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LCI METHODOLOGY AND DATABASES

Environmental assessment of copper production in Europe: an LCA case study from Sweden conducted using two conventional software-database setups

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Abstract

Purpose This study focuses on the environmental assessment of European copper production. Life cycle assessment is applied to analyse copper cathode production in Sweden, including its mining (an open-pit mine) and refining (pyrometallurgy), and using two combinations of software and databases: SimaPro software with ecoinvent database and GaBi software with GaBi database. The results are compared with results from other case studies from literature.

Methods A cradle-to-gate LCA was conducted considering 1 tonne of copper as functional unit. The inventory for the foreground system was elaborated using primary data gathered by the staff from the mine, the concentrator and the smelter. For the background data, LCA databases are used considering datasets for the Swedish market whenever possible. As the smelter has multiple useful outputs, economic allocation was applied at the inventory level. The calculation method CML-IA baseline 3.5 was considered for both combinations of software and database, reporting all the impact categories of the method plus the Cumulative Energy Demand.

Results and discussion The inventory of the system and the main environmental hotspots were presented, such as the explosives for blasting (due to their supply chain) or the electricity used in the concentrator. The results obtained with the two combinations of LCA software and databases yield large differences for categories such as abiotic depletion (7.5 times higher for SimaPro and ecoinvent), possibly due to differences in the system boundaries of the databases and the characterisation factors of the method. Although the case study has a relatively high cumulative energy demand (140/168 kMJ/tonne Cu) compared to other mines, its performance in global warming (3.5/4.7 tonne CO_2eq/tonne Cu) is much better due to the low greenhouse gas emissions from electricity, which shows that the electricity mix is a key aspect.

Conclusions The environmental performance of mining depends partially on the specific conditions of the deposit, e.g., the ore grade and the mining type. LCA practitioners should consider the potential different results that can be obtained using different combinations of software and database and exert caution when comparing cases, especially for abiotic depletion, human toxicity and ecotoxicity categories. Finally, the use of renewable energies can be key to improve the environmental sustainability of copper production.

Keywords Life cycle assessment · Life cycle analysis · CML-IA · European mining · Raw materials · Copper inventory

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1 Introduction

Mining is a key sector, as it provides materials that are valuable for the green transition of the global economy. In the past decades, the concern about environmental sustainability has grown, becoming also a relevant topic for raw materials extraction. Similar to large companies from other sectors, mining companies started to release environmental performance reports to stakeholders already in the early 1990s (Perez and Sanchez 2009). For instance, the Canadian mining and metals company Noranda started to publish annual reports in 1991 (Noranda Minerals Inc 1991), and by 2002, eight out of the ten large mining companies were publishing annual environmental reports (Jenkins and Yakovleva 2006).

In this context, the mining industry has integrated different methods to assess its activities from an environmental perspective. An example is the risk assessment method, which is a systemic process that includes hazard identification, risk analysis of the hazards and risk estimation (Verma and Chaudhari 2016). There is extensive literature for the application of risk assessment to the mining industry around the world (Shooks et al. 2014; Li et al. 2014; Verma and Chaudhari 2016). Its application has provided valuable information to reduce accidents in mining.

Life cycle assessment (LCA) has been developed over the past decades as a standardised scientific method (ISO 2006a, b) to quantify the environmental burdens at the product and service level, unlike environmental reports or risk assessment, which focused on mining activities and companies. One of the main strengths of the method lies in the comprehensive consideration of different environmental issues along the entire life cycle of the product. The European Commission has enhanced the application of LCA in the framework of the Integrated Product Policy (IPP), publishing comprehensive guidelines for LCA such as the ILCD handbook (European Commission—Joint Research Centre—Institute for Environment and and Sustainability 2010) and the Product Environmental Footprint (PEF) initiative (European Commission 2018).

LCA has been adopted by the mining industry to assist in addressing the environmental impacts of the sector (e.g. Munyongani et al. 2017; Farjana et al. 2019). It must be highlighted that the mining industry does not provide final end-user products, but instead materials that are to be used in products manufactured by downstream sectors. As stakeholders require higher environmental standards and better traceability for such end-user products, the environmental standards of mining and metal production as upstream processes also come into play. For this reason, the demand to apply LCA in the mining sector increases (Alvarenga et al. 2019).

Several LCA studies have been elaborated in the scope of a particular mining product, e.g. copper (Table 1). As can be observed in Table 1, many of these studies were conducted in Australia, but also in Chile, China and Europe. However, the studies from European mines in Norway and Poland all focus on a specific part of the system, i.e. mining/beneficiation and

Table 1 Relevant scientific articles and datasets analysing copper production with life cycle assessment

Author, year	Provides inventory	Impact categories (or life cycle impact assessment method)	Country	System
Norgate et al. (2007)	No	GW, AC, GER, SWB	Australia	P, H
Norgate and Haque (2010)	Yes	GW, GER	Australia	Mining/beneficiation
Norgate and Jahanshahi (2010)	Yes (only energy)	GW, GER	Australia	ISL, P
Memary et al. (2012)	No	GW, AC, POC	Australia	P
Northey et al. (2013)	Yes (energy, water)	GW	Many[a]	Many[a]
Song et al. (2014)	Yes (key parameters)	Eco-indicator99 (all)	China	P
Haque and Norgate (2014)	Yes	GW	Australia	ISL
Kulczycka et al. (2016)	Yes (only energy)	ReCiPe (all)	Poland	P (only smelter)
Moreno-Leiva et al. (2017)	Yes (only energy)	GW	Chile	P, H
Song et al. (2017)	Yes	ReCiPe (all)	Norway	Mining/beneficiation
Hong et al. (2018)	Yes	ReCiPe (all)	China	H
ecoinvent	Yes		Many[b]	Many[b]
GaBi	No		Many[b]	Many[b]

AC acidification, *GER* gross energy requirement, *GW* global warming, *H* hydrometallurgical copper production, *ISL* in situ leaching, *P* pyrometallurgical copper production, *POC* photochemical ozone creation, *SWB* solid waste burden

[a]Based on many case studies, using data from their environmental reporting

[b]Provides datasets for different regions of the World (e.g., Europe) based on average data

smelting, respectively. Therefore, no scientific article was found presenting a comprehensive LCA study of copper production in Europe. There are datasets for copper production available in LCA databases such as ecoinvent (Table 1), which provides average data for the production of copper in Europe and GaBi, which includes a dataset for the production of copper in Sweden, but it focuses only on the smelter. Moreover, there is a lack of a comprehensive inventory for pyrometallurgical copper production, as the articles available for pyrometallurgy provide the environmental impacts without an inventory or only for some key features of the inventory such as energy. Finally, it can be observed that many of these studies only analyse one or a few environmental impact categories, being global warming and gross energy requirement (or cumulative energy demand) the most commonly used categories.

Regarding the application of LCA, previous studies analysing various systems with LCA show that using different databases to model background processes can result in substantially different impacts (Peereboom et al. 1998; da Silva et al. 2007; Werner and Frischknecht 2018). Similarly, using one or another software can influence the results, as some characterization factors from the same method can be different between software or for characterization factors are added by the software developers (Turconi et al. 2011; Herrmann and Moltesen 2015; Speck et al. 2016). In this sense, it seems interesting to develop an LCA study using different combinations of software and databases, to address this uncertainty. Moreover, it can provide interesting insights on the influence of the software and the database selected when a complex system (copper cathode production) is analysed.

Considering the information stated above, analysing a comprehensive case study of copper production in Europe can provide useful insights on both the mining, beneficiation and processing of copper cathode but also on the potential differences in the results of an LCA conducted with different combinations of tools and databases.

The main objective of this study is to assess the environmental performance of pyrometallurgical copper cathode production in Europe, in Sweden, including its mining and refining, applying LCA with two different combinations of software and databases (for background data), and compare the results with other similar case studies reported in the scientific literature. The specific aims are:

- To provide a detailed inventory of a comprehensive case study of copper cathode production (including mining, beneficiation and processing) in Sweden
- To assess the environmental impacts of copper cathode production with LCA using (i) Simapro software and ecoinvent database and (ii) GaBi software and GaBi database (the databases are only used for background data)
- To analyse the differences between the LCA results with the two combinations of software and databases performed
- To compare the results obtained at the inventory and environmental impact level with previous literature

2 Methods

2.1 Description of the case study

The study applies LCA to the production of copper cathode with 99.99% purity (hereafter just copper for the sake of simplicity) by Boliden Mineral AB in Sweden. A cradle-to-gate LCA is conducted as the focus is on copper, and the use phase and the end of life phase vary greatly depending on the specific product in which copper is used for. The system under assessment takes place in two locations: (1) mining and mineral processing (concentrator) activities at Aitik (Gällivare, Sweden) and (2) smelting and refining activities at Rönnskärsverken (Skellefteå, Sweden). At the Aitik open-pit mine, copper ore is extracted. The flow diagram of the process system is shown in Fig. 1.

Firstly, the ore is mined in horizontal slices, and heavy trucks haul ore and waste rock on ramps. Rock crushers are used for ore crushing before it is transported by a conveyor belt up from the mine to the concentrator plant. Secondly, in the concentrator, the ore containing copper and subsidiary metals is milled to produce sand with a grain size smaller than 250 µm. The sand is then carried to open stirred tanks to which chemicals are added and air is injected, causing the ore minerals to float up and forming a froth on the surface (flotation). Tailings sand (depleted in ore minerals) is collected on the bottom of the tank. The mineral froth in the tanks is gathered up and dewatered, obtaining the copper concentrate (25% Cu). The concentrate is then transported by train to the smelter (Rönnskärsverken, Skellefteå, Sweden), 410 km from Aitik.

The smelter in Rönnskärsverken processes various metals such as copper, zinc, lead, gold and silver; including primary concentrates from various mines, as well as secondary (recycled electronic wastes) materials from the recycling of copper and precious metals. Thus, different co-products other than copper are obtained from this plant, which requires the application of allocation procedures to define the share of the environmental impacts generated by the production of copper using copper ore from Aitik. The primary copper concentrate is subjected firstly to a drying process followed by pyrophoric smelting in the flash unit, which uses oxygen-enriched air. In the flash oven, an upper layer of slag is formed, with the lower phase (matte) containing 55–70 wt.% Cu and a range of other metals such as Fe, Zn, Au, Ag, Ni,

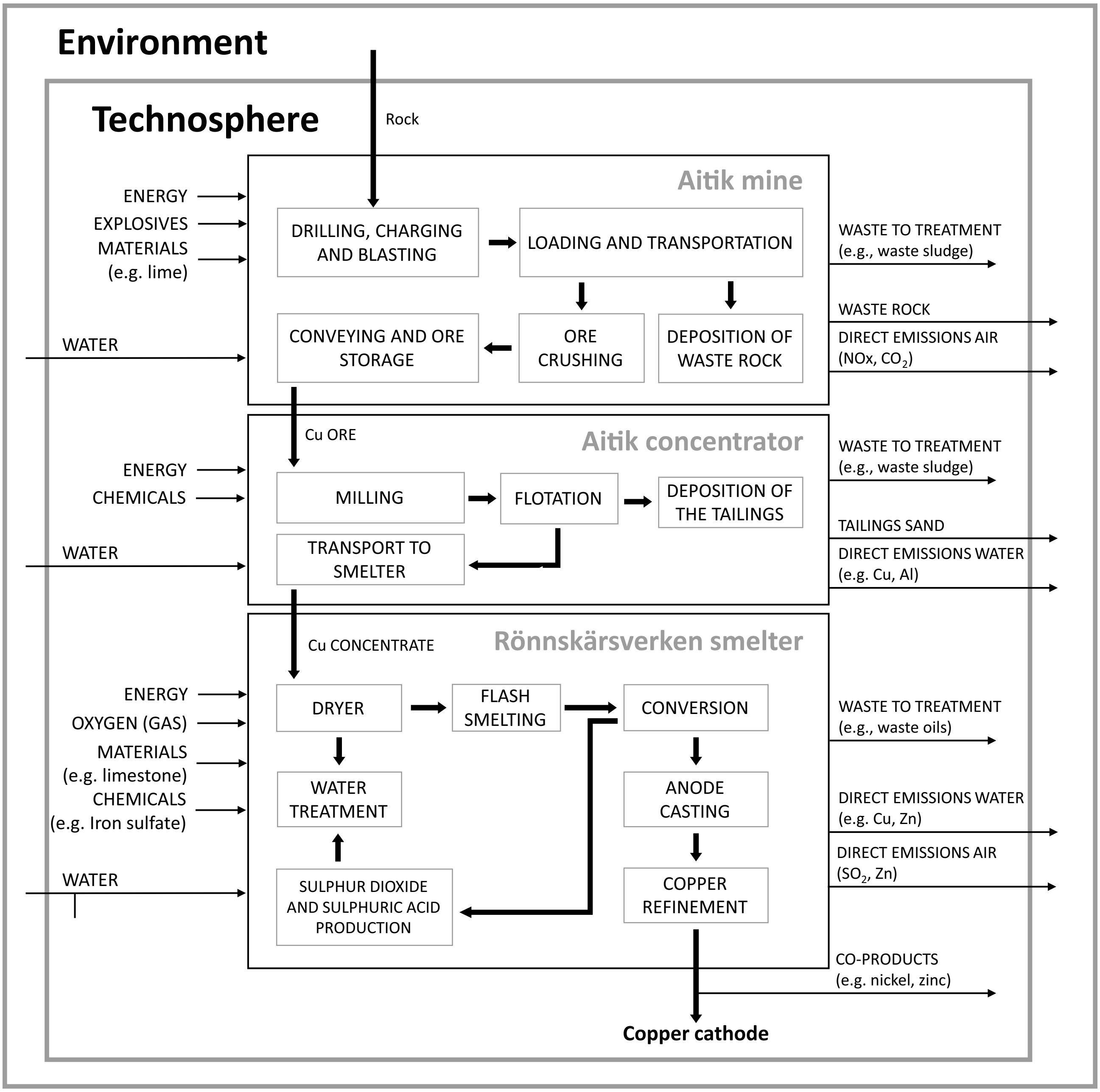

Fig. 1 Flow diagram of the copper production system showing the Aitik operation, including the Rönnskär smelter. Only primary processes that are relevant for copper are shown. Boxes represent processes, thick arrows represent copper flows and flows within the system, thin arrows represent inputs and outputs to and from the system, large rectangles represent the boundaries of the subsystems, the Technosphere and the environment

Se and Pt. This matte phase is transported to a converter unit while the flash slag is recycled back to the concentrator plant in Boliden, Sweden, for further milling and flotation. The exhaust gas from the flash step is used to produce sulphuric acid and sulphur dioxide, which are co-products from the system.

In the converter, the matte is enriched from approximately 60 to 97 wt.% Cu content, which requires the addition of slag forming agent (SiO_2) and air. This process is conducted batch-wise in cycles of 8 h. The enriched copper is then transported to the electrolysis unit, where it first goes through the anode casting and then to electrolysis resulting in copper with a purity of 99.99 wt.% Cu. The electrolyte is thereby purified from Sb, Zn, Au, Ag, Ni and Bi contamination. These metals form a sludge that is recycled. The anode forms a Cu sludge which is removed and sent to the precious metals' unit for extraction of metals and other components, such as Au, Ag, Pd and Se, which are co-products from the system.

2.2 Life cycle inventory

The inventory analysis was conducted using primary data from the mine and the concentrator at Aitik and the smelter at Rönnskärsverken, which was gathered by the staff from Boliden Mineral AB. All the data for the inventory is based on operation data from 2015, and all the quantities were scaled to the functional unit (1 tonne of copper). The resulting foreground inventory can be found in Supplementary Information A and B presenting the unit process data for Boliden in Sweden. Regarding the energy flows in the inventory, diesel and gasoline are combusted in trucks and cars, respectively, within the mine. Datasets from background LCA databases are considered taking into account the amount of fuel burnt in the mine.

For the background system, data from LCA databases were used considering average values for Sweden whenever possible and the closest option if this was not possible (e.g., average for the European market). For ecoinvent, datasets are available for nearly all the flows in the inventory, except for the gaseous oxygen (injected in the smelter). For GaBi database, a dataset could be found for most of the relevant flows in the system. As a rough estimation of the completeness, the mass processes (emissions, waste outputs and mass inputs) that are included represent 99.8% of the total for the GaBi approach and 95.1% for ecoinvent. From an environmental impact perspective, the flows excluded in the GaBi modelling account for between 0.1 and 0.7% for the impacts assessed following the SimaPro and ecoinvent approach (for which the related datasets are available). Similarly, the oxygen excluded with SimaPro and ecoinvent accounts for between 0.7 and 2% in GaBi. Thus, the flows for which no corresponding dataset is included in the LCA databases are considered negligible and are not accounted for in the study. However, it must be highlighted that for some waste treatment processes, the same generic dataset was used due to the lack of specific datasets that would suit each of the processes better.

Within the smelter, the flows of the inventory were classified in three categories in accordance with the subprocesses they were linked to: (1) flows that belong to subprocesses related to copper (but also to other co-products), (2) flows that are only related to other co-products (but not copper) and (3) other flows that could not be assigned to any particular co-product (generic flows). For the first and the third categories, economic allocation is applied considering the amount of the valuable outputs from the process and their price. Economic allocation is used (only for the smelter) since it is considered more appropriate for downstream processes of the mining sector such as smelting or refining, in accordance with previous literature (Santero and Hendry 2016). Note that the same amount of copper produced is considered in categories (1) and (3), but the allocation in (1) was done considering copper and some other co-products whereas for (3), all the co-products from the system were considered for the allocation. The details of the economic allocation conducted can be found in Supplementary Information C for more information on this regard. The allocation was applied to all the flows at the inventory level and the flows in the inventory for the smelter, provided in Supplementary Information B.

In order to address the uncertainty of the study, the pedigree matrix (Weidema and Wesnæs 1996) has been applied to the inventory (see Supplementary information A and B). It must be highlighted that the uncertainty of the study is low because all the information was provided by the company, achieving the highest score (1 out of 5) in all fields except for temporal correlation (2 out of 5). As most articles in the field do not address uncertainty, it is not possible to take it into account for the comparisons. This is a recognised weakness of the study, because the influence of uncertainty is unknown.

Table 2 Comparison of the two combinations of LCA software and databases used to assess the production of copper by Boliden Mineral AB in Sweden. *CED* cumulative energy demand

	GaBi	SimaPro
Functional unit	1 tonne Cu cathode	1 tonne Cu cathode
Software	GaBi ts 9.2	SimaPro 9.0
Database	GaBi database SP39 (and other data-on-demand)	ecoinvent 3.5 (system model: cut-off, by classification)
Method/impact categories	CML-IA baseline 3.05 (all categories) and CED	CML-IA baseline 3.05 (all categories) and CED
Allocation at smelter	Economic	Economic

2.3 LCA Software, databases and LCIA methods

Regarding the software and the database used, this study analyses the results of assessing the studied system using the two most common combinations of LCA software and database (Silva et al. 2019). Table 2 summarises the relevant features of each assessment. The calculation method CML-IA baseline 3.05 is considered, including all the impact categories. However, the impact category Stratospheric Ozone Layer Depletion is left out of the assessment as the results obtained for GaBi are inconsistent, presenting substantial differences in the orders of magnitude for the components of the system, which were not the results from SimaPro and ecoinvent. Moreover, the impact category Cumulative Energy Demand is included, as energy is relevant for the system and this impact category has been included in most of the previous studies (allowing for comparison). The functional unit selected for the assessment is 1 tonne of copper cathode with 99.99% purity (hereinafter called just copper for simplicity), as this will ease the comparison with other case studies from the literature. Most of the articles considered for comparison do not mention the purity of the copper produced, but the one that mentions it (Moreno-Leiva et al. 2017) holds the same purity as this study (99.99%). Therefore, an assumption was made that all the case studies compared have a purity of 99.99% in the final product.

The system model selected for ecoinvent, i.e., "cut-off, by classification" (used in this article) or "allocation at point of substitution" can also affect the results of the study. The former system model gives no credits to the waste producer for recycling the waste and therefore the recycled material only has the impacts of the recycling process. In contrast, the allocation at point of substitution attributes the benefits from recycling materials to the market processes that provide the secondary materials (Ecoinvent 2021). An assessment is performed considering the most relevant ecoinvent datasets to analyse the influence of using one or another option. The results of this assessment (presented in Supplementary Information E) reveal that changing the system model has a small influence in the results. The dataset for the explosives used in the mine is the only one that has a substantial variation only for the impact categories Abiotic Depletion and Terrestrial Ecotoxicity. However, even considering these variations, the results remain in the same line (still similar differences are found when comparing with GaBi software and database).

The data that support the findings of this study (datasets from GaBi and ecoinvent databases) are available through the vendors of these databases, but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available.

3 Results and discussion

3.1 Analysis of the foreground inventory for copper production and comparison with other cases from literature

The inventory elaborated for the assessment of copper production by Boliden Mineral AB can be found in Supplementary Information A and B. This inventory provides all the information regarding the case study, including the quantities for all the flows in the mine, the concentrator and the smelter as well as the datasets from ecoinvent and GaBi database used for the application of the LCA. Regarding the energy demand in the system, most of the electricity is used in the concentrator at Aitik (78% of the total electricity demand) whereas most of the fossil fuels (more than 99%) are diesel used in the trucks within the mine. Actually, the waste rock in the mine represents the largest flow in the system. The direct impact of these rocks to the environment is considered irrelevant, but its required transportation generates a substantial demand in fossil fuels (the diesel being combusted in the trucks). Other important flows in terms of mass in the mine are the explosives used for the blasting, the waste the lime used and the sludge generated. Regarding the latter, a part of the run-off water from the industrial area and the waste rock dump is acidic and contains heavy metals. The acidic water is therefore treated with slaked lime for pH-adjustment that forms sludge. The sludge is a mixture of gypsum, metal hydroxides plus sulphates and is mixed with the tailings. For the smelter, the gaseous oxygen injected in the furnace and the sand used as a slag-forming agent are the most relevant flows.

Table 3 presents a comparison of key flows of the inventory with the same flows from other case studies from the literature. As can be observed, there are substantial differences depending on aspects such as the ore grade, the mining type and the type of processing. The ore grade of a mine differs depending on the geology, i.e. the deposit type and the specific geological setting. For instance, porphyry copper deposits such as Aitik have, on average, lower ore grades than e.g. volcanic-hosted massive sulphide (VHMS) deposits (Rötzer and Schmidt 2018). A lower ore grade requires extraction of higher quantities of rock to produce the same amount of metal. For this reason, the quantity of ore extracted at Aitik is relatively large, due to the low ore grade in the mine, even compared with other porphyry copper deposits elsewhere (e.g. Wanhainen et al. 2012).

Moreover, the use of a large quantity of explosives is necessary due to the type of mining. It can also be observed that pyrometallurgy copper production requires oxygen, which is used in the smelter as described in "Sect. 2.1". The energy consumption also varies greatly. The ore grade is a key variable influencing energy consumption in mining and

Table 3 Comparison of the unit process data of the foreground system for 1 tonne of copper (functional unit) from this study and by other cases reported in literature

Parameter	This study		Song et al. (2014)		Song et al. (2014)		Hong et al. (2018)		Haque and Norgate (2014)	
COUNTRY	*Sweden*		*China*		*China*		*China*		*Australia*	
Ore grade (% Cu)	*0.18*		*0.81*		*1.02*		*0.8*		*0.1*	
Mining type	*OP*		*UM*		*UM*		*NS*		*ISL*	
Process	*P*		*P*		*P*		*H*		*ISL*	
Feedstock (ore) (kg)	*540,000*		*128,977*		*106,064*		*125,000*		-	
Energy										
Electricity (MJ)	47,432	75%	15,740	40%	19,330	47%	4,307	36%	10,087	100%
Diesel (MJ)	14,409	23%	11,743	30%	9,657	23%	283	2%	44	0%
Heavy fuel oil (MJ)	1,350	2%	9,886	25%	1,869	5%	0	0%	0	0%
Coal (MJ)	0	0%	1,987	5%	10,454	25%	2	0%	0	0%
Coke (MJ)	0	0%	0	0%	0	0%	7223	61%	0	0%
Total energy (MJ)	63,192	100%	39,356	100%	41,311	100%	11,817	100%	10,131	100%
Auxiliary materials										
Explosives (kg)	375.3		0.0		0.0		0.3		0.0	
Lime (kg)	126.1		0.0		0.0		0.0		126.0	
Limestone (kg)	15.9		0.0		109.4		110.0		0.0	
Sand (kg)	255.8		574.6		1,092.1		400.0		0.0	
Oxygen (kg)	705.3		1,007.4		1,469.4		0.0		0.0	
Sulphuric acid (kg)	0.0		9.9		6.8		12.3		9,000.0	
Hydrochloric acid (kg)	0.1		0.0		0.0		1.7		0.0	
Emissions to air										
CO_2 (kg)	1,050.4*		2,092.3		2,203.6		398.2		NS	
SO_2 (kg)	12.9*		75.5		63.8		0.6		NS	

NS not specified, *OP* open-pit, *UM* underground mining, *H* hydrometallurgical copper production, *P* pyrometallurgical copper production, *ISL* in situ leaching

*Includes direct emissions from diesel and fuel oil burning (from the databases) and the smelter

beneficiation, as lower grades require more energy to mine and concentrate the copper. This has been proven in previous studies, which have found a clear negative correlation between the ore grade and the energy demand of mining (Memary et al. 2012; Moreno-Leiva et al. 2017). The type of mining and the process are also key to understand the energy consumption. For instance, open-pit mining requires the transportation of materials (copper ore or rocks) within the mine. In contrast, in situ leaching only requires the pumping of the solution through the ore, avoiding the transportation of copper ore and rocks and avoiding also the concentration of copper. For this reason, in situ leaching has the least requirements since only the energy for the pumping of the solution is required (without mining or concentration). Regarding the materials used, pyrometallurgy uses more slag-forming agents (e.g. sand, lime; see "Sect. 2.1"), whereas in situ leaching uses a substantial amount of sulphuric acid. The CO_2 and SO_2 emissions to air are lower in the study of Hong et al. (2018), probably due to the type of mining conducted (not specified in the article).

3.2 Environmental impacts of copper production

The absolute environmental impacts from the system can be observed in Table 4 and Fig. 2. The impacts using the SimaPro software with the ecoinvent database and the GaBi software and database are shown, as well as the ratio comparing both. As can be observed, the differences found between the combination of software and databases are substantial, particularly for Abiotic Depletion, but also for Human Toxicity and Ecotoxicity impact categories. The smallest differences are found for Photochemical Oxidation and Cumulative Energy Demand, followed by Abiotic Depletion (Fossil Fuels), Global Warming and Acidification. Indeed, Cumulative Energy Demand is a straightforward impact category in terms of modelling as it simply accounts for all the energy used through the life cycle of the system. The environmental impacts are higher for SimaPro and ecoinvent for all impact categories except for Terrestrial Ecotoxicity, for which GaBi showed a higher impact. This might indicate that there is a systematic difference between the two options that results in SimaPro and ecoinvent

Table 4 Comparison of the absolute environmental impacts for 1 tonne of copper (functional unit), applying LCA with SimaPro software and ecoinvent database (SS&ED) and GaBi software and databases (GS&GD). The highest value has been underlined for each impact category

Impact category	Unit	SS&ED	GS&GD	Ratio (highest/lowest)
Abiotic depletion	kg Sb eq	<u>1.56E−02</u>	2.09E−03	7.49
Abiotic depletion (fossil fuels)	MJ	<u>5.13E+04</u>	3.99E+04	1.28
Global warming	kg CO_2 eq	<u>4.75E+03</u>	3.51E+03	1.35
Human toxicity	kg 1,4-DB eq	<u>1.54E+03</u>	5.52E+02	2.79
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	<u>6.98E+01</u>	3.45E+01	2.02
Marine aquatic ecotoxicity	kg 1,4-DB eq	<u>1.65E+06</u>	5.77E+05	2.85
Terrestrial ecotoxicity	kg 1,4-DB eq	9.53E+00	<u>1.55E+01</u>	1.63
Photochemical oxidation	kg C_2H_4 eq	<u>1.45E+00</u>	1.21E+00	1.19
Acidification	kg SO_2 eq	<u>3.21E+01</u>	2.32E+01	1.38
Eutrophication	kg PO_4-- eq	<u>3.86E+00</u>	2.72E+00	1.42
Cumulative energy demand	MJ	<u>1.68E+05</u>	1.40E+05	1.20

providing relatively higher impacts. These differences are in line with differences found in other studies. Lasvaux et al. (2015) analysed the environmental impacts of 28 construction materials from different databases. On average, Global Warming, Cumulative Energy Demand and Abiotic Depletion (Fossil Fuels) showed a difference between 26 and 34%, whereas Acidification, Abiotic Depletion and Photochemical Oxidation showed differences of 62, 212 and 347% on average, respectively. Another study from Takano et al. (2014) also found that for simple systems, using different databases for the assessment leads to differences of up to 33% in the results in Global Warming (using the same calculation method as in this study). It must be highlighted that these two articles address individual materials or simple systems, whereas the current article focuses on a complex system which can result in larger uncertainties. As most products in the economy are the result of complex systems and many LCA practitioners need to analyse them, it is of interest to provide information on the potential differences of using different combinations of software and databases for LCA. In this sense, a similar approach to the one in this study was adopted by Turconi et al. (2011), who assessed waste incineration using SimaPro software and ecoinvent database on one hand and EASTECH software and various databases on the other hand. Although the differences found for Global Warming, Acidification and Photochemical Oxidation in this article are relatively low, substantial differences are only found for toxicity categories, in line with this study.

Figure 3 shows the relative contribution of the different components of the system to the environmental impacts, but a table with the absolute impacts obtained can be found in Supplementary Information D. For Abiotic Depletion (Fossil Fuel), Global Warming and Eutrophication, the results are quite consistent, showing a similar distribution of the impacts among the components. A considerable contribution comes from the transportation of ore with trucks within the mine, particularly due to the impacts along its supply chain of diesel and its emissions when it is combusted. Another substantial contributor are the explosives used in the mine, mostly due to the production of nitric acid and ammonia in

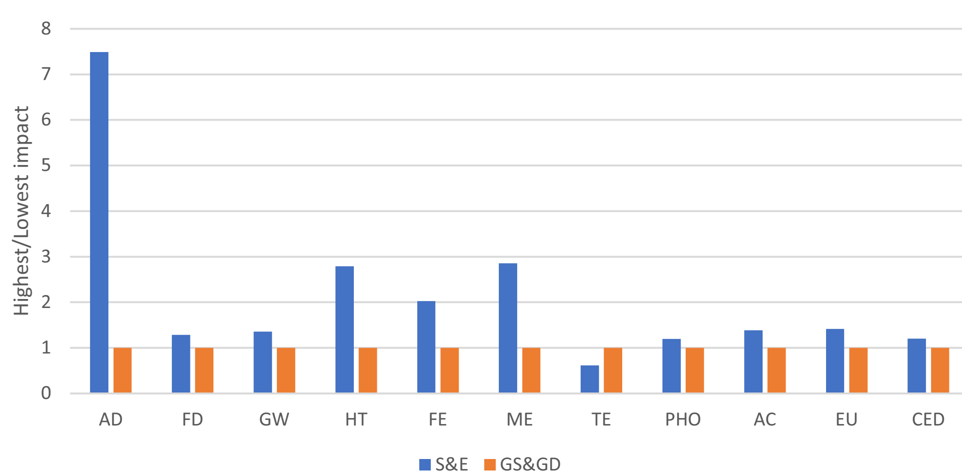

Fig. 2 Comparison of the relative environmental impacts for 1 tonne of copper (functional unit), applying LCA with SimaPro software and ecoinvent database (S&E) and GaBi software and databases (GS&GD). AD abiotic depletion; FD fossil depletion; GW global warming; HT human toxicity; FE freshwater eutrophication; ME marine eutrophication; TE terrestrial eutrophication; PHO photochemical oxidation; AC acidification; EU eutrophication, CED cumulative energy demand

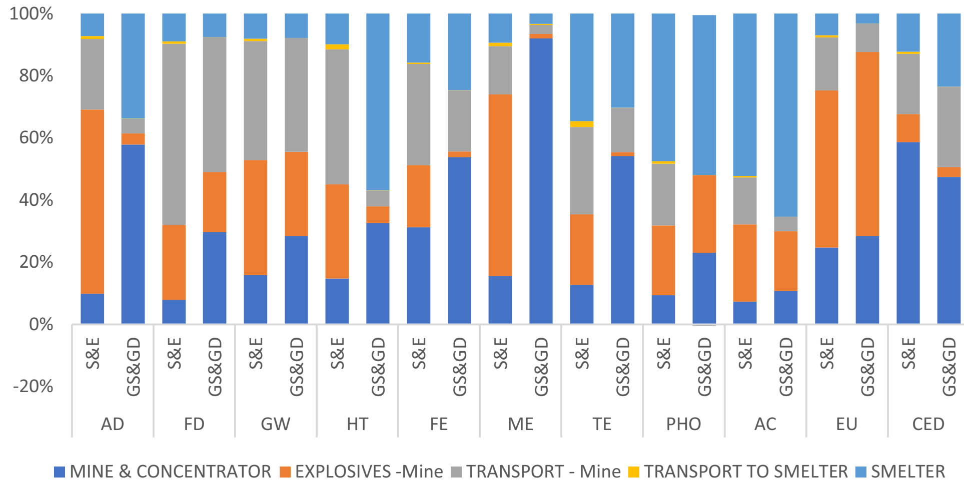

Fig. 3 Comparison of the contribution of different elements of the life cycle to the environmental impacts of copper production using SimaPro software and ecoinvent database (S&E) and GaBi software and databases (GS&GD) for the assessment. AD abiotic depletion; FD fossil depletion; GW global warming; HT human toxicity; FE freshwater eutrophication; ME marine eutrophication; TE terrestrial eutrophication; PHO photochemical oxidation; AC acidification; EU eutrophication, CED cumulative energy demand

their supply chain, which release emissions such as carbon dioxide, nitrous oxide, sulphur oxides, nitrogen oxides and ammonia. The transportation with trucks within the mine and the explosives together account for between 63 and 82% of the impacts in the previously mentioned categories. Similarly, the Cumulative Energy Demand presents very consistent results, being the main contributor to the impacts the electricity used in the concentrator. Note that the distribution of these impacts is very different from those in Global Warming. The reason for this is that the Swedish national electricity mix relies heavily on hydropower and nuclear energy and thus has relatively low contribution to Global Warming. This point will be further discussed in “Comparison of the environmental impacts of copper production”. The results for Photochemical Ozone Formation and Acidification are also quite similar in the two software-database combinations, being the most relevant contribution to the environmental impacts the sulphur dioxide emissions generated at the smelter, followed by the explosives used for mining.

Substantial differences were found in the distribution of the impacts of the two options for various impact categories (especially toxicity ones). In general, the relative contribution of the explosives and the transportation within the mine has a relatively higher contribution in SimaPro and ecoinvent, whereas the electricity used in the concentrator and the emissions from the smelter have a relatively higher contribution in GaBi, but in all cases, SimaPro and ecoinvent show higher environmental impacts (between 63 and 185% higher). Most of these differences originated from the databases considered, as observed in previous literature. For instance, in the GaBi database, the credits from recycling are accounted for, and the avoided impacts are subtracted if necessary. This is not the case in ecoinvent, which leads to higher impacts in end of life processes (e.g., the recycling of steel in the smelter in Human Toxicity) and other processes that have credits from end of life treatments within their supply chain (e.g., use of truck for the transportation of ore in the mines). Therefore, approaching differently the allocation of recycling is one of the factors that can generate differences in the results. Another factor that might be key in this regard is how the system boundaries are established in each database. For instance, the national electricity mix that is used in ecoinvent includes the electricity imported to the country, whereas in GaBi, imports of electricity are not considered. As Sweden imports electricity from Denmark, which is partially based on hard coal, this has a certain influence in the environmental impacts for the categories of Acidification and Eutrophication to a lower extent. Moreover, there might be differences in the consideration of the upstream impacts of the processes, i.e. the impacts in the supply chain of a product, in the databases considered. Whereas ecoinvent does include the impacts of, for instance, the infrastructure for the manufacturing of chemicals, it is not clear if this type of impacts is included in GaBi, as insufficient information is provided and the datasets are aggregated.

Finally, a key question remaining is how much of the difference between one and another combination of software and databases comes from differences in the datasets and from differences in the application of the calculation method. Whereas it is difficult to dig into the databases, the characterisation factors implemented are available both in GaBi and SimaPro. The characterisation factors that contributed the most to the calculation of the environmental impacts were analysed against the original CML-IA method (Van Oers 2015) searching for differences. The results show that some characterisation factors are different in the adapted version within the software. However, this does not influence the results in most impact categories, with the exception of Abiotic Depletion. Indeed, the distribution of the environmental impacts between the elements of the system is completely different for the two options in this impact category. In general, the coupling between the LCI and the characterisation factors in the impact assessment sometimes can go wrong due to different names and/or CAS numbers. Moreover, the CML-IA provides characterisation factors for specific substances, whereas some emissions in the LCI are for substance groups (e.g. NOx, non-methane organic volatile compounds), and different software addresses these substance groups differently (e.g. using a weighted average of the original characterisation factors). This can result in differences in the results from the application of the calculation method. In this particular case, one of the characterisation factors that are modified in GaBi (sodium chloride, rock salt) has a considerable influence on the results, generating most of the impacts. The characterisation factors for Abiotic Depletion are only provided for elements in the original method, but for sodium chloride, GaBi provides an extra characterisation factor.

Similarly to Abiotic Depletion, the results for the impact category Stratospheric Ozone Depletion are completely different. For GaBi, the impacts for the different components of the system have different orders of magnitude, being the overall impact orders of magnitude smaller than for SimaPro and ecoinvent. As mentioned above, the results for Stratospheric Ozone Depletion are not included in the article due to their inconsistency.

3.3 Comparison of the environmental impacts of copper production

The comparison of the environmental impacts from copper production across different studies is difficult, as the impact categories displayed vary from one article to the other. However, Global Warming and Cumulative Energy Demand are used in many of the articles assessing copper production. Table 5 compares the results for these two categories found in this article with those reported in the literature. These results should be interpreted with caution, as not all the details about the case studies are provided in the articles: there might be other factors affecting these environmental impacts which might not be taken into account.

As explained in “Analysis of the foreground inventory for copper production and comparison with other cases from literature”, the three major factors affecting Global Warming and Cumulative Energy Demand are the ore grade, the mining type and the (national) electricity mix. Note that, unlike what might be expected, the impacts are very different for Global Warming and Cumulative Energy Demand due to the different electricity mixes of the countries. This is due to the carbon intensity of the (national) electricity mix: mines using electricity generated with fossil fuels, and coal in particular, can perform worse in Global Warming in spite of being relatively low in terms of energy consumption, e.g. due to relatively high ore grades. This is the case of the copper production from Aitik, which is analysed in this study. The energy consumption in this case is the highest among all the cases presented in Table 5, which can be explained with the lower ore grade, as more material must be managed, but also because it operates through open-pit mining, which might be more energy consuming than, e.g. in situ leaching, as materials must be transported with trucks within the mine. However, the electricity mix from Sweden (this study) relies heavily on hydropower and nuclear energy, which implies lower carbon emissions. This means that the upstream emissions from the concentrator and the smelter are relatively low. Moreover, the trucks that transport material within the mine use diesel which, in spite of being a fossil fuel, is not as polluting as, e.g. coal. In contrast, the electricity mix from Australia (Norgate et al. 2007; Haque and Norgate 2014) uses mainly coal (nearly 80% of

Table 5 Comparison of the impacts for global warming (GW) and cumulative energy demand (CED) from 1 tonne of copper production for this study and for studies from literature

Authors, year	*Country*	*Ore grade (% Cu)*	*Mining type*	*Process*	GW (kg CO_2 eq)	CED (MJ)
Norgate et al. (2007)	*Australia*	*2*	*NS*	*H*	**6200**	**64,000**
Moreno-Leiva et al. (2017)	*Chile*	*0.71*	*NS*	*P*	**6000**	**NS**
Moreno-Leiva et al. (2017)	*Chile*	*0.71*	*NS*	*H*	**4900**	**NS**
Haque and Norgate (2014)	*Australia*	*0.1*	*ISL*	*ISL*	**4780**	**61,000**
This study — S&E	*Sweden*	*0.18*	*OP*	*P*	**4750**	**168,000**
This study — GaBi	*Sweden*	*0.18*	*OP*	*P*	**3510**	**140,000**
Norgate et al. (2007)	*Australia*	*3*	*NS*	*P*	**3300**	**33,000**
Hong et al. (2018)	*China*	*1.02*	*NS*	*H*	**1910**	**NS**
Ecoinvent	*Europe*	*	*	*	**1637**	**29,811**

S&E Simapro software and ecoinvent database; *NS* not specified; *OP* open-pit; *H* hydrometallurgical copper production; *P* pyrometallurgical copper production; *ISL* in situ leaching

*No data

the mix) and thus, the electricity used in these case studies has a much higher contribution to Global Warming. Therefore, although the cases of copper production using in situ leaching and hydrometallurgy require much less energy than the case presented in this study, the carbon emissions from copper end up being higher. The emissions during the generation of the electricity to be used in the mine are a key contribution to the (upstream) environmental impacts of copper as a product.

4 Conclusions

This article provides a case study of the environmental assessment of copper production with an open-pit mine with pyrometallurgical refining in Europe. Firstly, the study provides a comprehensive foreground inventory of the system. Secondly, LCA is applied using the two most common combinations of LCA software and databases, i.e., SimaPro and ecoinvent and GaBi software and databases.

The flows of materials, energy and emissions linked to the production of copper are in part defined by the geological features of the copper deposit. The ore grade is negatively correlated with the amount of energy required to obtain the copper concentrate (Memary et al. 2012; Moreno-Leiva et al. 2017), and there are other factors affecting it (e.g. depth of a mine/deposit). Moreover, the type of mining influences greatly the flows in the inventory. For instance, the case study presented is an open-pit mine, which may imply the use of explosives and the transport of substantial amounts of rock with trucks within the mine. The type of refining process is also an important point; in this case study, pyrometallurgy requires gaseous oxygen and more slag-forming agents like sand and lime, whereas hydrometallurgy uses more chemicals such as sulphuric acid. However, these features are usually not a choice, especially in the context of an increasing global demand for copper which implies the increasing necessity to mine deposits with lower ore grades. Therefore, the environmental improvement of the copper production on a local level is partially limited by the geological and geometallurgical conditions of the ore deposit.

The contribution of the different components of the system to the environmental impacts varies depending on the impact category, but the main environmental hotspots identified are the energy consumption, including the electricity used in the concentrator and the diesel used for transportation with trucks within the mine, and the use of explosives for blasting due to their supply chain. Future improvements to reduce these environmental impacts might include a change in the electricity mix towards a higher share of renewables, use of electric vehicles to reduce the demand for diesel and a better environmental performance of the supply chain of explosives.

The environmental impacts show variations depending on the combination of software and databases used, being higher for most impact categories if SimaPro and ecoinvent are used compared to GaBi. The largest differences are found for Abiotic Depletion, Human Toxicity and Ecotoxicity categories. These variations might be due to differences in the databases used, such as the consideration of credits from recycling (environmental impacts that are considered to be avoided due to the substitution of virgin material by recycled material) or in the system boundaries (considering or not electricity imports and upstream impacts). Moreover, the coupling of the LCI and the characterisation factors might go wrong due to different names and/or CAS numbers, differences between emissions for specific substances and groups of substances (e.g., NOx) and additional characterisation factors provided in the software (e.g. for NaCl). At the user level, LCA practitioners should be aware of these differences and exert caution in the result interpretation, particularly when comparing case studies that have used different combinations of software and databases. Moreover, these results show the importance of harmonising LCA software and databases and to separate as much as possible method choices such as allocation from (measured) data to improve the comparability among them and enhance the transparency and the consistency of LCA results. Vendors of LCA software and databases should clearly communicate the current limitations of their products, so that practitioners can properly deal with the variations that can take place.

Finally, the comparison between the environmental impacts of studies addressing copper production is limited to Global Warming and Cumulative Energy Demand, as most studies focus only on these categories. Future studies may include more impact categories to allow comparison. An important finding of the present study is that the Cumulative Energy Demand does not hold a correlation with Global Warming for copper production since the electricity mix depends largely on the host country of the mine. This is particularly illustrated by the case study presented, which has the highest energy demand of all the cases compared due to the low ore grade and the type of mining (open-pit), but its performance in Global Warming is relatively good due to the low carbon intensity of the electricity used. Therefore, a greener electricity mix can contribute to reduce substantially the carbon footprint of copper, which is in line with the findings from previous studies analysing the use of photovoltaic cells for copper production in Chile (Moreno-Leiva et al. 2017).

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