CHALMERS
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Assessment of anthropogenic material flows in a circular economy

A case study on zinc used in the construction sector

Master's thesis in Master Program Industrial Ecology

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Master's thesis ACEX30
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Cover: The zinc-clad Jewish Museum in Berlin, Germany. Photo by Tanja Cotoaga on Unsplash

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Abstract

In the transition to a circular economy, an increased understanding regarding anthropogenic material flows is required in order to advocate towards a sustainable management of materials. The construction sector consumes about one third of all material resources, while generating the largest waste stream in the European Union - thus having a high potential for circularity. The aims of this study are to **1**/evaluate the availability of data of anthropogenic flows of zinc in Sweden - a metal of both societal and environmental relevance due to its scale of use, as well as to **2**/analyze the assessment to support a transition to a circular economy - with focus on the construction sector. Anthropogenic mass flows of zinc were estimated using Material Flow Analysis along with a review of the literature on assessment of circular economy. This study shows that current data regarding waste flows are not sufficient to estimate flows to waste management and recycling on an elemental level due to low level of detail for aggregated waste flows. Therefore, a complete Material Flow Analysis could not be done. Furthermore, a large focus is being put on waste flows and waste management, i.e. higher recycling rates and an increasing use of secondary raw materials, however with low attention paid to the qualitative aspects of recycling. The understanding, quantification and estimation of anthropogenic flows of materials through the economy provides an important knowledge base when deciding on measures and policy instruments related to circular economy. Recycling is important to reduce the demand for virgin raw materials. However, the initial material and energy resources used to build a construction are for the most part lost through recycling - a transition to a circular economy, therefore requires measures beyond efficient recycling.

Keywords: circular economy, resource efficiency, material flow analysis, zinc, construction sector, reuse, recycling.

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Lovisa Persson, Gothenburg, May 2020

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Acronyms

BAT Best Available Techniques.
BF Blast Furnace.
BOF Basic Oxygen Furnace.

C&D Construction and Demolition.
CR Collection Rate.
CRM Critical Raw Materials.

EAF Electric Arc Furnace.
EEE Electrical and Electronic Equipment.
ELV End-of-Life Vehicles.
EoL End-of-Life.
EoL-RR End-of-Life Recycling Rate.
EPA Environmental Protection Agency.
EU European Union.
EWC-Stat European Waste Classification for Statistics.

ICT Information and Communications Technologies.

LCA Life-Cycle Assessment.
LoW List of Waste.

MFA Material Flow Analysis.

OSR Old Scrap Ratio.

RC Recycled Content.
RIR Recycling Input Rate.
RMI Raw Material Initiative.

WEEE Waste Electrical and Electronic Equipment.

1

Introduction

"A circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems" (Ellen MacArthur Foundation, 2017b, para. 1) - meaning that resources coming into the economy are not allowed to become waste or lose their value. Metal recovery is therefore an important contribution to a circular economy. It is also a priority within the European Union (EU) due to the importance of raw materials to the EU economy. The Raw Material Initiative (RMI) adopted by the EU in 2008 is one initiative to ensure a continued supply of metals - emphasizing the need for "resource efficiency and supply of secondary raw materials" (European Commission [EC], 2018, p. 13).

The construction sector is identified as one of the sectors using most resources - consuming about a third of all material resources - while generating the largest waste stream in the EU, thus having a high potential for circularity (European Environment Agency [EEA], 2020; Stahel, 2019). Furthermore, the construction sector is classified as one of the key product value chains in the new Circular Economy Action Plan adopted in 2020 (EC, 2020b).

Metals are used increasingly in a large variety of applications (UNEP, 2010). The “Metal Wheel” by Reuter also shows that the uses are interconnected, and material recycling can recover a share of metals, while others become part of ashes and slags, which are in turn used in construction materials (UNEP, 2013b). In that case, metals become part of another type of use, where they do not necessarily contribute to the function, but are considered as non-hazardous as they do not contribute to leaching and subsequently elevated levels in water and soil (UNEP, 2011).

Increasing attention is paid to metals and minerals which are considered as “critical”, meaning they are economically relevant for important industries while coming from a limited number of supplying countries, which could limit or restrict exports (EC, 2018) – the example of China’s restriction of rare earth elements exports is cited (Johnson & Groll, 2019). Other metals are of societal relevance due to their scale of use, such as iron (Fe), aluminium (Al), copper (Cu), zinc (Zn) and lead (Pb) - see figure 1.1 (UNEP, 2013a).

Some metals are known to be toxic, including cadmium (Cd), mercury (Hg) and lead (Pb), and are therefore of environmental relevance (UNEP, 2013a). Considering the Life Cycle Impact due to energy consumption of mining and refining, metals used in large quantities tend to have dominating impacts.

Zinc is not on the EUs Critical Raw Materials (CRM) list and it has comparatively low toxic impacts. But due to its scale of use and therefore, potential Life Cycle Impact, zinc is considered to be of both societal and environmental relevance (UNEP, 2013a).

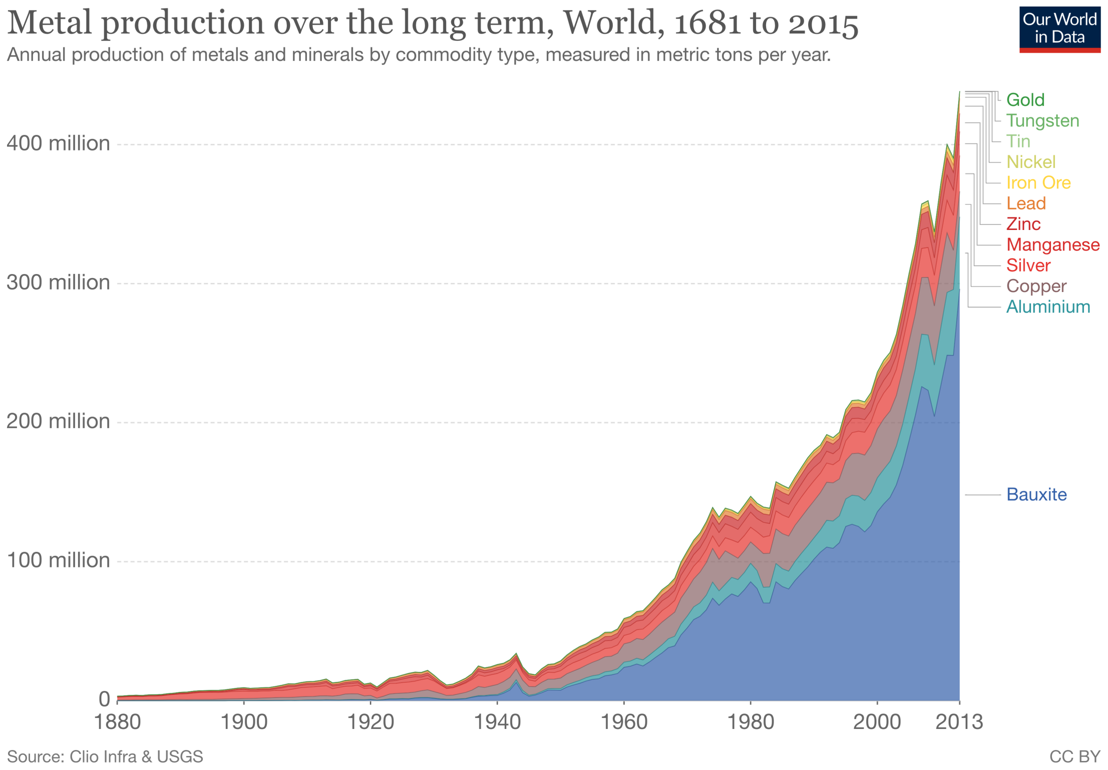


Figure 1.1: “Metal production over the long term, World, 1681 to 2015: Annual production of metals and minerals by commodity type, measured in metric tons per year.” by Our World in Data is licensed under CC BY.

1.1 Problem formulation

Usage and application of metals grew rapidly in the 20th century - from production of various electronic goods to manufacturing of buildings and infrastructure - hence having a core role in the global economy (UNEP, 2010). The backside of this trend are potential environmental impacts due to expanding mining activities and resource constraints. So called "urban mining" - the process of reclaiming raw materials from anthropogenic stocks such as products, industry, buildings and infrastructure, a term often used for any kind of material recycling today (Cossu & Williams, 2015) - is therefore considered increasingly important in today’s society and the understanding, quantification and estimation of flows of metals through the economy provides important information about the potential to meet a future demand with metal recycling.

Anthropogenic stocks are "the metal stocks in society, already extracted, processed, put into use, currently providing service, or discarded or dissipated over time" - an area less studied today (UNEP, 2010, p. 12). In terms of number of estimates - iron, copper, zinc and lead are the top four metals for which studies of metal flows and estimates of in-use stocks have been performed according to UNEP (2010). However, UNEP claims that information enough to provide reliable estimates of in-use stocks of metals are only available for "perhaps only copper, iron, aluminium, and lead, and only for the more-developed countries" (UNEP, 2010, p. 20) - zinc is not on the list.

An increased understanding regarding anthropogenic metals flows are required in order to advocate towards a sustainable management of metals. Such information provides an important knowledge base when deciding on measures and policy instruments related to circular economy.

The issue is reflected in Sweden's National Waste Plan and Waste Prevention Program 2018–2023, stating that "today, there is limited knowledge about the in-use stocks, both its importance as an economic resource and its environmental- and health impacts" (Swedish Environmental Protection Agency [Swedish EPA], 2018, p.26). Furthermore, the importance of increasing the knowledge and information regarding in-use stocks is emphasized in order to dimensioning recycling as well as accelerating the development towards resource efficiency.

1.2 Aim and research questions

Through Material Flow Analysis (MFA), materials flowing into, out of, and through a system can be characterized and quantified - increasing the understanding of anthropogenic flows of zinc in society. Such information provides an important knowledge base in the transition to a circular economy. Furthermore, visions and targets for circular economy are widely assessed using environmental indicators - which are important to support the transition.

Research questions that this study aims to answer are:

1/Is the existent data sufficient enough to perform a MFA of anthropogenic flows of zinc in Sweden?

2/Is the current assessment sufficient to support a transition to a circular economy?

1.3 Delimitations

The main focus of this study is anthropogenic flows of zinc, zinc flows in nature and living organisms will therefore not be estimated. Furthermore, due to its interconnection with other metals, zinc cannot be treated in isolation - associated metals flows will not be estimated but discussed if relevant. Geographical limitations are set to Sweden to estimate the material flows of zinc on a national level. The anthropogenic flows of zinc will be included regardless of end-use sector. However, the result will mainly be discussed in relation to the construction sector.

2

Background

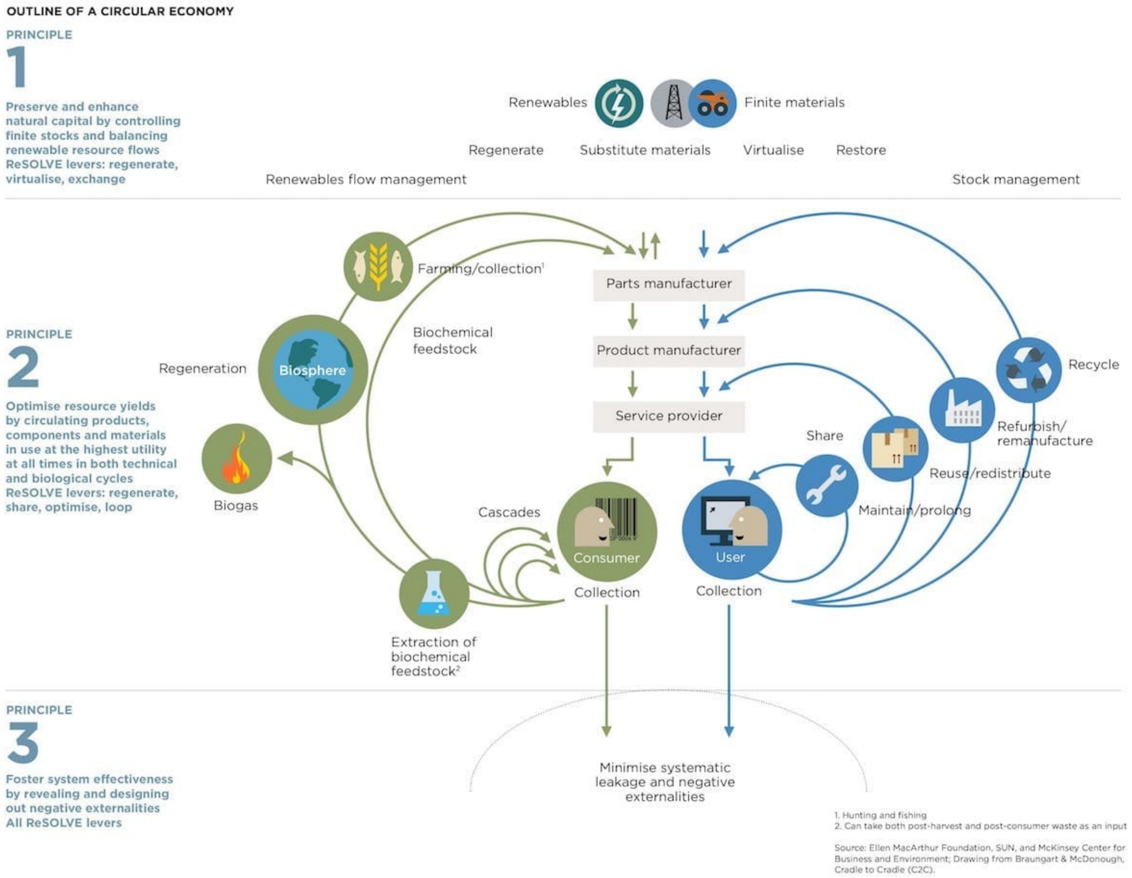
2.1 Circular economy

The industrial revolution and a developing linear industrial economy led to the introduction of emissions of chemicals, man-made materials and synthetic fibers into the society - ultimately creating a society of abundance (Stahel, 2019). With the linear industrial economy, the dependency on resource imports and waste exports are maintained as well as the need for managing wastes. According to Stahel, mentioned downsides are what partly drives a transition towards a circular economy.

The linear industrial economy has been described as "take, make, sell, consume and dispose" (Stahel, 2019, p. 7) where focus is to create value added, to optimize flows and to increase the efficiency (not in the sense of resource efficiency) of producing goods. Hence, the manufacturing activities are characterized by intensive use of energy and materials.

In a circular economy, the concept of growth is redefined - economic activity is decoupled from exploitation of limited resources and resources are not allowed to become waste (Ellen MacArthur Foundation, 2017a). According to the Ellen MacArthur Foundation, a circular economy is built on three principles: "Design out waste and pollution", "Keep products and materials in use", and "Regenerate natural systems".

The 'butterfly diagram' developed by the Ellen MacArthur Foundation has been famous for capturing the essence of the circular economy (see figure 2.1). It distinguishes between flows of the Biosphere - biological materials that can re-enter the environment safely, and flows of the Technosphere - technical materials that cannot re-enter the environment (including metals, plastics and synthetic chemicals), instead, their value is captured through continuously re-circulation within the system (Ellen MacArthur Foundation, 2017a; Stahel, 2019).



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Figure 2.1: The ‘butterfly diagram’ by the Ellen MacArthur Foundation. Copyright © Ellen MacArthur Foundation (2017), www.ellenmacarthurfoundation.org.

The loops of the technosphere are described as the circular industrial economy in which Stahel (2019) differentiates between two main domains - the era of ’R’ and the era of ’D’. In the era of ’R’, the value and usability of manufactured objects are maintained and in the era of ’D’, the quality and purity of molecules and atoms are preserved. Tasks and values differs between the two eras which should be considered in terms of ownership and control. The owner and users control the era of ’R’ whereas the economic actors responsible for "end-of-service-life objects" control the era of ’D’. Strategies and measures related to the two domains are presented in table 2.1.

Furthermore, Stahel (2019) argues that the strategies of the era of ’R’ should be preferred to those of the era of ’D’ based on a basic economic principle - "The use value of a product is higher than the sum of the value of the materials it is made of" (p. 23).

Table 2.1: Strategies and measures related to the era of 'R' and the era of 'D' (Stahel, 2019, p. 27, 39)

The era of 'R'	The era of 'D'
Reuse	**D**e-polymerise
Repair	**D**e-alloy
Remarket	**D**e-laminate
Rmanufacture	**D**e-vulcanise
Re-refine	**D**e-coat materials
Reprogramme goods	**D**e-construct high-rise buildings and major infrastructure

2.1.1 Circular economy in the European Union

"Resource efficiency and supply of secondary raw materials" (EC, 2018, p. 13) is one of the three pillars of the Raw Material Initiative (RMI), adopted by the European Union (EU) in 2008 to ensure a sustainable and continued supply of raw materials due to their importance for the EU economy. The RMI has led to several initiatives and the EC (2018) mention the adoption of the Circular Economy Action Plan in 2015 as one important milestone to achieve a secured supply of raw materials.

The Circular Economy Action Plan included measures to facilitate a transition towards a circular economy through giving "a new boost to jobs, growth and investment and to develop a carbon neutral, resource-efficient and competitive economy" (EC, 2019a, p. 1). In 2020, a new Circular Economy Action plan was adopted, including measures that aims to (EC, 2020a):

- Make sustainable products the norm in the EU.
- Empower consumers and public buyers.
- Focus on the sectors that use most resources and where the potential for circularity is high such as: electronics and Information and Communications Technologies (ICT), batteries and vehicles, packaging, plastics, textiles, construction and buildings, and food, water and nutrients.
- Ensure less waste.
- Make circularity work for people, regions and cities.
- Lead global efforts on circular economy.

2.1.2 Circular economy in Sweden

Despite many efforts in the area of circular economy initiated by politics, research and business, Sweden lacks a strategy and action plan for circular economy (SOU 2017:22). A delegation for circular economy was established by the government in 2018 to develop a strategy for the transition to a circular and bio-based economy, both at regional and national level in society (Tillväxtverket, 2020).

Sweden's environmental objectives are guiding for all environmental work in Sweden (SOU 2017:22). The objectives include one generational goal - defining the overarching vision of environmental efforts - and 16 environmental quality objectives and a number of milestone targets to enable such efforts (Swedish EPA, 2018). However, the vast majority of the environmental quality objectives and associated indicators are concerned with the state of environment (SOU 2017:22). Only the environmental quality objective *A Good Built Environment* includes clarifications relating to resource efficiency - "natural resources are used in an efficient, resource-saving and environmentally-friendly manner aiming to minimize their use" and "waste is diminished, while the resources in waste are better used, and the impact of waste on health and environment are minimized" (Swedish EPA, 2018, p. 38). One of the milestone targets relates to waste in the construction sector specifically. The target, also found in the EUs directive on waste, states that "Measures are to be taken so that, by 2020, at least 70 per cent by weight of non-hazardous construction and demolition waste is prepared for reuse, recycling and other material recovery" (Swedish EPA, 2018, p. 39).

2.2 Indicators

In everyday life we use indicators to manage the flows of information we use to understand systems (Meadows, 1998). Indicators are one of many tools for sustainability assessment, often used for decision-making, as they can represent the development of the economic, social and/or environmental state (Ness et al., 2007). Most often indicators are quantitative, meaning that if continuously measured and calculated, they enable to track long-term sustainability trends.
At the European level, ten indicators are used to monitor progress towards a circular economy, presented in table 2.2.

Table 2.2: Circular economy indicators in the EU (EC, 2019b)

Thematic areas Indicator
Production and consumption
EU self-sufficiency for raw materials
Green public procurement (as an indicator for financing aspects)
Waste generation (as an indicator for consumption aspects)
Food waste
Waste management
Recycling rates
Recycling/recovery for specific waste streams (C&D waste, biowaste, e-waste, etc.)
Secondary raw materials
Contribution of recycled materials to raw materials demand
Trade of recyclable raw materials between the EU Member States and with the rest of the world
Competitiveness and innovation
Private investments, jobs and gross value added
Number of patents related to recycling and secondary raw materials

Recycling is central for the RMI and the Circular Economy Action Plan as it enables secondary raw material to re-enter the economy while improving resource efficiency and providing a solution to scarcity of non-renewable resources - widely monitored using indicators (EC, 2018; UNEP, 2011). Depending on perspectives and life cycle stages, many different definitions of recycling rates exists. Based on previous work towards a more consistent use of definitions, UNEP (2011) uses five measures that defines recycling efficiencies, both at End-of-Life (EoL) and in production of metals. Figure 2.2 illustrates flows in a simplified life cycle of metals related to recycling of new- (generated during production) and old- (EoL products) scrap (same nomenclature as in the equations presented below).

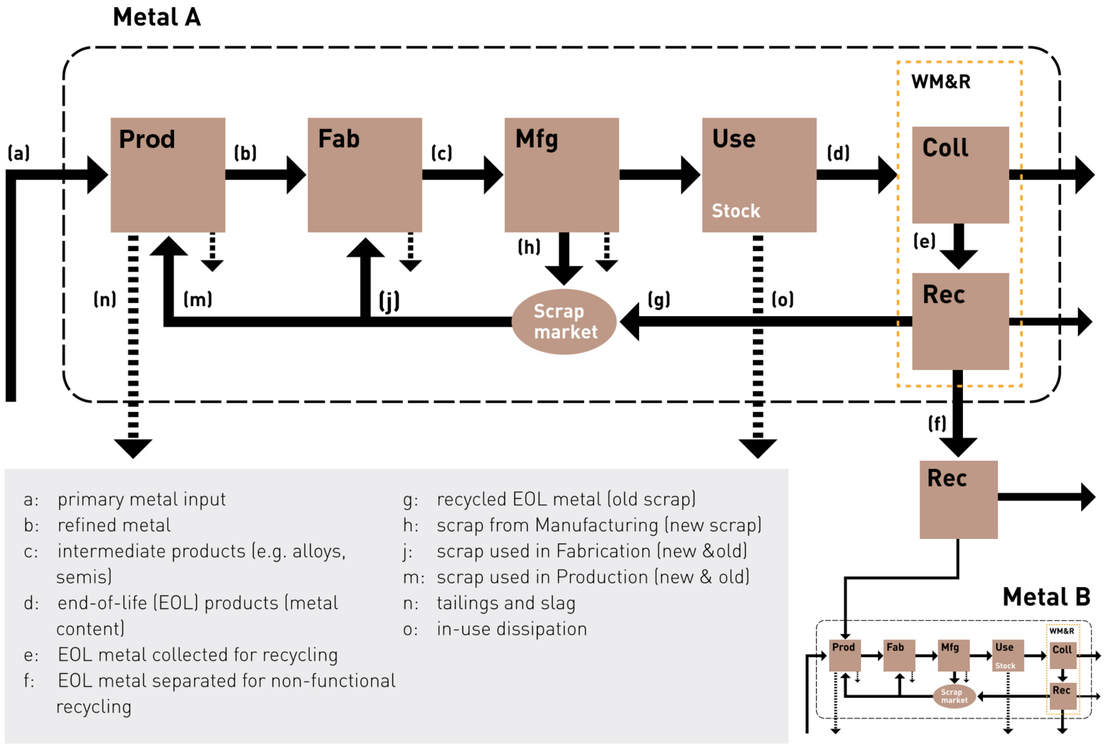


Figure 2.2: Main processes of a metal life cycle: production (Prod), fabrication (Fab), Manufacturing (Mfg), waste management and recycling (WM&R), collection (Coll), recycling (Rec). Dashed lines indicates yield losses. Metals discarded to waste management may be "recycled (e), lost into the cycle of another metal (f, as with copper wire mixed into steel scrap), or landfilled" (UNEP, 2011, p. 16).

There are three levels at which the efficiency of recycling at EoL can be measured: the metal collected at EoL entering the chain of recycling - *old scrap Collection Rate (CR)* (Eq. 2.1), the yield from the recycling process - *Recycling process efficiency rate* (Eq. 2.2), and the amount of metal that is recycled relative to what is collected at EoL - *End-of-Life Recycling Rate (EoL-RR)* (Eq. 2.3). The EoL-RR always relate to functional recycling whereas the non-functional EoL-RR is the share of collected metal which in the main collected metal becomes an impurity.

$$CR = \frac{e}{d} \tag{2.1}$$

$$Recycling\ process\ efficiency\ rate = \frac{g}{e} \tag{2.2}$$

$$EoL - RR = \frac{g}{d} \tag{2.3}$$

Two measures that are important in metal production are: the fraction of secondary metal input in production - *Recycled Content (RC)* (Eq. 2.4), also called *Recycling Input Rate (RIR)*, and the share of secondary metals in the recycling process - *Old Scrap Ratio (OSR)* (Eq. 2.5).

$$RC = \frac{(j+m)}{(a+j+m)} \tag{2.4}$$

$$OSR = \frac{g}{(g+h)} \tag{2.5}$$

2.3 Zinc

Apart from being essential to all life on earth - meaning that humans, animals and plants need zinc to function, zinc is central in today's industrial society (Landner & Lindeström, 1998; Meylan & Reck, 2017). Zinc, together with copper, lead and nickel are examples of the most common base metals, i.e. they are non-ferrous (contain no iron) and they are important components for our infrastructure (Geological Survey of Sweden [SGU], 2019).

As illustrated in figure 2.3, production of zinc has increased drastically in the last decades. The world zinc resources identified are 1.9 billion tons and the world zinc reserves - what is economically feasible to extract - in 2019 was estimated to 250 million tons (U.S. Geological Survey [USGS], 2020c). Zinc reserves are mainly found in China and Australia which are also leading ore-producing countries together with Peru, accounting for 33 %, 10 % and 11 % of the global mine production respectively (see figure 2.4 and 2.5). The global mine production the same year was 13 million tons, a 4 % increase from that of 2018. Refined zinc production and metal consumption globally 2019 was 13.49 million tons and 13.67 million tons respectively.

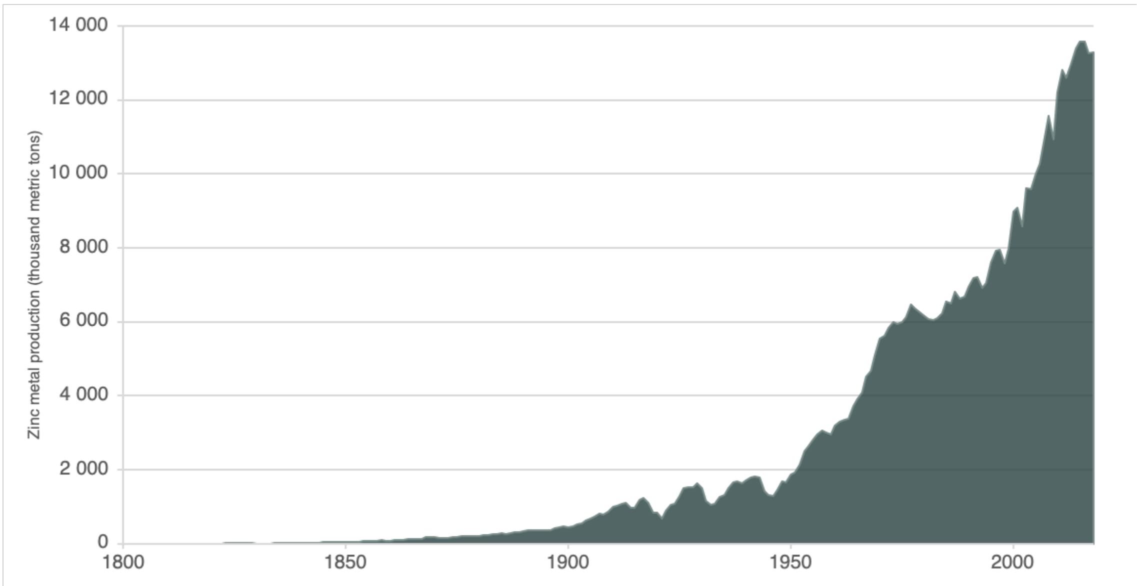


Figure 2.3: Global zinc metal production, 1800 to 2019, in thousand metric tons (International Lead and Zinc Study Group [ILZSG], 2020b; "Metal production over the long term, World, 1681 to 2015: Annual production of metals and minerals by commodity type, measured in metric tons per year." n.d.).

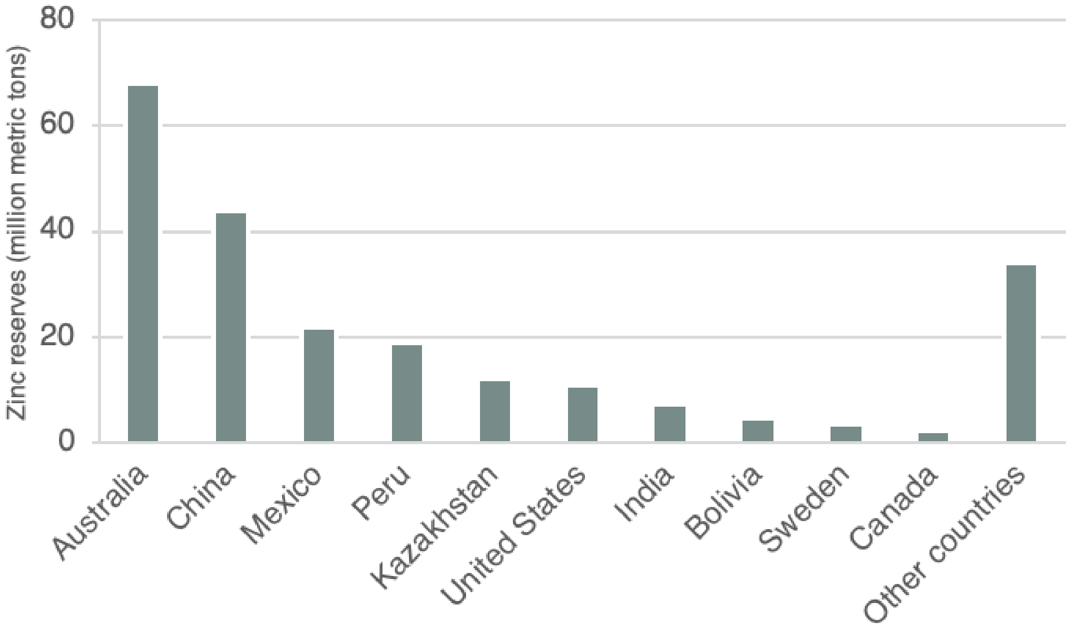


Figure 2.4: Global distribution of zinc reserves 2019 in million metric tons (USGS, 2020a).

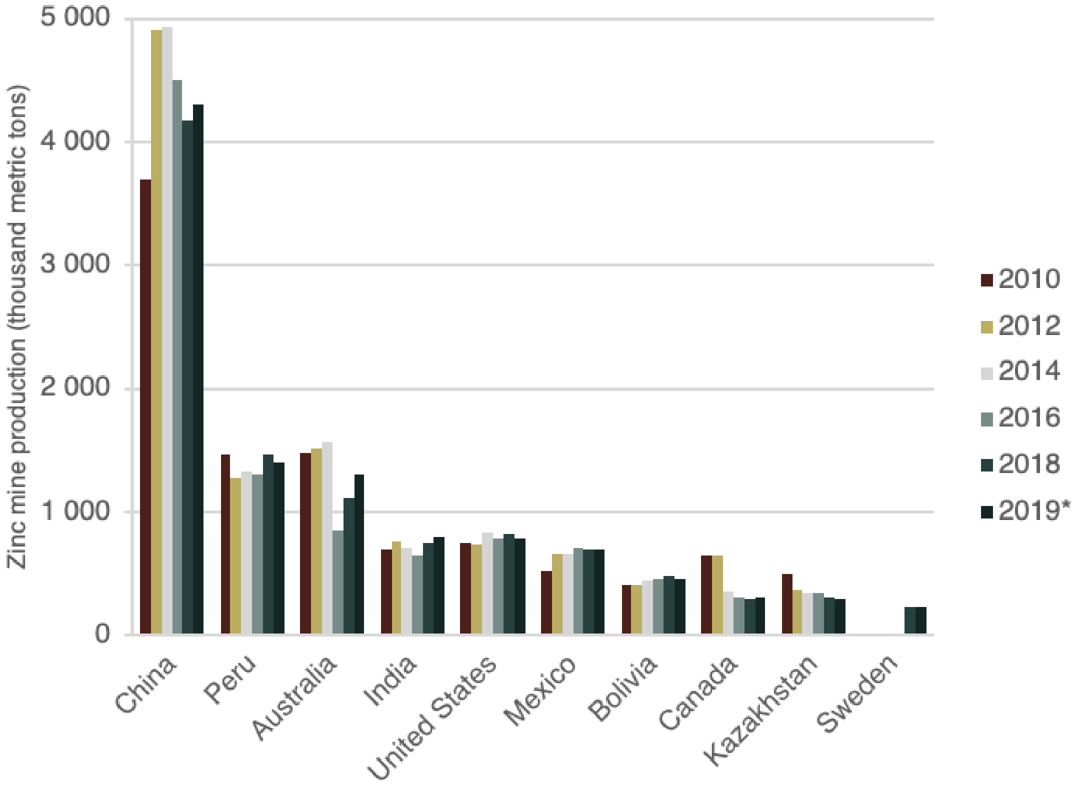


Figure 2.5: Major countries in global zinc mine production from 2010 to 2019 in thousand metric tons. *Estimated. (USGS, 2020b).

Zinc ores often contain lead, meaning that production of zinc and lead are interconnected (SGU, 2019). As main applications of the two metals are different, future demand is controlled by different sectors. Zinc is mainly used for galvanizing steel and demand is thus controlled by the construction sector whereas the main usage for lead is in batteries for cars, dependent on trends in the transportation sector.

Both zinc and lead are so called carrier metals as they supply many other minor elements that are important for sustainable technologies, such as indium (In) and germanium (Ge) (Reuter et al., 2015). The interconnection of metals are captured by the 'Metal Wheel' by Reuter, illustrated in figure 2.6 (UNEP, 2013b). The inner blue circle contains carrier metals, which historically have been targeted for primary production. It also shows the metallurgical technology generally used for processing each carrier metal - both ores and recycled raw materials such as residues and EoL products. Each slice includes metals that can be extracted or co-produced within the same technology - other carrier metals are found in the light blue area and other metals of value are found in the white area. Losses of metals and other elements are found in the outer green area as those cannot be economically recovered with the given technology. The metal wheel are created based on current Best Available Techniques (BAT), in the context of pollution prevention and control (*Industrial Emissions* Directive 2010/75/EU (integrated pollution prevention and control))

🟦 **Society's Essential Carrier Metals: Primary Product** Extractive Metallurgy's Backbone (primary and recycling metallurgy). The metallurgy infrastructure makes a "closed" loop society and recycling possible.

▢ **Dissolves mainly in Carrier Metal if Metallic (Mainly to Pyrometallurgy)** Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).

☐ **Compounds Mainly to Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy)** Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).

🟩 **Mainly to Benign Low Value Products** Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

El **Mainly Recovered Element** Compatible with Carrier Metal as alloying Element or that can be recovered in subsequent Processing.

El **Mainly Element in Alloy or Compound in Oxidic Product, probably Lost** With possible functionality, not detrimental to Carrier Metal or product (if refractory metals as oxidic in EoL product then to slag/slag also intermediate product for cement etc.).

El **Mainly Element Lost, not always compatible with Carrier Metal or Product** Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.

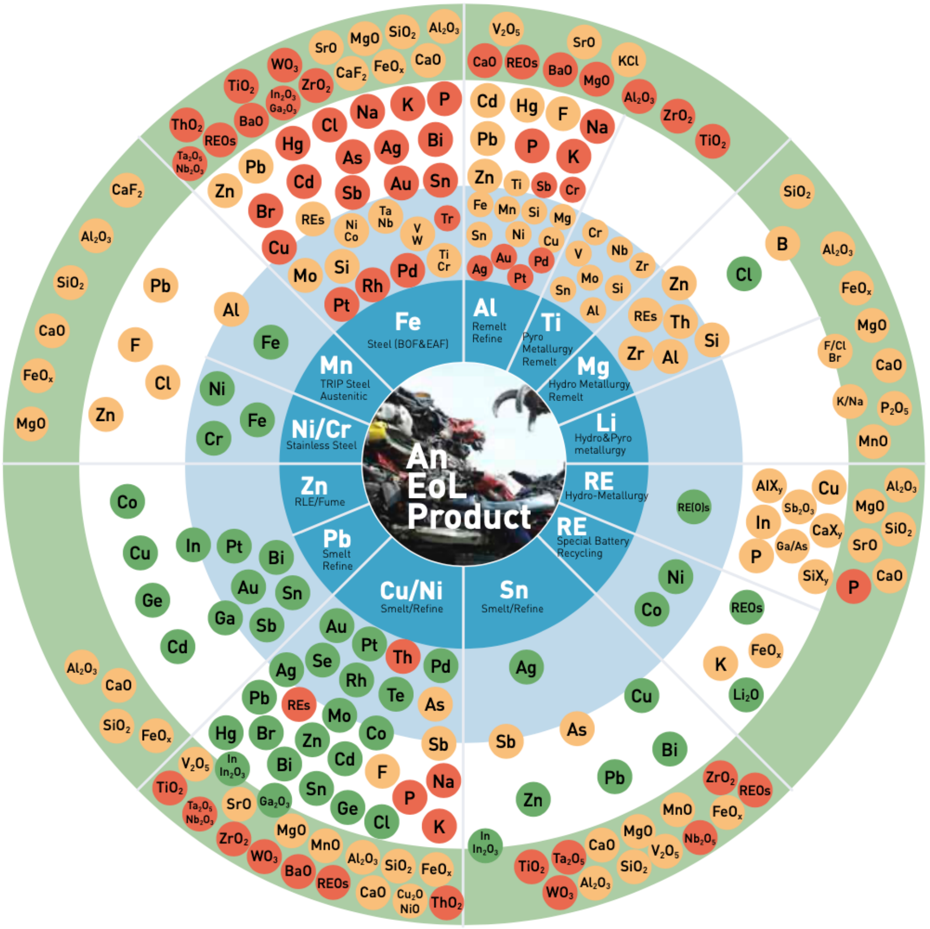


Figure 2.6: The Metal Wheel by Reuter (UNEP, 2013b)

Zinc in soil, rocks and sediments are naturally cycling through nature by erosion processes, driven by wind, rain and solar heat (International Zinc Association [IZA], 2015b). Human activities - mining, production of products, use and ultimately disposal - leads to anthropogenic emissions of zinc. On a global scale, this does not add to the overall environmental zinc levels but elevated levels at a local scale may have environmental impact. The environmental impact of zinc is determined by the presence of a form in which it is available for uptake by organisms - zinc's

bioavailability.
Zinc in the mineral form - mainly zinc sulfide (ZnS) - is transformed into metallic zinc through extraction and refining processes (IZA, 2015b). During production and use, zinc compounds with varying solubility are formed which interact with components in soil, sediments and water once in the environment. Ultimately, zinc returns to its original form - ZnS, a process called mineralization which closes the 'natural cycle'. ZnS, the original and ultimate form of zinc is very stable and has low solubility, hence low bioavailability. It is instead the complex interactions in between those phases that pose a potential risk.
For essential elements such as zinc, the 'optimal window of essentiality' - being the values in which concentrations below and above may have negative effects on health etc. - are desirable (IZA, 2015b). According to the International Programme on Chemical Safety (IPCS, 2001), "The total concentration of an essential element such as zinc in an environmental compartment is not, taken alone, a good predictor of its bioavailability" (Environment section, para. 4). In the end, toxicity of zinc depends on organism age, size and previous exposure of organisms and site-specific physical and chemical characteristics that determine how zinc are transported, distributed and bioavailable in the environment (IPCS, 2001; IZA, 2015b).

2.3.1 The anthropogenic cycle of zinc

Gordon et al. (2003) provides a detailed description of the life cycle of zinc, divided into four stages: production, fabrication and manufacturing, use and ultimately waste management and recycling, illustrated in figure 2.7.

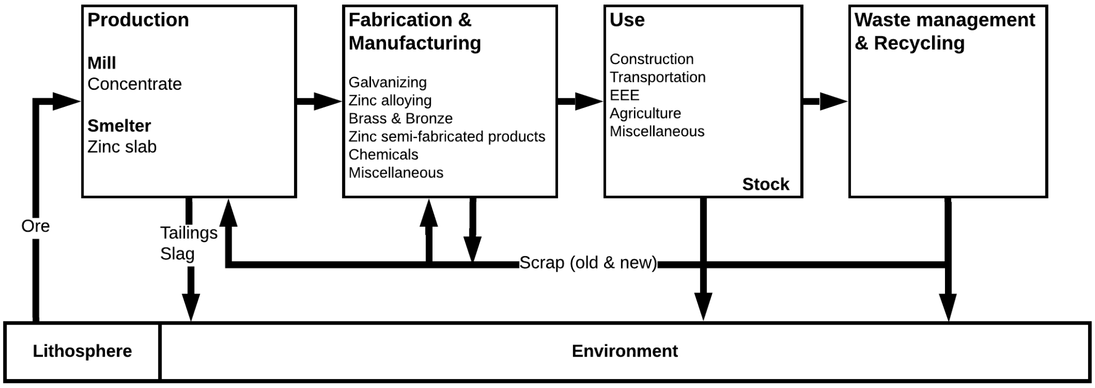


Figure 2.7: The life cycle of zinc.

Production

Production of zinc includes mining of zinc ore where 90 % of the zinc origins from the mineral sphalerite (ZnS), also called blende, and the rest from various zinc minerals collectively called calamine, such as smithsonite ($ZnCO_3$) (Gordon et al., 2003). Depending on deposits, the zinc ore has a concentration of 3-10 % zinc.
The zinc ore is milled, i.e. zinc-containing minerals are mechanically separated from other minerals (Gordon et al., 2003). This process generates waste called tailings

containing up to 1 % zinc which are often deposited in ponds. After milling, zinc concentrates containing up to 60 % zinc are obtained.
The zinc concentrates are fed to primary zinc smelters to produce zinc slabs, i.e. refined zinc (Gordon et al., 2003). Secondary raw materials, mainly zinc oxides (more explained under *Waste management and Recycling*), can be added to the smelter. According to Grund and van Genderen (2020), 10-15 % secondary raw materials are fed to smelters on average. The two main production processes for refined zinc are electrometallurgical zinc smelting and pyro-metallurgical zinc smelting, where the former accounts for more than 95 % of the production worldwide (Van Genderen et al., 2016). The electrometallurgical smelting yields residues called jarosite or geothite containing valuable metals. However, the residues are not not usable as filling material due to leaching, instead it is landfilled (Rämä et al., 2018; Van Genderen et al., 2016).

Fabrication and Manufacturing

Semi-fabricated products - so called first-uses - are produced from zinc slabs (Meylan & Reck, 2017). Statistics shows six main categories of first-uses of zinc: galvanizing, zinc alloying, brass and bronze, zinc semi-fabricated products, chemicals and miscellaneous (ILZSG, 2020a). The distribution of zinc among the categories is presented in figure 2.8.

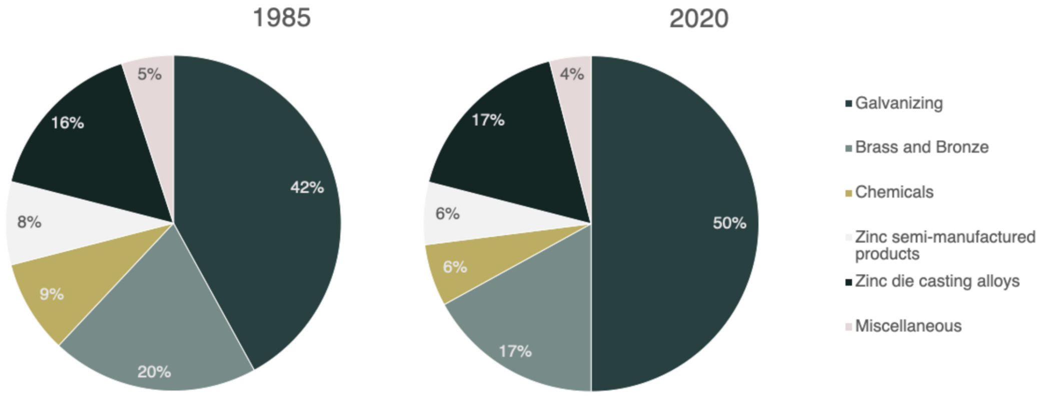


Figure 2.8: Main first-uses of zinc (SGU, 2004; ILZSG, 2020a).

Making brass (alloy with copper) was the earliest use of zinc, followed by production of grave markers and casting statues in the later part of the 19th century (Gordon et al., 2003). Today, more than 50 % of the global zinc production is used as corrosion protection of steel through galvanizing, i.e. covering the steel with a thin zinc layer which increases the technical lifetime of steel constructions. About 35 % of the zinc is used as alloy in die casting and brass. Semi-manufactured products such as zinc sheet used for facades, roofings and gutters etc. and chemicals such as zinc oxide (ZnO) used in paint, as vulcanization of rubber in tires, pharmaceuticals and fertilizers accounts for 6 % respectively (Gordon et al., 2003; Grund & van Genderen, 2020).

First-use products are further processed into end-use products and ultimately used in end-use sectors: construction, transportation, industrial and metal working machinery, electrical and electronic products, agriculture, and miscellaneous (Meylan & Reck, 2017).

Use

The in-use stock of zinc in society will depend on material flow to the reservoir, the lifetime of the reservoir and ultimately, End-of-Life (EoL) flows (Gordon et al., 2003).
During use phase, zinc is lost to the environment through dissipation. Some zinc in galvanized steel is oxidized when exposed to weather, accounting for about 63 % of all in-use losses (Ciacci et al., 2015). Other losses occur from use of tires containing zinc oxide and all zinc used in agriculture for fertilizers and animal feed are dissipated through use (Meylan & Reck, 2017). A study by Ciacci et al. (2015) showed that almost 20 % of the total zinc flow into use is lost through dissipation. As materials are lost for further recovery and reuse, primary resource dependency increases (Ciacci et al., 2015).

Waste management and recycling

Both new scrap generated in fabrication and manufacturing of products and old scrap from metal EoL products are flows entering waste management and recycling (Meylan & Reck, 2017). Due to the broad variety of zinc uses, collection rates and recycling technologies differ between and among the end-use products and end-use sectors. Different end-uses of zinc have different lifetimes - varying from less than a year in batteries to more than 100 years in constructions. Availability of secondary zinc will therefore depend on application.
Zinc die casted products and zinc sheet are re-melted, saving about 95 % of the energy needed to produce primary zinc from ores (Grund & van Genderen, 2020). Due to its high value, zinc sheet scrap are likely to have a 100 % collection rate (Antrekowitsch et al., 2014; Grund & van Genderen, 2020).
Brass is recycled in the copper industry and is mainly remelted to produce new brass (Antrekowitsch et al., 2014; Grund & van Genderen, 2020). In some recycling processes, the zinc is volatilized and recovered in the flue dust, ultimately returned to the zinc industry.
The main application of zinc being galvanizing steel, supply of secondary zinc will largely depend on waste management and recycling processes of steel. Due to its inherently high value, recycling rates for steel are high (Björkman & Samuelsson, 2014). As the Basic Oxygen Furnace (BOF) mainly uses pig iron as feed with a limitation of up to 30 % scrap, the Electric Arc Furnace (EAF) - with possibility to process up to 100 % scrap - is the main recycling technology, accounting for about 29 % of the global crude steel production (Antrekowitsch et al., 2015; World Steel Association, 2019).
Steelmaking takes place at temperatures exceeding 1600 °C, meaning that zinc - having a boiling point of 907 °C - and other metals with high volatility accumulates in the EAF dust (Gordon et al., 2003; Nyirenda, 1991). According to Antrekowitsch

et al. (2015), about 15-23 kg of dust is generated for every ton of crude steel produced in EAFs.
The composition of the steelmaking dust varies greatly and is mainly determined by the type of steel being produced and the quantity and quality of scrap and alloy added (Nyirenda, 1991). EAFs are used for both stainless- and carbon steelmaking. The dust that arises from both processes are rich in iron (Fe), 22.2-46.9 %. In general, stainless steelmaking generates dusts low in zinc but rich in alloying elements whereas dusts generated from carbon steelmaking can be distinguished between dusts rich in zinc and dusts with zinc content less than 1 %. Despite the high concentration of iron, the dust cannot be directly recycled within the steelmaking due to intolerable levels of zinc, other elements and halides (Cl, F, Br) which reduces the furnace efficiency and the quality of steel produced. Ultimately, costs increases and it leads to build-up of impurities in the steel. Elemental composition of EAF dust is presented in table 2.3.

Table 2.3: Elemental composition of EAF dust (Antrekowitsch et al., 2015)

	Zn	Pb	FeO	CaO	MgO	SiO_2	Cl	F	S
wt%	17-32	0.1-3	23-45	3.5-15	1.7-9	1-8	0.1-4	0.1-0.5	0.2-1

Note. The abbreviation wt% stands for percentage by weight.

Of all EAF dust generated globally, 45-50 % is recycled and the rest is landfilled, whereas in Europe, recycling rates of EAF dust reaches 95 % (Antrekowitsch et al., 2015; IZA, 2018). The Waelz kiln technology have been and is still considered the BAT for extracting zinc from EAF dust (Gianluca et al., 2017) and according to Antrekowitsch et al. (2019), about 90 % of the recycled dust is treated using this technology.
The dust is reduced at 1100 °C together with different additives (Antrekowitsch et al., 2015). Air is introduced during the reduction, making the zinc vaporize and re-oxidize. This separates most of the zinc from the rest of the material but some halogen compounds and other unwanted elements follow the zinc. The product is crude zinc oxide, so-called Waelz oxides, which are used to feed primary smelters and for production of chemicals (Antrekowitsch et al., 2014; Grund & van Genderen, 2020). Before used as feed material in zinc smelters, the waelz oxide is washed to remove halides (Antrekowitsch et al., 2015).
The revenues generated from the recovered zinc will have to cover all costs for the process, hence a minimum of 15-20 % zinc in the feed is required (Nyirenda, 1991). Ironmaking in Blast Furnace (BF)s and steelmaking in Basic Oxygen Furnace (BOF)s also generates dusts containing zinc but at much lower concentrations, it is therefore not economically feasible to extract the zinc with today's technologies (Kerry et al., 2020).
The waelz kiln processes is a fairly simple, well-known and established technology that, compared to alternatives, have relatively low energy consumption (Antrekowitsch et al., 2019; Antrekowitsch et al., 2015). However, the technology only has the possibility to recover one metal - zinc, the produced zinc oxide is contaminated with halides and it generates great amounts of residues. The Waelz process generates about 700-800 kg residues per tonne of charged dust (Antrekowitsch et al.,

2015). The produced Waelz slag can be used as a construction material for e.g. road building depending on physical properties and chemical composition (Befesa, n.d.). Mentioned disadvantages do not coincide with future trends, e.g. limited space for landfilling with increasing fees and a transition towards a circular economy (Antrekowitsch et al., 2019). Multi metal recovery and potential usage of the slag in the construction sector are therefore main focuses in research of better technologies, pushing towards more cost efficient solutions.

Alternative methods to the Wealz process have not yet gained industrial scale due to high energy demands and poor quality of the products (Antrekowitsch et al., 2015). According to S. Grund (International Zinc Association, personal communication, March 4, 2020), innovation towards closing material loops for zinc and steel includes dezincing galvanized steel scrap before steel recycling and co-operation between the zinc- and steel industry to recycle both metals from EAF dust but also from BF- and BOF dusts. For the latter, a rotary hearth furnace is already in operation in Japan and a process called HIsarna is under development in Europe.

3

Methods

There are many methods for analyzing, monitoring and assessing aspects of sustainability. Material Flow Analysis (MFA) - further described below - was the main method used and constituted the base in this thesis. A review of the literature on assessment of circular economy and aspects of it was also made.

3.1 Material Flow Analysis

Societal metabolism - the flow of materials and energy occurring within a society and the exchange with its environment - can be studied applying MFA. MFA builds on conservation of mass, "a principle stating that mass cannot be created or destroyed" (Stevenson & Lindberg, 2011), hence mass does not change within a process. In 1970s, the first studies of resource conservation and environmental management appeared, mainly analyzing metabolism of cities and the pathways of pollutants in urban areas and watersheds (Brunner & Rechberger, 2016). Today, MFA is a method widely used in several areas such as waste and wastewater treatment, resource conservation and recovery, product design, process control and Life-Cycle Assessment (LCA) (Brunner & Rechberger, 2016).

The general procedure for MFA is iterative and includes four steps: problem definition, system definition, determination of flows and stocks, and illustration and interpretation of results (Brunner & Rechberger, 2016).

The problem to be studied and formulation of study objectives are defined in *problem definition*. *System definition* includes defining the scope and system boundaries of the study, i.e. what material or elements and processes to include, where the flows start and end, and also temporal and spatial boundaries. *Determination of flows and stocks* is done through mass balance between quantified inputs and outputs for each (sub)process, i.e. the sum of the mass of all inputs equals the sum of the mass of all outputs plus stock, this is mathematically expressed in Eq. 3.1 (Brunner & Rechberger, 2016).

$$\sum_i m_i = \sum_o m_o + m_s \tag{3.1}$$

where m_i is the mass of input i, m_o is the mass of output o and m_s the stock. If materials entering and leaving the system are not balanced, materials will accumulate or deplete within the system, changing the stocks which are reservoirs for materials (Brunner & Rechberger, 2016). Balancing is important to check data accuracy and quantify missing data. In *illustration and interpretation*, the results should be presented in an easy and comprehensible way and *evaluated* in relation to the study objectives (Ayres & Ayres, 2002; Brunner & Rechberger, 2016).

Mass-based flows of zinc were estimated using MFA. Applying a life-cycle perspective - production, fabrication and manufacturing, use and ultimately waste management and recycling - a steady-state flow model was employed for assessing the anthropogenic flows of zinc in Sweden. All flows are given as mass flows of zinc. The data from the year of 2018 was the most recent available data to be found.

3.2 Estimation of zinc flows

Data and information for this study was collected from official statistics, through communication with companies and literature study.

International trade statistics can be obtained at Statistics Sweden's statistical database, the EUs statistical office Eurostat and the United Nations commercial trade database (UN Comtrade). As the aim of this thesis is to study anthropogenic flows of zinc within Sweden, data available on Statistics Sweden was considered the most reliable source, hence used primarily.

Companies and organisations that have been contacted are Nordic Galvanizers, Swedish Foundry Association, Nordic Brass Gusum, Swedish Chemicals Agency, Gjuteriteknik, Statisticts Sweden (SCB), Stena Recycling, Jernkontoret, AB Järnbruksförnödenheter, Boliden Rönnskär, Befesa ScanDust, International Zinc Association (IZA), Swedish Environmental Protection Agency (EPA) and PROASSORT.

All the data, information and assumptions used for the zinc flow calculations are described in detail in following sections. The data is representative for the year of 2018.

3.2.1 Production

Data for produced zinc ore and concentrates with corresponding zinc concentrations was obtained from the SGU (2019), presented in table 3.1 and 3.2, respectively. Six non-ferrous ore mines were used for production of zinc ore in Sweden for the year of 2018: Zinkgruvan (Lundin Mining), Lovisagruvan (Lovisagruvan AB), Garpenberg, Kristineberg, Maurliden and Renstrom (Boliden Mineral AB). The ore produced in Lovisagruvan is similar to that of Zinkgruvan and is therefore assumed to have the same zinc concentration (SGU, 2019). The ore from Lovisagruvan was exported whereas the remaining ore was milled to obtain concentrates before export.

Losses in the milling process were estimated using mass balance between produced ore and obtained concentrates.

As there are no zinc smelters in Sweden, all produced zinc ore and concentrates was assumed to be exported.

Table 3.1: Extraction of zinc ore in Sweden for the year of 2018 (SGU, 2019)

Company *Mine*	Ore (metric ton)	Zn (wt%)	Zn (metric ton)
Lovisagruvan AB			
Lovisagruvan	41 730	7.03 %	2934
Zinkgruvan Mining			
Zinkgruvan	1 312 679	7.03 %	92 281
Boliden AB			
Garpenberg	2 621 502	4.12 %	108 006
Boliden	1 747 646	3.54 %	61 867

Note. The abbreviation wt% stands for percentage by weight.

Table 3.2: Concentrates obtained after milling in Sweden for the year of 2018 (SGU, 2019)

Company *Mine*	Concentrate (metric ton)	Zn (wt%)	Zn (metric ton)
Zinkgruvan Mining			
Zinkgruvan	147 097	52.10 %	76 638
Boliden AB			
Garpenberg	190 971	52.90 %	101 024
Boliden	364 226	53.11 %	19 346
	55 152	57.74 %	31 845
	11 856	45.65 %	237 715

Note. The abbreviation wt% stands for percentage by weight.

3.2.2 Fabrication and Manufacturing

Data for import of unwrought zinc was obtained from Statistics Sweden's statistical database for foreign trade of goods (SCB, 2020a), see appendix A.

Average global distribution among first-uses of zinc presented in figure 2.8 was not used to allocate imported zinc slab as it might not be representative for Sweden. For example, according to Nordic Galvanizers (2019), 70 % of zinc is used for corrosion protection in Sweden - compared to a global average of 50 %. Distribution among remaining applications was not found. Instead, each first-use was studied individually.

Production data for galvanizing and die casting was provided by respective industry association (A. Hirn, Nordic Galvanizers, personal communication, April 24, 2020; Swedish Foundry Association, personal communication, April 24, 2020) and production data for brass was provided by Nordic Brass Gusum (P.-E. Persson, Nordic Brass Gusum, personal communication, April 24, 2020), presented in table 3.3.

According to the Swedish Chemicals Agency, zinc chemicals are not produced in Sweden (E. Diurlin, Swedish Chemicals Agency, personal communication, June 2, 2020).

No information was found regarding production of semi-manufactured products within Sweden, e.g. zinc sheets, plates, rods. Based on trade statistics, these commodities are mainly imported. It is therefore assumed that there is no production of semi-manufactured products in Sweden.

Table 3.3: Production of first-use products in Sweden for the year of 2018

	Production (metric ton)	Zn (wt%)	Zn (metric ton)
Galvanizing	94 925	4 %	4272
Die casting	9645	95 %	9163
Brass	24 000	35 %	8400
Zinc semis	-		
Chemicals	0		
Miscellaneous	-		

Note. The abbreviation wt% stands for percentage by weight.

Hot-dip galvanizing was assumed to be the method used for all galvanized steel as it is the most commonly used method for corrosion protection (Nordic Galvanizers, 2019). Zinc with a purity of 99.995 % zinc is used for hot-dip galvanizing and the process generates mainly two by-products containing zinc: hard zinc (95 wt%) and zinc ash (70 wt%). According to Nordic Galvanizers (2019), both hard zinc and zinc ash can be fully recycled. 65 kg zinc is required per tonne galvanized steel, which yields 10 kg of hard zinc and 15 kg of zinc ash (Nordic Galvanizers, 2019). On average, the zinc used for hot-dip galvanizing in Sweden contains 36 % secondary zinc (A. Hirn, Nordic Galvanizers, personal communication, April 24, 2020).

There are two main zinc die casting companies in Sweden: Gjuteriteknik and Zinkteknik. According to J. Abrahamsson (Gjuteriteknik, personal communication, March 31, 2020), about 97 % of the used raw materials end up as finished products. The remaining 3 % are sent to external remelt of which two thirds are slag (80 % of this becomes new zinc) and the remaining one third are products that have been surface treated and can therefore not be internally remelted. This information was assumed to be representative for all die casting in Sweden and was used to estimate zinc consumption and yield losses in fabrication.

Nordic Brass Gusum is the leading company for brass production in Sweden. The produced brass is made of 90 % old and new scrap, including copper products, and 10 % primary raw material. According to P.-E. Persson (Nordic Brass Gusum, personal communication, May 6, 2020) one of the few primary refined raw-materials they use is zinc. It is therefore assumed that primary zinc consumption for brass are 10 % of the yearly production. The average zinc content for brass is 35 %, remaining zinc is assumed to origin from brass scrap. Scrap yield in fabrication are internally recycled. Furthermore, Nordic Brass Gusum offers to take care of customers residual material from manufacturing and new scrap. Process losses in fabrication and manufacturing are minimal and are therefore assumed to be zero.

Statistics Sweden's statistical database for foreign trade of goods (SCB, 2020a) was used to identify trade of first-use products, following the approach of the study by Meylan and Reck (2017). First-use products that are traded include galvanized steel, brass, zinc semis such as rods, wire and sheets, and zinc chemicals. Net weight of each good was multiplied with respective estimated zinc content, see appendix A.

Table 3.4: Allocation among the main end-use sectors for first-uses of zinc produced in Sweden

	Construction	Transportation	EEE
Galvanizing	75.6 %	-	-
Die casting	20 %	20 %	25 %
Brass	90 %	10 %	0 %

Losses in manufacturing of first-use products into end-use products - so called new scrap - could not be estimated, except for brass, further described under *Waste management and Recycling*.

Prefabricated building components, vehicles, Electrical and Electronic Equipment (EEE) and batteries are end-use products containing zinc that are traded. For building components, Statistics Sweden's statistical database for foreign trade of goods (SCB, 2020a) was used to identify trade of prefabricated building components containing zinc. Net weight of each good was multiplied with respective estimated zinc content, see appendix A. Data available on the Urban Mine Platform was used for estimations of zinc flows in vehicles, EEE and batteries.

The Urban Mine Platform created through the ProSUM project is the first Urban Mine Knowledge Data Platform. The database holds country-specific data and information regarding flows and stocks as well as treatment of waste for End-of-Life Vehicles (ELV), Waste Electrical and Electronic Equipment (WEEE) and batteries - specified on an elemental level. Through easily accessible data, the project aims to contribute to the improvement of waste management and resource efficiency of these resources. All data until the year of 2015 are reported data whereas the data for the years of 2015 to 2020 are projected.

Estimated zinc content for vehicles and EEE in the study by Meylan and Reck (2017) were high compared to those presented at the Urban Mine Platform. Furthermore, the Urban Mine Platform distinguishes between types of products within each product group, giving a more accurate estimation. Therefore, the Urban Mine Platform was considered the most reliable source.

The Urban Mine Platform does not provide information regarding origin of commodities placed on the market, i.e. produced within the country or import. It does therefore exist a risk of double counting for some flows of zinc, e.g. if the flows are assumed to be imported when some products might have been manufactured in Sweden, containing zinc products fabricated in Sweden.

About 90 % of the passenger vehicles and 97-98 % of the lorries produced by Swedish vehicle manufacturers are sold at the export market (BIL Sweden, 2019). Zinc flows related to vehicles at the Urban Mine Platform are therefore assumed to be imported.

Based on Statistics Sweden's statistical database for production of commodities and industrial services (SCB, 2020b), production of EEE are mainly zero or marked with ".." (meaning that data have been removed for reasons of confidentiality). Zinc flows related to EEE at the Urban Mine Platform are therefore assumed to be imported.

Based on Statistics Sweden's statistical database for production of commodities and industrial services (SCB, 2020b), no batteries containing zinc appear to have been produced in Sweden for the year of 2018. Zinc flows related to batteries at the Urban Mine Platform are therefore assumed to be imported.

3.2.3 Use

Existing in-use stock was not estimated as it requires historical records of zinc applications due to varying lifetimes for vehicles, EEE, constructions etc. (Meylan & Reck, 2017). Dissipative losses was therefore estimated based on zinc entering use in 2018.

A dissipation rate of 0.4 % per year was used to estimate dissipative losses from galvanized steel (Ciacci et al., 2015). As the MFA applies a steady state for flows and stocks, there is no change - accumulation or depletion - in stock over the year. Losses were based on the amount of galvanized steel placed on the market in 2018 - net import of galvanized steel plus steel galvanized in Sweden. In reality, existing in-use stock contributes to more dissipative losses.

Dissipative losses from alloys, brass and rolled zinc applications in outdoor environments were assumed to be negligible as these applications do not have galvanizing purposes (Ciacci et al., 2015). Die cast products are mainly used in protected environment, dissipative losses are therefore assumed to be minimal.

80 % of all chemicals were assumed to be lost through dissipation (Ciacci et al., 2015).

It was assumed that no zinc containing products are reused as no information or data regarding reuse was found.

Using the mass balance principle between zinc entering and leaving use, net addition to in-use stock can be estimated. This could however only be done for vehicles, EEE and batteries as data regarding flows of zinc to waste management could not be obtained for remaining applications, i.e. galvanized steel, die casting and brass products.

3.2.4 Waste management and Recycling

Waste flows statistics available at the Urban Mine Platform for ELVs, WEEE and batteries were used to quantify waste flows leaving the in-use stock. Statistics are only available up to 2015, these were therefore assumed to be representative for 2018. There appeared to be some errors regarding ELVs waste flows for the years of 2014 and 2015, 2013s years statistics was therefore used for ELVs. Chosen parameters for ELV, WEEE and battery waste flows are presented in figure 3.1.

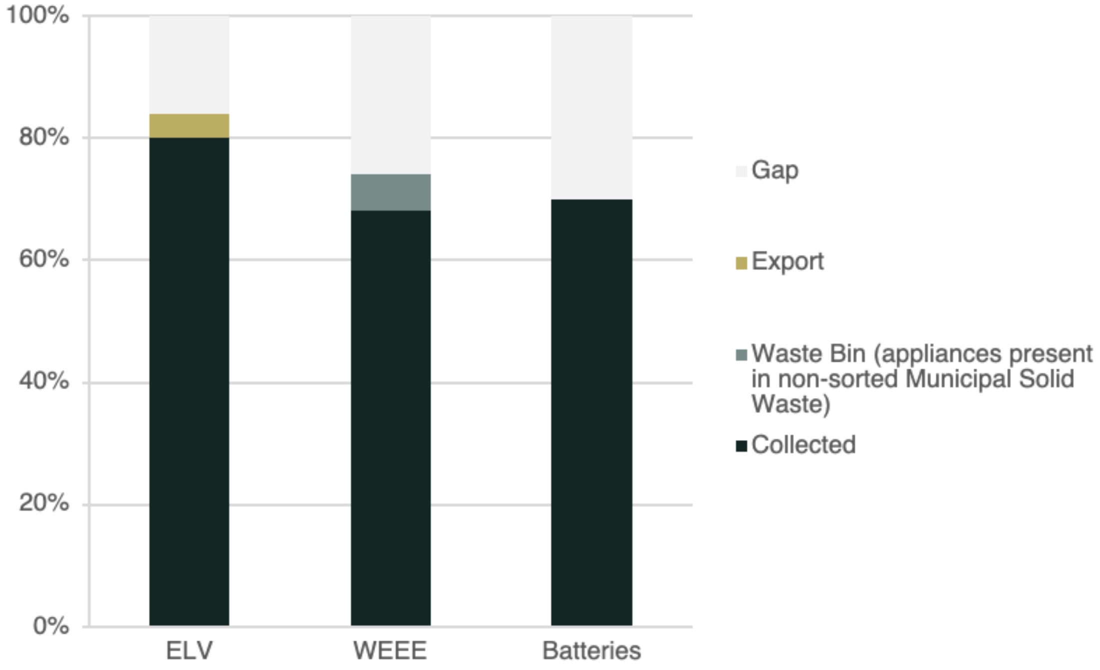


Figure 3.1: Assumed waste flows in percentage of products leaving the stock for ELVs, WEEE and batteries.

Collected WEEE at recycling centers is shipped to companies specialized in WEEE treatment. Metal-rich fractions obtained through dismantling and various automated sorting operations are ultimately sold to metal refineries (Andersson et al., 2019). All zinc in the collected WEEE was assumed to end up at Boliden Rönnskär in northern Sweden, one of the largest recycler of WEEE worldwide. According to T. Vikström (Boliden Rönnskär, personal communication, April 24, 2020), the zinc in WEEE undergoes several processes and is partly recovered. Along with the new leaching plant at Boliden Rönnskär, these processes are being developed for a more efficient metal recovery from residues. More specific data for process losses was not obtained.

At initial dismantling of ELVs, tires along with liquids and other hazardous components are removed. Components rich in alumunium, copper and iron are removed for recycling, hence zinc in galvanized steel is recycled within the steel industry. Electronic components - likely to contain zinc - are often left in the ELV, being too costly to remove and ship or unusable as spare parts. What remains of the ELV is sold for further automated treatment. Iron-rich materials are sold to metal refineries, a potential flow of zinc. Remaining materials are down-cycled as construction materials, incinerated or landfilled with no functional recycling possible (Andersson et al., 2019). Potentially recycled zinc in ELVs are galvanized steel. Remaining applications of zinc - tires, die casting and EEE are likely to be lost for functional recycling.

In the recycling process of alkaline batteries, the ones containing zinc, a fraction called Black-Mass is obtained. Black-Mass contains high concentrations of zinc, manganese and carbon. There is no domestic recycling facility in Sweden for treatment of Black-Mass, instead it is exported for further processing at Waelz kiln plants in Europe (Swerim AB, 2020).

The Swedish EPA is responsible for statistics on the generation and treatment of waste available at Statistics Sweden. waste flows are classified by economic sector and 51 waste categories in line with the European Waste Classification for Statistics (EWC-Stat) according to the EU regulation on *waste statistics* (Regulation 2150/2002).

Economic sectors of interest would have been *C24-25 Manufacture of basic metals and fabricated metal products, except machinery and equipment* and *F41-43 Construction*, capturing both generation of new scrap from manufacturing and old scrap from EoL products. Fractions of generated metal wastes available at statistics Sweden are: *metallic wastes, ferrous*, *metallic wastes, non-ferrous*, and *metallic wastes, mixed.*

Statistics on the generation and treatment of waste was not useful as (1) the most recent data was for 2016 which does not correlate with remaining data used in this MFA and (2) the waste classification was too general to make any assumptions of zinc waste flows.

In Sweden, waste flows are reported to the Swedish EPA using so called "avfallskoder" in line with the European List of Waste (LoW) - according to "Avfallsförordning" (SFS 2011:927) - data that can be ordered from Statistics Sweden for a fee. The problem with old data and too broad classification would still remain, and several relevant waste categories was marked with ".." for the year of 2016, meaning that data had been removed for reasons of confidentiality.

For example, categorization of metal waste from Construction and Demolition (C&D) is presented in table 3.5, a fraction that was assumed to have a 100 % collection rate (Husson & Lagerqvist, 2018). As distribution among copper, bronze and brass in *17 04 01* and the share of galvanized steel in iron and steel *17 04 07* are unknown, zinc waste flows and hence stock accumulation or depletion could not be determined using this information. Relevant LoW-entries for zinc residues and zinc metal scrap are presented in appendix C.

Table 3.5: Categorization of C&D metal waste

LoW code	Description
17 04 01	Copper, bronze, brass
17 04 02	Aluminum
17 04 03	Lead
17 04 04	Zinc
17 04 05	Iron and steel
17 04 06	Tin
17 04 07	Mixed metals

Stena Recycling, being one of Sweden's leading recycling companies, could not provide more detailed data due to lack of staff during covid-19.

An alternative source of information for galvanized steel scrap is the steel industry. It was found that neither Jernkontoret - Swedish steel producers' association, nor AB Järnbruksförnödenheter - an intermediary for steel scrap, keep data on generation of galvanized steel scrap (H. Axelsson, Jernkontoret, personal communication, April 17, 2020; Ab Järnbruksförnödenheter, personal communication, April 17, 2020).

Galvanized steel scrap is raw material for steelmaking in EAFs where the zinc is collected in the EAF dust. Some of the zinc-rich EAF dust generated in Sweden is treated at Boliden Rönnskär while the rest is exported for recovery of zinc.

During 2018, 4.7 million metric tons of crude steel was produced in Sweden, of which 39.2 % was produced in EAFs (World Steel Association, 2019). Assuming a generation of 15 kg per ton steel produced in an EAF (Antrekowitsch et al., 2015), this would result in 27 thousand metric tons of EAF dust. As alloy steels represent close to 60 % of the total steel production in Sweden, i.e. avoiding galvanized steel scrap (Swedish EPA, 2018), assuming a global average zinc concentration of the generated EAF dust would not be correct according to H. Axelsson (Jernkontoret, personal communication, April 17, 2020). Estimation of zinc flows related to the steelmaking process could therefore not be done.

At Boliden Rönnskär, zinc-rich EAF dust is added to a slag which is yielded from copper production. The slag undergoes various processes from which a zinc-rich dust is recovered called Zinc Clinker. Zinc Clinker is raw material for the zinc smelter Boliden Odda in Norway (T. Vikström, Boliden Rönnskär, personal communication, April 24, 2020). Out of the 31 thousand metric tons of Zinc Clinker (72 wt%) that was produced at Boliden Rönnskär in 2018, 10-15 % originated from EAF dust (Boliden, 2015, 2020).

Statistics Sweden's statistical database for foreign trade of goods (SCB, 2020a) was used to identify trade of scrap containing zinc. Scrap sorts that are traded include ferrous waste and scrap, zinc waste and slag ash and residues containing zinc. Net weight of each good was multiplied with respective estimated zinc content, see appendix A. It was assumed that all ferrous waste and scrap was galvanized due to the low demand of galvanized steel scrap in Sweden. Copper waste was not included as the share of brass in copper waste is unknown.

Both studies of Meylan and Reck (2017) and Graedel et al. (2005) present MFAs for zinc flows in Sweden and have been used to check the reasonableness of the obtained results.

4

Results

A complete MFA could not be done, limited by availability of data and information - mainly regarding flows to waste management and recycling. The data and information that was obtained is illustrated as a sankey diagram, i.e. the width of the arrows is proportional to the flow, presented in figure 4.1. The flows are given as mass flows of zinc in metric tons and are representative for the year of 2018. A summarized description of flows and underlying data, estimations and assumptions used is presented in appendix B.

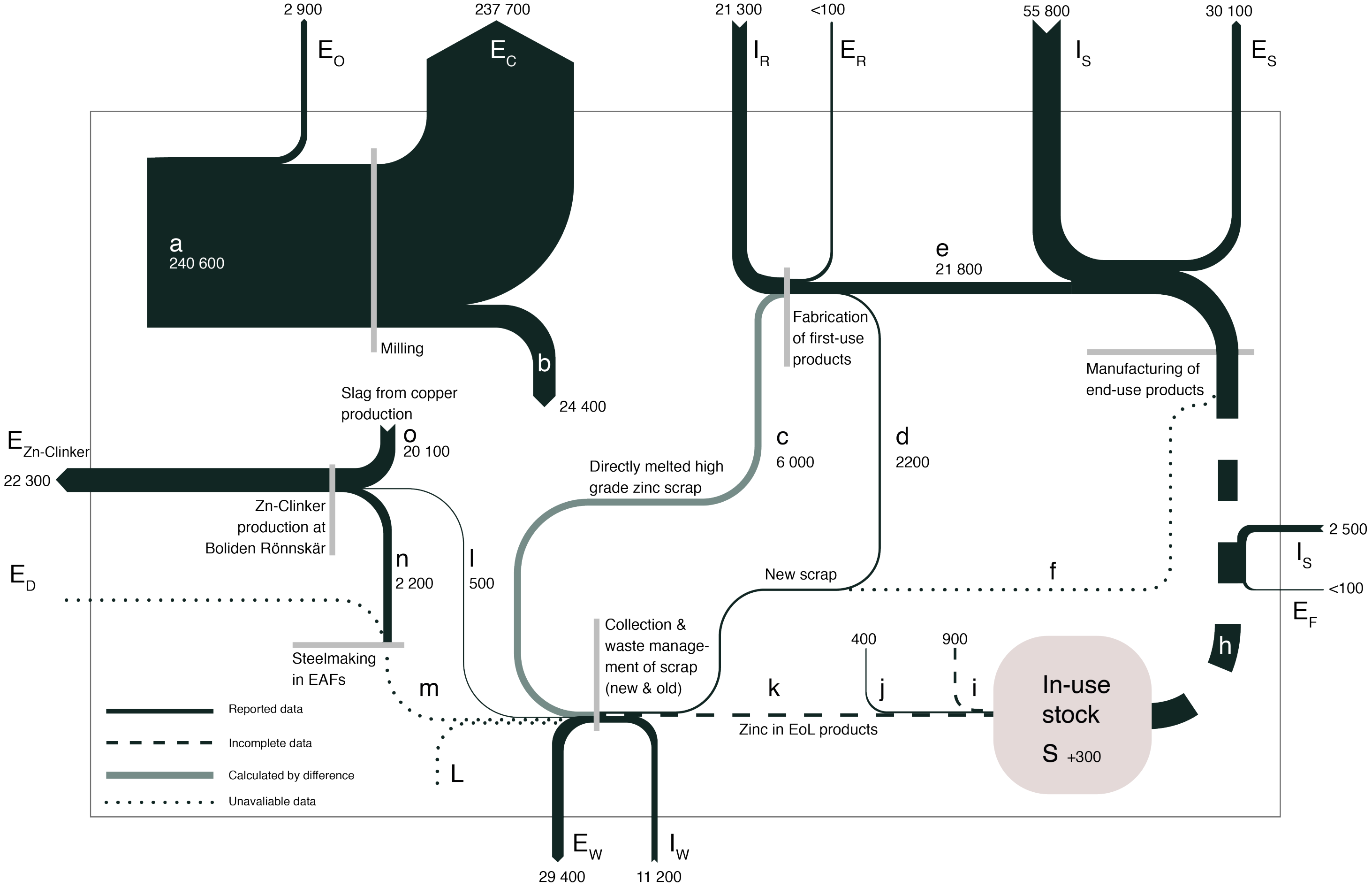


Figure 4.1: MFA of zinc in Sweden for the year of 2018 in metric tons.

5

Discussion

First, the procedure and results found for the MFA of zinc in Sweden will be analyzed, followed by a discussion of zinc in relation to the construction sector in terms of circular economy, taking the viewpoint by Stahel - maintaining the value and usability of manufactured objects (the era of 'R') and preserving the quality and purity of molecules and atoms (the era of D') (Stahel, 2019). Lastly, an analyze of the assessment to support a transition to a circular economy with focus on the construction sector will be made.

5.1 Material Flow Analysis of Zinc

It was found that information regarding zinc flows into use was better compared to zinc flows out of use. Furthermore, the level of detail of information decreased with increasing complexity of products - which is not astonishing - resulting in decreasing certainty of estimated zinc flows along the technical life-cycle. No data was found regarding reuse of studied zinc products, i.e. galvanized steel, brass or zinc die casting. Possible explanations may be that this is not an area in which data are collected as part of national statistics or that these products are simply not reused. Current data regarding waste flows are not sufficient to estimate flows to waste management and recycling on an elemental level due to low level of detail for the aggregated material flows and lack of transparency. Therefore, a complete MFA of zinc could not be done.

In Sweden, there is no responsible agency to continuously monitor material flows. An example where this is done is in Germany. The German Environment Agency (Umweltbundesamt) (UBA, 2019) - the corresponding authority to the Swedish EPA - states that a reliable database with relevant indicators is required to measure the contribution to resource efficiency through effective and high-quality management of material flows. As a result of insufficient waste statistics, the UBA developed a new approach for expanding the system of waste statistics where (UBA, 2019):

- The waste fractions that occur are largely classified according to the materials they contain.
- The actual recycling qualities, the recycling efforts and the disposition of the materials are described.
- By-products and secondary materials are taken into account that are not or no longer considered waste, and are therefore not subject to any information or notification obligation under waste legislation.
- Flows and exchanges are recorded that take place within the production stage

and between processors of primary materials.

- Typical primary material routes, which are replaced by secondary material processes are used for comparison.

MFAs for 30 materials, including zinc, are provided at their web-page. Furthermore, indicators are used to assess the effects of recycling, but also for reporting on circular economy while providing a base in the work for better material flow management. The need for targets and indicators to monitor material consumption and anthropogenic in-use stocks have been identified by the Swedish EPA (2018) in the transition towards a resource efficient circular economy - something that was found to be lacking in Sweden.

5.1.1 Indicators

Evaluation of environmental indicators could not be done due to lack of waste flow data. Estimated values for recycling indicators found in literature (RC and EoL-RR) are presented in table 5.1. Due to different methodological choices underlying estimated values such as reference year, system boundaries and used data, the values should be compared with caution.

Table 5.1: Recycling indicators for zinc

RC	EoL-RR	Systems boundaries	Reference
25 %	45 %	Global, 2018	(IZA, 2018)
27 %	33 %	Global, 2010	(Meylan & Reck, 2017)
-	55 %	Europe, 2018	(IZA, 2018)
50 %	46 %	Europe, 2010	(Meylan & Reck, 2017)

Estimated recycling indicators for zinc, which are relatively high, are similar to those of other base metals according to the study by UNEP (2011). This can be explained due to their magnitude of use and sufficiently high value in combination with well established recycling infrastructure (UNEP, 2011, 2013b).

Lower EoL-RRs in developing regions are due the the lack of developed "recycling networks and regulatory initiative at reducing industrial waste" (IZA, 2015a), something which may be a possible explanation for lower recycling indicators globally compared to those of Europe.

As metal products often have long life-times, meaning that it can take decades before metals become available for recycling, and the demand is increasing - recycled content for metal products is likely to remain below 100 % (Grund & van Genderen, 2020). In this aspect, RC might not be the most appropriate measure to reflect efficiency of recycling, however, it can be used to show circular efforts. The EoL-RR better reflects the efficiency of systems for collection and recycling (Grund & van Genderen, 2020). It should be noted that about 60 % of all zinc production are still in use when discussing recycling indicators for zinc.

5.1.2 Product Centric view

Mines, smelters, factories, the built environment and scrap yards are infrastructural nodes between which metals flow (UNEP, 2013b). Having a systems perspective of metals as 'stocks-and-flows' are important to understand the recovery potential of metals.

In a Product Centric view, determining factors for the performance of recycling such as design, collection and sorting, and processing are understood as a system according to UNEP (2013b). Also, in order to optimize recycling, the complex mineralogy of products - the many metals, both alloys and compounds - must be considered (UNEP, 2013b). Such perspective is becoming more important as the mineralogy of products are becoming increasingly complex. Thus, zinc must be understood, not only as an individual flow within a system, but as an element interacting with many other metals and materials.

5.2 Circular economy

In a circular 'industrial' economy, i.e. the technosphere, Stahel (2019) distinguishes between the era of 'R' - maintaining the value and usability of manufactured objects - and the era of 'D' - preserving the quality and purity of molecules and atoms. In accordance with the EUs waste hierarchy, i.e. prevention, preparing for reuse, recycling, recovery and lastly disposal, strategies of the era of 'R' should be preferred to those of the era of 'D' (Stahel, 2019; Swedish EPA, 2018).

Recycling was found to be the predominant method for recovery of zinc. According to Allwood (2014), most recycling processes today means that solid waste streams are broken down into liquids that are purified - a process limited by today's available technologies rather than by what is physically feasible. Moreover, for some applications, such as in EEE, where metals are finely distributed, the recycling process requires more energy than that of extracting primary raw materials. If energy origins from fossil fuels, which is inevitable in the near future, this would rather accelerate global warming due to the release of greenhouse gases. As climate change is an urgent challenge, Allwood claims that delivering products at minimum energy should therefore be the primary priority.

5.2.1 The era of 'R'

Through reuse and service-life extension of goods - the objectives of the era of 'R' - the volumes of production and end-of-pipe waste are directly reduced as the resource flows through the economy are slowed down (Stahel, 2019).

The demand for virgin materials is reduced if the full technical lifetime of materials in buildings and infrastructure are utilized. In the construction sector, the main end-use sector for zinc, galvanizing plays a central role in prolonging the technical lifetime of steel constructions. However, Allwood (2014) argues that replacements of steel-intensive buildings and infrastructure are mainly driven by the change of users' needs, such as changes in regulations and fashion along with technology developments (e.g. heating, ventilation, air conditioning and communication services) rather then being worn out. Allwood further claims that replacement are often preferred to refurbishment or repurposing "as a means to an uncompromised development" (p. 454), and since labor is the dominating cost of construction in developed countries, refurbishment is often the same as replacing the building. As the components and sub-assemblies of which buildings (and other goods) are made of are not likely to fail at the same time, buildings have to be designed in such a way that service systems can easily be removed with possibilities to install new technology with adjustments (Allwood, 2014). If not, the structural core in which the dominating part of the energy is embodied cannot be maintained. Therefore, the trend within the construction sector of so called "active buildings" - meaning that electronics are becoming increasingly integrated - poses a challenge to the idea of long lasting products if such viewpoint is not taken according to Allwood.

The characteristics of steel remain unchanged as long as the construction is not exposed to fire, corrosion or fatigue (Husson & Lagerqvist, 2018). Zinc therefore plays an important role in sustaining the characteristics of steel and increasing the technical lifetime of steel constructions through galvanizing, hence enabling for reuse. Despite the characteristics and the fact that standardized components are used in most steel constructions, a very small share of the steel used today is reused according to Husson and Lagerqvist (2018). A study by Densley Tingley et al. (2017) showed that cost, availability and storage, and no client demand were the top three main barriers for reuse of structural steel. However, Husson and Lagerqvist claim that there are no legal barriers for reuse of steel components.

In the project Nordic Component Reuse conducted by Vandkunsten Architects in cooperation with Nordic partners, discarded material components were transformed into new designs in full scale material prototypes (Nielsen & Manelius, 2017). Among 19 concepts, all designed and built for disassembly, a facade cladding from galvanized metal ventilation ducts was full-scale prototyped (see figure 5.1). LCA results showed the potential for reduced environmental impact compared to new alternatives based on virgin materials.

About a third of all material resources are consumed by the construction sector (Stahel, 2019). If more efforts were put on remanufacturing or designing buildings for disassembly, using standard components in a modular system, Stahel argues that resource consumption and associated impacts could be reduced substantially. This would require the establishment of storage facilities for materials, tracking systems for the available components, testing and certification.

Figure 5.1: "Prototype of a ventilation duct facade" by Manelius et al. is licensed under CC BY 3.0.

5.2.2 The era of ’D’

Once the measures related to the era of ’R’ - reuse and extending the service-life - have been exhausted, maintaining the highest usability and purity, i.e. value, of atoms and molecules through recovery is essential in a circular (industrial) economy (Stahel, 2019).
Antrekowitsch and Schatzmann (2019) argues that "high costs for energy and labor, strict environmental legislations and safety regulations and the lack of innovative concepts for processing complex low grade materials" (p. 507) pose a barrier for Europe in the search of becoming resource independent. Slags, sludge and dust are metal bearing by-products that are receiving more focus in research and industry as they are becoming increasingly important for the European industry - providing a potential source for raw materials (Antrekowitsch & Schatzmann, 2019).
The main application of zinc both globally and in Sweden is for galvanizing steel. As the galvanized steel gets recycled within the steel industry, a large share of zinc becomes part of steel mill dusts, in particular EAF dust, as shown in the Metal Wheel by Reuter (see figure 2.6). Processing of EAF dust was found to be a debated subject in literature (Antrekowitsch & Schatzmann, 2019; Kerry et al., 2020; Lanzerstorfer, 2018). The Waelz kiln technology is considered the BAT to recover zinc from EAF dust - being cost effective in relation to comparatively low zinc prices and low costs for landfilling of Waelz-kiln slags (Gianluca et al., 2017; UNEP, 2013b).
However, Waelz kilns are only found at a few places within Europe as they require large volumes of EAF dust to become profitable, thus resulting in increased transportation (Antrekowitsch et al., 2019; Nyirenda, 1991). Furthermore, zinc is the only metal recovered through the process while other metals, in particular iron, end up in the considerable volumes of generated residues (Antrekowitsch et al., 2015).

The residues can be recycled as construction materials, recycling that implies a significant loss of material value, i.e. down-cycling. Consequently, the metals are also removed from economic flows and are no longer available for a functional use, which is relevant when considering a circular economy.

Some of the zinc-rich EAF dust which is generated in Sweden is processed at Boliden Rönnskär along with slag from copper production and WEEE recycling. Many valuable metals can be recovered, but as for the Waelz kiln technology, the iron is lost for functional recycling (T. Vikström, Boliden Rönnskär, personal communication, April 24, 2020). However, the process at Boliden Rönnskär yields an iron bearing slag that is processed into a cleaner by-product which have new uses, unlike for the Waelz slag which often is landfilled according to T. Vikström.

This means that through the process of zinc recovery from EAF dust using today's BAT, the usability and value of other metals are lost. Ongoing research is made to enable recovery of both zinc and iron from EAF dust. According to Antrekowitsch et al. (2015), stricter environmental legislation and increased prices for steel scrap would benefit development towards simultaneous recovery of zinc and iron.

In the future, more steel scrap is predicted to be the dominating material source in the making of steel, leading to an increasing generation of EAF dust. Direct recycling of the iron-rich dust in the steelmaking plant is limited by the presence of zinc - even at low concentrations - as it causes problems in the steelmaking process and could harm the quality of steel (Ma, 2018; Omran & Fabritius, 2017). One solution to circumvent the forementioned problem is to use non-galvanized steel scrap in the steelmaking, i.e. avoiding zinc contamination of steelmaking by-products (Ma, 2016, 2018). Thus, the usability and value of the iron could be maintained.

However, the availability of non-galvanized steel scrap is limited while the demand for it is increasing (Ma, 2016). A lower share of steel scrap is used in ore-based steelmaking, resulting in dusts with zinc concentrations that are not economically feasible to extract. Instead, such plants purchases only clean (non-galvanized) scrap (Björkman & Samuelsson, 2014). There is also an increasing demand for specialty alloyed steels for the automotive manufacturing industry and other high performance industries - steelmaking which also requires clean scrap (M. Pillkahn, PROASSORT, personal communication, April 15, 2020).

To enable direct recycling of the iron-rich dust in the making of steel, and to meet the demand of clean scrap, while increasing the range of steel scrap that can be used for all steelmaking processes, several different methods for dezincing steel scrap have been developed, while few have been commercialized (Björkman & Samuelsson, 2014; Jernkontoret & MISTRA, 2013; Ma, 2016). More recent research projects are "The Steel Eco-cycle" in Sweden and PROASSORT in Germany.

PROASSORT has set up a test facility where sulfuric acid is used to chemically decoat steel - taking off every kind of coating and oil (M. Pillkahn, PROASSORT, personal communication, April 15, 2020). In order to make it profitable, a large scale facility is required. However, further investments have been difficult to find due to a declining steel industry in Germany according to M. Pillkahn. In addition, the highly fluctuating zinc price also poses a barrier for such investment. M. Pillkahn suggests that there exists a reluctance for the steel industry to step into a new field, such as the chemical industry. A reason for that is the strict regulations in the chemical industry, which according to M. Pillkahn, are being tightened every year - making the process costlier and more risky. Furthermore, due to the cost structure in Europe, European companies are having a hard time competing with Chinese and Indian steel companies - resulting in a declining innovation power in Europe. The experience of M. Pillkahn and PROASSORT is in line with the viewpoint of Antrekowitsch and Schatzmann (2019).

Mining and refining of primary resources are associated with negative environmental impacts, including considerable amounts of mining wastes and large consumption of water and energy - something which can be prevented if secondary resources are recovered according to Stahel (2019). Moreover, investments in new technology entails fixed costs with long payback time while prices for commodities are highly fluctuating. The market value is a determining factor for recycling, meaning that a high market value incentivises recovery of resources (Ciacci et al., 2015). Recovered resources will always compete with those from primary sources (Stahel, 2019). Problem arises when the market value is not sufficiently high and the social cost for primary resources are not internalized. The situation with PROASSORT exemplifies an important question raised by Stahel (2019) - how can research in the era of 'D' be financed when it is not a priority to maintain the value of materials in terms of economy and resources?

5.3 The transition to a circular economy

While the generational goal is in line with circular economy, few objectives and targets with associated indicators relates to circular 'industrial' economy (SOU 2017:22). Furthermore, it was found to be a large focus on waste management and recycling - measures of the era of 'D'. For buildings and infrastructure at their end-of-service-life, demolishment implies tearing it down into small bits for potential recovery rather than disassembly for reuse of components due to time pressure (Stahel, 2019). Stahel argues that initial material and energy resources used to build a construction, which could be preserved in the era of 'R' through reuse and repair, are instead for the most part lost in the era of 'D'.

Following-up on the milestone target regarding 70 % recovery of C&D waste - also covered by the indicators used to monitor the progress towards a circular economy in Europe - showed that only 50 % was recycled in Sweden in the year of 2016 (Swedish EPA, 2018). Mentioned reasons behind the low recovery rate are fractions of wood waste mainly being incinerated, landfilling of mineral waste and sorting of mixed waste which gives rise to fuel fractions for incineration. The Swedish EPA also states that "statistics regarding preparation for reuse of Construction and Demolition waste were not included in the follow-up, as there is no safe method for calculating these quantities" (p. 46).

The target according to the EU includes measures such as backfilling (defined as "a recovery operation where suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials" (Backfilling section, para. 1)) and low-grade recovery, e.g. recycling mineral waste as aggregates in road constructions (EEA, 2020). A study by the EEA showed that these measures were found to be the predominant

base for relatively high recovery rates in countries within the EU. Accordingly, the EEA states that the inherent value of resources are lost due to open-loop recycling, i.e. recycled materials used for purposes different from their original and "qualitative aspects of recycling are not systematically addressed".
In order to overcome barriers and improving circularity in the construction sector, it is identified by the EEA (2020) that "more ambitious waste management policy objectives with a focus on management quality, such as the introduction of requirements for re-use of C&D waste, would reorient current waste management practices to a more circular approach" (Considerations for policymakers section, para. 6). Identification and discussion of policy instruments to accelerate a transition to a circular economy was done in a study by Høibye and Sand (2018), based on interviews with stakeholders in the construction sector in the Nordic countries. Suggested policy instruments were: "Requirements for documentation of the content and quality of the building materials", "Requirements for the documentation of the use of reused building products and building products containing recycled resources in buildings" and "Requirements for waste and demolition plans" (Høibye & Sand, 2018, p. 53-54).

6

Conclusion

This study aimed to **1**/evaluate the availability of data of anthropogenic flows of zinc in Sweden - a metal of both societal and environmental relevance due to its scale of use, as well as to **2**/analyze the assessment to support a transition to a circular economy - with focus on the construction sector.

Through the use of MFA of zinc in Sweden, this study shows that current data regarding waste flows are not sufficient to estimate flows to waste management and recycling on an elemental level due to low level of detail for aggregated waste flows, which also means that classifications are not applied in a similar way by all organisations. Therefore, a complete MFA could not be done. Consequently, evaluation of zinc flows in terms of circularity was not possible. However, comparing estimated regional recycling indicators for zinc, European estimates are in general higher compared to the global average - showing that ambitious targets and established recycling infrastructure have a large impact. Even though the infrastructure for zinc recycling is well established today, with increasingly complex products, a Product Centric view is crucial to optimize recovery of materials - not only for vehicles and EEE, but also for buildings that are becoming more and more 'active'. More information regarding the properties at their end of use is required to decide whether they can be used with minor changes (reuse, refurbishment etc.) or whether it is necessary to choose a recycling path.

An increased understanding regarding anthropogenic 'stocks-and-flows' of resources is required to utilize the potential of material recovery to supply a future demand. Furthermore, the understanding, quantification and estimation of anthropogenic flows of materials through the economy provides an important knowledge base when deciding on measures and policy instruments as well as to monitor targets and indicators related to circular economy - a need identified by the Swedish EPA in the transition towards a resource efficient circular economy.

There appears to be a large focus on downstream measures, such as waste flows and waste management, i.e. higher recycling rates and an increasing use of secondary raw materials, however, with low attention paid to the qualitative aspects of recycling. Recycling is indeed an important contribution to a circular economy - reducing the demand for virgin raw materials, but the quality of it must be assessed. Furthermore, the initial material and energy resources used to build a construction are partly lost through recycling. Product and component recycling (era of 'R') is suitable to conserve the resources for processing materials, whereas recycling (era of 'D') is suitable for material recovering and refining - a transition to a circular economy, therefore requires measures beyond efficient recycling.

There are few incentives for the construction sector to move away from traditional supply chains - adopting measures such as reuse, repurposing etc. Policy making has an important role in creating a market pull through more ambitious requirements, thus accelerating the transition. Meadows (1998) argues that "we measure what we care about...we care about what we measure" (p. 2) meaning that indicators are created by values that in turn create values. Due to lacking methodologies to assess qualitative aspects of recycling and other measures of circularity, there is a risk of those aspects being neglected and valued less in policy making. Also, because recycling is already seen as a step up from waste handling, the fact that better recirculation options are available might be overlooked.

In some sense, sustainability is the definition of complexity - comprising the economic, social and environmental dimensions. Each decision related to circular economy, i.e. sustainability, entails some sort of trade-off, a systems thinking is therefore crucial. Furthermore, and possibly more important, "if demand is growing, the circle cannot remain closed" (Allwood, 2014, p. 446) - slowing down the material flows must be a priority for all actors in the transition to a circular economy.

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A

Foreign trade of goods

Table A.1: Trade of zinc containing commodities (Meylan & Reck, 2017; SCB, 2020a)

Commodity	Commodity code	Zn (wt%)
Refined zinc		
Zinc; unwrought, (not alloyed), containing by weight 99.99 % or more of zinc	790111	100 %
Zinc; unwrought, (not alloyed), containing by weight less than 99.99 % of zinc	790112	100 %
Galvanized steel		
Iron or non-alloy steel; flat-rolled, width 600mm or more, electrolytically plated or coated with zinc	721030	4 %
Iron or non-alloy steel; flat-rolled, width 600mm or more, corrugated, plated or coated with zinc (not electrolytically)	721041	4 %
Iron or non-alloy steel; flat-rolled, width 600mm or more, (not corrugated), plated or coated with zinc (not electrolytically)	721049	4 %
Iron or non-alloy steel; flat-rolled, of a width less than 600mm, electrolytically plated or coated with zinc	721220	4 %
Iron or non-alloy steel; flat-rolled, width less than 600mm, plated or coated with zinc (not electrolytically)	721230	4 %
Iron or non-alloy steel; wire, plated or coated with zinc	721720	4 %
Steel, alloy; flat-rolled, width 600mm or more, n.e.c. in heading no. 7225, electrolytically plated or coated with zinc	722591	4 %
Steel, alloy; flat-rolled, width 600mm or more, n.e.c. in heading no. 7225, plated or coated with zinc (other than electrolytically)	722592	4 %
Zinc alloying/Die casting		
Zinc; unwrought, alloys	790120	95 %
Brass		
Copper; copper-zinc base alloys (brass) unwrought	740321	35 %
Copper; bars, rods and profiles, of copper-zinc base alloys (brass)	740721	35 %
Copper; wire, of copper-zinc base alloys (brass)	740821	35 %
Copper; strip, of a thickness exceeding 0.15mm, of copper-zinc base alloys (brass), in coils	740921	35 %

Commodity	Commodity code	Zn (wt%)
Copper; plates and sheets, of a thickness exceeding 0.15mm, of copper-zinc base alloys (brass), not in coils	740929	35 %
Copper; tubes and pipes, of copper-zinc base alloys (brass)	741121	35 %
Zinc semis		
Zinc dust	790310	100 %
Zinc; powders and flakes	790390	100 %
Zinc; bars, rods, profiles and wire	790400	100 %
Zinc; plates, sheets, strip and foil	790500	100 %
Zinc; articles n.e.c. in chapter 79	790700	100 %
Chemicals		
Zinc oxide; zinc peroxide	281700	80 %
Construction		
Iron or steel wire; grill, netting and fencing, welded at the intersection, n.e.c. in item no. 7314.20, plated or coated with zinc	731431	4 %
Iron or steel wire; grill, netting and fencing, plated or coated with zinc	731441	4 %
Scrap		
Ferrous waste and scrap; of alloy steel (excluding stainless)	720429	4 %
Copper; waste and scrap	740400	-
Zinc; waste and scrap	790200	95 %
Slag, ash and residues; (not from the manufacture of iron or steel), containing mainly zinc, hard zinc spelter	262011	90 %
Slag, ash and residues; (not from the manufacture of iron or steel), containing mainly zinc, other than hard zinc spelter	262019	12 %

Note. The abbreviation wt% stands for percentage by weight and n.e.c. for not elsewhere classified.

B

Zinc flow estimations

Table B.1: Definition of flows

Flow	Description	Estimation
a	Domestic mining	Reported data with reported zinc concentrations.
E_O	Export of zinc ore	Assumed that all obtained zinc ore not being milled are exported.
b	Losses during milling (e.g. tailings)	Estimated using the mass balance principle.
E_C	Export of concentrates	Assumed that all obtained zinc concentrates are exported.
I_R	Import of refined zinc	Reported data with estimated zinc concentrations, includes unwrought -zinc and -zinc alloys.
E_R	Export of refined zinc	Reported data with estimated zinc concentrations, includes unwrought zinc and unwrought zinc alloys.
c	Scrap (new and old)	Assumed that 71 % of the zinc in brass origins from brass scrap.
d	New scrap from fabrication	Estimated based on data collection from communication with companies and publications.
e	First-use products fabricated in Sweden	Estimated based on production data of galvanized steel, brass and die casting.
I_S	Import of semi-fabricated products	Reported data with estimated zinc concentrations, includes galvanized steel, brass, zinc semis and chemicals.
E_S	Export of semi-fabricated products	Reported data with estimated zinc concentrations, includes galvanized steel, brass, zinc semis and chemicals.
f	New scrap from manufacturing	Could not be estimated due to lack of data.
g	End-use products manufactured in Sweden	All first-use products plus net trade of semi-fabricated products minus scrap yield.
I_F	Import of finished products	Reported data with estimated zinc concentrations for construction, data from the Urban Mine Platform for vehicles, EEE and batteries of which all are assumed to be imported.
E_F	Export of finished products	Reported data with estimated zinc concentrations, includes construction.

Flow	Description	Comment
h	Flow into use	Assumed that all end-use products plus net trade of finished products are used in end-use sectors.
S	In-use stock accumulation/depletion	Data from the Urban Mine Platform for vehicles, EEE and batteries.
i	Losses during use (e.g. dissipation)	Estimated based on galvanized steel put on the market in the year of 2018 (underestimated as the existing in-use stock of galvanized steel contributes to more dissipation). 80 % of all chemicals are assumed to be lost through dissipation.
j	Gap (i.e. products that should enter the waste flow due to expired technical life-time)	Data from the Urban Mine Platform for ELVs, WEEE and batteries.
k	Old scrap	Data from the Urban Mine Platform for ELVs, WEEE and batteries. Remaining product categories could not be estimated due to low level of detail for waste statistics.
I_W	Import of scrap	Reported data with estimated zinc concentrations. All ferrous waste and scrap are assumed to be galvanized. The share of brass waste and scrap in *Copper; waste and scrap* are unknown and could therefore not be estimated.
E_W	Export of scrap	Reported data with estimated zinc concentrations. All ferrous waste and scrap are assumed to be galvanized. The share of brass waste and scrap in *Copper; waste and scrap* are unknown and could therefore not be estimated. Data from the Urban Mine Platform for export of ELVs.
L	Landfill	Zinc in residues not economically feasible to extract etc.
l	WEEE	Assumed that all WEEE are processed at Boliden Rönnskär. Data from the Urban Mine Platform.
m	Galvanized steel scrap used for steelmaking in EAFs	No data was found.

Flow	Description	Comment
n	Zinc-rich EAF dust	Estimated based on Boliden Rönnskär's zinc clinker production of which 10 % is assumed to origin from steel mill dusts.
E_D	Export of zinc-rich EAF dust	Assumed that all zinc-rich EAF dust not processed at Boliden Rönnskär are exported. Could not be estimated as no data regarding generation of zinc-rich EAF dust was found.
o	Slag from copper production	Assumed that remaining zinc in Zinc Clinker origins from slag yielded in copper production.
$E_{\text{Zn-Clinker}}$	Export of zinc clinker for zinc metal production	Estimated based on reported data and reported zinc concentration.

Note. The flows are given as mass flows of zinc.

C

The European List of Waste

Table C.1: Relevant LoW-entries for zinc residues and zinc metal scrap

LoW code	Description
02	**wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing**
02 01	*wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing*
02 01 10	waste metal
10	**wastes from thermal processes**
10 02	*wastes from the iron and steel industry*
10 02 07*	solid wastes from gas treatment containing hazardous substances
11	**wastes from chemical surface treatment and coating of metals and other materials; non-ferrous hydro-metallurgy**
11 05	*wastes from hot galvanizing processes*
11 05 01	hard zinc
11 05 02	zinc ash
16	**wastes not otherwise specified in the list**
16 01	*end-of-life vehicles from different means of transport (including off-road machinery) and wastes from dismantling of end-of-life vehicles and vehicle maintenance (except 13, 14, 16 06 and 16 08)*
16 01 17	ferrous metal
16 01 18	non-ferrous metal
17	**construction and demolition wastes (including excavated soil from contaminated sites)**
17 04	*metals (including their alloys)*
17 04 01	copper, bronze, brass
17 04 02	Aluminium
17 04 03	Lead
17 04 04	Zinc
17 04 05	iron and steel
17 04 06	Tin
17 04 07	mixed metals
17 04 09*	metal waste contaminated with hazardous substances

LoW code	Description
19	**wastes from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use**
19 10	*wastes from shredding of metal-containing wastes*
19 10 01	iron and steel waste
19 10 02	non-ferrous waste
19 12	*wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising) not otherwise specified*
19 12 02	ferrous metal
19 12 03	non-ferrous metal
19 12 11*	other wastes (including mixtures of materials) from mechanical treatment of waste containing hazardous substances
19 12 12	other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11
20	**municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions**
20 01	*separately collected fractions (except 15 01)*
20 01 40	Metals