Differences in background data quality were minimized by using LCI data from the GaBi 6 2013 databases throughout the model.

9 Summary

This study continues the history of the zinc industry attempting to quantify the impact of their products for all users of zinc. The goal of this effort is to provide stakeholders—both internal and external to the zinc industry—a more accurate and defensible estimation of the environmental impacts of zinc. The representativeness of the study, however, is limited by the willingness of sites to provide primary data. While technology and temporal representativeness are deemed to be high,

Table 5 Sensitivity analyses of mass and metal allocation methods for concentrate and smelting co-products

Process (co-products)	Site A		Site B		Site C		Site D		Site E		Aggregate average difference
	Metal	Mass	Metal	Mass	Metal	Mass	Metal	Mass	Metal	Mass	
Concentrate											
Zinc	95.1 %	95.4 %	47.1 %	49.0 %	47.3 %	45.4 %	63.1 %	67.4 %	78.1 %	78.6 %	−0.1 %
Lead	4.9 %	4.8 %	52.9 %	51.0 %	19.6 %	16.6 %	29.0 %	29.1 %	21.0 %	20.2 %	1.2 %
Copper	–	–	–	–	33.1 %	37.9 %	2.9 %	3.5 %	0.9 %	1.7 %	−1.5 %
Smelting											
Zinc sulfate solution	99.3 %	99.8 %	99.2 %	99.8 %	98.9 %	(by volume)	98.4 %	98.1 %	–	–	−0.3 %
Copper cement	0.6 %	0.1 %	0.7 %	0.1 %	0.0 %	–	0.5 %	0.7 %	1.3 %	2.4 %	0.0 %
Cadmium	–	–	0.1 %	0.0 %	–	–	–	–	0.4 %	0.4 %	−0.1 %
Cobalt cement	–	–	–	–	0.1 %	–	0.1 %	0.1 %	0.1 %	0.2 %	−0.1 %
Cadmium cement	–	–	–	–	0.2 %	–	0.2 %	0.3 %	–	–	−0.1 %
SHG zinc	–	–	–	–	–	–	–	–	90.8 %	89.6 %	1.2 %

Table 6 Impact of global mix transportation, per metric ton of SHG zinc

Impact category (CML 2001–April 2013)	Total SHG zinc	Unit	Sensitivity to distance	
			5th percentile	95th percentile
Global warming potential (GWP)	2660	kg CO_2-eq.	−2 %	0 %
Acidification potential (AP)	17.5	kg SO_2-eq.	−7 %	1 %
Eutrophication potential (EP)	2.55	kg PO_4^3-eq.	−5 %	1 %
Photochemical ozone creation potential (POCP)	0.932	kg C_2H_2-eq.	−8 %	1 %

geographic representation suffers from a lack of participation from sites in Asia and South America. Inclusion of Indian and Chinese sites would presumably increase the environmental burdens, due to the high use of hard coal in the regions' electricity grid mixes. Some of this increased burden could be offset with the inclusion of regions with large hydropower representation, such as Brazil, but given the regional dependency of emission regulations and variations in technology and efficiency, this is impossible to predict without further data collection. Future studies should promote involvement of sites within underrepresented regions.

As LCA methodologies evolve to be more accurate and data collection becomes more comprehensive, the results of the zinc life cycle assessment will continue to lead to more transparency for interested stakeholders. Additionally, the provision of unit process details on concentrate production and SHG zinc smelting will be useful in future temporal comparisons and allows for greater transparency of the underlying study.

References

Drielsma J, Russell-Vaccari A, Drnek T, Brady T, Weihed P, Mistry M, Perez Simbor L (2016) Mineral resources in life cycle impact assessment—defining the path forward. Int J Life Cycle Assess 21(1):85–105

ILZSG (2016) Monthly bulletin of the International Lead and Zinc Study Group 56(1):42–44

PE INTERNATIONAL (2012) GaBi 6 dataset documentation for the software-system and databases, LBP, University of Stuttgart and PE INTERNATIONAL GmbH, Leinfelden-Echterdingen, (http://documentation.gabi-software.com/)

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

USEPA (1995) AP-42—compilation of air pollutant emission factors. Volume 1: stationary point and area sources. Fifth Edition. Office of Air Quality Planning and Standards. Research Triangle Park, NC