STUDY N° 2018-01

ENVIRONMENTAL IMPACTS OF MINING ACTIVITIES FOR SOME RAW MATERIALS

EXECUTIVE SUMMARY

October 2020

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SCORE LCA is an association that has been created to financially support collaborative research on LCA and related topics. It aims to promote and organize cooperation between companies, institutional and scientists in order to support the evolution of LCA methods and its practical implementation at European and international level.

✓ This work has been supported by ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie) www.ademe.fr

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1. Introduction

Mining activities are an essential business segment to the current society, and provide raw materials for numerous industries spearheading most of the goods that are daily used (Carvalho, 2017). Even if mines are not threatened in a near future (Elshkaki et al., 2018), this industry can cause serious damages on the environment, impacting landscapes but also water resources and air quality. On a global scale, the mining sector currently represents 2.7% of energy consumption, contributing at the same time to greenhouse gases (GHG) emissions (IPCC, 2007). To satisfy the 21st century consumptive bustle, the raw materials demand is constantly increasing, whereas because of a lack of anticipation of the exploration, quality and content of ore deposits are logically declining.

The analysis of the mining sector can lead to misreading, in particular concerning importation, manufacturing, obsolescence of reserves and mining prospective (reserves or resources). Furthermore, there are many databases used by LCA experts, identifying a wide range of raw materials coming from mines exploitation and the environmental impacts associated with this exploitation. This data can have a considerable influence on the final results of the LCA of a product or service and must be consequently updated regularly, in particular concerning the extraction techniques, processes and other evolution related to the mining sector. Indeed, the quality of an LCA highly depends on the availability and quality of the data used during its achievement (Jolliet et al., 2010).

The objective of the study is then to check how and to what extent the complex framework of mining activities is represented in the currently available LCA databases (according to Table 1) and if it exists complementary information to overcome the identified limitations. The LCA databases analyzed in this study are ecoinvent, GaBi, the ELCD node of the LCDN and possible PEF/OEF studies. The raw materials under the scope of the study are copper, aluminum, lithium, rare earth, platinum group metals, cobalt, cadmium and nickel. The analysis will be the basis to produce recommendations on the functional and correct use of the databases.

Table 1. Process parameters under study linked to mining activities in the LCA databases and in literature.

Parameter	Details
Access to data and transparency	Information is not substantial in the free LCA databases and documentation is not standardized. However, the public consultation of the chargeable databases allows to access to the specificities of the aggregated inventory and to supplementary data.
Representativeness	Inventory data is often annual, geographic, sectorial average (weighted or not) or specific data is used instead of others (proxies). All the variations between the different possible scenarios are generally not considered.
Obsolescence	Many mining LCA models today are based on relatively old data (15 - 20 years) as it can be the case in the Ecoinvent database. This may constitute a lack of representativeness for current models since mining activity has evolved somewhat in the recent years (little technological change but decreasing ore quality for example).
Allocation	The LCA approach of mining activities often describes multi-output processes and a solution must be found to allocate impacts between the different products. The allocation methods used in the datasets can be analyzed according to the information available in the documentation.
Completeness and scope	Some databases inventories may be less complete than others, while having a similar name. In general, models can simplify the variety of mines and existing mining methods.
Likelihood	A comparison with the literature and industry experts can be used to assess the likelihood of the datasets.

2. State-of-the-art and specific recommendations

2.1. Copper

Copper deposits are part of the sulfide deposit family. The mineralogical composition can vary greatly from one deposit to another, or even within the same deposit. With copper minerals, it is therefore possible to encounter minerals of other metals, which are desirable to recover: lead, zinc, silver, nickel, cobalt, gold, platinum, etc.

The copper extraction processes in the ecoinvent v3.6 and GaBi v8.7 databases are summarized in Table 2. Several processes are identified for the production of copper concentrate on ecoinvent. Conversely, GaBi proposes processes only for the production of refined copper. Among the GaBi processes, two of them are available for purchase on demand.

Table 2. Datasets available in the databases for copper concentrate and copper production. Shaded processes are not available with the standard software license.

	Ecoinvent v3.6	GaBi v8.7
Copper concentrate	○ Copper concentrate, sulfide ore {AU}| copper mine operation, sulfide ore ○ Copper concentrate, sulfide ore {RAS}| copper mine operation, sulfide ore ○ Copper concentrate, sulfide ore {RER}| copper mine operation, sulfide ore	No processes.

	o Copper concentrate, sulfide ore {RLA}| copper mine operation, sulfide ore o Copper concentrate, sulfide ore {RNA}| copper mine operation, sulfide ore o Copper concentrate, sulfide ore {RoW}| copper mine operation, sulfide ore	
Refined copper	o Copper {GLO}| nickel mine operation, sulfidic ore o Copper {RU}| platinum group metal mine operation, ore with high palladium content o Copper {ZA}| platinum group metal mine operation, ore with high rhodium content o Copper {RoW}| gold-silver-zinc-lead-copper mine operation and refining o Copper {SE}| gold-silver-zinc-lead-copper mine operation and refining o Copper, from solvent-extraction electro-winning {GLO}| copper production, solvent-extraction electro-winning	o Copper (99.99%; cathode) from pyrometallurgical (including secondary) and hydrometallurgical production GLO o Copper mix (99,999% from electrolysis); from electrolysis; consumption mix, to consumer GLO o Copper (99.999%; electrolyte copper) production; technology mix; production mix, at plant IN[1] o Copper; from electrolysis; production mix, at plant; 99,999% Cu SE[1]

The data collected and the associated considerations allow the formulation of some recommendations. For the moment, the scenarios represented in the databases are the following:

- Concentrated copper mining in Europe, Australia, Asia, North America, Latin America and the rest of the world,
- Production of refined copper by electrolysis (pyrometallurgy) worldwide, in India and Sweden,
- Production of refined copper by electrowinning (hydrometallurgy) worldwide,
- Production of refined copper by hydrometallurgy and pyrometallurgy worldwide,
- Refined copper production by unspecified route in Sweden, South Africa, Russia and the rest of the world.

Not all processes are totally reliable and representative of the scenario they are describing. In general, it can be said that, if the supply chain of the copper used in the production chain is not well known, the use of ecoinvent LCA processes with global geographical coverage represents a sufficiently reliable choice, which models the reality by taking into account the different datasets currently available. Different geographical coverage and different types of mines and minerals are therefore included when modeling global processes. Nevertheless, the allocation method used to take into account the impact of the different sub-processes is not transparent.

The search for information in the scientific literature and other sources, such as sector associations and ongoing projects, allowed to identify inventory data that are globally more recent (and sometimes more specific and complete). Above all, the information extracted from the literature allows a partial validation of the existing LCA databases, since the potential impacts of the exploitation activities analyzed are of the same order of magnitude as the impacts calculated using the existing LCA databases. However, the LCA databases are associated with potential impacts that are generally minor.

If the actual percentage of secondary copper consumption is not known, it is possible to use a value between 21% and 35%, depending on the scenario considered. These are the percentages of semi-finished products composed of secondary raw material, according to ICA and - Glöser et al, (2013), respectively. Gloser et al, (2013) estimated this data in a project of the Fraunhofer Research Institute to describe the overall copper flow.

2.2. Aluminum

The primary ore used in the manufacture of aluminum is bauxite. Depending on the quality of the ore, 4 to 6 tons of bauxite are required to be refined into 2 tons of alumina, which are then melted down into approximately 1 ton of metal (IAI, 2018).

The bauxite extraction processes in the ecoinvent v3.6 and GaBi v8.7 databases are summarized in Table 3. There is only one process on ecoinvent whereas four processes are available in GaBi. The data of the EI process as well as those from the GaBi process which is available by default (in black in the table) are from a 2015 survey by the IAI, which was then published (IAI, 2017).

Table 3. Datasets available in databases for bauxite production. Shaded processes are not available with the standard software license.

	Ecoinvent v3.6	GaBi v8.7
Bauxite	○ *Bauxite, without water {GLO}| bauxite mine operation*	○ *Bauxite, primary production; consumption mix, at plant; RNA*[1] ○ *Bauxite, technology mix; consumption mix, to consumer; 89% imported, 11% local production; EU-28 3.45E-3* ○ *Bauxite mining 2015, bauxite extraction and processing; single route, at plant; minerals gibbsite Al(OH)3, boehmite y-AlO(OH) and diaspore a-AlO(OH); GLO* ***(empty)*** ○ *Bauxite, at mine; GLO*[1]

Considering the relatively recent publication date, the reliability of the association providing the data and the near unavailability of regionalized data, it makes sense to recommend the use of the inventory provided by the IAI. The only regionalized data sets available for consultation in the GaBi database are for Europe and North America, but North American and European bauxite production represents only a very limited fraction of overall production. In addition, the source of the European process data is not clearly indicated.

The two global processes that have the IAI report as their source (and are therefore recommended) are:

- *Bauxite, without water {GLO}| bauxite mine operation*, in Ecoinvent,
- *Bauxite mining 2015, bauxite extraction and processing; single route, at plant; minerals gibbsite Al(OH)3, boehmite y-AlO(OH) and diaspore a-AlO(OH); GLO,* in GaBi.

In addition, it is important to note that the European aluminum industry recommends the distribution of the benefits derived from recycling according to the substitution method, which considers that "recycled aluminum replaces primary aluminum so that only metal losses during the entire life cycle need to be replaced by primary aluminum". It is therefore crucial to correctly assess metal losses during the recycling phase.

2.3. Lithium

Its main source currently comes from extraction from spodumene pegmatites, followed by the exploitation of intracontinental lithiniferous brines. Lithium is not a rare metal. On the one hand, its mining is possible due to the presence of this metal in pegmatites formed at medium depth, rich in lithium, cesium, and tantalum. On the other hand, the exploitation of lithium from brines is possible thanks to the existence of salt lakes related to recent volcanism, particularly in the Andes (Chile, Argentina, Bolivia). In this case, lithium is obtained by chemistry, from the evaporation of brines.

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[1] Data on demand.

The spodumene and brine extraction processes in the ecoinvent v3.6 and GaBi v8.7 databases are summarized in Table 4. The EI database has the advantage of offering datasets based only on the extraction of raw materials, i.e. spodumene or brine, whereas GaBi offers data sets only for intermediate products. Moreover, the EI database considers lithium carbonate as the only product that can be obtained directly from brines or ores. Indeed, lithium chloride and lithium hydroxide are, in EI, only obtained from lithium carbonate and do not have a process corresponding to their direct obtention from brines or ores. The GaBi processes are all available only on request and therefore subject to a charge.

Table 4. Datasets available in the databases for the production of spodumene, brine and lithium carbonate. Shaded processes are not accessible via a standard software license and are therefore subject to a fee.

	Ecoinvent v3.6	**GaBi v8.7**
Spodumene	○ *Spodumene {RER}| production | Alloc Def, U* ○ *Spodumene {RoW}| production | Alloc Def, U*	○ *No processes.*
Brine	○ *Lithium brine, 6.7 % Li {GLO}| lithium brine inspissation | APOS, U*	○ *No processes.*
Lithium carbonate	○ *Lithium carbonate {GLO}| production, from concentrated brine | APOS, U* ○ *Lithium carbonate {GLO}| leaching of spodumene with sulfuric acid | APOS, U*	○ *Lithium carbonate (from brine); extraction from brine; production mix, at plant; 2.11 g/cm3, 73.89 g/mol CL* ○ *Lithium carbonate (spodumene route); spodumene route; production mix, at plant; 2.11 g/cm3, 73.89 g/mol CN* ○ *Lithium Carbonate mix; technology mix; production mix, at plant; 2.11 g/cm3, 73.89 g/mol GLO* ○ *Lithium carbonate mix (brine); extraction from brine; production mix, at plant; 2.11 g/cm3, 73.89 g/mol GLO* ○ *Lithium carbonate mix (spodumene); spodumene route; production mix, at plant; 2.11 g/cm3, 73.89 g/mol GLO*

The scenarios for lithium mining from ore and brine represented in ecoinvent are as follows:

- Extraction of lithium from brine in Chile (Atacama Desert) extrapolated to a global scale for global process utilization,
- Global and European production of lithium from spodumene.

The collected data and associated considerations allow the formulation of some recommendations. In general, it can be stated that, if the supply chain of lithium carbonate used in the production chain is not well known, it is preferable to create a new process corresponding to the current market share of lithium from spodumene and brine rather than using the available "market for" process, in which 98% of the lithium comes from brines. When the origin of the lithium is known with more or less precision, attention will have to be paid to the choice of a process whose system boundaries are adapted to the product of interest (brine, spodumene, lithium carbonate, lithium hydroxide, lithium chloride etc...) remembering that all lithium derivatives are modeled in ecoinvent from lithium carbonate.

The spodumene extraction process is not totally reliable and representative of the scenario it describes because it actually corresponds to an extrapolation of iron production. Conversely, the brine extraction process is based on industrial data from plants located in the Atacama Desert (Chile). The literature also provides inventory data that could be used as an alternative or complement to LCA databases, as well as results of the calculation of potential impacts for specific case studies. In particular, for modelling the specific extraction of spodumene, it is advisable to use literature rather than databases. In general, the information extracted from the literature mainly allows a partial validation of the existing LCA databases, as the potential impacts of the mining activities analyzed are generally higher than the impacts calculated using the existing LCA databases.

Finally, it is important to remember to consider a percentage of secondary raw material when modeling and analyzing a finished or semi-finished product. If the actual percentage is not known, a search for the average recycling rate will have to be performed for lithium carbonate depending on the application.

Recommendations from the database and literature review are shown in Table 5.

Table 5. Recommendations for the modelling of spodumene, brine and lithium carbonate in LCA.

Origin	Chile	Rest of the world	Unknown
Spodumene	-	Prefer specific data or data from the literature (e.g. Ambrose and Kendall, 2018).	Prefer specific data or data from the literature.
Brine	Use the "GLO" brine extraction process.	Use the "GLO" brine extraction process by adapting the energy mixes.	Use the "GLO" brine extraction process.

Production route:	From spodumene	From brine	Unknown
Lithium carbonate	Prefer specific data or data from the literature.	Use the "GLO" process for the production of lithium carbonate from brine.	Use the "market for" process by modifying the market shares according to the current situation (brine/spodumene). Use data from the literature for the spodumene production share.

2.4. Rare Earth Elements

Rare earths represent the lanthanide group (elements with atomic numbers between 57 and 71, from lanthanum to lutetium). Due to similar chemical properties, yttrium (Y) and scandium (Sc) are associated with them. A distinction is made between ceric, light earths (lanthanum, cerium, praseodymium, neodymium, samarium, europium, and gadolinium) and yttric, heavier earths (the other rare earths), europium and gadolinium being sometimes classified as heavy rare earths. Rare earths are present in significant quantities in monazite and bastnaesite ores. Despite their name, the elements constituting rare earths are not rare. Rare earths are mainly contained in rocks associated with alkaline magmatism.

The extraction processes of rare earths in the ecoinvent v3.6 and GaBi v8.7 databases are summarized in Table 6. The ecoinvent database again provides access to datasets representing the production of rare earth concentrate or rare earth oxides while GaBi provides direct access to the production of rare earths and rare earth oxides and the intermediate is not available. The inventories available on EI are differentiated by the origin of production of the rare earth ore (China or RoW). Nevertheless, the quantities of inputs and outputs are exactly the same and only the origin of some datasets differs. The RoW process is in fact a copy of the original CN process with adjusted uncertainty. It should be noted that some rare earths do not have an existing dataset for their modeling in EI. This is justified by the very low percentages of some rare earths in bastnaesite and monazite. It is thus specified that 0.28% of the rare earth oxides in the modeled ore are not taken into account. An economic allocation is used between REOs (Rare Earth Oxides).

Table 6. Datasets available in the databases for REE, REO and REE concentrate production. Shaded processes are not included in the standard software license and can be purchased upon request.

	Ecoinvent v3.6	**GaBi v8.7**
Rare Earth concentrate	○ *Rare earth concentrate, 70% REO, from bastnasite {CN}| production | APOS, U* ○ *Rare earth concentrate, 70% REO, from bastnasite {RoW}| production | APOS, U*	○ *No processes.*
Rare Earth Oxides	○ *Cerium concentrate, 60% cerium oxide {CN}| rare earth oxides production from bastnasite concentrate | APOS, U Rare earth concentrate, 70% REO, from bastnasite {RoW}| production | APOS, U* ○ *Neodymium oxide {CN}| rare earth oxides production from bastnasite concentrate | APOS, U* ○ *Praseodymium oxide {CN}| rare earth oxides production from bastnasite concentrate | APOS, U* ○ *Lanthanum oxide {CN}| rare earth oxides production from bastnasite concentrate | APOS, U* ○ *Samarium europium gadolinium concentrate, 94% rare earth oxide {CN}| rare earth oxides production from bastnasite concentrate | APOS, U*	○ *All REOs are available individually.*
Rare Earth Elements	○ *No processes.*	○ *All REEs are available individually.*

The data collected and the associated considerations allow the formulation of some recommendations. For the time being, the scenarios represented in the databases are as follows:

- Rare earth concentrates production (70%) in China and worldwide,
- Production of dysprosium oxides in China and worldwide,
- Production of lanthanum oxides in China and around the world,
- Production of cerium oxides in China and around the world,
- Production of neodymium oxides in China and around the world,
- Production of samarium-europium-gadolinium concentrate in China and worldwide.

Concerning the geographical representativeness of the datasets, it is possible to conclude that the production of rare earths in China by the producers Northern Rare Earth and Shenghe Resources is very representative (and almost exclusive). The following considerations can be applied for rare earth LCA modelling depending on the type of product considered (concentrate, oxide or refined metal) and its origin (Table 7).

Table 7. Rare earth LCA modeling advices according to the origin of the material.

Origin of the raw material		**China**	**Rest of the world**	**Unknown**
Rare Earth concentrate		Use the "CN" ecoinvent process as it is.	Use the "RoW" process by modifying the energy mix according to the origin.	Modify the "market for" ecoinvent process with the current market shares between China and the rest of the world.
Rare Earth Oxide	Cerium Dysprosium Neodymium Samarium Europium Gadolinium	Use the "CN" ecoinvent processes by modifying the economic allocation based on current market values.	Use the "RoW" ecoinvent processes by modifying the economic allocation based on current market values and adapting the energy mix.	Modify the "market for" ecoinvent process and the economic allocation of the "CN" and "RoW" processes with current market shares and market values.
	Other heavy rare earths	Use specific data or buy the GaBi extension (a priori no available data in the literature).		
Rare Earth Element		Use data from the literature (e.g. Vahidi and Zhao, 2018) or purchase the GaBi extension.		

2.5. Platinum-Group Metals

Platinum is obtained from ores along with other Platinum Group Metals (PGMs). PGMs are a group of six elements: iridium (Ir), osmium (Os), platinum (Pt), palladium (Pd), rhodium (Rh) and ruthenium (Ru). Global PGM reserves are estimated at 100 million kilograms, more than 80% of which is contained in the South African Bushveld Igneous Complex (Junge et al., 2015).

PGM extraction processes in the ecoinvent v3.6 and GaBi v8.7 databases are summarized in Table 8. Three types of PGMs are represented in the ecoinvent database while GaBi allows the modeling of 4 types of PGMs. However, the GaBi datasets are not available with the standard software license and require additional payment.

Table 8. Available datasets in the databases for the production of platinoids.

	Ecoinvent v3.6	**GaBi v8.7**
Platinoids	○ *Platinum {ZA}| group metal mine operation, ore with high rhodium content | APOS, URare earth concentrate, 70% REO, from bastnasite {RoW}| production | APOS, U* ○ *Platinum {RU}| group metal mine operation, ore with high palladium content | APOS, U* ○ *Palladium {ZA}| platinum group metal mine operation, ore with high rhodium content | APOS, U* ○ *Palladium {RU}| platinum group metal mine operation, ore with high content | APOS, U* ○ *Rhodium {ZA}| platinum group metal mine operation, ore with high content | APOS, U* ○ *Rhodium {RU}| platinum group metal mine operation, ore with high palladium content | APOS, U*	○ *Platinum mix; primary production; production mix, at plant* ○ *Palladium mix; primary production; production mix, at plant* ○ *Rhodium mix; primary production; production mix, at plant* ○ *Ruthenium; mining, transport, separation: mechanical separation, smelting, magnetic separation, chemical refining; production mix, at plant*

The data collected and the associated considerations allow the formulation of some recommendations. The scenarios represented in the databases are the following:

- Platinum production in South Africa and Russia,
- Palladium production in South Africa and Russia,
- Rhodium production in South Africa and Russia.

The following considerations may apply for PGM LCA modeling depending on its origin and if specific data are not available (Table 7). In terms of data quality, it should therefore be noted that allocations should be modified according to changes in the market situation. Many websites, such as the London Metal Exchange (LME), reference the prices of precious metals such as platinum, palladium and rhodium (LME, 2020). It is advisable to take an average of the selling price over the last few years in order to limit the influence of strong price fluctuations on the LCA results. All PGMs are always present in greater or lesser quantities in PGM ores. Thus, to model osmium, ruthenium, iridium and rhenium with EI, it is possible to adapt the existing process by adding co-products and adjusting the allocation factors according to the concentration and market price of these materials.

Table 9. Advices on PGMs LCA modeling according to the origin and nature of the material.

Origin	South Africa or Russia	Rest of the World	Unknown
Platinum Palladium Rhodium	Use the "ZA" or "RU" ecoinvent process by modifying the economic allocation applied to co-products.	Use the "ZA" or "RU" processes which are closest to the extraction technology (see full report).	Modify the "market for" ecoinvent process with the current market shares between South Africa and Russia and apply an economic allocation according to current market values.
Other PGMs	Use the "ZA" or "RU" ecoinvent processes by adding co-products according to the concentration of the other PGMs in the ore and modify the allocation according to the current value of the metals.	Use the "ZA" or "RU" processes which are closest to the extraction technology (see full report) by adding co-products according to the concentration of the other PGMs in the ore and modifying the allocation according to the current value of the metals.	Modify the "market for" ecoinvent process and the economic allocation of the "ZA" and "RU" processes with current market shares and market values.

2.6. Nickel and cobalt

In the earth's crust, nickel, cobalt, and chromium are always closely associated with basic and ultrabasic rocks. As these rocks systematically contain high copper grades, the exploited deposits may combine copper, nickel, and cobalt. Thus, copper deposits are by far the main primary source of cobalt and represent half of the primary source of nickel.

2.6.1. NICKEL

Nickel is produced in equal parts from two types of ores: sulfide ores, almost exclusively copper, and oxidized ores.

The nickel and ferronickel extraction processes available in the ecoinvent v3.6 and GaBi v8.7 databases are summarized in Table 10. The EI database provides access to a dataset that is representative only of the nickel extraction process from Quebec. Then several nickel production processes are available depending on the initial ore type: PGM ores in South Africa and Russia, or copper-nickel sulfide ores. The databases ecoinvent and GaBi also offer several ferronickel production processes. The GaBi processes available with the standard software license are both based on the Nickel Institute's 2017 report.

Table 10. Available datasets in the databases for nickel ore production. Shaded processes are not available with the standard software license.

	Ecoinvent v3.6	**GaBi v8.7**
Nickel ore (sulfidic)	○ *Nickel ore, beneficiated, 16% {CA-QC}| mining and benefication of nickel ore | APOS, U*	○ *No processes.*
Nickel > 99.5% (sulfidic ore)	○ *Nickel, 99.5% {GLO}| nickel mine operation, sulfidic ore | APOS, U* ○ *Nickel, 99.5% {GLO}| smelting and refining of nickel ore | APOS, U* ○ *Nickel, 99.5% {RU}| platinum group metal mine operation, ore with high palladium content | APOS, U* ○ *Nickel, 99.5% {ZA}| platinum group metal mine operation, ore with high rhodium content | APOS, U*	○ *Nickel mix; ore mining and processing, roasting, reduction, magnetic separation; production mix, at plant; 99.9% Nickel* [2] ○ *Nickel (Class 1, 99.95%) ILCD 2017; technology mix; production mix, at plant; 99.9% Ni*
Ferronickel (lateritic ore)	○ *Ferronickel, 25% Ni {GLO}| production | APOS, U*	○ *Ferro nickel (29%); mining, separation, electric arc furnace; production mix, at plant; 29 % nickel* [3] ○ *Ferro Nickel (29% Ni) ILCD 2017; technology mix; production mix, at plant; 29% Nickel*

The collected data and the associated considerations allow the formulation of some recommendations for the modelling of nickel and ferronickel via LCA databases. As a reminder, the scenarios represented in the databases are the following:

- Nickel sulfidic ore production in Quebec,
- Class I nickel production:
    - From Ni-Cu sulfidic ores extracted worldwide, aggregated, or disaggregated in relation to the extraction phase,
    - From sulfidic ores mined in Australia, Canada, Finland, France, Japan, Norway, the United Kingdom and Russia,
    - From Pt-Pd-Rh-Ni-Cu sulfidic ores mined in Russia,
    - From Pt-Pd-Rh-Ni-Cu sulfidic ores mined in South Africa,
- Ferronickel production:
    - From laterite ores worldwide,
    - From laterite ores in Brazil, Colombia, Venezuela, New Caledonia and the Dominican Republic.

The following considerations can be applied for the modeling of Cu-Ni sulfidic ore, nickel and ferronickel LCA depending on their origin (Table 11).

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[2] Extension database V : nonferrous metals 2020

[3] Extension database XVII : full US 2020

Table 11. Advices on the modeling of nickel products according to the origin and nature of the raw material.

Origin of the raw material	**Brazil, Colombia, Venezuela, New Caledonia, Dominican Republic**	**Rest of the world**	**Unknown**
Ferronickel	Use the GaBi process « *Ferro Nickel (29% Ni) ILCD 2017* ».	Use the GaBi process "Ferro nickel (29%)" or the ecoinvent process "Ferronickel, 25% Ni {GLO}| production | APOS, U" by modifying the energy mix according to the country under consideration.	Use the ecoinvent process "market for" or the GaBi process "Ferro nickel (29%)".

Origin of the raw material	**China**	**Russia, South Africa**	**Rest of the world**	**Unknown**
Cu-Ni sulfidic ore	Use the ecoinvent process "Nickel ore, beneficiated, 16% {CA-QC}| mining and benefication of nickel ore | APOS, U" by modifying the energy mix according to the country under consideration.			Use the ecoinvent "market for" process by updating market shares.
Class I nickel	Use the ecoinvent process « *Nickel, 99.5% {GLO}| nickel mine operation, sulfidic ore* | *APOS, U" or "Nickel, 99.5% {GLO}*| *smelting and refining of nickel ore* | *APOS, U"*	Use the EI "ZA" or "RU" processes by adding co-products according to the concentration of other PGMs in the ore and modify the allocation according to the current value of the metals.	Use the GaBi process "Nickel (Class 1, 99.95%) ILCD 2017" or the ecoinvent "GLO" processes by modifying the energy mixes according to the country modeled.	Use the ecoinvent "market for" process.

2.6.2. COBALT

Cobalt is primarily the co-product of copper ore mining in the Democratic Republic of Congo and Zambia. It also comes from the extraction of nickel-copper sulfidic ores in Russia, Canada and Australia, as well as lateritic nickel ores in New Caledonia, Cuba, Indonesia, Australia, the Philippines and Madagascar. In South Africa, cobalt is sometimes a co-product of the mining of precious metals.

The cobalt extraction processes in the ecoinvent v3.6 and GaBi v8.7 databases are summarized in Table 12. The databases only provide access to datasets describing refined metal production: modelling of ore extraction alone is not available.

Table 12. Available datasets in the databases for the production of cobalt. Shaded processes correspond to data which is not included in the standard software license.

	Ecoinvent v3.6	GaBi v8.7
Cobalt	○ *Cobalt {GLO}| production | APOS, U*	○ *Cobalt, refined (metal) CDI GLO* ○ *Cobalt (only Cu/Co route) GLO* ○ *Cobalt (only Ni/Co route) AU* ○ *Cobalt (only Ni/Co route) GLO* ○ *Cobalt mix (Ni/Co and Cu/Co route) GLO*

The collected data and associated considerations allow the formulation of some recommendations for cobalt modeling via LCA databases. The scenarios represented in the databases are the following:

- Refined cobalt production on a global scale,
- Production of cobalt mined in Canada, Cuba, DRC, and New Caledonia and beneficiated in Belgium, Canada, Finland, Japan, Norway, Philippines, and Zambia.

The following considerations can be applied for LCA modeling of cobalt depending on its origin (Table 13).

Table 13. Advice on LCA modeling of cobalt depending on the origin of the material.

Origin of the raw material	Canada, Cuba, DRC, New Caledonia	Rest of the World	Unknown
Cobalt	Use the Gabi process or data from the literature, (e.g. Dai et al.,2018).	Use the GaBi process and modify the energy mix according to the country or use data from the literature (e.g. Dai et al., 2018).	Use the GaBi process.
	Avoid the use of the ecoinvent process.		

2.7. Cadmium

Greenockite (CdS) is the most common ore of Cd. It is a relatively common mineral found in zinc-rich and cadmium-containing hydrothermal veins and in the cavities of some basic rocks. It usually occurs as a lemon-yellow powdery coating or as an earthy crust on sphalerite and contiguous minerals; it has an adamantine to resinous luster.

Cadmium extraction processes in the ecoinvent v3.6 and GaBi v8.7 databases are summarized in Table 14. The ecoinvent database provides access to representative datasets of the intermediate process of extraction and concentration of zinc, a source of cadmium sludge by-product. Several cadmium sludge production processes are also present in ecoinvent. The ecoinvent and GaBi databases then propose 3 processes for the production of cadmium from cadmium sludge. Contrary to ecoinvent, the GaBi database does not propose a process for the modeling of cadmium production intermediates. The two ecoinvent inventories of primary cadmium production are based on the same production data. The only difference corresponds to the origin of the energy mix: a specific process is proposed for Canada. Conversely, the GaBi process represents the overall average situation, based on the main existing technologies and specific and/or imported characteristics. Nevertheless, the free documentation provides very little information.

On ecoinvent, cadmium is, as expected, a by-product of zinc and lead extraction but also surprisingly of molybdenum production, whereas cadmium sludge is normally never a by-product of this value chain. The existence of these processes is explained by the specific construction of the molybdenum production dataset. Indeed, molybdenum is produced from molybdenite by MoO_3 roasting followed by metallurgical steps. As no specific process data was available, the roasting and metallurgical processes of zinc production were used as a proxy by ecoinvent. The zinc concentrate and molybdenite are sulfide and the metal concentration is similar. Therefore, the production inventory of 1 kg of "zinc, at regional storage" is used directly to describe the production of 1 kg of molybdenum. Thus, the same by-products of zinc production appear for molybdenum production hence the existence of these datasets.

Table 14. Available datasets in the LCA databases for the production of ore, cadmium sludge and cadmium. The processes described in red are involved in the production of cadmium sludge due to the use of proxies for modeling molybdenum production and therefore not representative. The processes shaded in grey correspond to data which is not available with the standard version of the software license.

	Ecoinvent v3.6	**GaBi v8.7**
Zinc concentrate	○ *Zinc concentrate {CA-QC}| gold-silver-zinc-lead-copper mining and benefication | APOS, U* ○ *Zinc concentrate {GLO}| metalliferous hydroxide sludge to market for zinc concentrate | APOS, U* ○ *Zinc concentrate {GLO}| zinc-lead mine operation | APOS, U* ○ *Molybdenite {GLO}| mine operation | APOS, U* ○ *Molybdenite {RAS}| copper mine operation, sulfide ore | APOS, U* ○ *Molybdenite {RLA}| copper mine operation, sulfide ore | APOS, U* ○ *Molybdenite {RNA}| copper mine operation, sulfide ore | APOS, U*	○ *No processes.*
Cadmium sludge	○ *Cadmium sludge from zinc electrolysis {CA-QC}| primary zinc production from concentrate | APOS, U* ○ *Cadmium sludge from zinc electrolysis {RoW}| primary zinc production from concentrate | APOS, U* ○ *Cadmium sludge from zinc electrolysis {RoW}| molybdenum production | APOS, U* ○ *Cadmium sludge from zinc electrolysis {RER}| molybdenum production | APOS, U*	○ *No processes.*
Cadmium	○ *Cadmium {CA-QC}| cadmium production, primary | APOS, U* ○ *Cadmium {RoW}| cadmium production, primary | APOS, U*	○ *Cadmium; technology mix; production mix, at plant; 8.65 g/cm3, 112.4 g/mol*

The collected data and the associated considerations allow the formulation of some recommendations for cadmium modelling via the LCA databases. The scenarios represented in the databases are the following:

  - Zinc concentrate production:
    - From Zn-Pb ore on a global scale,
    - From metalliferous hydroxide sludges worldwide,
    - From Au-Ag-Zn-Pb-Cu ore mined and beneficiated in Quebec.
  - Production of cadmium sludge:
    - From the electrolysis of zinc as a by-product in Quebec,
    - From the electrolysis of zinc as a by-product in the rest of the world,
    - From the electrolysis of zinc as a by-product (molybdenum production) in Europe,
    - From the electrolysis of zinc as a by-product (molybdenum production) in the rest of the world,
  - Production of refined cadmium:
    - From cadmium sludge refined in Quebec,
    - From cadmium sludge refined in the rest of the world.

In view of the identified process limitations, the following recommendations may apply for the LCA modeling of cadmium depending on the scope of the study (Table 15).

Table 15. Recommendations for the modeling of cadmium value chain products in LCA.

Modelling of the product	Foreground process	Background process
Zinc concentrate	• Use specific data or from literature (e.g., Van Genderen et al., 2016).	• Use the ecoinvent "GLO" process and adapt the energy mix to the country of origin if it is known.
Cadmium sludge	• Avoid the use of processes resulting from molybdenum production. • Use specific data.	• Avoid the use of processes resulting from molybdenum production. • Use the "CA-QC" or "GLO" ecoinvent process, adapt the energy mix to the country of origin if known. • Adjust the allocation factors according to the scope of the study. • Be careful when interpreting the results if cut-off is used.
Cadmium	• Use specific data or from literature (e.g., Fthenakis et al., 2009).	• Use the "CA-QC", "GLO" or "market for" ecoinvent process and adapt the energy mix to the country of origin if known. • Be careful when interpreting the results if cut-off is used.

3. General limitations

The body of the analysis identified specific limitations to the modeling of each metal studied in this report. However, some general limitations have been identified and are reported in this section, including data access and transparency, geographic representativeness, allocation, obsolescence, and completeness. Based on the previous analysis, it is possible to identify and categorize two types of limitations of the LCA databases describing mining activities:

Limitations related to the modeling in the LCA approach:

- The allocation method used is often not identifiable in detail and always involves an approximation that causes distortions in the distribution of potential impacts between different co-products.

- Data are sometimes aggregated, which causes a lack of transparency and difficulty in producing an analysis of the contribution of the sub-processes.
- The documentation supporting the LCA databases is not completely transparent: it is often incomplete and does not always mention all the aspects relating to data sources, system limitations, the types of mines considered, the proxies used, etc.
- LCA database documentation is also not standardized (the information reported can be more or less detailed depending on the process considered and the authors, even within the same database), which makes it difficult, among other things, to compare the different processes.

Limitations related to the variety and updating of the databases:

- Geographical representativeness is incomplete, with often average data and/or different geographical areas used as proxies and especially a lack of data representative of the major producers of the different ores. In particular, ecoinvent sometimes adapts some datasets to other regions by modifying only the origin of the energy mix while all other data remain the same (as for example in the case of copper concentrate).
- Relative obsolescence and failure to include new technologies.

In terms of transparency and data access, existing databases do not allow an easy access to all the modeling parameters. Indeed, the consultation of ecoinvent processes is free of charge but the inventory data are provided in an aggregated way and without allocation. For GaBi, the access to the "Professional database" is included with the software license but some unit processes are available on request or present only in extensions to be paid separately. The consultation of the documentation is free of charge, but only a general description of the process, some literature references and modeling considerations can be accessed, but not the inventory data. The consultation of the existing datasets is public with registration at the respective sites. As mentioned, Ecoinvent provides access to the specifics of the aggregated inventory (without distinctions between sub-processes) and flows, while GaBi allows to simply read some additional information. On the other hand, the documentation is non-standardized, even within the same database. The information provided can be different and more or less complete.

Finally, for many ores, the models used to represent their extraction are "multi-output" systems, as several raw materials are derived from the same ore. This poses the problem, common in LCA, of allocating impacts between different co-products and by-products. By not being able to avoid allocation with an expansion of the system (as suggested by ISO 14044), two main scenarios are possible, namely economic allocation and mass allocation. ISO 14044 indicates a preference for mass allocation, although economic allocation is probably the most widely adopted by LCA practitioners. In any case, both solutions imply choices that may distort the distribution of impacts. In the context of mining:

- *Economic allocation* → Risk of an impact distribution that is too dependent on the price of precious metals in the same ore. In addition, the prices considered are not often updated, even though they can fluctuate quickly.
- *Mass Allocation* → Risk of an impact distribution that is too dependent on the density and/or composition of the ore without taking into account the effective demand (product and by-product hierarchy).

The system modeling chosen for this analysis among those proposed by Ecoinvent is the "APOS" method (Allocation at the Point of Substitution). This method uses the average production and prefers the economic allocation. It is difficult to extrapolate the specific allocation used in each unit process because the figures reported in the inventory flows are already allocated. GaBi only applies an attributional modeling, sometimes without allocation or using an economic allocation.

4. General recommendations

When the source of the metal is known with more or less precision, the LCA databases should be searched for the process that is most representative of the product of interest. In particular, it is advisable to pay attention to the following points:

- Select processes whose system limits are adapted to the product of interest (concentrated ore, refined metal, transport inclusions).
- Select processes that are representative of the country of supply (when available), or of the geographical area of interest. This can result in a significant difference in the quantities of inventory inputs and a significant difference in the impacts caused by the energy mixes used.
- For refined raw materials, select processes that consider the right type of metallurgical treatment.

When the LCA databases are not representative and depending on the importance of the mining process of the raw material under consideration in relation to the complete production process, an integration of the databases may be necessary. Significance is here understood in terms of environmental impacts and data integration can be done either by using inventory data found in the literature or by using specific data.

A flowchart to guide the selection of LCA databases processes when analyzing the production of a finished or semi-finished product is proposed in Figure 1.

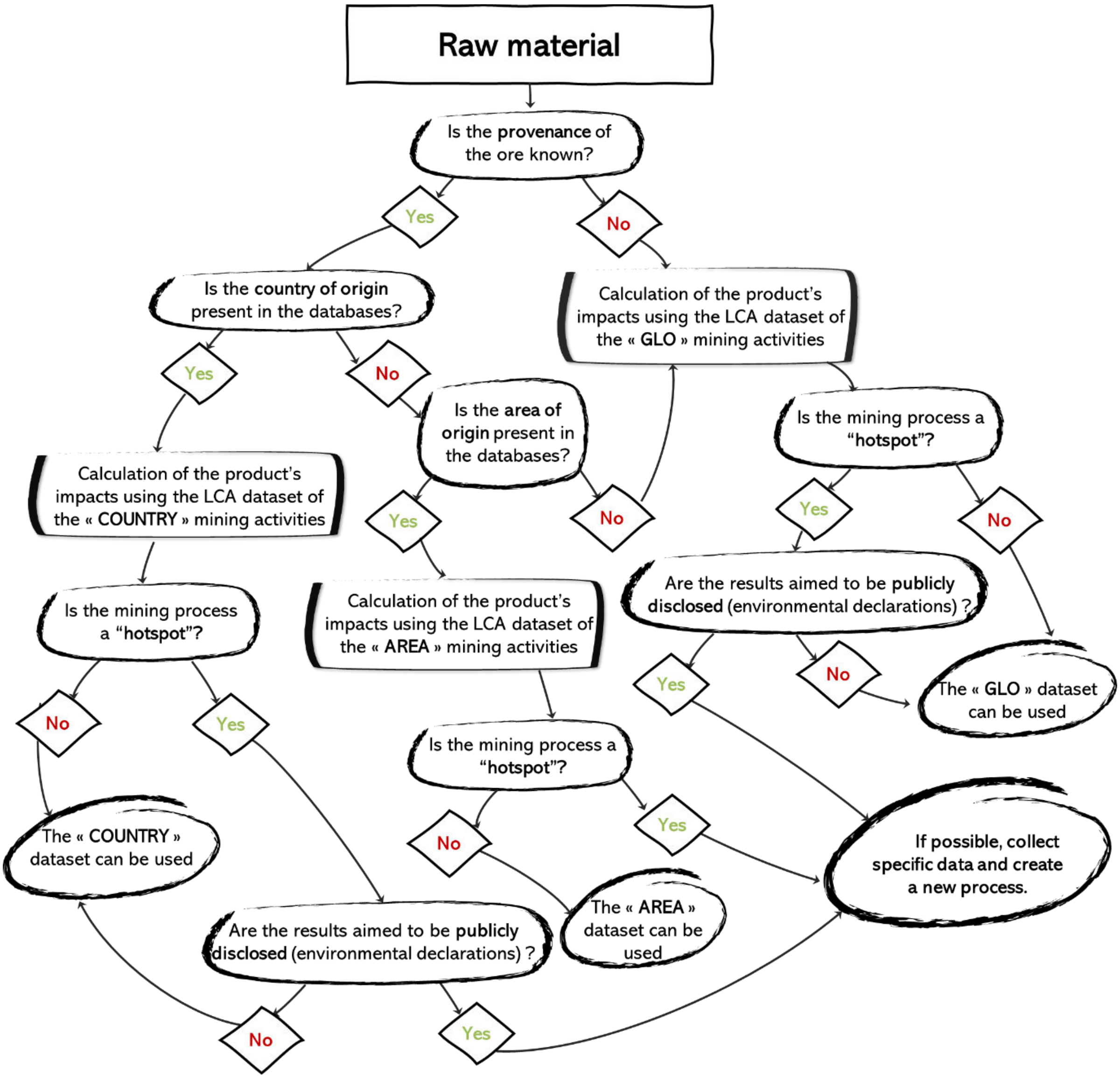

Figure 1. Decision tree to support the choice of datasets related to mining activities in an LCA study.

The PEF Pilot Guidance (EC, 2016) suggests thresholds for assessing whether a process can be considered a hotspot in an LCA. In particular, processes are identified as more significant if they contribute at least to 80% of the potential impacts of an impact category, before normalization and weighting. Hotspots should be identified at the level of the entire life cycle. A "contribution analysis" is one of the methods also recommended by ISO 14044:2006 and one of the examples presented, the "ranking criteria" considers as more important the inputs that have a major contribution of 50%. In any case, it is important to remember that different criteria can be chosen, depending on the specific case and the purpose of the analysis.

Care should always be taken to ensure that the choice of system boundaries is consistent, for example to avoid double counting or to analyze metallurgical processing and mining separately. The overall ecoinvent process that describes the production of primary copper ("market for") includes for example also transport, which is not considered in the other processes. The objectives of the analysis also play an important role in the use of LCA databases. Indeed, a screening analysis, without external dissemination and/or comparison, normally requires less accurate and complete data. The use of LCA databases may therefore vary depending on knowledge of the supply chain and production process, the relative importance of the sub-process in calculating potential impacts, but also on the characteristics of the scenario under consideration (which may be represented more or less accurately) and the purpose of the analysis (limits of the system, objectives and field of study).

Once these aspects have been considered, it will be possible to better select existing LCA datasets. The literature also provides inventory data that could be used as an alternative or complement to the LCA databases as well as results from the calculation of potential impacts for specific case studies. Finally, it is important to remember to consider a percentage of secondary raw material when modeling and analyzing a finished or semi-finished product.

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