LCA Elemetal

LCA of Demo 2 – Update 2023

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Version

This is the third version of this study. The first was carried out in 2020 and focussed on the Elemetal process Demo 1. In that previous study, Elemetal Demo 1 was referred to as Elemetal **Now**. The previous study also tentatively studied Elemetal Demo 2 (referred to as Elemetal **Future**).

In this study, the focus is on Elemetal Demo 2. The LCA of the previously called Elemetal **Future** process has been updated using the most recently available process data. In addition, some LCA choices made in the previous study were revisited.

In this report, the LCA background and process data have been updated if changed compared to the previous study. The LCA results of the reference cases relevant for Elemetal Demo 2 have been updated only been updated with the most recent LCA background data. In addition, both Elemetal Demo 2 and reference case results were analysed using more recent versions of LCA software SimaPro and IPCC climate impact methods.

Content

Summary

About Elemetal

Elemetal focuses on the development of hydrometallurgical processes to reclaim zinc and copper from waste streams. Elemetal has received a LIFE subsidy to conduct two different demonstrations of the developed technology. One of the requirements of the LIFE subsidy is that two life cycle assessments (LCA's) are conducted, one for each of the demonstrations.

This study

This study is the second of two life cycle assessments. The first was carried out in 2020 and focussed on the Elemetal process Demo 1. In that previous study, Elemetal Demo 1 was referred to as Elemetal **Now**. The previous study also tentatively studied Elemetal Demo 2 (referred to as Elemetal **Future**).

In this study, the focus is on Elemetal Demo 2. The LCA of the previously called Elemetal **Future** process has been updated using the most recently available process data. In addition, some LCA choices made in the previous study were revisited.

Goal of this study

The goal of this study is two-fold:

1. Compare Elemetal system Demo 2 for treatment of copper/zinc concentrate from WTE (waste-to-energy) bottom-ash with the conventional treatment.
2. Compare the production of zinc sulphate monohydrate from zinc/copper concentrate from WTE bottom-ash (Elemetal **Demo 2**) with the conventional production of zinc sulphate monohydrate from primary zinc ores.

Methodology

The LCA methodology is used to determine the impact of a product or service on the environment throughout its entire life cycle, and has been standardised in ISO 14040 and 14044 (ISO, 2006a, 2006b). It can be used to compare the environmental impact of different products or services that fulfil the same function.

Conclusions Goal 1: Elemetal in comparison with conventional CuZn-concentrate treatment

When copper and zinc is recovered from CuZn-concentrates from WTE bottom-ash, less primary copper and zinc needs to be produced[1]. Both the Elemetal treatment route and the conventional treatment at New Boliden in Rönnskär and at Aurubis in Lünen therefore lead to a climate change impact reduction.

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[1] Assuming that recovering copper and zinc does not have an impact on the world demand for copper and zinc. Which is highly unlikely seeing the quantity.

When comparing Elemetal Demo 2 with the conventional treatment at New Boliden and Lünen we can conclude that the climate change impact reduction is higher for the Elemetal route in both cases.

Table 1 shows a range in between which we estimate the reduction in climate change impact to be when switching from conventional treatment to Elemetal Demo 2.

Furthermore, Table 1 indicates the maximum electricity use in the Netherlands due to the Elemetal process per tonne of CuZn-concentrate treated after which it is more environmentally beneficial to treat the concentrate at New Boliden or Aurubis (‘tipping point’).
This electricity use refers to electricity use at Elemetal.

Table 1 - Range of climate change impact reduction of Elemetal route in comparison with conventional treatment of CuZn-concentrate

Elemetal route	New Boliden, Rönnskär	Aurubis, Lünen	Unit
Demo 2	Higher reduction (510 kg CO_2-eq.) Tipping point: ~1,100 kWh	Higher reduction (113 to 234 kg CO_2-eq.) Tipping point: ~350 kWh	Per tonne CuZn-concentrate

Note: Range based on highest uncertainty observed due to (1) zinc recovery rate or (2) climate change impact of primary copper production.

The reduction in comparison to both conventional treatment routes of CuZn-concentrate can be increased with approximately 25 kg CO_2-eq. per tonne concentrate by utilizing the hydrogen for electricity production.

Conclusions Goal 2: Elemetal in comparison with conventional zinc sulphate monohydrate production

When comparing the Elemetal Demo 2 with conventional zinc sulphate monohydrate production we can conclude that Elemetal produces zinc sulphate monohydrate that has a lower climate change impact than conventional primary zinc sulphate monohydrate. The estimated impact reduction can be found between 4,000 kg CO_2-eq. per tonne of zinc sulphate monohydrate produced when producing zinc sulphate monohydrate from CuZn-concentrate from WTE bottom-ash instead of from primary zinc ore.

The reduction is lower when allocating the energy and transport associated to WTE bottom-ash treatment to Elemetal Demo 2. In the base analysis in this study, we allocate these inputs to the waste incineration plant, as the removal of metals is prescribed as a minimum standard for waste incinerators (RWS, 2019). The sensitivity analysis in which energy and transport associated to WTE bottom-ash treatment is allocated to Elemetal Demo 2 is therefore a worst case analysis. The climate change impact reduction compared to conventional zinc sulphate monohydrate would be 4,300 kg CO_2-eq. per tonne of zinc sulphate monohydrate produced.

Comparison to results Elemetal Future previous study

Table 2 shows the difference between the results of the current LCA and the results of the 2020 study. The differences between the two studies are mostly caused by changes in the environmental background data (from the Ecoinvent database) and the updated IPCC methodology in SimaPro. This is the case for all contributors to the carbon footprint. The largest effect of these updates can be seen for copper, for which the climate change impact changed from 3.9 kg CO_2-eq./kg copper in 2020 (Ecoinvent v2.5, IPCC GWP100 2013, SimaPro 9.0) to 6.5 kg CO_2-eq./kg copper in 2023 (Ecoinvent v3.8, IPCC GWP100 2021, SimaPro 9, v4.2).

The difference between the climate change impact of the Elemetal process between 2020 and 2023 is partly caused by changes in the databases and methods, but also partly because of changes in the inputs used to run the process. The addition of natural gas and the replacement of ammonia with potassium hydroxide have the largest extra impact. Towards the future, when upscaling, it is recommended to research whether it is possible to replace the natural gas use by electricity use. If possible, the impact would likely decrease, especially as the electricity mix will increasingly consist of renewably sourced energy.

Table 2 - Comparison of climate change impact results of current study ('LCA 2023') and 2020 study ('LCA 2020'), in kg CO_2-eq./kg zinc sulphate monohydrate

	LCA 2023	LCA 2020	Difference
	Demo 2	**Elemetal Future - Lünen**	
Elemetal process	256	217	+18%
Copper smelter	598	630	-5%
Zinc production	137	135	+1%
Copper recovered	-5,279	-3,155	-67%
Transport	67	67	0%
Total	**-4.221**	**-2.106**	**-100%**

1 Introduction

About Elemetal

Elemetal focuses on the development of hydrometallurgical processes to reclaim zinc and copper from waste streams. Elemetal has received a LIFE subsidy to conduct two different demonstrations of the developed technology. One of the requirements of the LIFE subsidy is that two life cycle assessments (LCA's) are conducted, one for each of the demonstrations. As the LIFE subsidy is ending, the LCA of the current technology route employed by Elemetal ('Demo 2', in the previous study referred to as 'Elemetal Future'), is updated in this study.

Goal of this study

The goal of this study is twofold:
1. Compare Elemetal system Demo 2 for treatment of copper/zinc concentrate from WTE (waste-to-energy) bottom-ash with the conventional treatment.
2. Compare the production of zinc sulphate monohydrate from zinc/copper concentrate from WTE bottom-ash (Elemetal **Demo 2**) with the conventional production of zinc sulphate monohydrate.

Methodology

The LCA methodology is used to determine the impact of a product or service on the environment throughout its entire life cycle, and has been standardised in ISO 14040 and 14044 (ISO, 2006a, 2006b). It can be used to compare the environmental impact of different products or services that fulfil the same function. An LCA study consist of four phases:
1. Goal and scope definition: Defining the research question and the boundaries of the study.
2. Life cycle inventory (LCI): Inventory of all the elementary flows to and from the production system within the system boundaries, e.g. extraction of water and emission of CO_2.
3. Life cycle impact assessment (LCIA): Translation of all elementary flows to environmental impacts by means of an environmental impact assessment methodology. E.g. converting methane emissions to climate change impact.
4. Interpretation: Interpretation of the results of the LCIA, a critical evaluation of the results and drawing of conclusions.

Report structure

The four LCA phases are described in the following four chapters:
- Chapter 2: Methodology including goal and scope definition.
- Chapter 3: Life cycle inventory.
- Chapter 4: Life cycle impact assessment.
- Chapter 5: Interpretation and conclusions.

2 Methodology

This Chapter describes the methodology that we apply in this study. Section 2.1 describes the goal of the study as well as the scope. Section 2.2 describes the environmental impacts under consideration and Section 2.3 through 2.5 describe a number of other methodological choices.

2.1 Goal and scope definition

2.1.1 Goal of the study

The goal of this study is twofold:

1. Compare Elemetal system Demo 2 for treatment of copper/zinc concentrate from WTE (waste-to-energy) bottom-ash with the conventional treatment.
2. Compare the production of zinc sulphate monohydrate from zinc/copper concentrate from WTE bottom-ash (Elemetal **Demo 2**) with the conventional production of zinc sulphate monohydrate from primary zinc ores.

2.1.2 Functional unit

In this study, we use the following functional unit to determine the answer to the goals:

- for Goal 1: Treatment of one tonne of copper/zinc concentrate from WTE bottom-ash.
- for Goal 2: Production of 1 tonne of zinc sulphate monohydrate from WTE bottom-ash.

2.1.3 Scope of the study

In this study cradle-to-gate system boundaries are used. Gate-to-grave is out of scope, as this part of the life cycle is independent of the production process, in both, the conventional route and the Elemetal system. This means that the production of copper and zinc sulphate monohydrate is followed until the moment that it is placed on the market. The product that is produced (e.g. an electricity cable) and the end-of-life of these products (gate-to-grave) are not studied.

The treatment of bottom-ash to CuZn-concentrate is considered to make a fair comparison with primary zinc sulphate monohydrate production.

The system boundaries for this study are indicated in Figure 1 for the first functional unit, Figure 2 for the second functional unit.

The **geographical scope** is Europe for the treatment of copper/zinc concentrate as this is most relevant for Elemetal, while the primary production of copper and zinc are based on the average world market of primary copper and zinc production. The **temporal scope** is the technology as applied at this moment (2023).

Figure 1 – Scope of the study for the first goal of the study: compare Elemetal Demo 2 and the conventional treatment of copper/zinc concentrate from WTE bottom-ash

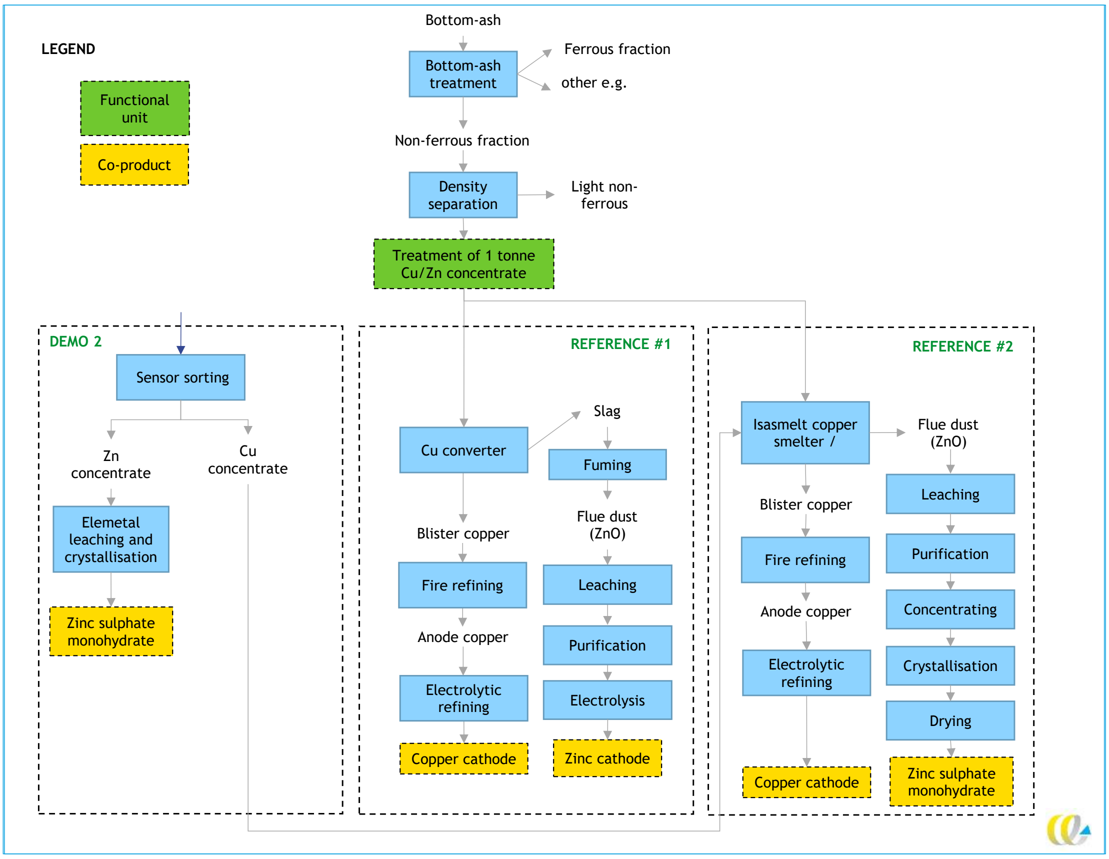
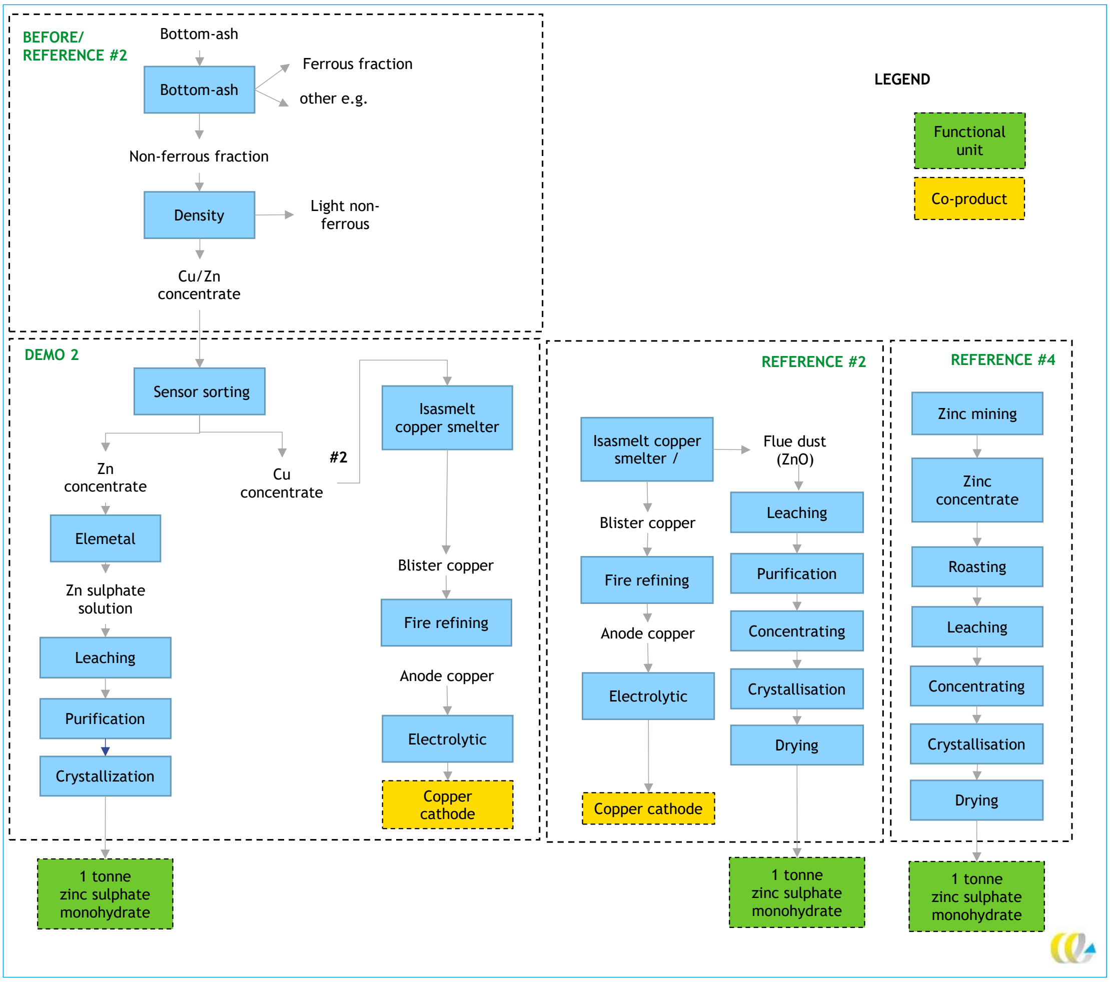


Figure 2 - Scope of the study: compare the Elemetal system *Demo 2* with conventional zinc sulphate monohydrate production



2.2 Environmental impact categories

Life Cycle Assessments can provide insight in a broad variety of environmental impacts, for example global warming, eutrophication, acidification, resource depletion and water use. Not all impact categories are considered in every LCA. In this study, the focus is on the environmental impact category climate change because of the high-energy intensity of metal production. We will determine the climate change impact based on IPCC (Intergovernmental Panel on Climate Change) 2021 global warming potentials for different greenhouse gasses, on a 100-year horizon[2]. Specifically the methodology as included in the SimaPro 9, version 4.02[3].

Other environmental impact categories are also of interest but due to the complexity of metallurgical processes, these have not been included.

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[2] In the previous study IPCC 2013 GWP on a 100 year horizon was used.

[3] In the previous study SimaPro 9.0, version 1.03 was used.

2.3 Multifunctionality and allocation

Co-products are being produced when looking at the two goals of this study.
These co-products are clearly indicated in yellow in the figures showing the scope of the study (Figure 1 and Figure 2). Therefore, these production processes are called multifunctional.

Different methods exist to account for this multifunctionality of a system into an LCA. These include allocation of the environmental impact of the different products/services based on their economic or physical properties, system expansion and substitution. In this study, we apply a substitution approach, which means that we assume the production of each of the co-products prevents the conventional production of this product somewhere else. In this case recycling copper to produce copper cathode reduces the necessity to produce new copper from copper ore, and the same holds for zinc cathode production.

The Ecoinvent database that is used in this research (See Section 2.5) for all the background data applies economic allocation when multiple products are produced. This means that the emissions from a process are allocated over the different (co-)products, based on the division of economic value of each of the (co-)products produced.

2.4 Sensitivity analyses

In each (LCA) study there is some degree of uncertainty about the results, due to uncertainties around data, or choices and assumptions in the scope. In this study, we perform a sensitivity analysis to investigate the impact on the results of (past) changes to the Elemetal process, as well as data uncertainties.

We assess specifically:
- Changes to the Elemetal process: Utilizing the produced hydrogen in the Demo 2 process to generate electricity for use in their own system.
- Data uncertainty: Uncertainty of the climate change impact of primary copper production.
- Data uncertainty: Uncertainty of the climate change impact of primary zinc production.

The sensitivity analysis can be found in Section 4.2.

2.5 Data sources and average estimate

The data sources used in this study include primary information from Elemetal on their processes as well as literature data and data from the Ecoinvent v3.8 database as it is included in the SimaPro 9 v4.02 software. Throughout the Life Cycle Inventory in Chapter 3, we will clearly indicate the source of the data.

Data on metal treatment processes is not easy to come by. Therefore, an estimate is made of the average environmental impact of the different processes. This means the following data is used for the different processes:
- treatment of zinc leachate from Elemetal: average European market based on literature data.
- treatment of copper concentrate from Elemetal sensor sorting: Treatment at Aurubis (Lünen) or treatment at New Boliden (Rönnskär). Both based on literature data.
- conventional treatment of copper/zinc concentrate: Treatment at Aurubis (Lünen) or treatment at New Boliden (Rönnskär). Both based on literature data.
- conventional production of zinc sulphate monohydrate: average World market based on literature date.

3 Life cycle inventory

3.1 Elemetal process Demo 2

In the Demo 2 Elemetal process, zinc sulphate monohydrate production is included, instead of sending the zinc solution to Nyrstar, Budel, which was done with previous technology routes researched by Elemetal.

The inputs and outputs of Demo 2 are given in Table 3, Table 4.

3.1.1 Sensor sorting

The inputs and the outputs of the sensor sorting process are given in Table 3.
20% of the input ends up in a zinc concentrate, while the other 80% is sorted out as copper concentrate. We take into consideration transport of 217 kilometres from Maastricht (where the copper/zinc concentrate is produced) to Plant One in Rotterdam.

Table 3 - Inputs and outputs of sensor sorting (*Demo 2*)

Inputs		
Input	***Quantity***	***Unit***
CuZn-concentrate	1,000	kg/tonne CuZn-concentrate
Of which copper	55% * 1,000 = 550	kg/tonne CuZn-concentrate
Of which zinc	25% * 1,000 = 250	kg/tonne CuZn-concentrate
Of which other metals	12% * 1,000 = 120	kg/tonne CuZn-concentrate
Of which other non-metals	8% * 1,000 = 80	kg/tonne CuZn-concentrate
Electricity	12.5	kWh/tonne CuZn-concentrate
Outputs		
Output	***Quantity***	***Unit***
Zinc concentrate	200	kg/tonne CuZn-concentrate
Of which copper	12% * 200 = 24	kg/tonne CuZn-concentrate
Of which zinc	76% * 200 = 152	kg/tonne CuZn-concentrate
Of which other metals	9% * 200 = 18	kg/tonne CuZn-concentrate
Of which other non-metals	3% * 200 = 6	kg/tonne CuZn-concentrate
Copper concentrate	800	kg/tonne CuZn-concentrate
Of which copper	66% * 800 = 526	kg/tonne CuZn-concentrate
Of which zinc	12% * 800 = 98	kg/tonne CuZn-concentrate
Of which other metals	13% * 800 = 102	kg/tonne CuZn-concentrate
Of which other non-metals	9% * 800 = 74	kg/tonne CuZn-concentrate

3.1.2 Elemetal leaching

The inputs and outputs of the Elemetal leaching process are given in Table 4.

Table 4 - Inputs and outputs of Elemetal leaching (*Demo 2*)

Inputs			
Input	*Quantity*	*Unit*	*Changes compared to previous report*
Zinc concentrate	1,000	kg/tonne Zn concentrate	-
Of which copper	12% * 1,000 = 120	kg/tonne Zn concentrate	
Of which zinc	76% * 1,000 = 760	kg/tonne Zn concentrate	
Of which other metals	9% * 1,000 = 90	kg/tonne Zn concentrate	
Of which other non-metals	3% * 1,000 = 30	kg/tonne Zn concentrate	
Electricity	375	kWh/tonne Zn concentrate	Decreased
Sulphuric acid solution	1,408	kg/tonne Zn concentrate	-
Of which sulphuric acid	97% * 1,408 = 1,366	kg/tonne Zn concentrate	
KOH (50% solution)	55.8	kg/tonne Zn concentrate	KOH is used now instead of Ammonia solution (100%)
ZnO	0.123	tonne/tonne Zn concentrate	-
N_2	74.88	m^3/tonne Zn concentrate	Increased substantially for safety reasons
Water	300	Kg/tonne Zn concentrate	Increased
Natural gas	98.6	Nm3/tonne Zn-concentrate	Natural gas is used as heat source for drying now instead of steam.
Outputs			
Output	*Quantity*	*Unit*	
Zinc sulphate monohydrate	2,252	kg/tonne Zn concentrate	-
Of which zinc	36.4% * 2,252 = 821	kg/tonne Zn concentrate	
Hydrogen	25	kg/tonne Zn concentrate	-
Leach residue	253	kg/tonne Zn concentrate	-
Of which copper	47% * 253 = 120	kg/tonne Zn concentrate	
Of which zinc	15% * 253 = 38	kg/tonne Zn concentrate	
Of which other metals	26% * 253 = 65	kg/tonne Zn concentrate	
Of which other non-metals	12% * 253 = 30	kg/tonne Zn concentrate	
Alunite [4]	164	kg/tonne Zn concentrate	
N_2	20.82	m^3/tonne Zn concentrate	

3.1.3 Copper concentrate Elemetal treatment/leach residue treatment

The conventional secondary copper production, in which the copper concentrate from Elemetal is treated, is described in Section 3.1.4. The inputs and outputs that are used for the two types of copper treatment (primary and conventional secondary copper production) are shown in Table 5. The leach residue is also treated at a copper smelter.

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[4] Alunite is not further treated and landfilled.

We assume transport of copper concentrate from Elemetal to:

- Rönnskär Sweden: 1,000 km by truck and 1,400 km by electric train;
- Lünen Germany, by truck: 300 km.

Impact of this transport is calculated based on Ecoinvent data per tonne transported over the distance of a kilometre (tonne*km).

Table 5 - Inputs and outputs treatment of copper concentrate/leach residue - Per tonne copper content to copper treatment

	Primary copper | Rönnskär	Secondary copper - one step | Lünen
Inputs		
Smelting: fuel oil	NA	75 kg
Smelting: reducing agent (coke)	NA	13 kg
Smelting: electricity	69 kWh	-
Fire refining: heat (natural gas)	2,473 MJ	2,420 MJ
Fire refining: natural gas	9.9 Nm^3	9.7 Nm^3
Electrolytic refining: electricity	359 kWh	351 kWh
Electrolytic refining: electrolyte	20 kg	19.6 kg
Outputs		
Copper cathode	970 kg	949 kg
Spent electrolyte[5]	39 kg	38 kg
Copper lost	30 kg	51 kg

Table 6 - Additional inputs and outputs treatment of zinc in copper concentrate/leach residue - Per tonne zinc content to copper treatment

	Primary copper | Rönnskär	Secondary copper - one step | Lünen
Inputs		
Smelting: Electricity	69 kWh	-
Smelting/converting: Coke	-	13 kg
Smelting/converting: Fuel oil	-	75 kg
Fuming: Hard coal	1.20 ton	-
Fuming: Fuel oil	0.03 kg	-
Leaching: electricity	92 kWh	81 kWh
Solution purification: electricity	53 kWh	47 kWh
Electrowinning: electricity	2,269 kWh	-
Concentration/Crystallisation/Drying	-	336 kWh
Steam from natural gas	-	2,287 kg
Ammonia solution	-	22 kg
ZnO	-	104 kg
Water	-	116 kg
N_2 (gas)	-	22 kg
Outputs		
Zinc cathode	709 kg	-
Zinc sulphate monohydrate	0 kg	1,903 kg
Zinc lost	291 kg	390 kg

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[5] The treatment of spent electrolyte is not included explicitly, but energy use of the different treatment steps is assumed to include also the treatment of the electrolyte.

	Primary copper | Rönnskär	Secondary copper - one step | Lünen
Leach residue[6]	243 kg	214 kg
Jarosite[7]	-	138 kg
N_2 (emission to air)	-	22 kg

Note: Both New Boliden in Rönnskär and Aurubis in Lünen do not produce zinc on-site. This is done at a different location. For more information, see Sections 3.2.1 and 3.2.2.

3.1.4 Bottom-ash treatment

When comparing Elemetal treatment with conventional zinc and zinc sulphate monohydrate production from zinc ore, the bottom-ash treatment has to be considered. With bottom-ash treatment in this case we refer to the production of copper/zinc concentrate from WTE bottom-ash.

In the previous study, there was some debate as to how to allocate the treatment of WTE bottom ash to Elemetal's technology. It was decided to allocate the treatment of WTE bottom ash to waste incineration in the base analyses, i.e. no environmental burden was attributed to Elemetal. In a sensitivity analysis, the entire environmental burden of WTE bottom ash treatment was attributed to Elemetal. It was recommended to revisit this choice in an update of the LCA.

In this update, we have chosen to follow the same approach as before. The reason for this is that treatment of bottom ash (removal of ferrous and non-ferrous metals) is the minimum standard in the Dutch waste management directive (RWS, 2019). This means that it is the legal responsibility of the WTE's to have their bottom ash treated. Hence, CuZn-concentrate would also be produced if no technology existed to recover Cu and Zn. Rules on resource recovery from waste streams like bottom ash will presumably only become more strict in the coming years. Elemetal is not yet at TRL9 and therefore large scale implementation of the technology is not now but in the future. Upon taking these factors into account, it makes sense to consider WTE bottom ash treatment as part of the waste incineration plant and, accordingly, attribute its environmental impact to waste incineration.

The following information was obtained from Elemetal on bottom-ash treatment:
- Electricity use: 17.65 kWh/tonne bottom-ash treated.
- Diesel use: 0.49 liter diesel/tonne bottom-ash treated.
- Bottom-ash on average contains 0.5% of heavy non-ferrous fraction; we assume that this is the CuZn-concentrate.
- The bottom-ash is transported from Moerdijk to Amsterdam by barge ship. Per tonne of CuZn-concentrate this amounts to 200 tonne of transported bottom-ash for a distance of 110 kilometres.
- The nonferrous metal containing material is transported from Amsterdam to Maastricht by truck over a distance of 215 kilometres. We assume that at this point approximately 7.5% of the weight of the bottom-ash remains to be transported, this amounts to 15 tonne of nonferrous metal containing material per tonne of CuZn-concentrate.

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[6] The leach residue is treated to recover precious metals, the remaining slag is landfilled. The exact process and inputs/outputs are unknown and are therefore not taken into consideration.

[7] Jarosite is not further treated and landfilled.

3.2 Reference: Conventional treatment of copper/zinc concentrate

The conventional treatment of copper/zinc concentrate in Europe can occur in both primary and secondary copper smelters. As indicated in Table 7, a large number of primary copper smelters only produce primary copper and do not add any secondary material to the process. When secondary material such as copper/zinc concentrate from bottom-ash is treated at a smelter, this does not mean that both copper and zinc are being recovered. For example when adding the copper/zinc concentrate to the Kaldo furnace at New Boliden's plant in Rönsskär, zinc is not being recovered. Also at Umicore in Hoboken (Belgium), zinc is not recovered.

We take into consideration the best case scenario for the conventional treatment in which both copper and zinc are recovered. This means that there are three conventional treatment routes for copper/zinc concentrate:

1. Secondary copper production via primary copper production route: such as in the New Boliden plant in Rönsskar (Sweden). The copper/zinc concentrate is added to the converter and skips the smelter.
2. Secondary copper production in a one-step process: such as in the Aurubis plant in Lünen (Germany).
3. Secondary copper production in a two-step process: such as in the Aurubis plant in Beerse (Belgium) or the New Boliden plant in Rönnskär (Sweden). Since treatment at New Boliden of copper/zinc concentrate occurs by adding the concentrate to the converter, this treatment is the same as indicated under 1. Unfortunately, not enough data was available on the treatment at the Aurubis plant in Beerse to make an analysis of that treatment location. The known information can be found in Annex A.

Table 7 - Primary and secondary copper smelters in operation in Europe

Country	Name Company	Smelter type	Converter type	Zinc recovery?
Primary copper production				
Spain, Huelva	Atlantic Copper S.A.	Only primary copper production		
Poland, Glogów (two production sites)	KGHM Polska Miedz	Only primary copper production		
Poland, Legnica	KGHM Polska Miedz	Only primary copper production		
Romania, Baia Mara	Cuprom	Only primary copper production		
Romania, Zlantna	Zlantna Metallurgical	Only primary copper production		
Secondary copper production via primary copper production				
Germany, Hamburg	Aurubis	Outotec Flash	Pierce-Smith	Unknown
Sweden, Rönsskär[8]	New Boliden	TBRC	Pierce-Smith	Yes
Finland, Harjavalta/Pori[9]	New Boliden	Unknown	Unknown	Yes
Belgium, Olen	Aurubis	Unknown	Unknown	Unknown
Bulgaria, Pirdop	Aurubis	Unknown	Unknown	Unknown
Slovakia, Krompachy	Umcor	Blast furnace	Unknown	Unknown
Secondary copper production - two steps				
Belgium, Beerse	Aurubis	TBRC/Kaldo	TBRC	Yes
Sweden, Rönsskär	New Boliden	E-Kaldo	Pierce-Smith	Yes
Austria, Brixlegg	Umcor	Blast shaft furnace	Pierce-Smith	Unknown
Spain, Berango	Aurubis	Unknown	Unknown	Unknown

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[8] The annual report of New Boliden (Boliden, 2020) indicates on page 15: 'The Rönnskär and Harjavalta copper smelters produced 322 ktonnes of copper, of which recycling accounted for 20% in 2018.'

Country	Name Company	Smelter type	Converter type	Zinc recovery?
Secondary copper production – one step				
Belgium, Hoboken	Umicore	Integrated Isasmelt		No
Germany, Lünen	Aurubis	Integrated Isasmelt/TBRC		Yes

Sources: (Schlesinger et al., 2011); (Gusano et al., 2017).

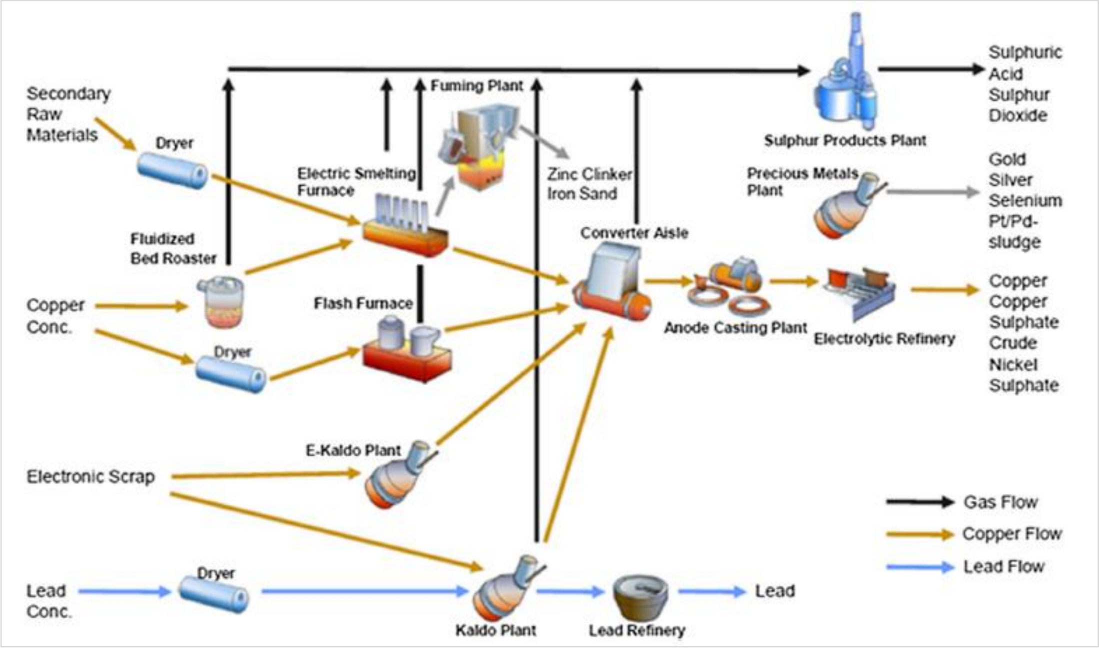
3.2.1 Reference 1: Treatment via converter – zinc clinker

Zinc at **New Boliden (Rönnskär, Sweden)** is recovered from material that is added to the electric smelting furnace (primary copper smelter), from material (mostly WEEE) that is added to the e-Kaldo furnace (Lennartsson et al., 2018) or from material that is added to the converter. Zinc is recovered via a zinc fuming plant. New Boliden has indicated that the copper/zinc concentrate is added to the converter furnace because of its higher copper concentration (55% copper content)[9]. The slag from different processes is treated in the fuming plant, which produces a zinc clinker. This zinc clinker is being send to a zinc smelter also owned by New Boliden to produce zinc cathodes.[10]

Figure 3 shows the treatment process present at Rönnskär Sweden, this image is not complete since multiple waste streams are re-looped and treated, but it gives a general overview.

Reference 1 is used for Goal 1.

Figure 3 – Treatment process at New Boliden (Rönsskär, Sweden)



Source: (Lennartsson et al., 2018).

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[9] Personal contact Elemetal with New Boliden.

[10] Extracting zinc through steel mill dust recycling at Rönnskär

Pierce-Smith converter

The converter used at New Boliden is a Pierce-Smith converter. Data on the inputs and outputs of this converter are given in Table 8. We assume transport of the copper/zinc concentrate from Maastricht to Rönnskär in Sweden, a distance of 2,400 km. Of this 1,000 km occurs by truck and the other 1,400 by train.

Table 8 - Inputs and outputs Pierce-Smith converter at New Boliden (Rönnskär, Sweden)

Inputs	**Quantity**	**Data source**
Copper matte	350 tonne/cycle (55% copper)	Table 8.2 (Schlesinger et al., 2011)
Copper scrap	90-130 tonne/cycle	Table 8.2 (Schlesinger et al., 2011)
Slag	30 tonne/cycle	Table 8.2 (Schlesinger et al., 2011)
Outputs	**Quantity**	**Data source**
Blister copper	290-310 tonne/cycle (99% copper)	Table 8.2 (Schlesinger et al., 2011)
Slag	150-160 tonne/cycle *5% copper, zinc % unknown*	Table 8.2 (Schlesinger et al., 2011)
Filter dust (off-gas)	Unknown *8.3% copper, 15.1% zinc*	Table 21.4 (Schlesinger et al., 2011)

The converter is fed with a copper matte with a content of approximately 55%, as well as with copper scrap. The copper/zinc concentrate would be added as part of the copper scrap. The fates of the copper and the zinc are:

- Zinc: converter slag (86%), blister copper (11%) and off-gas (3%) (Schlesinger et al., 2011).
- Copper: mostly the blister copper but a part of it also ends up in the slag, we estimate based on the data in the table that 3% of the copper ends up in the converter slag, and that the amount in the filter dust is negligible. See Annex B.

The blister copper is treated in a fire refining and anode casting plant (**see fire refining and anode casting**). We assume that all zinc is lost from this process because only a small amount of anode slag is produced here while there is no zinc in anode copper and all off-gas is being dedusted but stored and not further treated (Gusano et al., 2017). The converter slag is re-looped to the electric smelting furnace (see **Electric smelting furnace**).

The dust from the converter is collected in a baghouse (Schlesinger et al., 2011).
At this moment, the filter dust is stored[11]. New Boliden is investing in a hydrometallurgical treatment process for the flue dust treatment, this plant expected to be operational by the end of 2020. In this analysis, we focus on the current treatment of flue dust, which is storage. This means that all zinc and copper that has ended up in the flue dust lost in this process.

We do not attribute any energy use to the treatment of the CuZn-concentrate in the converter because the material can be added to the converter to cool the process. It is also possible that the material is not used for cooling, this scenario is not taken into consideration.

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[11] MKB- avseende lakverk för F1/K1 stoft mm vid Boliden Rönnskärs industriområde

Electric smelting furnace

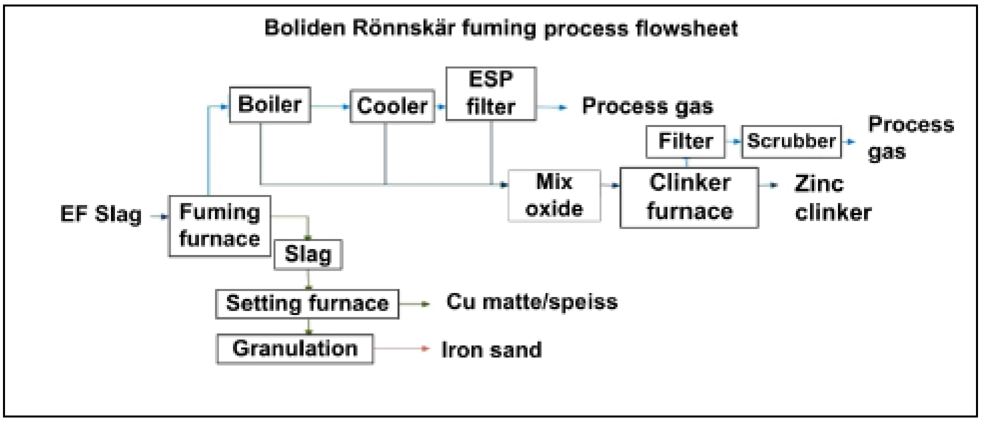
The slag is being re-looped to the electric smelting furnace to retrieve copper in the copper matte. The slag produced from the electric smelting furnace is treated in the slag fuming plant. The dust produced in the electric smelting matte is for 100% recycled into the electric smelting furnace (Schlesinger et al., 2011). This means that no copper or zinc is lost in this process.

The energy use for this process is 300 kWh per tonne of new concentrate inputs. We assume the same amount of energy is used for the treatment of converter slag (Schlesinger et al., 2011).

Fuming plant

The process as it occurs in the fuming furnace is shown in Figure 4. The recovery rate of zinc is approximately 85% and the zinc oxide content in the zinc clinker is approximately 70-75% (Gusano et al., 2017). The zinc clinker is treated in a conventional zinc process at New Boliden in Odda (Norway). We assume that all copper is lost from this process. This makes the total zinc recovery 86% (n the converter) * 85% equals 73% from zinc input to zinc clinker.

Figure 4 – Detailed process fuming furnace at New Boliden (Rönsskär, Sweden)



Source: (Gusano et al., 2017).

Values for the use of coal for fuming of zinc ranges between 2.8 tonne per tonne of zinc recovered (Sinclair, 2005) to 1.39 tonne of coal per tonne of zinc input (Gusano et al., 2017)[12].
We assume the newest available data. In addition, a limited amount of fuel oil is used. We take into consideration 0.03 kg per tonne zinc input to the fumer based on the same source[13].

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[12] See calculations in Annex B.

[13] See calculations in Annex B.

Zinc clinker treatment

The Odda smelter in Norway is based on a direct leaching process, which means that material entering the plant is not roasted first. The material therefore enters the zinc treatment in the same place as the Elemetal material would; in the leaching stage. As indicated in Section 3.3 we assume a 97% efficiency for zinc recovery in the conventional zinc production process. Energy use/inputs for zinc production is as follows (also see Section 3.3):

- leaching: 130 kWh/tonne zinc cathode produced;
- solution purification: 75 kWh/tonne zinc cathode produced;
- electrowinning: 3,300 kWh/tonne zinc cathode produced.

We assume transport by truck of the zinc clinker from Rönnskär Sweden to Odda in Norway, a distance of 1,300 km.

Fire refining and anode casting

Fire refining uses between 2,000 and 3,000 MJ of fuel per tonne of anode copper produced (Schlesinger et al., 2011). We assume a use of 2,500 MJ originating from natural gas. As a reducing agent natural gas is used, approximately 10 m^3 per tonne of copper (Gusano et al., 2017). Furthermore, we assume an efficiency of 99%, since most material that does not end up in the anode copper is remolten and re-cast. A small amount of anode slime is produced (Gusano et al., 2017).

Electrolytic refining

The yield from electrolytic refining is more than 95% (Gusano et al., 2017). Two sources give information on electrolytic refining of copper. According to (Schlesinger et al., 2011) the electricity consumption per tonne of copper cathode is between 300 and 400 kWh, while (Gusano et al., 2017) refers to between 360 to 380 kWh per tonne copper cathode. We assume 370 kWh per tonne copper cathode based on the newest available source.

Table 9 - Inputs and outputs electrolytic refining

Inputs	Quantity (per tonne copper cathode produced)	Source
Anode copper and anode scrap (99% copper)	1,020 kg	(Lehtonen, 2013)
Electrolyte (Sulphuric acid)	~20 kg/tonne copper input	(Lehtonen, 2013)
Electricity	370 kWh/tonne copper cathode	Average, Table 3.28 (Gusano et al., 2017)
Output		
Copper cathode (99.9% copper)	1 tonne	Table 3.28 (Gusano et al., 2017)
Spent electrolyte	40 kg/tonne copper cathode	(Lehtonen, 2013)

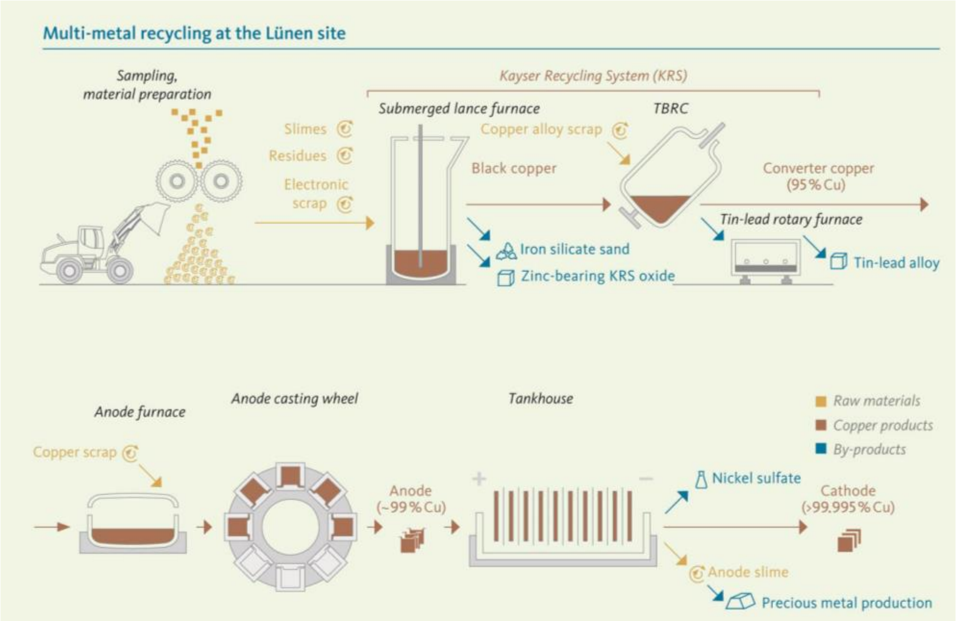
In general electrolytes for copper electrorefining mainly consist of sulphuric acid (Gusano et al., 2017), we assume 100% sulphuric acid content. This is not entirely accurate in reality, because electrolyte is always a solution. Since the exact composition at Rönnskär is unknown, we use the 100%.

3.2.2 Reference 2: Treatment via secondary copper smelter - filter dust

At Aurubis (**Lünen, Germany**), scrap copper including copper/zinc concentrates can be added directly to the Isasmelt process. A KRS oxide is produced which is further treated by Grillo-Werke to produce zinc sulphate. All the other material is returned to be treated at Aurubis. The treatment process at the Aurubis plant in Lünen is shown in Figure 5.

The copper/zinc concentrate would be added to the Isasmelt process (the submerged lance furnace as indicated in Figure 5). We assume transport by truck of the copper/zinc concentrate from Maastricht to Lünen in Germany, a distance of 200 km.
Reference 2 is used for Goal 1 and 2.

Figure 5 - Treatment process at Aurubis (Lünen, Germany)



Source: (Nolte, 2020).

Isasmelt smelter and TBRC converter

The KRS process uses an Isasmelt furnace (Gusano et al., 2017). The copper matte originating from the Isasmelt furnace containing approximately 80% copper is converted in a TBRC (top blown rotary converter) to form blister copper with a copper content of approximately 95%. The exact mass balance is unknown so we assume:
- 64% of the zinc that enters the Isasmelt smelter ends up in the KRS oxide, the remainder is lost via the iron silicate slag;
- 98% of the copper that enters the Isasmelt smelter ends up in the blister copper, the remainder is lost.

The calculation of these numbers can be found in Annex B.

Table 10 - Inputs and outputs smelter and converter at Aurubis plant (Lünen, Germany)

Inputs	Per tonne material in	Source
Copper scrap/slimes/residues	1 tonne	-
Fuel oil	50-70 kg/tonne material	Table 3.30 (Gusano et al., 2017)
Reducing agent (coke)	10 kg/tonne material	Table 3.30 (Gusano et al., 2017)
Outputs		
KRS oxide (filter dust)	50-100 kg/tonne material	Table 3.30 (Gusano et al., 2017)
Iron silicate slag[14]	300-500 kg/tonne material	Table 3.30 (Gusano et al., 2017)
Converter slag	150-200 kg/tonne material	Table 3.30 (Gusano et al., 2017)
Blister copper (95% copper)	200-300 kg/tonne material	Table 3.30 (Gusano et al., 2017)

The iron silicate slag is granulated to iron silicate sand. The KRS oxide contains copper (3-6 wt%), lead (15-20 wt%), zinc (35-50 wt%) and tin (2-4 wt%) (Gusano et al., 2017). The slag from the converter (TBRC) is processed in a tin-lead alloy furnace (Gusano et al., 2017).

Treatment of KRS oxide

The KRS oxide is treated at Grillo Werke. Grillo Werke produces zinc sulphate from the KRS oxide. The remainder, enriched filter dust, is re-used by Aurubis. This means that this route cannot be compared with conventional zinc production. This route is therefore only included in the first question to be answered in this study. Since no information is available on the treatment of the KRS oxide to produce zinc sulphate, we assume the following:

- The zinc oxide is leached by means of sulphuric acid in the same way as in conventional zinc treatment. The solution is then also purified (see **leaching** and **solution purification** in Section 3.3).
- The zinc leachate is concentrated, crystallized and dried to form zinc sulphate monohydrate. Since not enough data is available on the exact treatment process at Grillo Werke, we assume the same energy use and inputs, as is the case for the Elemetal process **future**.

Estimated inputs and outputs for the treatment at Grillo Werke are given in Table 11. We assume transport of 80 km from Aurubis in Lünen to Grillo Werke in Duisburg.

Table 11 - Inputs and outputs treatment of KRS oxide at Grillo Werke (Germany)

Inputs	Per tonne zinc content in KRS oxide
Electricity: leaching	126 kWh/tonne zinc content
Sulphuric acid solution (97%)	2,121 kg/tonne zinc content
Electricity: purification	73 kWh/tonne zinc content
Electricity: concentrating/crystallisation/drying	538 kWh/tonne zinc content
Steam from natural gas	3,560 kg/tonne zinc content
Ammonia solution (25% ammonia)	34 kg/tonne zinc content
ZnO	161 kg/tonne zinc content
N_2 (gas)	34 kg
Outputs	
Leach residue	329 kg/tonne zinc content
Jarosite[15]	333 kg/tonne zinc content
Zinc sulphate monohydrate	2,977 kg/tonne zinc content

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[14] It is assumed that iron silicate slag is used in construction, and does not have any further burden.

[15] Jarosite is not further treated and landfilled.

Fire refining and anode casting

The blister copper is treated in an anode furnace and is then casted into anode copper. The exact process used at Aurubis in Lünen is unknown so the same data is used as for **Reference 1**.

Electrolytic refining

The anode copper is eletrorefined to produce copper cathode. The exact process used at Aurubis in Lünen is unknown so the same data is used as for **Reference 1**.

3.3 Reference 3: Primary zinc production

This reference is not relevant for the scope of the 2023 study. It can be reviewed in the 2020 LCA report.

3.4 Reference 4: Primary zinc sulphate monohydrate

The production of primary sulphate monohydrate is the same up and until the solution purification step. Afterwards the zinc leachate is concentrated, crystallized and dried to form zinc sulphate monohydrate. Since not enough data is available on the exact treatment process we assume the same energy use and inputs as is the case for the Elemetal process **Demo 2**. Reference 4 is used for Goal 2.

Inputs for this process are given in Table 12.

Table 12 - Inputs and outputs for concentrating, crystallizing and drying per tonne of zinc sulphate monohydrate produced

Inputs	**Per tonne zinc sulphate monohydrate**
Zinc content in purified solution	364 kg/tonne zinc sulphate monohydrate
Electricity: concentrating/crystallisation/drying	181 kWh/tonne zinc sulphate monohydrate
Steam from natural gas	1,196 kg/tonne zinc sulphate monohydrate
Ammonia solution (25% ammonia)	11 kg/tonne zinc sulphate monohydrate
N_2 (gas)	12 kg/tonne zinc sulphate monohydrate
Outputs	
Zinc sulphate monohydraye	1 tonne/tonne zinc sulphate monohydrate
Jarosite[16]	1,617 kg/tonne zinc sulphate monohydrate

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[16] Jarosite is not further treated and landfilled.

4 Life cycle impact assessment

The results of the life cycle impact assessment are described in this Chapter. We first present the results (Section 4.1) and continue with a sensitivity analysis (Section 4.2).

How to read the results?

Climate change impact

All results and sensitivity analyses are given as climate change impact. Climate change impact is determined by multiplying all greenhouse gas emissions with their respective global warming potential. The global warming potential is expressed in carbon dioxide equivalent (CO_2-eq.). For example, dinitrogen monoxide (N_2O) has a climate change impact that is 298 times higher than the impact of CO_2, one kilogram of N_2O is therefore multiplied with 298 CO_2-eq., to give a climate change impact of 298 kg CO_2-eq. As indicated in Chapter 2 we use the most recent IPCC (Intergovernmental Panel on Climate Change) global warming potentials, on a 100-year horizon.

Reading the figures

The figures show climate change impacts above the x-axis and below the x-axis.
This means:

- Above the x-axis: A positive climate change impact (e.g. +1,000 kg CO_2-eq.) increases the amount of greenhouse gasses in the atmosphere and therefore increases global warming.
- Below the x-axis: A negative climate change impact (e.g. -1,000 kg CO_2-eq.) decreases the amount of greenhouse gasses in the atmosphere and therefore decreases global warming.

4.1 Results

In this section we describe the results of this study. Sub-section 4.1.1 describes the comparison of the Elemetal treatment system of Elemetal Demo 2 with the conventional CuZn-concentrate treatment. Sub-section 4.1.2 describes the comparison of the Elemetal treatment system Demo 2 with conventional zinc sulphate monohydrate production.

4.1.1 Comparison of Elemetal with conventional CuZn-concentrate treatment

The results of the comparison are shown in Figure 6 and Figure 7. Figure 6 shows the total climate change impact of the different treatment routes, Figure 7 shows the contribution of different inputs and outputs to the results.

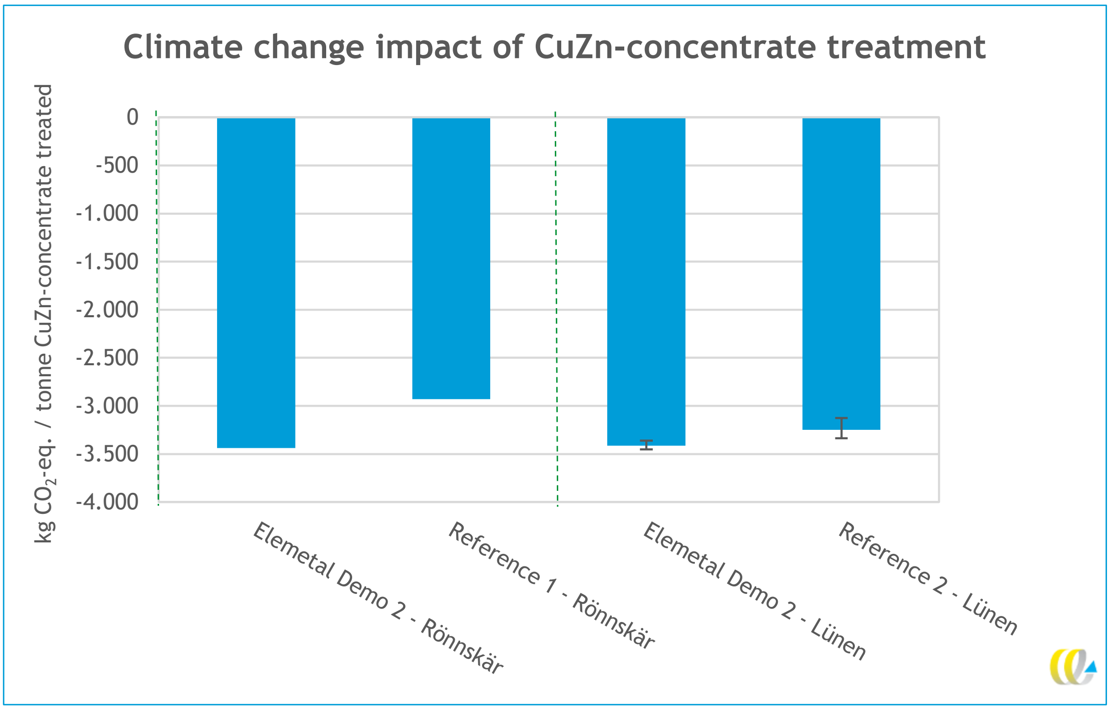
Overall results

Because of the treatment of CuZn-concentrate, no primary copper and zinc need to be produced. As this is what happens in all treatment routes (Elemetal Demo 2 as well as the reference routes), they all lead to a reduction in climate change impact because of the recovery of copper and zinc. This is shown in Figure 6. The two left bars represent the comparison between the Elemetal process Demo 2(including treatment of the Elemetal Cu-concentrate and leach products at Rönnskär) with the conventional treatment of CuZn-concentrate at Rönnskär. The two bars on the right represent the comparison between the Elemetal process Demo 2 (including treatment of Elemetal Cu-concentrate and leach products at Lünen) with the conventional treatment of CuZn-concentrate at Lünen.

Figure 6 shows an error margin for the comparison with treatment at Aurubis in Lünen. This error margin depicts the uncertainty of the zinc recovery, as is presently the case at Aurubis in Lünen. The exact recovery rate of zinc could not be determined based on literature. The blue bar shows the average recovery rate, while the error margin shows the range of where the results could lie with a lower and higher recovery percentage. A lower recovery rate would lead to a lower climate change impact reduction, while a higher recovery rate would lead to a higher climate change impact reduction.

As can be seen in the figure, the climate change impact results of all routes compared are negative (below the x-axis). A negative climate change impact is the desirable outcome: it decreases the amount of greenhouse gasses in the atmosphere and therefore decreases global warming.

Figure 6 - Climate change impact of CuZn-concentrate treatment - Total



Note: The error margin shows the impact of a higher or lower recovery rate of zinc at Lünen than the calculated average.

When comparing Elemetal Demo 2 with conventional treatment of CuZn-concentrates in which zinc is recovered, the climate change impact reduction is a lot higher than the current treatment at New Boliden in Rönnskär due to the higher impact of fuming of zinc. The reduction when moving from treatment at New Boliden in Rönnskär to treatment by Elemetal is ~510 kg CO_2-eq. per tonne of CuZn-concentrate treated.

When comparing the current climate change benefit of Elemetal Demo 2 with conventional treatment at Aurubis in Lünen there also is a climate change impact reduction. When moving from treatment at Aurubis in Lünen to treatment by Elemetal a reduction of approximately ~160 kg CO_2-eq. per tonne of CuZn-concentrate can be achieved.

The quantitative results for the totals and reduction in comparison to conventional treatment of CuZn-concentrate can be found in Table 13.

Based on a climate change impact of the current Dutch electricity mix we can determine the maximum electricity use for the Elemetal treatment method, before it is no longer the preferable route from a climate change perspective. In Table 13, we refer to this maximum electricity use as the ‘tipping point’. Electricity use in this case includes both the electricity use at the Elemetal treatment location.

Table 13 - Quantitative results for CuZn-concentrate treatment

Treatment method	Climate change impact	Climate change impact reduction in comparison to conventional treatment	Electricity use tipping point [17]
	(kg CO_2-eq./tonne CuZn-concentrate treated)		kWh/tonne CuZn-concentrate treated
Conventional treatment: New Boliden, Rönnskär			
New Boliden, Rönnskär	-2,929	Not applicable	Not applicable
Elemetal Demo 2	-3,439	510	~1,100
Conventional treatment: Aurubis, Lünen			
Aurubis, Lünen	-3,250 (range -3,126 to -3,338)	Not applicable	Not applicable
Elemetal Demo 2	-1,994 (range -3,361 to -3,451)	164 (range 113 to 234)	~350

Contribution of different inputs and outputs

The results can be explained by the quantity of copper and zinc cathode that is produced per tonne of copper/zinc concentrate treated and the energy needed for the treatment - these are the two aspects of the processes that outcome of the comparison is most sensitive for.

Of the total input of 550 kg copper and 250 kg zinc per tonne of copper/zinc concentrate, the amount recovered per treatment route is given in Table 14.

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[17] The maximum electricity use for the Elemetal treatment method, before it is no longer the preferable route from a climate change perspective compared to the reference treatment methods (based the climate change impact of the Dutch electricity mix).

Table 14 - Recovery of copper and zinc as well as energy use per tonne CuZn-concentrate treated

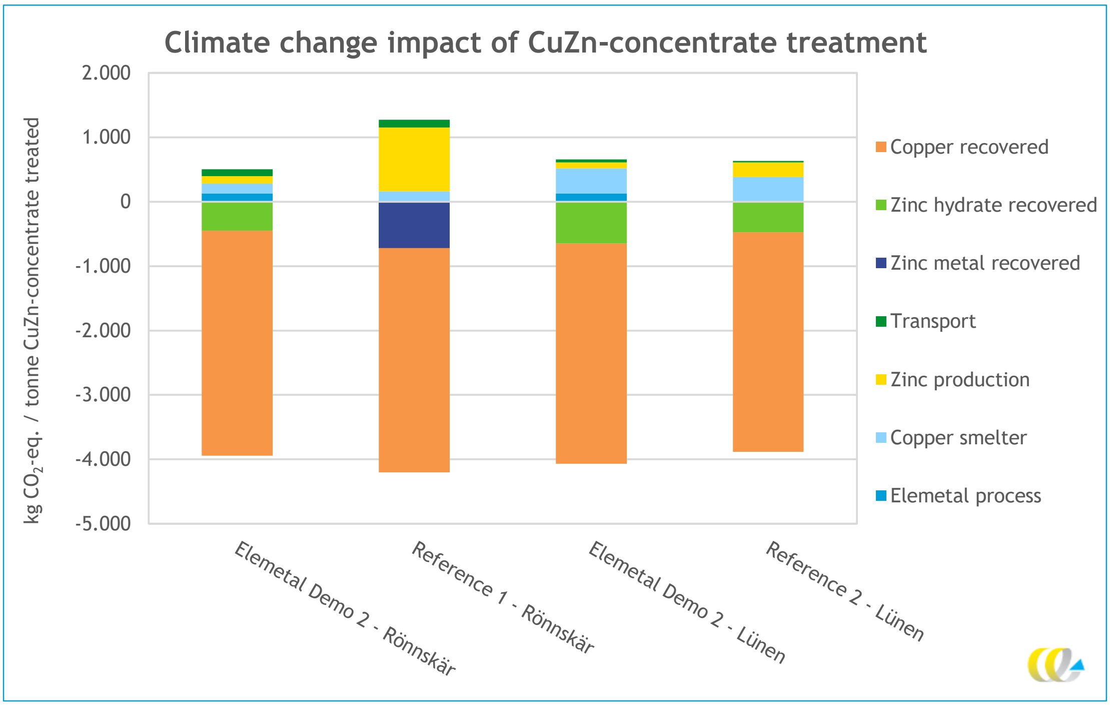
	Copper recovered	Zinc recovered
Elemetal - Demo 2 - Ref 1	535 kg (97%)	(c) 75 kg (h) 164 kg (1) (88%)
Elemetal - Demo 2 - Ref 2	524 kg (95%)	(h) 236 kg (1) (83%)
Reference 1	534 kg (97%)	(c) 177 kg (71%)
Reference 2	522 kg (95%)	(h) 174 kg (1) (61%)

Note: (c) zinc cathode and (h) zinc content in zinc sulphate monohydrate.

(1): Of the zinc sulphate monohydrate, 87.9% originates from the zinc in CuZn-concentrate, the remainder from ZnO input. The latter is not included in the efficiency.

Figure 7 shows the contribution of each of the aspects of the processes to the overall climate change impact of these processes. As can be seen in the figure, some aspects of the process have a positive climate change impact (above the x-axis) and some a negative (below the x-axis). A positive climate change impact increases the amount of greenhouse gasses in the atmosphere and therefore increases global warming. A negative climate change impact decreases the amount of greenhouse gasses in the atmosphere and therefore decreases global warming. When adding up all the contributions, this results in Figure 7.

Figure 7 - Climate change impact of CuZn-concentrate treatment - Contributions



Note: The results depicted are for calculated average zinc recovery at Aurubis in Lünen.

Comparison with Version 2 2020 study

Table 15 shows the difference between the results of the current LCA and the results of the 2020 study. The differences between the two studies are caused by changes in the environmental background data (from the Ecoinvent database) and the updated IPCC methodology in SimaPro. This is the case for all contributors to the carbon footprint. The largest effect of these updates can be seen for copper, for which the climate change impact changed from 3.9 kg CO_2-eq. in 2020 (Ecoinvent v2.5, IPCC GWP100 2013, SimaPro 9.0) to 6.5 kg CO_2-eq. in 2023 (Ecoinvent v3.8, IPCC GWP100 2021, SimaPro 9, v4.2).

Table 15 - Comparison of climate change impact results of current study ("LCA 2023") and 2020 study ("LCA 2020"), in kg CO_2-eq./kg zinc sulphate monohydrate

	LCA 2023 Demo 2 - Rönnskär	LCA 2020 Elemetal Future - Rönnskär	Difference	LCA 2023 Demo 2 - Lünen	LCA 2020 Elemetal Future - Lünen	Difference
Elemetal process	129	134	-4%	129	134	-4%
Copper smelter	154	156	-2%	388	408	-5%
Zinc production	116	111	4%	96	95	1%
Copper recovered	-3,495	-2,088	67%	-3,420	-2,043	67%
Zinc metal recovered	0	0	-	0	0	-
Zinc hydrate recovered	-450	-437	3%	-650	-633	3%
Transport	107	107	0%	44	43	0%
Total	**-3,439**	**-2,017**	**71%**	**-3,414**	**-1,995**	**71%**

4.1.2 Comparison Elemetal Demo 2 with conventional zinc sulphate monohydrate production

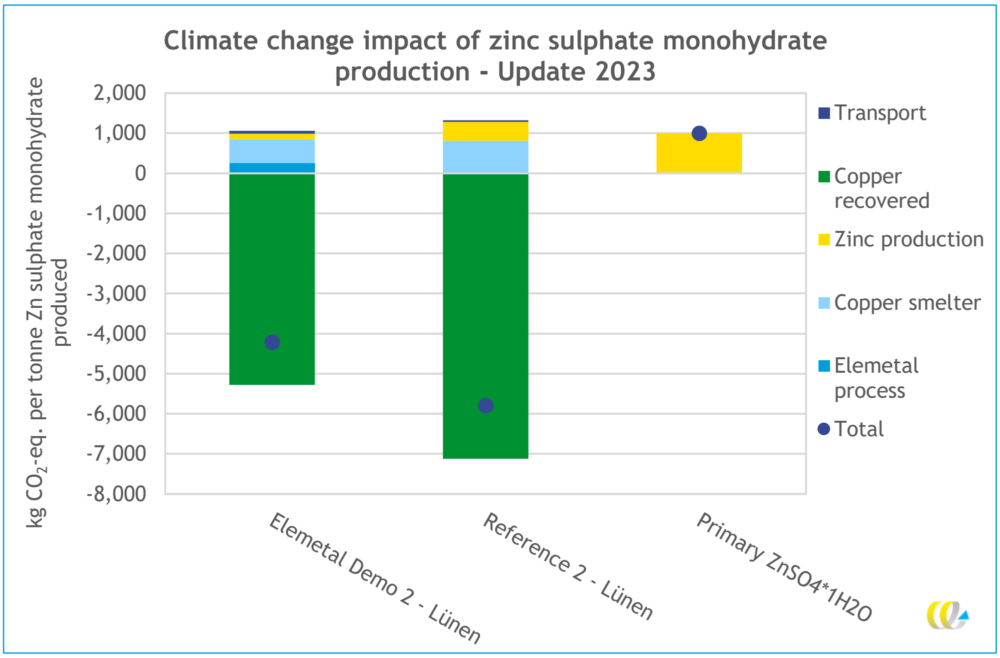
Comparing with conventional zinc sulphate monohydrate production

The results of the comparison of Elemetal **Demo 2** treatment with conventional zinc sulphate monohydrate production is shown in Figure 8. Figure 8 shows both the total impact (indicated with a dot) as well as the contributions of different aspects to the climate change impact.

The results show that the Elemetal Demo 2 treatment as well as conventional treatment at Aurubis in Lünen lead to a lower climate change impact than primary zinc sulphate monohydrate production. The reduction for the Elemetal **Demo 2** process in comparison with primary zinc sulphate monohydrate production amounts to approximately 5,000 kg CO_2-eq. per tonne of zinc sulphate monohydrate produced. We obtain this number by subtracting the climate change impact of the production of primary zinc sulphate monohydrate (~1,000 kg CO_2-eq.) from the climate change impact of the Elemetal **Demo 2** process (~ -4,000 kg CO_2-eq.).

As Figure 8 shows, some aspects of the process have a positive climate change impact (above the x-axis) and some a negative (below the x-axis). A positive climate change impact increases the amount of greenhouse gasses in the atmosphere and therefore increases global warming. A negative climate change impact decreases the amount of greenhouse gasses in the atmosphere and therefore decreases global warming.

Figure 8 - Climate change impact of zinc sulphate monohydrate production



Comparison with Version 2 2020 study

Table 16 shows the difference between the results of the current LCA and the results of the 2020 study. The differences between the two studies are mostly caused by changes in the environmental background data (from the Ecoinvent database) and the updated IPCC methodology in SimaPro. This is the case for all contributors to the carbon footprint. The largest effect of these updates can be seen for copper, for which the climate change impact changed from 3.9 kg CO_2-eq. in 2020 (Ecoinvent v2.5, IPCC GWP100 2013, SimaPro 9.0) to 6.5 kg CO_2-eq. in 2023 (Ecoinvent v3.8, IPCC GWP100 2021, SimaPro 9, v4.2).

The difference between the climate change impact of the Elemetal process between 2020 and 2023 is partly caused by changes in the databases and methods, but also partly because of changes in the inputs used to run the process. The addition of natural gas and the replacement of ammonia by potassium hydroxide have the largest extra impact. Towards the future, when upscaling, it is recommended to research whether it is possible to replace the natural gas use by electricity use. If possible, the impact would likely decrease, especially as electricity will be produced from renewable sources more and more.

Table 16 – Comparison of climate change impact results of current study ("LCA 2023") and 2020 study ("LCA 2020"), in kg CO_2-eq./kg zinc sulphate monohydrate

	LCA 2023	LCA 2020	
	Demo 2	Elemetal Future - Lünen	Difference
Elemetal process	256	217	+18%
Copper smelter	598	630	-5%
Zinc production	137	135	+1%
Copper recovered	-5,279	-3,155	-67%
Transport	67	67	0%
Total	**-4.221**	**-2.106**	**-100%**

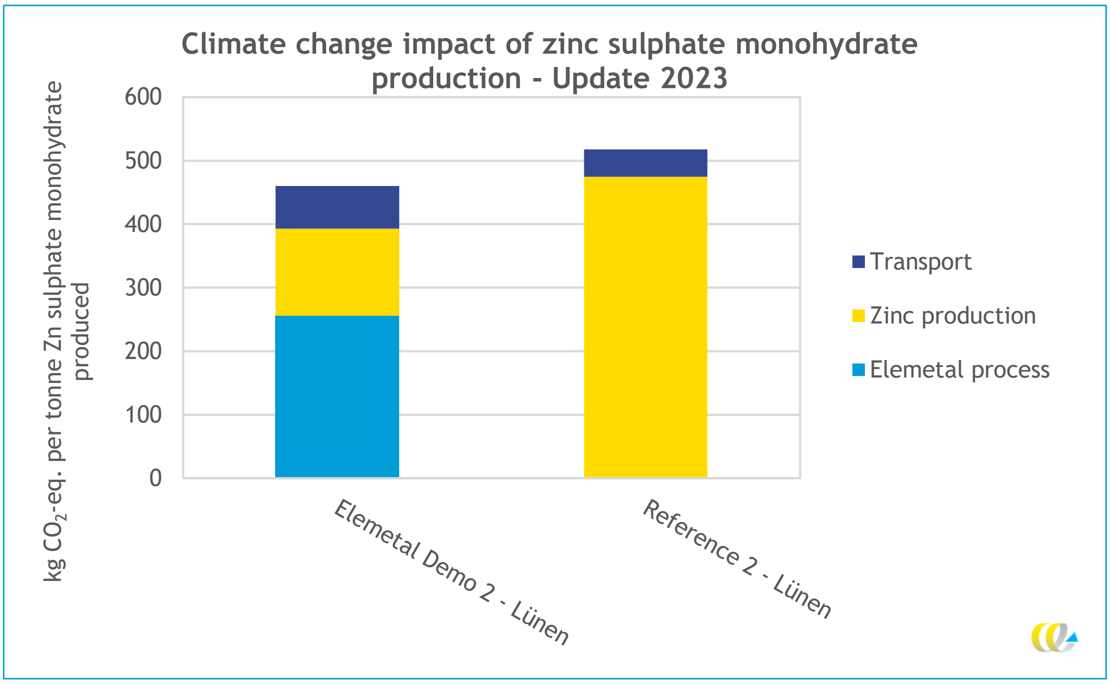
Comparing Elemetal Demo 2 with conventional treatment of CuZn-concentrate for zinc monohydrate production

In the different processes considered, different amounts of CuZn-concentrate need to be treated to obtain one tonne of zinc sulphate monohydrate. The quantities of CuZn-concentrate that need to be treated are:
- Elemetal Demo 2: 1.5 tonne CuZn-Concentrate;
- conventional treatment at Aurubis, Lünen: 2.0 tonne CuZn-Concentrate.

Because copper and zinc are combined in the concentrate this also means that, more copper enters the copper smelter in the case of conventional treatment than in the case of the Elemetal route. This naturally leads to a higher copper recovery. The recovery of copper therefore slightly distorts the picture in comparing the three treatment routes.

In comparing the Elemetal routes with conventional treatment at Aurubis in Lünen it is therefore more fair, to exclude the impact of the copper retrieved and the copper smelter. Figure 9 shows that the Elemetal **Demo 2** treatment route has a lower climate change impact per tonne zinc sulphate monohydrate produced than production via the conventional treatment route of CuZn-concentrate at Aurubis in Lünen. In Figure 9 we attribute the climate change impact of the zinc production (indicated in yellow), the entire impact of the Elemetal process (indicated in blue) and the entire impact of the transport (indicated in dark blue/purple) to the zinc production.

Figure 9 - Climate change impact of zinc sulphate monohydrate production from CuZn-concentrate excl. copper smelter and copper retrieved



4.2 Sensitivity analyses

In this section, we describe the sensitivity analyses of the comparisons made in this study. Sub-section 4.2.1 describes the comparison of the Elemetal treatment system with the conventional CuZn-concentrate treatment. Sub-section 4.2.2 describes the comparison of the Elemetal treatment system with conventional zinc sulphate monohydrate production.

4.2.1 Comparison of Elemetal with conventional CuZn-concentrate treatment

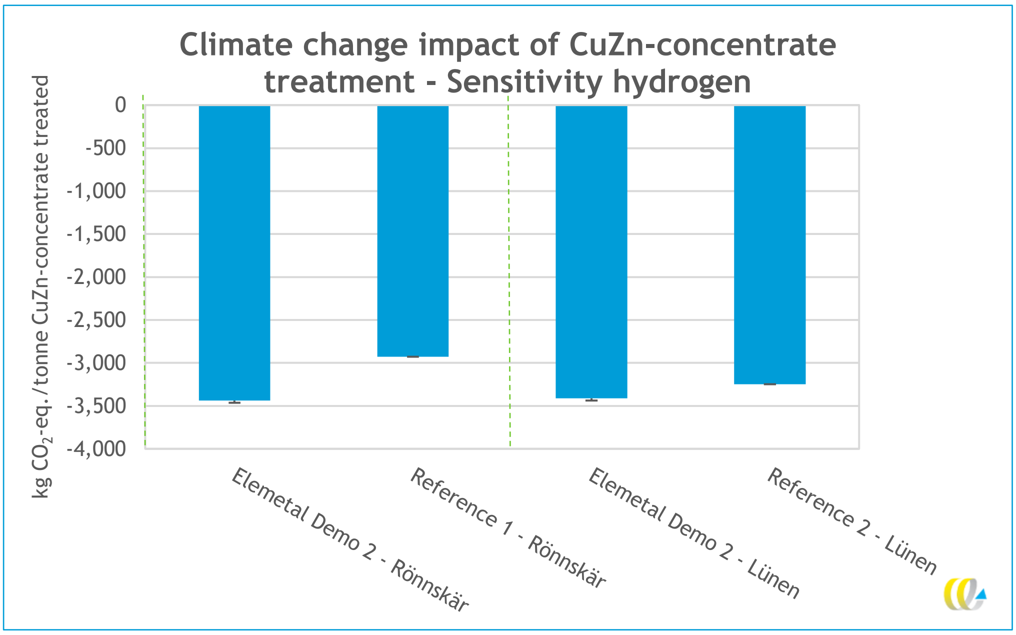
We conduct the following additional analyses for the comparison of the Elemetal treatment method in comparison to conventional CuZn-concentrate treatment:

- assessing the additional climate change benefit of utilizing the produced hydrogen in the Elemetal **Demo 2** process to generate electricity for use in the own use;
- assessing the uncertainty of the climate change impact of primary copper production.

Utilizing hydrogen

In the Elemetal **Demo 2** process a small quantity of hydrogen is produced, which can be used to produce electricity. If this electricity were used in the Elemetal process, it would reduce the electricity demand from the grid. We determine the potential by combining the produced hydrogen per tonne CuZn-concentrate treated (see Chapter 3) with the energy content of hydrogen (120 MJ per kg) and an electric efficiency of 44% (CE Delft, 2019). The results of the analysis are given in Figure 10. The error margin in this case represents the change in results from utilizing hydrogen. The utilization of hydrogen indeed leads to an additional reduction in climate change impact of ~25 kg CO_2-eq.

Figure 10 - Climate change impact of CuZn-concentrate treatment - Sensitivity analysis hydrogen



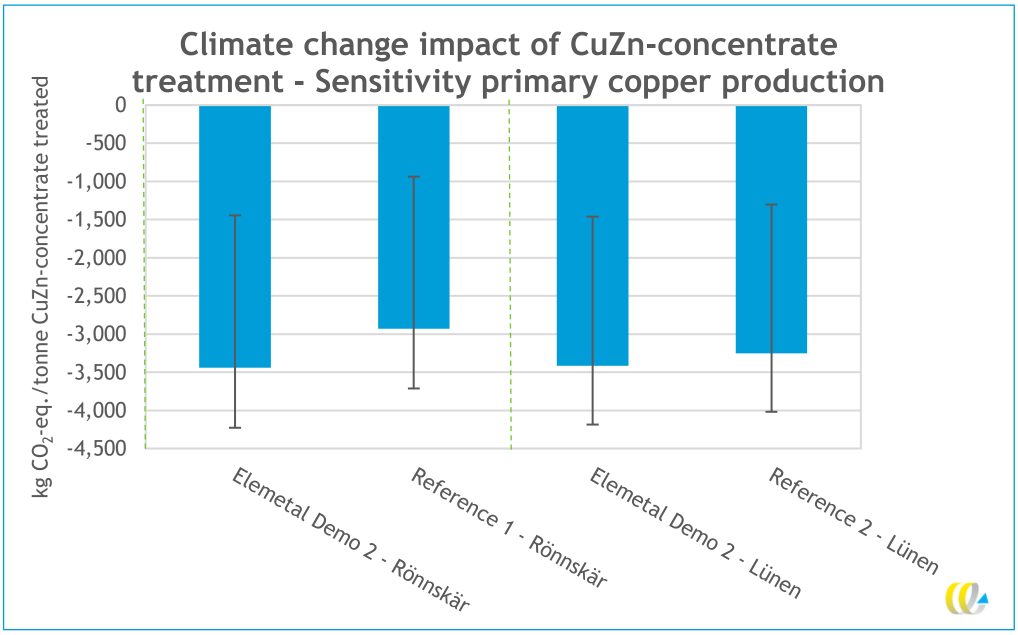
Note: The error margin shows the sensitivity of the results to utilizing the available hydrogen.

Climate change impact of copper production

The impact of global primary copper production according to (Ekman Nilsson et al., 2017) lies somewhere between 2.8 and 8 kg CO_2-eq. per kg of metal produced. In the current analysis we have used a climate change impact of 6,5[18] kg CO_2-eq. per kg of copper produced, based on the global production of copper as available in the Ecoinvent database (See Chapter 2 for a description of the database). In this sensitivity analysis, we investigate what would happen to the results if the climate change impact of primary copper production would be different.

The results of the analysis are given in Figure 11. The results per treatment route are highly impacted by the climate change impact of primary copper production. The comparison between the treatment routes does however not change much. Elemetal Demo 2 still leads to a higher climate change impact reduction in comparison with treatment at New Boliden in Rönnskär. Also, Elemetal Demo 2 still leads to a higher climate change impact reduction in comparison with treatment at Aurubis in Lünen.

Figure 11 - Climate change impact of CuZn-concentrate treatment - Sensitivity analysis primary copper production



Note: The error margin shows the sensitivity of the results to the climate change impact of primary copper production.

4.2.2 Comparison Elemetal with conventional zinc sulphate monohydrate production

In this section, we assess the sensitivity of the results to the choice not to include bottom-ash treatment in the analysis. As described in Section 3.1.4 as WTE bottom-ash treatment is considered the minimum standard practice in the Dutch waste management directive, we consider it part of the waste incineration. Bottom-ash treatment was therefore not included in the base case analysis.

Figure 12 shows the sensitivity of the results to the choice to not include bottom-ash treatment in the analysis. The results could, depending on the chosen allocation procedure, lay anywhere within the indicated error margin. The results show that Elemetal Demo 2 would even in the worst case still lead to a lower climate change impact than primary zinc

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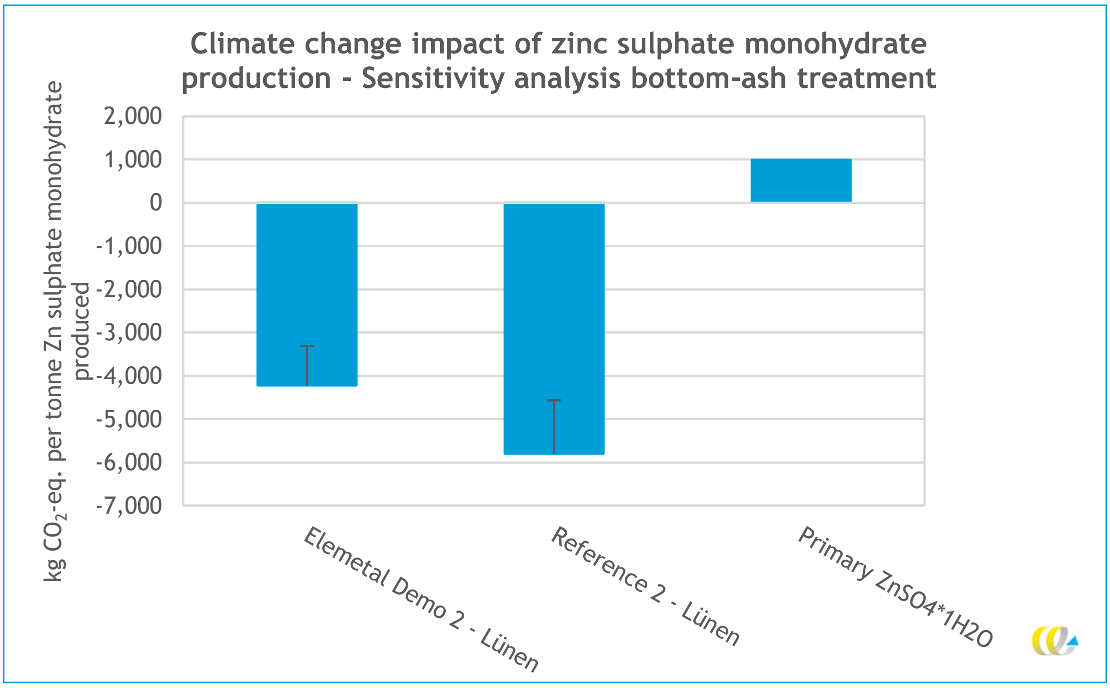
[18] In the previous study this was 3.9 kg CO_2-eq. per kg of copper.

sulphate monohydrate production, as does the conventional treatment at Aurubis in Lünen. The reduction of climate change impact can, however, be smaller than was indicated in the base case analysis. The reduction for the Elemetal **Demo 2** process in comparison with primary zinc sulphate monohydrate production could therefore be somewhere between 5,000 kg (base analysis) and 4,300 kg (this sensitivity analysis) CO_2-eq per tonne of zinc sulphate monohydrate produced.

Figure 12 - Climate change impact of zinc sulphate monohydrate production - Sensitivity analysis bottom-ash treatment



Note: The error margin shows the sensitivity of the results to not including bottom-ash treatment in the analysis.

5 Interpretation and conclusions

Conclusions Goal 1: Elemetal in comparison with conventional CuZn-concentrate treatment

When copper and zinc is recovered from CuZn-concentrates from WTE bottom-ash, less primary copper and zinc needs to be produced[19]. Both the Elemetal treatment route and the conventional treatment at New Boliden in Rönnskär and at Aurubis in Lünen therefore lead to a climate change impact reduction.

When comparing Elemetal Demo 2 with the conventional treatment at New Boliden and Lünen we can conclude that the climate change impact reduction is higher for the Elemetal route in both cases.

Table 1 shows a range in between which we estimate the reduction in climate change impact to be when switching from conventional treatment to Elemetal Demo 2.

Furthermore, Table 1 indicates the maximum electricity use in the Netherlands due to the Elemetal process per tonne of CuZn-concentrate treated, before which it is more environmentally beneficial to treat the concentrate at New Boliden or Aurubis. This is referred to as the 'tipping point' in Table 17.
This electricity use refers to all electricity use at the Elemetal treatment location .

Table 17 - Range of climate change impact reduction of Elemetal route in comparison with conventional treatment of CuZn-concentrate

Elemetal route	New Boliden, Rönnskär	Aurubis, Lünen	Unit
Demo 2	Higher reduction (510 kg CO_2-eq.) Tipping point[20]: ~1,100 kWh	Higher reduction (113 to 234 kg CO_2-eq.) Tipping point[20]: ~350 kWh	Per tonne CuZn-concentrate

Note: Range based on highest uncertainty observed due to (1) zinc recovery rate or (2) climate change impact of primary copper production.

The reduction in comparison to both conventional treatment routes of CuZn-concentrate can be increased with approximately 25 kg CO_2-eq. per tonne concentrate by utilizing the hydrogen for electricity production.

Conclusions Goal 2: Elemetal in comparison with conventional zinc sulphate monohydrate production

When comparing the Elemetal Demo 2 with conventional zinc sulphate monohydrate production we can conclude that Elemetal produces zinc sulphate monohydrate that has a lower climate change impact than conventional primary zinc sulphate monohydrate. The estimated impact reduction can be found between 4,000 kg CO_2-eq. per tonne of zinc

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[19] Assuming that recovering copper and zinc does not have an impact on the world demand for copper and zinc. Which is highly unlikely seeing the quantity.

[20] The maximum electricity that can be used for the Elemetal process per tonne of CuZn-concentrate treated, before which it is more environmentally beneficial to treat the concentrate at New Boliden or Aurubis.

sulphate monohydrate produced when producing zinc sulphate monohydrate from CuZn-concentrate from WTE bottom-ash instead of from primary zinc ore.

The reduction is lower when allocating the energy and transport associated to WTE bottom-ash treatment to Elemetal Demo 2. In the base analysis in this study, we allocate these inputs to the waste incineration plant, as the removal of metals is prescribed as a minimum standard for waste incinerators (RWS, 2019). The sensitivity analysis in which energy and transport associated to WTE bottom-ash treatment is allocated to Elemetal Demo 2 is therefore a worst case analysis. The climate change impact reduction compared to conventional zinc sulphate monohydrate would be 4,300 kg CO_2-eq. per tonne of zinc sulphate monohydrate produced.

Comparison to results Elemetal Future previous study

Table 2 shows the difference between the results of the current LCA and the results of the 2020 study. The differences between the two studies are mostly caused by changes in the environmental background data (from the Ecoinvent database) and the updated IPCC methodology in SimaPro. This is the case for all contributors to the carbon footprint. The largest effect of these updates can be seen for copper, for which the climate change impact changed from 3.9 kg CO_2-eq./kg copper in 2020 (Ecoinvent v2.5, IPCC GWP100 2013, SimaPro 9.0) to 6.5 kg CO_2-eq./kg copper in 2023 (Ecoinvent v3.8, IPCC GWP100 2021, SimaPro 9, v4.2).

The difference between the climate change impact of the Elemetal process between 2020 and 2023 is partly caused by changes in the databases and methods, but also partly because of changes in the inputs used to run the process. The addition of natural gas and the replacement of ammonia with potassium hydroxide have the largest extra impact. Towards the future, when upscaling, it is recommended to research whether it is possible to replace the natural gas use by electricity use. If possible, the impact would likely decrease, especially as the electricity mix will increasingly consist of renewably sourced energy.

Table 18 - Comparison of climate change impact results of current study ("LCA 2023") and 2020 study ("LCA 2020"), in kg CO_2-eq./kg zinc sulphate monohydrate

	LCA 2023	LCA 2020	
	Demo 2	Elemetal Future - Lünen	Difference
Elemetal process	256	217	+18%
Copper smelter	598	630	-5%
Zinc production	137	135	+1%
Copper recovered	-5,279	-3,155	-67%
Transport	67	67	0%
Total	**-4.221**	**-2.106**	**-100%**

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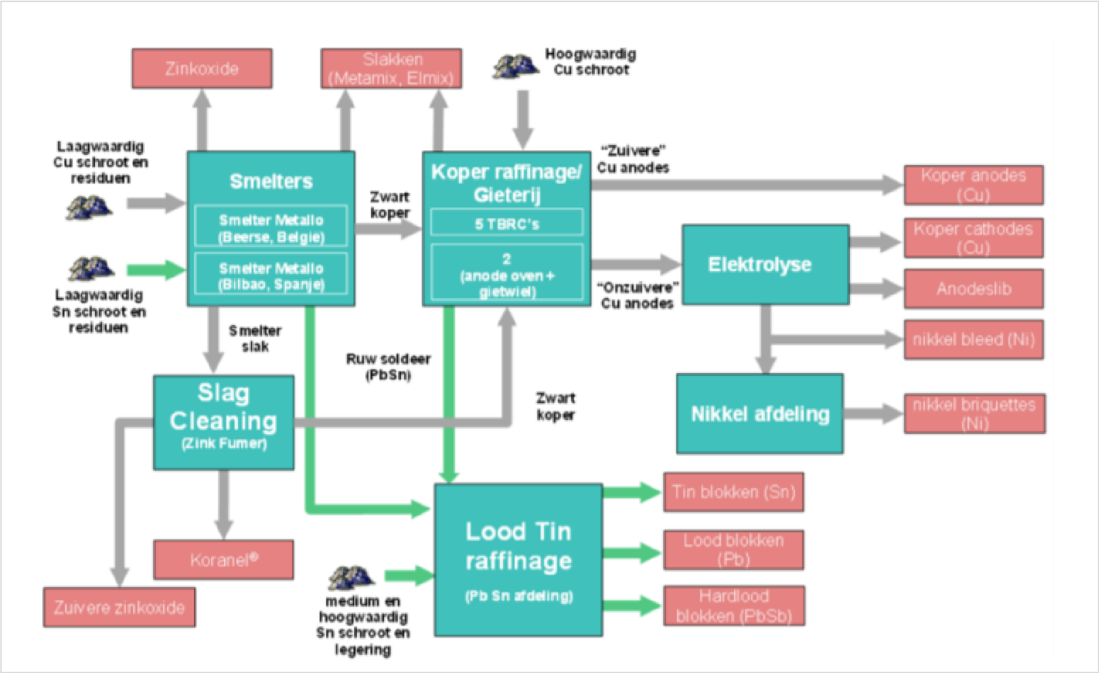
A Information Beerse

Zinc recovery at **Aurubis (Beerse, Belgium)** occurs in the form of recovery of zinc oxide dust. This treatment location was previously owned by Metallo-Chimique or more recently Metallo. Treatment of any material that contains copper is combined with treatment of a material that contains iron (Dierckx et al., 1972).

Figure 13 gives an overview of the treatment process at Aurubis in Beerse (Belgium). The image is in Dutch and indicates that materials with low copper content (‘laagwaardige Cu schroot en residuen’) are treated in the smelter. Since black copper (‘zwart koper’) generally has a copper content around 80% and the copper/zinc concentrates that we study have a copper content of ~54%, we can assume that the material would be categorized as material with a low copper content.

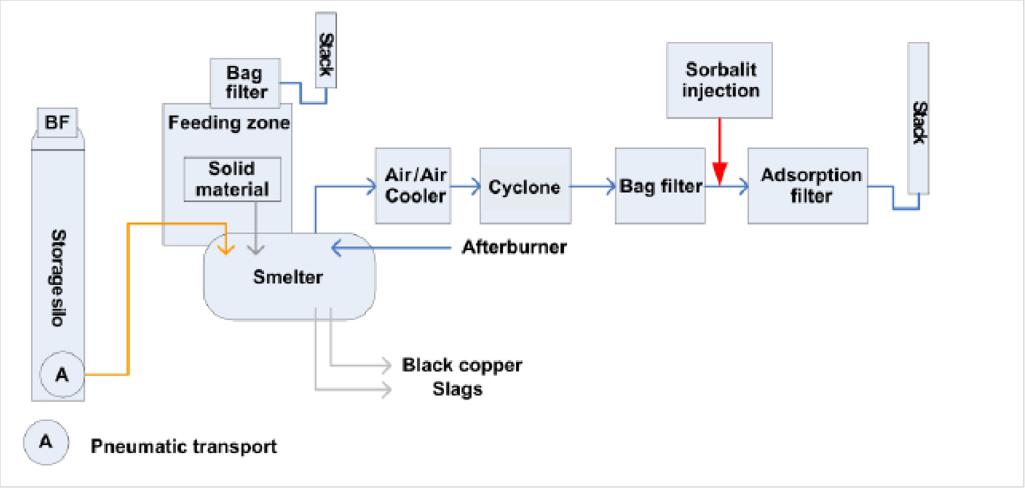
Figure 13 - Treatment process at Aurubis (Beerse, Belgium) - in Dutch (Nv, M. B., 2018)



Smelting

During the smelting stage, black copper (~80% copper content) is produced from secondary copper/iron scrap. Zinc is partly volatized during the smelting partly ends up in smelter slags and partly remains in the black copper. The dust in the off-gases from the smelter ends up in bag filter (Gusano et al., 2017), where zinc oxide is also collected. The bag filter has a sorbalit injection (a combination of lime and activated carbon. The reaction that takes place between oxygen and iron provides the energy needed for the smelting process (Nv, M.-C., 2013). The slag is being transported to the zinc fumer.

Figure 14 - Detailed process smelter at Aurubis (Beerse, Belgium)



Source: (Gusano et al., 2017).

Converting

In the TBRC converter, the black copper as well as copper scrap with a high copper content is treated to produce copper matte with a 98% copper content. Natural gas and oxygen is used in this process (Nv, M.-C., 2013). The exact energy use is unknown.

The slag from the converting process is treated in a TBRC slag oven. The materials from the slag; mainly copper, lead and nickel are being retrieved as much as possible. The copper is added to the converting process again. After some additional treatment, the remaining slag is granulated. It is unknown how much of the copper ends up in the blister copper.

Fire refining and anode casting

A TBRC is used for fire refining (Gusano et al., 2017). Natural gas is used as a reducing agent (Gusano et al., 2017). The off-gases from the anode furnace after being treated in an afterburner chamber are cleaned in a bag filter (Gusano et al., 2017). The slag from the refining furnace is treated in a TBRC slag furnace (Gusano et al., 2017). This furnace only aims at recovering copper, tin, lead and nickel. The slag treatment process exists of two steps the first step in which black copper is produced which is re-used into the fire-refining unit.

The exact process used at Aurubis in Beerse is unknown.

Electrolytic refining

The anode copper is electro refined to produce copper cathode. The exact process used at Aurubis in Beerse is unknown.

Slag fumer

The remaining slag material is sold on the market at Koranel. The zinc oxide that has been fumed out of the slag can be treated in the zinc industry. It has a zinc concentration of more than 70%. The remaining material, the bullion that still contains copper and a number of other metals is being used in the refining process.

Zinc oxide treatment

The zinc oxide produced at Aurubis, Beerse has a comparable composition as the zinc oxide produced by New Boliden in Rönnskär.

Zinc leaching

The zinc containing filter dust from the smelter and converter is sold to the zinc industry if the zinc content is high enough. If the zinc content is low, the material is added to the copper smelter again. The exact zinc content of this material is unknown.

B Recovery rates at New Boliden, Rönnskär

Recovery rate copper to blister copper

Table 19 gives an overview of the data that is used to determine the recovery rate of copper at New Boliden, Rönnskär. All information, except for the quantity of filter dust produced per cycle was available from (Schlesinger et al., 2011).

The filter dust quantity is based on the following data/assumptions:
- 5,000 tonne of filter dust from the converter is produced per year;[21]
- copper cathode production at New Boliden in Rönnskär is 224,000 tonne per year;
- copper cathode has a copper content of 99.99% copper;
- we assume a 97% efficiency from blister copper to copper cathode;
- we multiply the quantity of filter dust per tonne of blister copper with the quantity of blister copper produced per cycle.

Table 19 - Data used to determine the recovery rate of copper at New Boliden, Rönnskär

Output		Minimum	Maximum	Average	Copper content
Blister copper	Total quantity	290 tonne/cycle	310 tonne/cycle	300 tonne/cycle	99.0%
	Copper quantity	287.1 tonne/cycle	306.9 tonne/cycle	297.0 tonne/cycle	100%
Slag	Total quantity	150 tonne/cycle	160 tonne/cycle	155 tonne/cycle	5.0%
	Copper quantity	7.5 tonne/cycle	8.0 tonne/cycle	7.8 tonne/cycle	100%
Filter dust	Total quantity	6.7 tonne/cycle	7.1 tonne/cycle	6.9 tonne/cycle	8.3%
	Copper quantity	0.6 tonne/cycle	0.6 tonne/cycle	0.6 tonne/cycle	100%
Total	**Copper quantity**	**295.2**	**315.5**	**305.3**	**100%**

Source: Quantity and copper content of blister copper and slag based on Table 8.2 (Schlesinger et al., 2011). Copper content filter dust based on Table 21.4 (Schlesinger et al., 2011).

Based on this data we arrive at a recovery rate of 97% of copper from copper input to blister copper. 3% of the copper ends up in the slag.

Energy use zinc fuming plant

Table 20 gives an overview of the data that is used to determine the energy use per tonne zinc in copper slag treated in the fuming plant. All information, except for the zinc content in the copper slag was available from (Gusano et al., 2017). The zinc content of the slag is determined based on the known recovery rate of zinc in the fuming process of 85% (Gusano et al., 2017).

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[21] About 5,000 tonne is produced per year. See: MKB- avseende lakverk för F1/K1 stoft mm vid Boliden Rönnskärs industriområde

Table 20 – Data used to determine the energy for zinc fuming at New Boliden, Rönnskär

Input	Minimum energy use	Maximum energy use	Average energy use
Input: Copper slag	290 kt/year 12.2 wt% zinc	300 kt/year 10.9 wt% zinc	295 kt/year 11.6 wt% zinc
Input: Coal	45 kt/year	50 kt/year	47.5 kt/year
Input: WRD oil	1.1 tonne/year	1.1 tonne/year	1.1 tonne/year
Output: Zinc clinker	40 kt/year 75 wt% copper	40 kt/year 70 wt% copper	40 kt/year 72.5 wt% copper

Source: All information except for zinc content in copper slag (Gusano et al., 2017).

Based on this information we can determine that the energy use per tonne of zinc input into the smelter lays between:

- 1.28 and 1.52 tonne coal per tonne zinc input, with an average of 1.39;
- 0.031 and 0.033 kg fuel oil per tonne zinc input, with an average of 0.032.

C Recovery rates at Aurubis, Lünen

Recovery rate zinc to KRS oxide

Table 21 gives an overview of the data that is used to determine the recovery rate of zinc to KRS oxide at Aurubis, Lünen. All information except for the minimum zinc content in slag 2, was available from (Gusano et al., 2017) and (Aachen University).

The Aurubis plant can operate either by producing blister copper from the Isasmelt process (by smelting in two phases) or by smelting one phase in the Isasmelt process and converting in a TBRC furnace afterwards. The zinc content of the second slag coming from either the second stage of the Isasmelt process or from the TBRC furnace differs. We therefore assume a minimum zinc content of 0%.

Table 21 - Data used to determine the recovery rate of zinc at Aurubis, Lünen

Output		Minimum zinc recovery	Maximum zinc recovery	Average
Slag 1	Total quantity	500 kg/tonne input 5.0 wt% Zinc	300 kg/tonne input 2.5 wt% Zinc	400 kg/tonne input 3.75 wt% Zinc
	Zinc quantity	25 kg/tonne input	7.5 kg/tonne input	15 kg/tonne input
Slag 2	Total quantity	200 kg/tonne input 6 wt% zinc	150 kg/tonne input 0 wt% zinc	175 kg/tonne input 3 wt% zinc
	Zinc quantity	12 kg/tonne input	0 kg/tonne input	5 kg/tonne input
KRS oxide	Total quantity	50 kg/tonne input 35 wt% zinc	100 kg/tonne input 50 wt% zinc	75 kg/tonne input 42.50 wt% zinc
	Zinc quantity	17.5 kg/tonne input	50 kg/tonne input	32 kg/tonne input
Blister copper	Total quantity	200 kg/tonne input 0 wt% zinc	300 kg/tonne input 0 wt% zinc	250 kg/tonne input 0 wt% zinc
	Zinc quantity	0 kg/tonne input	0 kg/tonne input	0 kg/tonne input
Total	**Zinc quantity**	**54.5 kg/tonne input**	**57.5 kg/tonne input**	**52 kg/tonne input**

Source: All quantities and zinc content KRS oxide from (Gusano et al., 2017), zinc content of blister copper and slags except for minimum wt% in slag 2 from(Aachen University) (Anonymous, Aachen University).

All zinc that ends up in slag 1 is lost, because the slag is granulated and not further treated for metal recovery. The second slag is being treated in a lead-tin furnace. It is unknown how much of the zinc is recovered from this stream. We therefore assume that 0% at minimum and 100% at maximum is returned to the copper smelter, with an average of 50% recovery rate.

Combined we end up at a zinc recovery between 32 and 87% from input to KRS oxide, with an average of 64%.

Recovery rate of copper to blister copper

For the recovery of copper input to blister copper, we use the same data on quantities as used to determine the recovery rate of zinc. However, we do not take into consideration slag 2, because we assume that all copper is re-looped to the Isasmelt process. Table 22 gives an overview of the data used.

Table 22 – Data used to determine the recovery rate of copper at Aurubis, Lünen

Output		**Minimum copper recovery**	**Maximum zinc recovery**	**Average**
Slag 1	Total quantity	500 kg/tonne input 0.6 wt% copper	300 kg/tonne input 0.4 wt% copper	400 kg/tonne input 0.5 wt% copper
	Copper quantity	3.0 kg/tonne input	1.2 kg/tonne input	2.0 kg/tonne input
KRS oxide	Total quantity	100 kg/tonne input 6 wt% copper	50 kg/tonne input 3 wt% zinc	75 kg/tonne input 4.50 wt% zinc
	Copper quantity	6.0 kg/tonne input	1.5 kg/tonne input	3.4 kg/tonne input
Blister copper	Total quantity	200 kg/tonne input 95 wt% copper	300 kg/tonne input 98 wt% copper	250 kg/tonne input 96.5 wt% copper
	Copper quantity	190.0 kg/tonne input	294.0 kg/tonne input	241.3 kg/tonne input
Total	**Copper quantity**	**199.0 kg/tonne input**	**296.7 kg/tonne input**	**246.6 kg/tonne input**

Source: All quantities and copper content KRS oxide from (Gusano et al.), copper content of blister copper from (Aachen University).

All copper that ends up in slag 1, is lost because the slag is granulated and not further treated for metal recovery. Combined we end up at a copper recovery between 95 and 99% from input to blister, with an average of 98%.