

**Update and expansion of the life cycle inventories
for the primary production of scarce and critical metals
in the ecoinvent database**

Final report of the project phases I and II

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by

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Summary

The present report provides a synthesis of the research activities undertaken in Phases I and II of the Swiss Federal Office for the Environment (FOEN) commissioned project for an “update and expansion of the life cycle inventories for the primary production of scarce and critical metals in the ecoinvent database”.

First, a brief overview of the current ecoinvent life cycle inventory (LCI) data modelling approach for metals primary production is provided. We then present a new systematic LCI data modelling framework that links the primary production of critical and scarce (“companion”) metals as well as their respective “host” metals. To demonstrate the application of the proposed framework, a case study of the primary production of copper and its companion metals is presented. Finally, this report presents an overview of further work, to be undertaken in the subsequent Phase III of this research project in order to compile the actual LCI data for the database ecoinvent about the primary production of scarce and critical metals.

1. Introduction

Most of the data for metals primary production processes that are currently available in the ecoinvent v3 database were adopted with only minimal changes from the previous version. Those data are based to a large extent on sources dating back to the 1990s and in 2000. With the exception of aluminium and steel, the various primary metals are produced in complex, interconnected systems that comprise a variety of processes that result in the recovery or production of multiple metals, simultaneously. For many of these metals, their recovery and production is dependent on the recovery and processing of another. These so-called “companion metals” may be associated with a single or multiple “host metals” to varying extents as shown in Figure 1 below (taken from Nassar *et al.*, 2015).

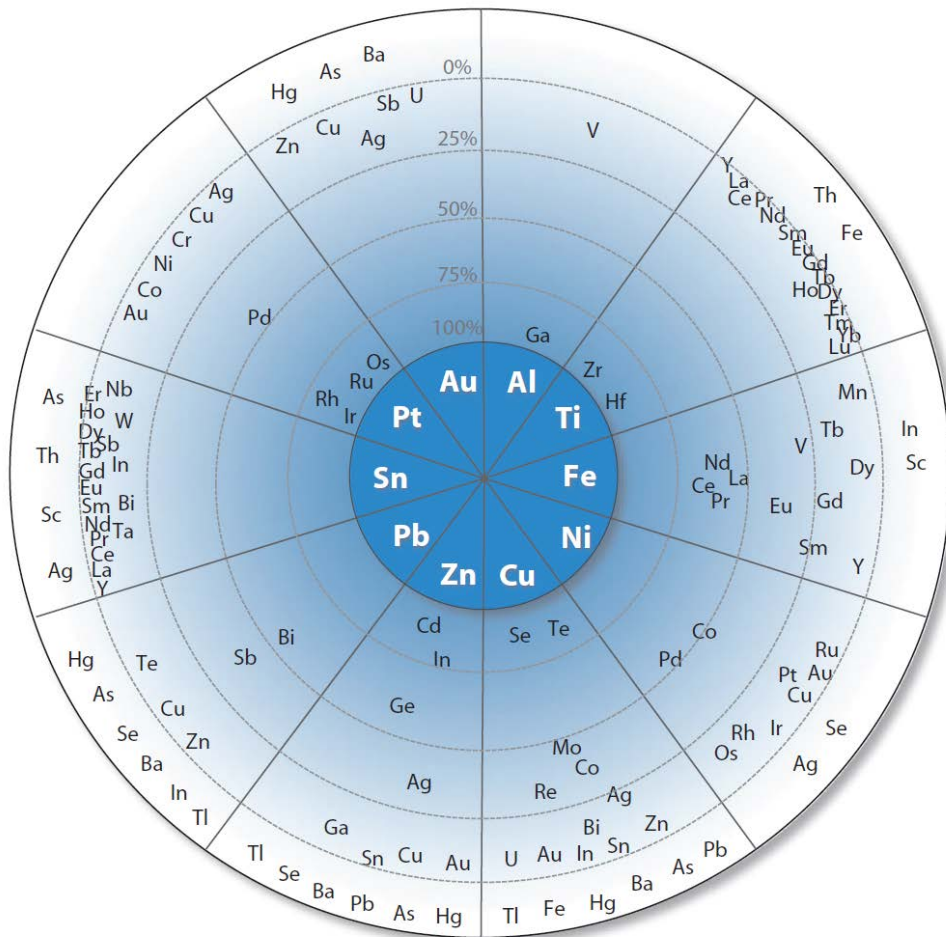


Figure 1. The wheel of metal companionship. The nine principal host metals form the inner circle. Companion elements appear in the outer circle at distances from the inner circle proportional to the percentage of their primary production (from 100% to 0%) that occurs with the respective host metal. The companion elements in the outermost zone of the outer circle are those for which the percentage of their primary production that occurs with the respective host metal has not been determined. Source: Nassar *et al.* (2015).

Recovery and production of these companion metals is often concentrated in a few countries and processing methods can vary considerably on a regional level. Hence, the primary production of metals must be considered as one interconnected system, rather than considering each metal independently and should account for these regional differences. At present, data for metals primary production processes in ecoinvent do not reflect this reality, with regional differences and system connections only considered in a few exceptional cases.

The aim of this project, which was commissioned by the Swiss Federal Office for the Environment (FOEN), is to update, in a consistent and flexible manner, the ecoinvent database with regards to scarce or ‘critical’ metals. The purpose of this research is to ensure that representative and regionalised LCI datasets for the extraction and processing of scarce or ‘critical’ metals are available to users of the ecoinvent database, which will broaden the potential application of the database.

The research within this project is being undertaken in three successive phases:

1. The identification and prioritisation of scarce or ‘critical’ metals
2. The development of a broadly-applicable, generic LCI data model
3. The compilation of the actual LCI data

This report, which consists of five sections, presents an overview of the research activities undertaken so far during Phases I and II of this project, i.e. the identification and prioritisation of the scarce and/or critical metals as well as the development of the LCI data model. Section 2, which follows this introduction, summarizes the first phase of this research, i.e. the categorisation and prioritisation of the various scarce or ‘critical’ metals within the scope of this project. The next section (i.e. Section 3) comprises a review of the existing ecoinvent approach to LCI data modelling for metals primary production, focusing in particular on the availability and quality of data on critical and scarce metals. The new proposed LCI data modelling framework is then described in detail. To demonstrate the application of the proposed framework to a complex, interconnected metals primary production system, a case study of the copper primary production system is presented in Section 4. Finally, Section 5 presents a plan of future work required to complete Phase III of this project.

2. Categorisation of scarce and critical metals

The objective of Phase I of this project, which was completed in January 2016, was two-fold: (i) an identification of all those scarce and critical metals that are yet missing in the database ecoinvent, and (ii) a first estimation of the need of action for all the scarce and critical metals that are already included in the database ecoinvent in order to bring them to a common level of quality. The starting point for these investigations was the following list of elements.

Table 1. Starting list of scarce and critical metals.

Critical metals according to EC (2014)				
Antimony	Sb		Terbium	Tb HREE
Beryllium	Be		Thulium	Tm HREE
Boron	B		Tungsten	W
Cerium	Ce	LREE	Ytterbium	Yb HREE
Chromium	Cr		Yttrium	Y HREE
Cobalt	Co			
Dysprosium	Dy	HREE	Further scarce metals	
Erbium	Er	HREE	Arsenic	As
Europium	Eu	HREE	Bismuth	Bi
Gadolinium	Gd	HREE	Cadmium	Cd
Gallium	Ga		Gold	Au precious metal
Germanium	Ge		Hafnium	Hf
Holmium	Ho	HREE	Mercury	Hg
Indium	In		Molybdenum	Mo
Iridium	Ir	PGE, precious metal	Rhenium	Re
Lanthanum	La	LREE	Scandium	Sc
Lithium	Li		Selenium	Se
Lutetium	Lu	HREE	Silver	Ag precious metal
Magnesium	Mg		Tantalum	Ta
Neodymium	Nd	LREE	Tellurium	Te
Niobium	Nb		Thallium	Th
Osmium	Os	PGE, precious metal	Tin	Sn
Palladium	Pd	PGE, precious metal		
Platinum	Pt	PGE, precious metal	Further metals	
Praseodymium	Pr	LREE	Strontium	Sr
Rhodium	Rh	PGE, precious metal	Titanium	Ti
Ruthenium	Ru	PGE, precious metal	Vanadium	V
Samarium	Sm	LREE	Zirconium	Zr
Silicon (metal)	Si			

LREE, light rare earth element; **HREE**, heavy rare earth element; **PGE**, platinum group element.

This list in Table 1 – integrated into the offer to the commissioner – was established in the H2020 project ProSUM¹, using the definition for critical metals according to the European Commission (EC) (EC, 2014) as starting point. All elements of this list have been analysed concerning the following four issues:

- (i) is the metal already available in the database ecoinvent,
- (ii) in what ore types the metal can be found,
- (iii) in which geographical areas the metal is mined and/or processed, and
- (iv) what are the market forms that can be found of this metal.

While the first issue has been investigated by a thorough analysis of the content of the ecoinvent database v3.2, all further issues have been investigated with the support of a thorough literature review (see Annex 1). The result from this investigation is a grouping of the elements into three different groups of metals:

- **Group I**, comprising metals that, *a priori*, are extracted/mined in isolation (i.e. not in any kind of combination with other metals);
- **Group II**, representing groups of metals that can clearly be linked to one single “host” element; and
- **Group III**, representing all those elements that are mined in interconnected systems with one or multiple host metals (see Figure 2).

¹ ProSUM: Prospecting Secondary raw materials from the Urban Mine and Mining waste – a H2020 project, coordinated by the WEEE Forum, Brussels (BE). More at <http://www.weee-forum.org/prosum-0>

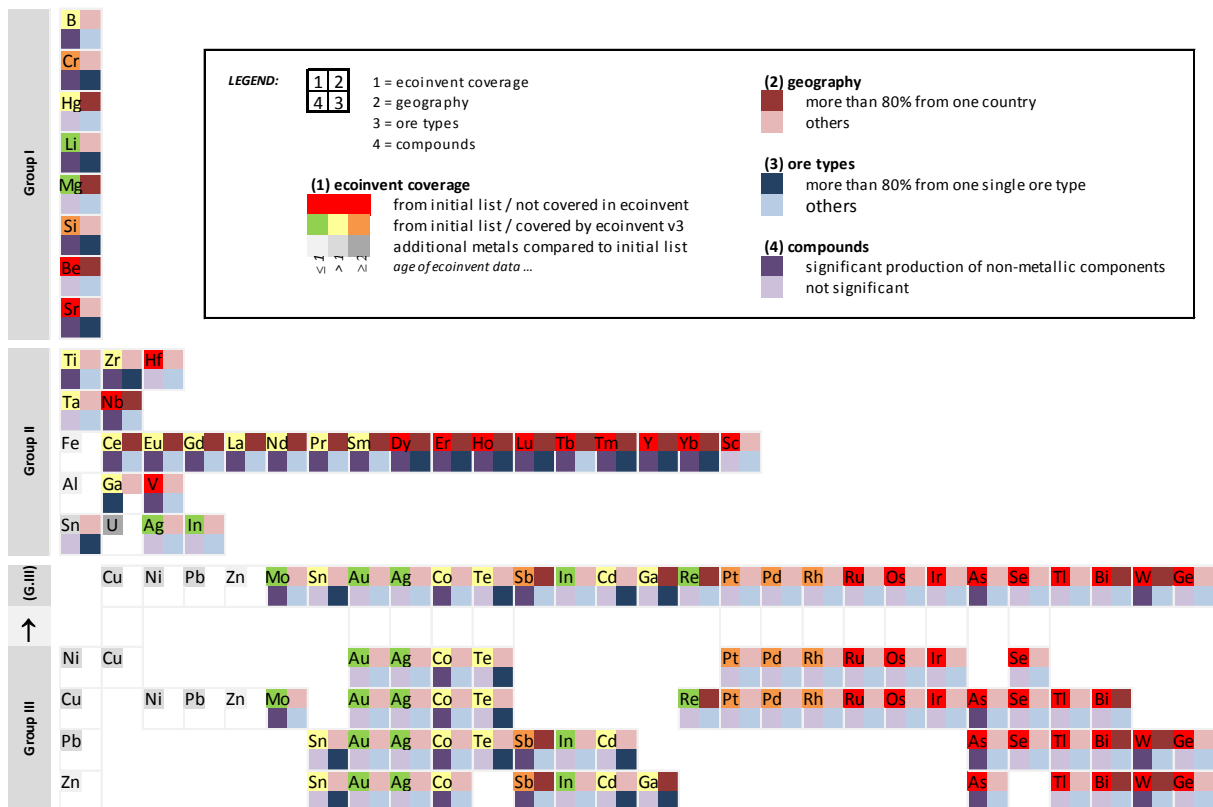


Figure 2. Overview of the grouping of the here examined scarce and critical metals, together with the result of the investigation of the four issues described above in Chapter 2.

According to Figure 2, there are a total of seven host metals that are concerned when analysing the supply chains of these various scarce and critical metals. Four of these seven – i.e. Cu, Ni, Pb and Zn – are part of the interlinked Group III metals, while the three others represent separate chains within the Group II. Also based on this overview, a priority list for the further modelling of the various elements was defined, stipulating:

- 1st priority: **Group III metals** (i.e. the Ni, Cu, Pb and Zn host metal production systems) → all four additional (host) elements (Cu, Ni, Pb, and Zn) are modelled as an integral part of this group of metals.
- 2nd priority: **Group II metals** (i.e. the Ti, Ta, Fe, Al, and Sn host metal production systems) → the three additional elements are not modelled in the framework of this project here; but only the linking to the process chains of these (host) metals.
- 3rd priority: **Group I metals** → this group will be modelled only if the budget for Phase III hasn't been spent already for the first two priority areas above.

3. Metals primary production system modelling

3.1. Current ecoinvent metals primary production LCI modelling approach

The current ecoinvent database coverage of critical and scarce metals is summarised in Figure 2 above. Of these 61 metals identified as being critical or scarce in Phase 1 of this project, datasets are available for the primary production of 30 of those. Datasets for 18 of those metals are based on data sources that are between 12 and 20 years out of date, whilst 6 are based on sources >20 years old (see Table 2). Many of these datasets have not been updated since ecoinvent v1.1 or 1.3. Datasets for over 50% of metals identified as being critical or scarce are not currently available in the ecoinvent database.

Table 2. Results of the analysis concerning the age of the information in the various metals datasets in the current ecoinvent version.

	No. of products	Age		No. of products	Age
uranium	15	33	gadolinium	2	15
antimony	2	21	boron	2	15
platinum	6	20	cerium	2	15
rhodium	6	20	cobalt	1	15
Silicon	29	20	titanium	18	14
tellurium	5	17	tin	20	13
Nickel	39	17	gallium	2	13
cadmium	16	16	lead	19	13
Copper	62	16	indium	7	12
chromium	18	16	molybdenum	3	12
tantalum	1	15	magnesium	12	12
praseodymium	2	15	silver	17	11
lanthanum	2	15	gold	18	11
neodymium	2	15	zinc	26	11
zirconium	4	15	lithium	11	9
samarium	2	15	iron	56	8
europium	2	15	aluminium	97	7

More generally, the ecoinvent database currently contains ~100 LCI datasets for metals primary production (see Annex 2). Four of the metal primary production systems have been modelled in a modular fashion (aluminium, iron and steel, copper, and lead and zinc), but the majority are modelled as ‘black boxes’, within which all the materials, resources and

emissions required for all activities in the various process stages (i.e. from mining to refining) are aggregated and listed without any relation to the specific activities to which they correspond. In using these existing datasets, practitioners face the following challenges:

- Firstly, as the datasets describe specific situations, there is a lack of flexibility in how they can be used. For example, if a user is interested in the impacts of a sphalerite concentrate production activity based on different ROM sphalerite-containing ore composition than that for which the dataset was developed, then post-processing of the data will be required to adjust the input ore composition accordingly, or else the user will be forced to adapt their study to the same ore composition as found in the database. However, users may not be familiar with the procedure for modifying default data.
- Secondly, there is a lack of transparency in the database as the metals production datasets are built to a large extent as ‘black boxes’. This hinders users from gaining an understanding of the key ‘hot spots’ of emissions in their systems.
- Thirdly, there is a general lack of interconnection between metals production systems. For example, there are datasets for the primary production of aluminium and gallium, but, despite gallium being a major companion metal of aluminium production, they are not connected. This approach does not adequately reflect the reality of metals primary production systems.
- Fourthly, the lack of harmonisation between metals primary production systems means that there are multiple datasets available that cover the same or very similar activities, e.g. open pit mining.

3.2. Proposed life cycle inventory modelling framework

In order to provideecoinvent users with more a representative, flexible, and transparent set of metals primary production LCI datasets, there is a need for a new LCI data model for the primary production of metals. The requirements for the model are that it must be:

- (i) easily adaptable and applicable for the full range of metal primary production systems, i.e. ensuring that all of the metal primary production systems can be modelled using the same framework; and
- (ii) duly reflective of the interconnectivity of real world metals primary production systems, with the recovery and production of companion metals, which includes the scarce and critical metals, linked to the primary production systems of host metals.

To meet these requirements, the new LCI data model has been developed with a high degree of modularity, with the primary production of a metal modelled by linking together modules that represent different processing stages. Critical and scarce metals (i.e. companion metals) are recovered from products of host metal primary production activities and sent for subsequent extraction and refinement to yield one or more primary products. The benefits of this approach are that it enables the wide variety of possible processing routes for different metals to be modelled, and it means that datasets can be developed to cover a variety of metal production systems, rather than a single, specific situation.

3.3. System description

In developing a modular approach to modelling metal primary production systems, it is first necessary to define a representative and appropriate decomposition of a ‘generic’ metal primary production system into modules corresponding to key processes (activities and products). Metals primary production comprises four principle processing stages: mining, concentration (‘mineral processing’), extraction, and refinement and casting. Each of these stages can be further subdivided into various processing stages, each of which may be performed using a number of different methods, either singularly or in combination.

Mining activities produce run of mine (ROM) ore that is processed (typically close to the mine site) to separate the gangue from the valuable minerals and yield a mineral concentrate product. This concentrate is then sold to metal producers who process it to separate and extract the valuable metal(s). Crude metal products are then sold directly to fabricators or undergo further refinement to increase the metal purity prior to sale. These processes stages also yield a variety of intermediate products (e.g. anode slime from electrowinning, slag from smelting, or hot flue gas from roasting) that may be further processed to recover other valuable, “minor” metals as by-products of the “host” metal production process.

A schematic of the generic metals primary production LCI model is shown in Figure 3. The figure shows metals production from cradle to gate and cover the four primary production stages, represented in the figure by different colours: mining (orange), concentration (green), extraction (purple), and refinement and casting (blue). Transforming activities are represented in the figure as rectangles, whilst processes are represented as hexagons. Their colours correspond to the primary production stages to which they belong. Market activities for products are represented as yellow trapezoids. Flows of products to market or transforming

activities are represented as arrows. Crude metals are refined into refined metals, which are then cast into marketable forms (e.g. ingots and wire bars). Marketable host metal products are represented as maroon hexagons. The production of a given host metal may will yield a number of by-products and waste outputs. In some cases, these waste streams (e.g. overburden/waste rock, tailings, and leach residues) require treatment to eliminate toxic or hazardous chemicals prior to disposal. Waste products that require treatment prior to disposal are represented as black hexagons in the figure. In other cases, these by-products may contain valuable metals that are profitable to recover. Valuable metal-bearing by-products that require further processing to yield marketable forms of their constituent metals are represented as light pink hexagons in the figure. Marketable forms of companion metals recovered from within the host metal primary production system are represented as bright pink hexagons.

The rest of this section comprises an overview of the various process stages of the metals primary production system. A non-exhaustive overview of the key LCI flows (excluding infrastructure), including identification of the reference product (R), for each process stage is also provided. This overview will provide the basis for the work to be undertaken in Phase III, i.e. to compile the actual data.

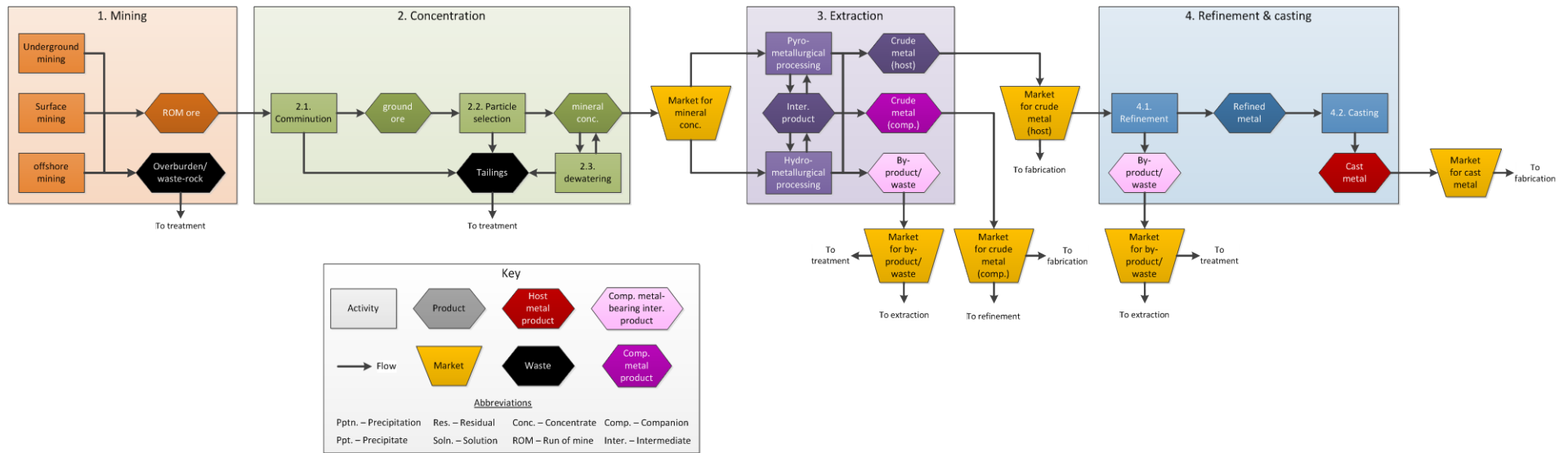


Figure 3. Schematic of the generic metals primary production LCI data model.

3.3.1. Mining

The mining phase encompasses the extraction of valuable metal ores from the Earth's crust. Mining activities are here grouped into three types: surface mining, underground mining, and offshore mining. The type of mining activity employed to extract a given ore will depend primarily on mining cost, which is a function of the ore grade, the depth of the ore deposit and the local geology: rich, shallow ore deposits are generally mined through surface methods whilst deep ore deposits are usually mined through subsurface methods. Some ore bodies are only present offshore and, hence, must be mined using offshore mining methods. Key LCI flows for mining activities are presented in Table 3.

Table 3. Key LCI flows for mining activities.

Inputs	Outputs
Elementary flows	
Ore, from ground	PM, to air
Inert rock, from ground	
Land use	
Product flows	
Transport	ROM ore (R)
Diesel	Overburden
Explosives	Waste rock

3.3.2. Concentration

Concentration (also known as mineral processing) involves the physical and/or chemical processing of ROM ores to change their physical and/or chemical properties and ultimately produce a mineral/ore concentrate that is either ready for use or suitable for further processing. Concentration activities entail three types of operation, which are undertaken sequentially: (1) comminution; (2) particle selection; and (3) dewatering.

3.3.2.1. Comminution

Comminution is the first step in concentration and encompasses all activities associated with the size reduction or severance of ores. These activities are here grouped into two types: (1) crushing, which almost invariably involves two or more stages of mechanical crushing of the ROM ore to a manageable size; and (2) grinding (milling), which involves the reduction in

particle size below the limits attainable through crushing. Key LCI flows for comminution activities are presented in Table 4.

Table 4. Key LCI flows for comminution activities.

Inputs	Outputs
Elementary flows	
Water	PM, to air
Land use	
Product flows	
ROM ore	Ground ore (R)
Electricity	Tailings

3.3.2.2. Particle selection ('mineral separation')

Particle selection involves the separation of one or more valuable mineral products, known as concentrates, from waste or gangue minerals (tailings). Particle selection processes can be divided into two main categories: sizing separation, which is applied to produce a product of a comminuted size required for subsequent processing, and concentration separation, which is applied to obtain valuable mineral concentrates.

There are two size separation processes, screening and classification. Screening essentially involves the mechanical separation of particles based on their size, with the undersize, or 'fines' allowed to pass through a screen or sieve whilst the oversize, or 'tails', are not. Classification, generally, is a process in which material aggregates of mixed sizes and different specific gravities are allowed to differentially settle in a medium (commonly water).

Concentration separation processes can be grouped into four categories: (1) physico-chemical separation methods, which include various flotation and colloidal methods, as well as in-situ leaching (see Section 3.3.3.2.1); (2) magnetic separation methods, in which materials are classified based on their magnetic characteristics; (3) gravity separation methods, in which materials are classified based on their specific gravities; and (4) electrostatic separation methods, in which materials are classified based on their electrostatic potential. Key LCI flows for particle selection activities are presented in Table 5.

Table 5. Key LCI flows for particle selection activities.

Inputs	Outputs
Elementary flows	
Water	PM, to air Metals, to surface water VOCs, to air
Product flows	
Ground ore	Tailings
Electricity	Mineral concentrate (R)
Lime	
Diesel	
Chemicals (e.g. flotation reagents)	

3.3.2.3. Dewatering

Since the majority of concentration operations are conducted wet, dewatering is typically essential to produce a dry mineral concentrate suitable for freight and/or for subsequent processing. The dewatering process comprises up to three sequential stages: (1) sedimentation, (2) filtration, and (3) thermal drying, with each stage producing an end product of increasingly reduced water content. Key LCI flows for dewatering activities are presented in Table 6.

Table 6. Key LCI flows for dewatering activities.

Inputs	Outputs
Product flows	
Mineral concentrate	Mineral concentrate, dewatered
Diesel	
Coagulants (salts containing charged cations, lime, sulfuric acid, etc.)	

3.3.3. Extraction

During extraction, the mineral/metal concentrates produced during concentration are proceeded to extract and purify metals. Extraction is performed using a variety of pyrometallurgical and hydrometallurgical methods, which are often combined in practice to exploit the best qualities of each. The extraction stage typically involves some form of feed preparation and/or concentration, followed by purification and metal recovery.

3.3.3.1. *Pyrometallurgical extraction*

Pyrometallurgy refers to the use of processes undertaken at high-temperatures to extract and refine metals from ores and concentrates. Pyrometallurgical extraction comprises three principle stages: (i) feed preparation; (ii) smelting; and (iii) converting.

3.3.3.1.1. *Feed preparation*

Following concentration, ores and metal concentrates will usually still contain some gangue and water, which must be removed as far as possible prior to extraction. Feed preparation methods include:

- i. Drying, which involves the removal of water from the feed (dehydration), either through heating or exposing the feed to reduced pressures, and is carried out in a variety of reactor types, such as a rotary kiln, fixed bed, fluidised bed, or vacuum retort (Gupta, 2003).
- ii. Calcination, which involves the conversion of metal carbonates to oxides and is typically carried out in a horizontal rotary kiln, although shaft furnaces and fluidised bed reactors may also be used.
- iii. Roasting, of which there are many different types of processes that may be used, with each intended to produce a specific chemical reaction and yield a product ('calcine') suitable for the particular subsequent processing operation. The five primary roasting types are: (i) oxidising roasting, which is mostly applied to sulphidic metals to convert (partially or fully) them into oxides prior to subsequent smelting and involves the heating of sulphides in air or oxygen; (ii) sulphatising roasting, in which sulphidic metals are converted to sulphates, (iii) reductive roasting, in which oxides are reduced (partially or fully) to metals; (iv) chloridising roasting, in which metal oxides are converted to chlorides by heating with a source of chlorine; and (v) volatising roasting, in which volatised oxides are eliminated through conversion to gases. Depending on the type of process, roasting may be carried out in a variety of appliances, including moving grate furnaces, multiple hearth furnaces, rotary kilns, and fluidised bed roasters.
- iv. Sintering, which involves the agglomeration of fine particles to yield a product of a sufficient size for subsequent smelting.

Key LCI flows for feed preparation activities are presented in Table 7.

Table 7. Key LCI flows for feed preparation activities.

Inputs	Outputs
Elementary flows	
	PM, to air
	SO ₂ , to air
	VOCs, to air
	Dioxins and furans, to air
	Metals, to air
Product flows	
Transport	Calcine (R)
Mineral concentrate	Off gas
Mineral concentrate, dewatered	
Heat	
Electricity	

3.3.3.1.2. Smelting

Smelting is a process in which the constituents of the metallic charge are heated to a molten condition, typically in the presence of a flux, and separated into two or more phases, which may be slag, matte, speiss, or metal. There are three different types of smelting:

- i. Reductive smelting, which involves the reduction of metal oxides with carbon and a flux and is typically carried out in a blast furnace.
- ii. Matte smelting, which involves the melting and subsequent fusion of the sulphidic metal charge with a flux to yield a homogenous matte product and may be carried out in one of many different types of furnace, although the reverberatory furnace is most commonly used.
- iii. Flash smelting, in which unroasted an sulphidic metal charge is oxidised at high temperatures to separate layers of slag and matte and produce a sulphuric acid-enriched off-gas.

Key LCI flows for smelting activities are presented in Table 8. Note that, depending on the metal and the operation, the reference product may be the matte, dross, speiss, or slag products.

Table 8. Key LCI flows for smelting activities.

Inputs	Outputs
Elementary flows	
	PM, to air
	SO ₂ , to air
	NO _x , to air
	VOCs, to air
	Dioxins and furans, to air
	CO ₂ , to air
	Nickel carbonyl, to air (Ni only)
	Metals, to air
Product flows	
Calcine	Off gas
Mineral concentrate, dewatered	Matte (R)
Heat	Dross (R)
Chemicals	Speiss (R)
Silica	Slag (R)
Lime	
Electricity	
Coke	

3.3.3.1.3. *Converting*

The Converting process involves the blowing of air through molten matte in a converter, resulting in two stages of oxidation: (i) slag formation, and (ii) base metal production. Key LCI flows for converting activities are presented in Table 9.

Table 9. Key LCI flows for converting activities.

Inputs	Outputs
Elementary flows	
	PM, to air
	SO ₂ , to air
	NO _x , to air
	VOCs, to air
	Dioxins and furans, to air
	Metals, to air
Product flows	
Electricity	Blister copper (Cu only) (R)
Heat	Slag
Matte	Off gas

3.3.3.2. Hydrometallurgical extraction

Hydrometallurgy refers to the use of processes that involve the use of aqueous chemistry to extract and refine metals from ores and concentrates. Following concentration, hydrometallurgical processing invariably begins with dissolution of metals contained within the starting material by leaching. Note that the leaching step may be performed as part of the particle selection stage during mineral concentration. Following this, the extracted metals may be processed directly for metal recovery or are, as is far more common, purified to remove impurities and produce a concomitant concentration of the metal solution prior to metal recovery.

3.3.3.2.1. Leaching

Leaching involves the treatment of minerals with water or acid solutions (solvents) to dissolve and separate metals from gangue/undesirable material. Techniques for the dissolution of metals from ores and concentrates are manifold and varied. Types of leaching include in-situ leaching, heap leaching, dump leaching, pressure leaching, and pneumatically or mechanically agitated leaching. Key LCI flows for leaching activities are listed in Table 10.

Table 10. Key LCI flows for leaching activities.

Inputs	Outputs
Elementary flows	
Water	Metals, to surface water
Product flows	
Transport	Leach residue
Mineral concentrate	Leach solution (R)
Leaching chemicals	Wastewater
	Acid mist

3.3.3.2.2. Purification

Following leaching, the resulting leach liquors will invariably still contain impurities. Leach liquors are therefore typically subjected to a purification phase prior to metal(s) recovery to remove undesirable impurities and, in certain cases, increase the metal concentration in the solution. The range of methods that are used or that may potentially be useful for the purposes

of solution purification is extensive (for details, see Gupta, 2003; Free, 2013). However, purification is typically achieved through one or a combination of the following processes:

- i. Solvent extraction ('liquid-liquid extraction'), which involves the contacting of a dissolved, non-aqueous organic solution with the metal-bearing aqueous solution, resulting in the preferential transfer of the metal from the solution in the aqueous phase to the solution in the organic phase. The non-aqueous, organic phase is then scrubbed through treatment with a fresh aqueous phase to remove impurities before the organic solvent is stripped, resulting in the separation of the metal from the non-aqueous medium.
- ii. Ion exchange, in which the metal-bearing aqueous solution is passed through a stationary organic resin, resulting in the sorption of the metal ions by ion-exchange reactions.
- iii. Carbon absorption, in which the metal-bearing aqueous solution is placed in contact with activated carbon, resulting in the stripping of the metal species that are absorbed on the activated carbon reagent.
- iv. Reverse osmosis ('ultrafiltration'), in which a metal-bearing solute is filtered out from a concentrated solution through a membrane at high pressure.
- v. Precipitation, which is commonly used as a hydrometallurgical metal recovery process but may be used during the leach liquor purification stage. Precipitation encompasses a wide variety of different physical and chemical processes (for details, see Gupta, 2003, p531) that, generally, result in the dissolution of metals from aqueous solutions following the addition of some chemical compound(s).

Key LCI flows for purification activities are presented in Table 11.

Table 11. Key LCI flows for purification activities.

Inputs	Outputs
Elementary flows	
Water	SO ₂ , to air CO ₂ , to air Water, to air
Product flows	
Leach solution	Metal-bearing solution (R)
Anode	Solid residue/sludge
Electricity	Wastewater
Chemicals	Acid mist

3.3.3.2.3. Metal recovery

The metal recovery stage involves the recovery of metals from concentrated solutions. Metals may be recovered from one or a combination of the following processes:

- i. Precipitation, which is described in the previous section.
- ii. Electrolysis ('electrowinning'), which involves the dissolution of metals as positive ions in an electrolyte that is subjected to an electric current applied between a positive (anode) and negative (cathode) electrode pair submersed within the electrolyte, with the positive metal ions drawn to and deposited on the negative cathode in their neutral metallic state. Electrolysis is the most extensively practiced hydrometallurgical metal recovery process.
- iii. Cementation, which works on the principle of contact reduction whereby, upon contact, the electrons from a less noble metal are given up to a more noble dissolved metal (the desired metal), resulting in the dissolution of the less noble metal and the reduction of the initially dissolved metal to the metallic state.
- iv. Gaseous reduction, in which metals are recovered from solution using a (typically gaseous) reducing agent, such as hydrogen gas, hypophosphite, or formaldehyde.

Key LCI flows for metal recovery activities are presented in Table 12.

Table 12. Key LCI flows for metal recovery activities.

Inputs	Outputs
Elementary flows	
Water	SO ₂ , to air CO ₂ , to air Water, to air Fluorides, to air (Al only) PFCs, to air (Al only)
Product flows	
Metal-bearing solution	Crude metal (R)
Electricity	Electrolyte bleed
Chemicals	Spent electrodes Sludge Wastewater Acid mist Anode slimes

3.3.4. Refinement and casting

3.3.4.1. Refinement

Metals recovered by pyrometallurgical or hydrometallurgical extraction methods often contain a number of impurities, such as sulphur, oxygen from the mineral concentrate, metal impurities present in the mined resource, or remnant reduction agents. The principle purpose of the refining phase is to remove these impurities to yield a high purity metal product as well as to recover valuable metals as by-products. The range of refinement processes that are used or that may be useful is extremely wide, with the type(s) used in each situation related to the specific objectives of the production operation (i.e. metal utilisation market demands), the particular metal, and the particular impurity or impurities that require removal (Gupta, 2003). In general terms, refining processes can be classified into the following four groups:

- i. Metal-slag processes ('fire refining'), which involves the preferential oxidation of less noble metals from more noble metals. Residual sulphur and the less noble metal impurities are removed through oxidation and slagging, with the slag periodically skimmed off, whilst residual oxygen is removed through subsequent deoxidation. This process yields (*inter alia*) a high purity metal product and a slag containing valuable metals that may be recovered following further processing.
- ii. Metal-gas processes (e.g. fractional distillation, vacuum treatment, carbonyl, disproportionation reaction, and iodide decomposition), in which metal refinement is based on metal-gas transfer reactions. Metal-gas processes, particularly fractional distillation, are the most widely used in metal refining (Gupta, 2003).
- iii. Metal-metal processes (e.g. liquation and zone refining), in which phase diagrams are utilised and the differences in the melting points and densities of the solvent (the metal) and the solute (the impurity) are exploited through selective melting to separate the constituents of the crude metal feed.
- iv. Electrolytic refining ('electrorefining'), which is a hydrometallurgical process similar to electrowinning but that differs in that the recovered metals of intermediate purity are utilised as the anode. The Electrorefining process then consists of electrolytically dissolving the metal from the anode and then recovering the higher purity metal after it has electrodeposited on the cathode. Undissolved impurities tend to settle at the bottom of the cell to form 'anode slime'. This slime often contains many scarce and critical metals and, consequently, are typically recovered and sent for further processing to recover the desirable metals.

The key LCI flows for refining activities will vary considerably depending on the type of refining process used. Hence, a summary table is not included here. The reference product of the refining process is refined metal.

3.3.4.2. Casting

During casting, refined metals are melted and cast into some unfabricated form (e.g. slab, ingot, etc.) suitable for subsequent fabrication/manufacturing. Key LCI flows for casting activities are presented in Table 13.

Table 13. Key LCI flows for casting activities.

Inputs	Outputs
Elementary flows	
	Water, to air
	CO ₂ , to air
Product flows	
Refined metal	Cast metal (R)
Heat	Wastewater
Electricity	Off gas

3.3.5. Off gas & dust management

Off gases, including (*inter alia*) flue gas, mists, and fumes, are produced during most metal production processes. For example, hot flue gases are generated during pyrometallurgical extraction (sintering, roasting, smelting, etc.) and refinement processes, acid mists are generated from electrolyte solutions during electrolysis, whilst metal fumes are generated during the melting and casting of molten metals. These gases contain a number of pollutants (e.g. particulate matter, sulphur dioxide, nitrogen oxides, dioxins and furans, and volatile organic compounds) that must be managed to prevent and control their emission to the environment. Off gases may also contain trace amounts of other metals – including, as well as base metals, a number of scarce and critical metals, such as tin, gold, silver, antimony, indium, cadmium, arsenic, selenium, thallium, bismuth, and germanium – in various forms and compounds. Where particles of high value are produced in sufficient quantities, recovery of these metals may be financially and practically viable (see Section [Secondary metal production]). This has resulted in the increased use of devices such as cyclones, scrubbers, and electrostatic precipitators that enable the recovery of these high value particles as well as

prevent and control the emission of pollutants to the environment. Furthermore, electrostatic precipitation and other dust removal methods can, following palletisation, yield a pelletised dust product that can be returned to the extraction processing.

Sulphur dioxide is produced during the processing of metal sulphide concentrates. Its concentration in the off gas stream varies widely depending on the composition of the feed. Where SO₂ is produced at concentrations of more than 5-7% of the gas stream, it can be utilised to produce marketable forms of sulphur, such as liquid sulphur dioxide, elemental sulphur, and, most commonly, sulphuric acid. However, due to the energy-intensive nature of the technologies used to yield the various sulphur products, SO₂ is typically only utilised in this manner if a direct application (i.e. a local market) for the sulphur product can be identified. Key LCI flows for off gas management activities are presented in Table 14. Note that, depending on the plant, the reference product may be liquid sulphur dioxide, sulphuric acid, or elemental sulphur.

Table 14. Key LCI flows for off gas management activities.

Inputs	Outputs
Elementary flows	
	PM, to air
	SO ₂ , to air
Product flows	
Off gas	Flue dust
Electricity	Sludge
Reaction catalysts (e.g. platinum)	Spent filter material
	Liquid sulphur dioxide (R)
	Sulphuric acid (R)
	Elemental sulphur (R)

3.4. Geographical context

Metal supply chains form a complex, globalised, and interconnected network of material flows (see Figure 4). Metals are heterogeneously distributed on the Globe and economically extractable ores are often found in a few countries only. Different metals are mined, processed and traded in different countries through interconnected global supply chains.

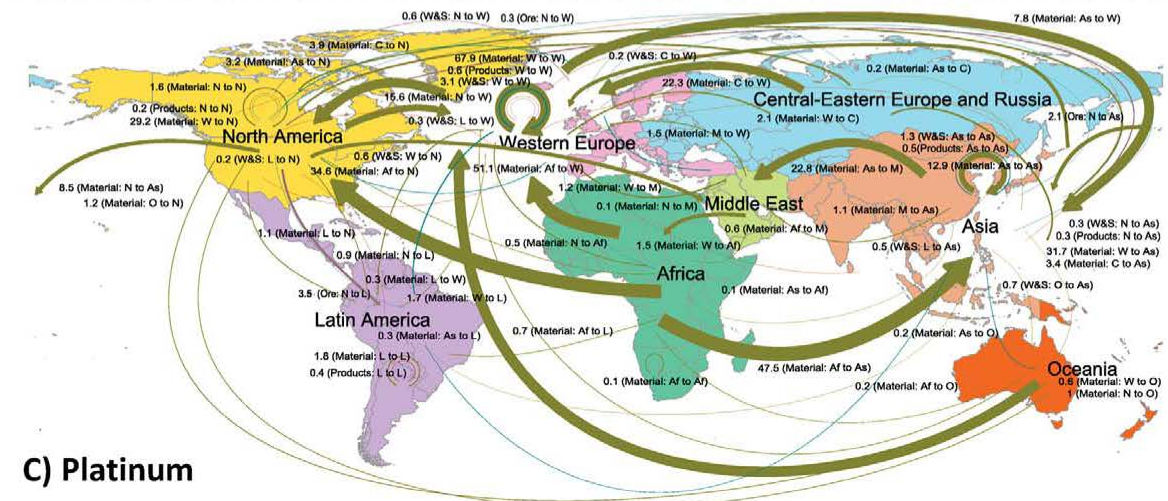
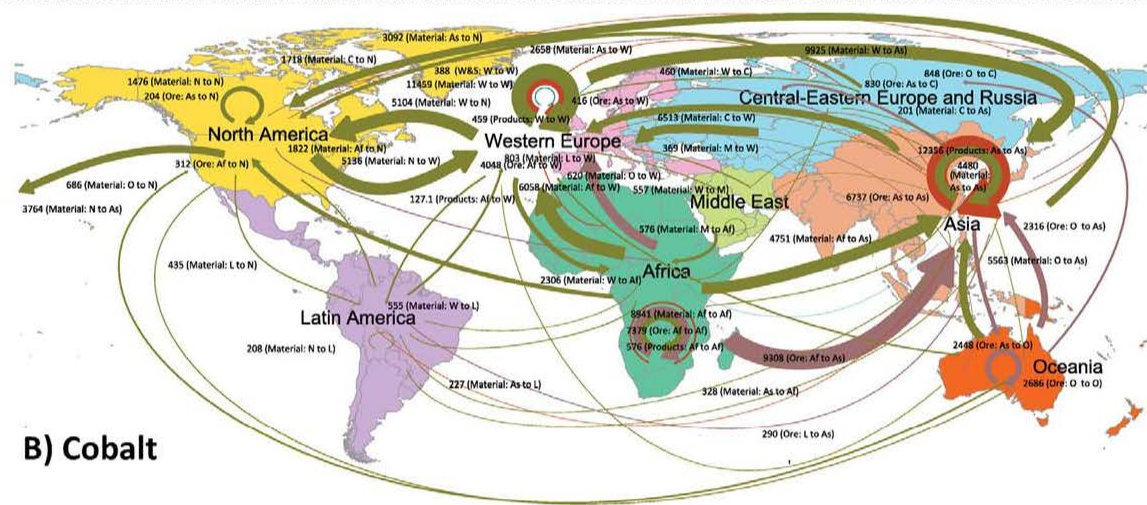
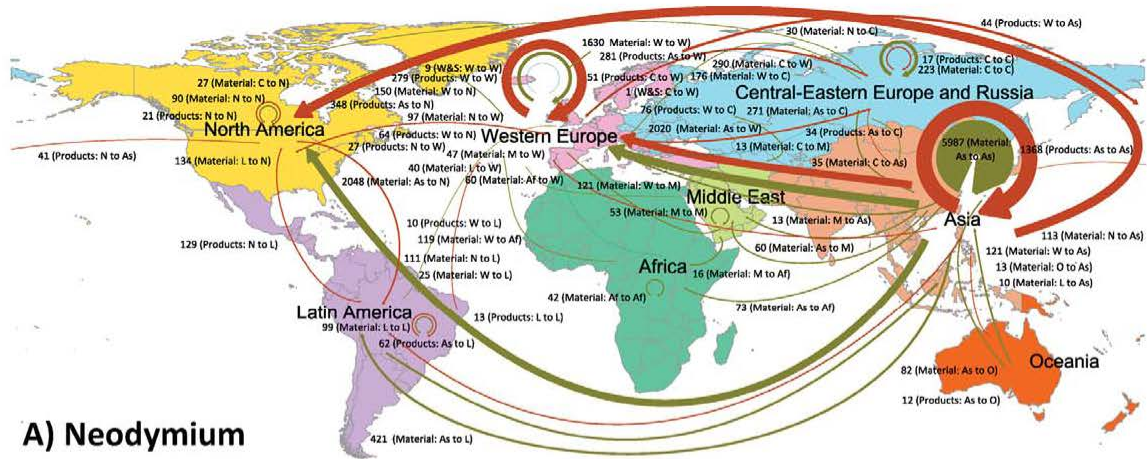


Figure 4. Global flows of Nd, Co and Pt amongst eight regions by four types of trade commodity (ore, materials, products, and waste and scrap) in 2005. Each legend indicates the quantity (in t for Nd and Pt, in kt for Co), the commodity type, and the regions driving the flow (As: Asia, Af: Africa, C: Central-Eastern Europe and Russia, L: Latin America, M: Middle East, N: North America, O: Oceania, W: Western Europe). Source: Nansai et al., (2015).

Regional specificities related to technological development, energy sources, importance of manual labour, or environmental regulations can have a large influence on the environmental burden of metal production systems. In order to be representative, LCI datasets on metal production should therefore be regionalised as much as possible, i.e. different LCI datasets should be available for different geographies. The latest version of the ecoinvent database (v.3) has improved capabilities for regionalisation of data. It now contains hundreds of non-European datasets related to energy production and other background data, as well as regional consumption mixes for various products.

The LCI modelling approach proposed here makes use of the improved capabilities of ecoinvent in order to provide regionalised LCI datasets on scarce and critical metals production. Production shares of different countries have been collected for each host and companion metals, in order to determine where metals are mostly mined, processed and refined (see Table 15). This table also shows the number of countries that need to be taken into account in order to cover at least 50% and 80% of the global supply of each metal. It serves as an indication of the number of regionalised datasets needed for each metal to cover most of the global supply, depending on the target level of representativeness. For some metals (e.g. gold, cadmium, and selenium), a large number of countries would need to be included to cover $\geq 80\%$ of global production. However, in many of these cases the same technology is used to produce the metals in each country. Hence, a single dataset can be used to reflect the production of the metal using this common technology. This dataset can be then adapted to reflect the different energy and material consumption mixes used in the different regions.

In other cases, different technologies may be used in different regions to produce the same metal and multiple datasets are required to reflect region-specific metal production. For example, to cover 80% of global palladium production, two country-specific datasets are required: one for Russia and one for South Africa (see Table 15). Palladium is produced in Russia as a by-product of nickel production and South Africa as a by-product of platinum production (see Annex 1). Hence, two separate datasets are required to represent the production of palladium from these two regions, with each reflecting a different technology.

Table 15. Share of metal global supply by mining and refining location. Based on this, the number of countries for which data must be collected to cover at least 50% or 80% of global supply is also presented.

Z	Element	Mining locations (USGS 2015) Share in global supply indicated in %	Refining locations (USGS 2015) Share in global supply indicated in %	Number of countries needed to cover:	
				≥50% of global supply (refining if mining unavailable)	≥80% of global supply (refining if mining unavailable)
51	Antimony	China (86), Tajikistan (3), Bolivia (3), South Africa (2), Russia (2), Turkey (1), Australia (1), other (2)		1	1
33	Arsenic		China (55), Chile (22), Morocco (18), Russia (3), Belgium (2)	1	3
4	Beryllium	USA (90), China (8), Mozambique (1)		1	1
83	Bismuth	China (86), Mexico (11), Canada (2), Russia (1)	China (90), Mexico (5), Japan (3), Canada (1), Kazakhstan (1)	1	1
5	Boron	Turkey (41), USA (33), Argentina (11), Chile (11), Peru (7), China (3), Bolivia (2), Kazakhstan (1)		2	3
48	Cadmium		China (32), Korea, rep. Of (18), Japan (8), Mexico (7), Canada (6), Kazakhstan (5), Russia (5), Peru (3), Netherlands (3), India (2), Bulgaria (2), Poland (2), Australia (2), Germany (1), Norway (1), Brazil (1), Korea, North (1)	2	7
58	Cerium	China (85), USA (8), Australia (4), India (1), Russia (3)		1	1
24	Chromium	South Africa (43), Kazakhstan (20), India (13), Turkey (7), Finland (3), Pakistan (2), Oman (2), Brazil (2), Russia (2), Zimbabwe (2), Other (4)	South Africa (33), China (31), Kazakhstan (15), India (9), Russia (6), others (6)	2	4
27	Cobalt	Congo, DR (56), China (6), Russia (6), Zambia (6), Canada (4), Australia (4), Cuba (3), Brazil (3), Morocco (3), New Caledonia (3), Philippines (2), South Africa (2), others (2)		1	5
66	Dysprosium	China (99), Australia (1)		1	1
68	Erbium	China (99), Australia (1)		1	1

Z	Element	Mining locations (USGS 2015) Share in global supply indicated in %	Refining locations (USGS 2015) Share in global supply indicated in %	Number of countries needed to cover:	
				≥50% of global supply (refining if mining unavailable)	≥80% of global supply (refining if mining unavailable)
63	Europium	China (93), USA (2), Australia (4), Russia (1)		1	1
64	Gadolinium	China (97), USA (1), Australia (2)		1	1
31	Gallium	Australia (27), China (17), Indonesia (15), Brazil (13), India (7), Guinea (6), Jamaica (4)	China (78), Germany (7), Kazakhstan (4), Korea rep. (3), Ukraine (3), Russia (2), Japan (2), Hungary (1)	3	2
32	Germanium		China (59), Canada (17), USA (15), Finland (6), Russia (3)	1	3
79	Gold	China (14), Australia (10), USA (9), Russia (7), South Africa (7), Peru (6), Canada (4), Indonesia (4), Uzbekistan (3), Ghana (3), Mexico (3), Argentina (2), Brazil (2), Papua New Guinea (2), Colombia (2), Tanzania (2), Chile (2), Mali (2), others (15)		6	16
72	Hafnium	Australia (56), South Africa (11), China (10), Indonesia (7)	France (47), USA (47), Russia (2), Ukraine (2)	1	4
67	Holmium	China (98), Australia (1), Russia (1)		1	1
49	Indium	Peru (50), Bolivia (24), Canada (12), Australia (8), others (6)	China (52), Korea, rep. Of (19), Japan (9), Canada (8), France (4), Belgium (4), Russia (2), Peru (1), Germany (1)	1	3
77	Iridium		South Africa (79), Russia (19), Zimbabwe (2), Canada (1)	1	2
57	Lanthanum	China (86), USA (8), Australia (3), India (1), Russia (2)		1	1
3	Lithium	Chile (45), Australia (34), Argentina (10), USA (5), China (5), Brazil (1), Portugal (1)		2	3
71	Lutetium	China (98), Australia (1), Russia (1)		1	1
12	Magnesium		China (86), Russia (5), Israel (4), Kazakhstan (3), Brazil (2)	1	1
80	Mercury	China (85), Kyrgyzstan (5), Chile (3), Russia (3),		1	1

Z	Element	Mining locations (USGS 2015) Share in global supply indicated in %	Refining locations (USGS 2015) Share in global supply indicated in %	Number of countries needed to cover:	
				≥50% of global supply (refining if mining unavailable)	≥80% of global supply (refining if mining unavailable)
		Peru (2), Tajikistan (2)			
42	Molybdenum	China (38), USA (22), Chile (15), Peru (10), Mexico (4), Canada (3), Iran (3), Armenia (2), Russia (2), Mongolia (1)		2	4
60	Neodymium	China (91), USA (4), Australia (3), India (1), Russia (1)		1	1
41	Niobium	Brazil (92), Canada (7), Nigeria (1)		1	1
76	Osmium		South Africa (79), Russia (19), Zimbabwe (2), Canada (1)	1	2
46	Palladium		Russia (46), South Africa (42), Zimbabwe (5), Canada (2), USA (2), Others (3)	2	2
78	Platinum		South Africa (72), Russia (14), Zimbabwe (6), Canada (4), USA (2), others (2)	1	2
59	Praseodymium	China (90), USA (6), Australia (3), India (1), Russia (1)		1	1
75	Rhenium		Chile (51), Poland (15), USA (15), Uzbekistan (11), Kazakhstan (5), Armenia (2), others (1)	1	3
45	Rhodium		South Africa (82), Russia (9), Zimbabwe (5), Canada (2), USA (2)	1	1
44	Ruthenium		South Africa (79), Russia (19), Zimbabwe (2), Canada (1)	1	2
62	Samarium	China (93), USA (2), Australia (3), India (1), Russia (1)		1	1
21	Scandium	China (70), Russia/Ukraine (30)	Distribution of metal production probably equal to mining distribution	1	2
34	Selenium		China (19), Japan (18), Germany (9.4), USA (6.4), Russia (6), Belgium (6), India (5), Canada (5), Norway (4), South Korea (4), Kazakhstan (3), Philippines (3), Chile (3),	4	10

Z	Element	Mining locations (USGS 2015) Share in global supply indicated in %	Refining locations (USGS 2015) Share in global supply indicated in %	Number of countries needed to cover:	
				≥50% of global supply (refining if mining unavailable)	≥80% of global supply (refining if mining unavailable)
			Mexico (2), Sweden/Finland (2), Peru (2), Others (4)		
14	Silicon		China (56), Brazil (11), Norway (8), USA (8), France (6), Russia (3), South Africa (3), Australia (2), Canada (2), Germany (2), Spain (2)	1	4
47	Silver	Mexico (18), China (16), Peru (14), Australia (8), Russia (6), Bolivia (5), Poland (5), Chile (5), USA (4), Canada (2), others (16)		4	10
38	Strontium	China (43), Spain (37), Mexico (10), Argentina (5), Iran (4), Morocco (1)	Unknown, but different from mining locations	2	2
73	Tantalum	Rwanda (52), Congo, DR (17), Brazil (8), Mozambique (7), China (5), Nigeria (5), Ethiopia (3), Burundi (1)		1	4
52	Tellurium		China (18), Japan (14), Belgium (13), Germany (8), Canada (6), Russia (6), Kazakhstan (4), Philippines (4), South Korea (4), Sweden/Finland (4), India (3), Indonesia (3)	4	10
65	Terbium	China (98), USA (1), Australia (1), Russia (1)		1	1
81	Thallium		China, Kazakhstan, Russia (breakdown not available)	1-3	1-3
69	Thulium	China (98), Australia (1), Russia (1)		1	1
50	Tin	China (39), Indonesia (32), Peru (9), Bolivia (7), Brazil (4), Australia (2), Vietnam (2), others (5)	China (46), Indonesia (13), Malaysia (10), Peru (7), Thailand (6), Bolivia (4), Brazil (4), Belgium (4), USA (3), Vietnam (1)	2	3
22	Titanium	Australia (21), South Africa (20), Canada (17), China (9), Ukraine (7), Norway (6), India (5), Vietnam (5), USA (3), Brazil (2), Sierra Leone (1), others (4)		3	6
74	Tungsten	China (84), Russia (5), Canada (3), Austria (1),		1	1

Z	Element	Mining locations (USGS 2015) Share in global supply indicated in %	Refining locations (USGS 2015) Share in global supply indicated in %	Number of countries needed to cover:	
				≥50% of global supply (refining if mining unavailable)	≥80% of global supply (refining if mining unavailable)
		Bolivia (1), Portugal (1), others (4)			
23	Vanadium		China (52), South Africa (27), Russia (19), USA (1), Australia (1)	1	3
70	Ytterbium	China (98), Australia (1), Russia (1)		1	1
39	Yttrium	China (100)		1	1
40	Zirconium	Australia (56), South Africa (11), China (10), Indonesia (7), India (3), Mozambique (3), Sri Lanka (3)		1	4

The aim here is to minimise the number of datasets that will be required by focusing on the regionalisation of single technology-specific datasets. Only in the more complex situations where different technologies are used in different countries to produce the same metal will it be necessary to produce region- and technology-specific datasets.

4. Case study: The copper primary production system

4.1. Introduction

To demonstrate the application of the new LCI model framework and how it applies to real world interconnected metals primary production systems, the copper primary production system is used here as a case study. Since copper is associated with other metals, its production and results in the recovery and production of other metals, including a number of critical and scarce metals, such as (*inter alia*) molybdenum, gold, silver, and cobalt. This section describes the production of primary copper from cradle to gate, i.e. from mining of the ore and the concentration of copper minerals through to the extraction of copper metal and its refinement and casting into marketable forms. It also describes the recovery of by-product or “companion” metals from intermediate products of the copper primary production processes.

4.2. Reserves and resources of primary copper

Copper is one of the most abundant metallic elements in the earth’s crust with an average estimated concentration of around 55 mg/kg (Manson, 1982). However, only a small fraction of this copper is concentrated in sufficient quantities to be economically exploitable. Almost all exploitable copper deposits are contained within igneous rocks in the form of disseminated sulphide minerals, such as chalcopyrite (CuFeS_2), chalcocite (Cu_2S), bornite (Cu_5FeS_4), and enargite (Cu_3AsS_4). Around 90-95% of global mine production of copper comes from sulphidic ores (Ayres *et al.*, 2002). By far the most important copper deposits are of the porphyry type, which contain one or a combination of the aforementioned minerals. These deposits typically contain $\leq 1\%$ Cu. The most extensive sources of copper porphyry deposits are located in the Andes Mountain region of Chile and Peru.

Copper also occurs in oxidised ores, which are the weathered products of sulphide minerals, such as malachite ($\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$), azurite ($2\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$), cuprite (Cu_2O), and chrysacolla ($\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$). Globally, around 5-10% of mined copper production is derived from oxidised mineral deposits (Ayres *et al.*, 2002).

Copper sulphide minerals are often found in association with other sulphide and sulfarsenide minerals in porphyry deposits. For example, a typical copper sulphide ore contains various amounts of iron sulphide minerals, such as pyrite (FeS_2) and pyrrhotite ($\text{Fe}_{(1-x)}$), whilst gold

and silver are often also present. Metallic elements frequently found in copper ores include nickel, iron, lead, zinc, antimony, arsenic, molybdenum, and cobalt; less common are selenium, tellurium, bismuth, silver, gold, rhenium, tin, and platinum group metals (PGM). The copper ore deposits in Zaire and Zambia are important sources of cobalt, whilst the porphyry deposits in southern USA (e.g. the Climax and Henderson deposits in central Colorado, and the Questa deposit in northern New Mexico) are an important source of molybdenum and rhenium.

Global copper resources have been estimated at 1.9 billion tonnes, of which porphyry deposits account for 1.6 billion tonnes of those resources (USGS, 2016). Global copper mine production and reserves by country for 2014 and 2015 are listed in Table 16.

Table 16. Mine production in 2014 and 2015 and reserves of copper by country (Mt).

	Mine production		Reserves
	2014	2015	
Australia	880	870	80,000
Canada	631	630	10,000
Chile	5,220	5,180	190,000
China	1,600	1,590	27,000
Congo (Kinshasa)	930	900	18,000
Mexico	467	500	42,000
Peru	1,250	1,450	74,000
Russia	673	670	27,000
United States of America	1,230	1,130	30,000
Zambia	642	540	18,000
Other countries	3,300	3,500	14,000
World total (rounded)	16,800	17,000	650,000

Source: adapted from USGS (2016).

4.3. Use/application of copper products

Blister copper is fire-refined and cast into copper anodes (HS 7402.00 unrefined copper, copper anodes for electrolytic refining) containing at least 97.5% Cu. Anodes are further refined by electrolysis to produce copper cathodes (HS 7403.00, refined copper & alloys (no mast alloy), unwrought) that are cast into semifabricated forms (known as “semis”), such as ingots (HS 7403.11), wire bars (HS 7403.12), and billets (HS 7403.13). Copper semis are then sent to first-stage manufacturers, where they are manufactured into commercial shapes and sold to component manufacturers. Manufactured copper components (e.g. motors, valves, and

insulated cables) are sold to final-stage manufacturers for use in a variety of applications, such as building construction, electric and electronic products, transportation equipment, consumer and general products, and industry machinery and equipment (Copper Development Association Inc., 2015).

4.4. *Copper primary production in ecoinvent version 2*

In ecoinvent version 2, copper is included as part of the group “copper, molybdenum and telluride and silver containing by-products”, which includes the co-production of copper and molybdenum and the recovery of tellurium and silver from copper electrorefining anode slimes (see Classen *et al*, 2009). The by-production of other metals during copper primary production is not included. The database contains 12 LCI datasets related specifically to primary production of copper and the processing of by-products (see Appendix 1). The reference years of these datasets ranges from 1994 to 2005, with the majority generated prior to 2000. Five of the datasets have not been altered since ecoinvent version 1.1.

Mining and concentration are modelled as coupled processes as part of the dataset “copper mine operation” with copper and molybdenite concentrates as products. The mining process was modelled to represent 70% open pit and 30% underground mining. The concentration process comprises comminution and flotation steps. Datasets for both the pyrometallurgical and hydrometallurgical copper extraction routes are included. The pyrometallurgical extraction dataset (“copper production, blister-copper”) was generated in 1994 and represents an average mix of technologies: 6.2% reverberatory furnace, 76% flash furnace, and 17.8% other. The hydrometallurgical processing dataset (“copper production, solvent-extraction electro-winning”) was generated in 1994 and is an aggregate of mining, concentration, and extraction (solvent extraction and electrowinning) processes. An electrolytic refinement process dataset (“electrolytic refining of primary copper”), generated in 1994, is also included.

4.5. Updated copper primary production system description

4.5.1. General overview

A schematic representation of the copper primary production LCI data model is presented in Figure 5. The model was developed based on a typical copper primary production process, as described by Schlesinger *et al.* (2011) and in the *Kirk-Othmer Encyclopedia of Chemical Technology* (2014). The figure shows copper production from cradle to gate and covers the four primary production stages (i.e. mining, concentration, extraction, and refinement and casting). For each copper primary production process stage, a description of the key transforming activities and their products is provided below. A description of the key by-products and wastes produced during each stage is also provided to highlight where companion metals are recovered within the copper primary production system.

4.5.2. Mining

4.5.2.1. Process description

Historically, underground methods have been used to mine porphyry ore deposits. However, as the prevalence of high grade copper ore deposits has diminished, the use of underground mining methods has become increasingly uncommon. As the concentration of copper minerals in sulphidic ore bodies is generally low, with typical recoverable copper ores containing less than 2% Cu, the majority of sulphidic copper ore deposits are now mined using open-pit methods (Berger *et al.*, 2008). Copper sulphide minerals are often associated with other economically significant metal-bearing minerals. The most common sulphidic copper mineral-bearing ore types include: Cu ores, Cu-Zn ores, Cu-Pb-Zn ores, Cu-Ni ores, Cu-Co ores, and Cu-Mo ores. Run-of-mine (ROM) ores of these various types comprise the products of copper mining activities. Copper oxide ores are typically mined using open pit methods.

4.5.2.2. By-products/wastes

Waste rock/overburden Mining generates large volumes of waste. Open pit mining requires the removal of overburden, which includes soil and rock, in order to gain access to the ore deposit. Subsurface mining produces large quantities of waste rock, which is removed during the mining operation. Overburden and waste rock is typically stored close to the mine site during operation and then used for landscaping and revegetation following the mine's closure.

4.5.3. Mineral processing ('concentration')

4.5.3.1. Process description

After mining, the ore is first run through a jaw or gyratory crusher before undergoing several stages of grinding to yield a ground ore of small (~50 µm) particles. The comminution stage is then followed by froth flotation to separate the valuable metal-bearing mineral particles from the gangue. Different copper ore types require the use of different flotation methods to separate the valuable metal-bearing minerals. Table 17 presents a summary of the different flotation methods used for common Cu-bearing sulphide ore types. The froth flotation process yields a copper concentrate of ~20-30% Cu and a tailings waste product.

Table 17. Typical flotation method used for different copper sulphide ore types.

Sulphide ore type	Flotation method
Cu ores	Bulk flotation (with sulphur-based thiol class collector reagents)
Cu-Zn ores	Differential flotation Step 1: selective Cu-bearing mineral flotation with lime Step 2: selective Zn (sphalerite) flotation with an alcohol frother
Cu-Pb-Zn ores	Bulk and differential flotation Step 1: bulk Cu-Pb flotation with xanthate, dithiophosphate, and flotation reagent blends Step 2.1: selective Cu-bearing mineral flotation after Pb (galena) depression (using, for example, sodium dichromate, sodium sulphite, or polysaccharide) Step 2.2: selective Zn (sphalerite) flotation with an alcohol frother
Cu-Ni ores	Bulk and differential flotation Step 1: bulk flotation with strong collector reagents (e.g. amyl xanthate or a combination of dithiophosphates/mercaptobenzothiazole and xanthate) Step 2: selective Cu-bearing mineral flotation after Ni (pentlandite & Ni-bearing Pb sulphide mineral) depression with lime and sodium cyanide
Cu-Co ores	Differential flotation Step 1: selective Cu-bearing mineral flotation with lime Step 2: selective Co-bearing mineral (e.g. cobaltite, carrollite, and linnaeite) flotation with sulphuric acid
Cu-Mo ores	Bulk and differential flotation Step 1: bulk Cu-Mo flotation Step 2: selective Cu-bearing mineral flotation with lime Step 3: selective Mo (molybdenite) flotation after Cu- and Pb-bearing sulphide mineral depression with lime

Source: based on Cheminova (2016).

4.5.3.2. *By-products/wastes*

Mineral concentrates Flotation activities undertaken during the concentration stage yield the by-products cobalt, zinc, lead, nickel, and molybdenum sulphide mineral concentrates. These concentrates are sold to metal-specific producers for metal extraction and refining (see Section 4.6.2).

Tailings Tailings comprise slurried ground rock and leach and flotation residues that remain after valuable minerals are removed during concentration activities. They are typically treated in so-called tailings ponds prior to storage at the mine site.

4.5.4. *Extraction*

4.5.4.1. *Process description*

Copper is separated from copper sulphide mineral concentrates using pyrometallurgical techniques. Pyrometallurgical extraction of copper involves three activity stages: (1) drying and roasting (feed preparation), (2) smelting, and (3) converting. In older processes, the concentrate first undergoes a partial oxidising roast (typically in a reverberatory or fluidised bed furnace) to reduce the sulphur and water content of the feed. The roasting stage produces copper oxide calcine and off gas. Many modern copper smelters (i.e. those using flash or bath smelting processes) forgo the preliminary roasting step in favour of direct smelting of the copper sulphide mineral concentrate. During the smelting process, the copper oxide calcine or the copper sulphide mineral concentrate is charged into a smelting furnace along with a silica flux. The smelting process yields three products: a molten Cu sulphide matte (50-70% Cu); slag, which is either cleaned and returned to the smelting furnace or sent for disposal; and off gas. The Cu matte is then charged into a converting furnace (the Pierce-Smith converter is most commonly used) along with a lime/silica flux and copper scrap. The conversion process yields three products: crude “blister” copper (>98% Cu); an iron-rich slag, which is returned to the smelting furnace; and off gas. The sulphur-rich off gases produced during pyrometallurgical extraction of copper are sent to a sulphuric acid plant.

4.5.4.2. By-products/wastes

Off gas The sulphur-rich off gases produced during pyrometallurgical extraction are cleaned and sent to sulphuric acid production plants where they are processed and used to produce marketable forms of sulphur, such as liquid sulphur dioxide, elemental sulphur, and, most commonly, sulphuric acid (see Figure 6).

Slag Slags produced by pyrometallurgical extraction activities are typically returned to the furnace and remelted to maximise metal recovery. A portion of the slag is, however, skimmed off and sent for treatment and subsequent recycling or disposal.

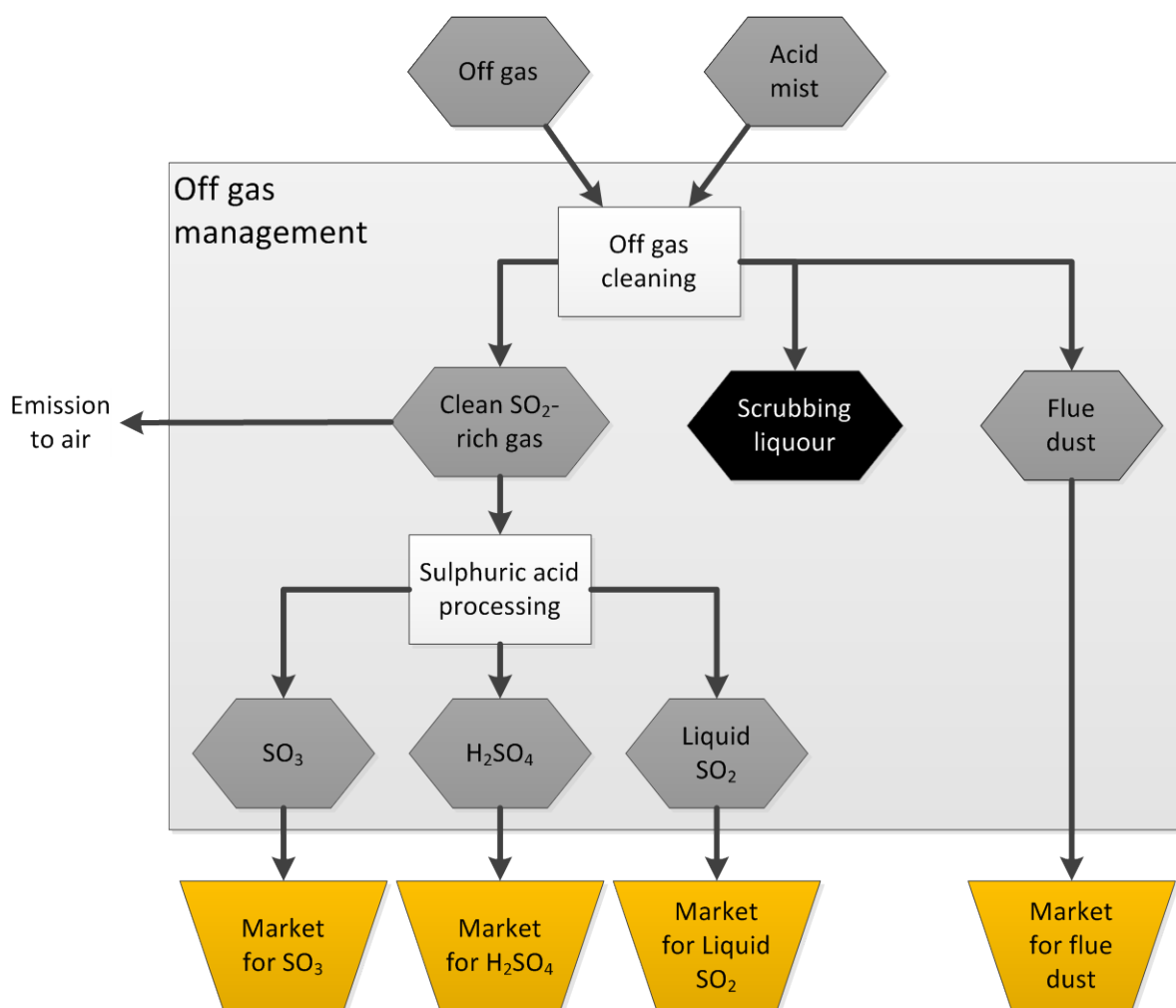


Figure 6. Schematic of off gas management LCI data model.

Flue dust Flue dust is expelled out of pyrometallurgical furnaces during processing and collected in the dust collection ('baghouse') or gas treatment ('Cottrell system') system. Flue

dust may be recirculated into the pyrometallurgical operation, possibly following treatment to remove hazardous materials and recover valuable metals (see Figure 6).

4.5.5. Refinement and casting

4.5.5.1. Process description

Copper refining comprises three stages: (1) fire refining, (2) electrorefining, and (3) remelting of copper cathodes and casting (an optional stage). First, the blister copper is charged into an anode furnace for a two stage fire refining process to first reduce its sulphur and iron content and then remove oxygen. The copper metal product (>99.5% Cu) is then cast into anodes and refined by electrolysis to yield the following products: cathode-grade copper (>99.9% Cu); spent cathodes, which are sent for recycling; electrolyte bleed, which is sent for treatment and metals recovery; and anode slimes, which are sent to a precious metal recovery facility for further processing to recover valuable metals. The copper cathodes are either sold directly to fabricators or are remelted and cast into commercial shapes (e.g. wire bars or rods for copper wire manufacturing).

4.5.5.2. By-products/wastes

Anode slimes Anode slimes are deposited at the bottom of the electrorefining tank during copper electrorefining. The slimes generally contain copper, precious metals, such as silver and gold, as well as other scarce and critical metals, such as selenium and tellurium. Due to the presence of these valuable metals and metalloids, anode slimes are typically processed to extract the metals from the slimes. The slimes are dewatered at the copper smelter/refinery and are then transported to an anode slime processing plant (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

Electrolyte bleed In copper electrorefining, arsenic, bismuth, antimony, and other metal impurities dissolve with copper into the electrolyte and accumulate. Increased concentrations of these impurities in the electrolyte may contribute to problems through contamination of the cathodes and anode passivation. To regulate the concentration of these metal impurities and maintain a constant copper concentration in the electrolyte, a portion of the electrolyte is continuously bled and treated. Electrolyte bleed is typically treated by electrowinning in 'liberator' cells, in which it is electrolysed with insoluble lead anodes to recover first copper

and then other metal impurities at the cathode (see Section 4.6.5). The decoppered electrolyte is then returned to the copper electrorefining cells.

Off gas Off gases are sent to sulphuric acid production plants where they are processed and used to produce marketable forms of sulphur, such as liquid sulphur dioxide, elemental sulphur, and, most commonly, sulphuric acid (see Figure 6).

Spent electrodes Spent electrodes from the electrolysis process are typically removed and sent to primary scrap metal recycling plants.

4.6. *Companion metals production systems*

4.6.1. *Introduction*

A number of metals are recovered from by-products and wastes of the copper primary production system. In particular, metals are recovered from four intermediate products: (1) sulphide mineral concentrates produced during the concentration stage; (2) copper smelting off gases and flue dusts; (3) copper electrorefining anode slimes; and (4) copper electrorefining electrolyte bleed. This section provides details of the how metals are recovered from these products within the copper primary production system. A description of the recovered metal production system is then also provided.

4.6.2. *Sulphide mineral concentrates*

4.6.2.1. *Molybdenum sulphide mineral concentrate*

Almost half of the global mine production of molybdenum is as a by-product of copper mining and mineral concentration (Nassar *et al.*, 2015). Porphyry Cu-Mo ores are first crushed and finely ground. Molybdenite, the principle molybdenum sulphide mineral of commercial significance, is then separated from the copper minerals through bulk and differential flotation (see Table 17) to produce a marketable molybdenite concentrate of 45-50% Mo (Schlesinger *et al.*, 2011). Molybdenite concentrate is sold to molybdenum producers for metal extraction and refinement (see Figure 7). The molybdenite concentrate is roasted to produce molybdenum trioxide.

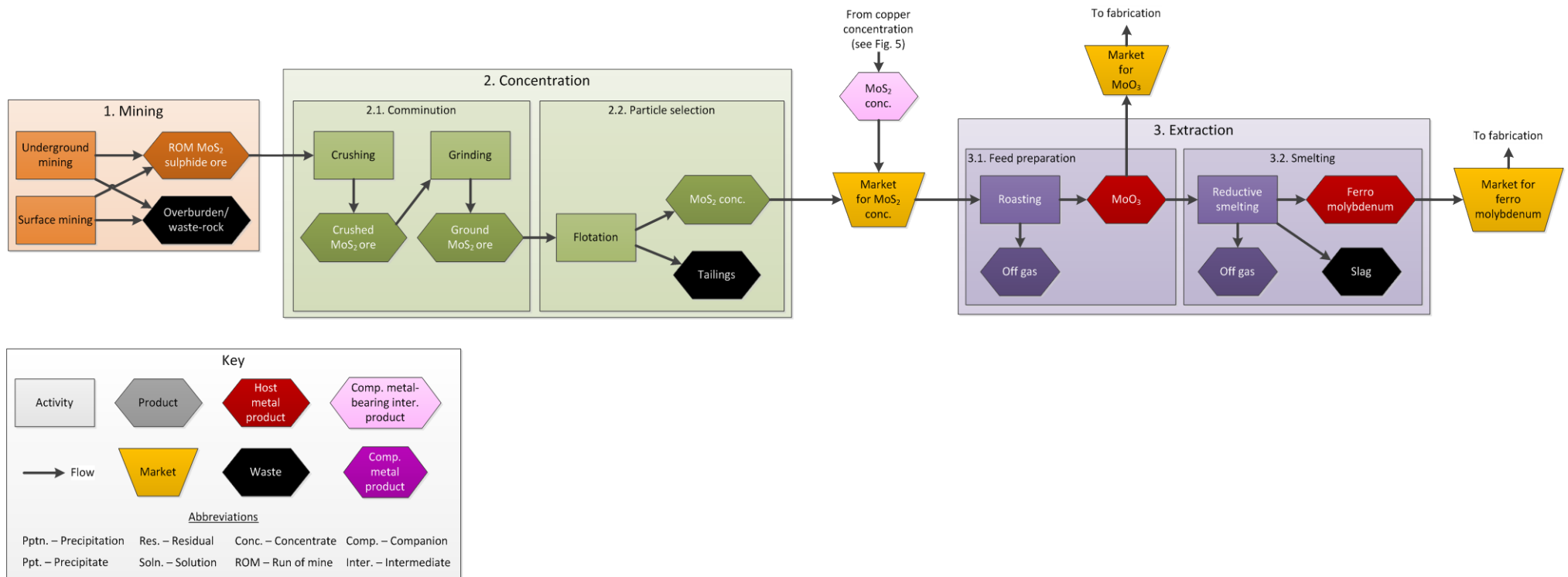


Figure 7. Schematic of the molybdenum primary production LCI data model.

The molybdenum trioxide is then either sold directly to steel manufacturers or is reductively smelted to produce ferromolybdenum (see Gupta, 1992; *Kirk-Othmer Encyclopedia of Chemical Technology*, 2014). Both products are used as alloying elements in steel production.

4.6.2.2. *Nickel sulphide mineral concentrate*

Nickel sulphide mineral concentrate produced as a by-product of the concentration stage of copper primary production is sold to nickel producers for metal extraction and refinement. Nickel production from nickel sulphide mineral concentrates typically follows a pyrometallurgical route. Hence, the nickel primary production system LCI model, presented in Figure 8, has been developed to reflect a typical nickel pyrometallurgical processing route, as described by Crundwell *et al.* (2011) and in the *Kirk-Othmer Encyclopedia of Chemical Technology* (2014). The nickel concentrate first undergoes an oxidising roast in a multi-hearth furnace, fluidised-bed roaster, or a rotary kiln. The sulphur dioxide-rich off gas produced during roasting is sent to a sulphuric acid plant (see Figure 6). The calcine roasting product is then smelted in either a reverberatory or blast furnace or by flash or electric arc-furnace smelting. The smelting process yields a siliceous slag of metal oxides, a sulphurous off gas, and a copper-nickel-iron-sulphur matte. The matte is then charged into a horizontal converter with silica and air. Iron is removed in a slag and most of the remaining sulphur is removed in the off gas, leaving a low-sulphur copper-nickel matte.

The copper-nickel matte may be processed in several different ways, depending on the desired marketable product and the copper content. If the matte has a low copper content, it may be cast directly into sulphide anodes for electrolytic refining. Typically, however, the copper content is not sufficiently low for this and requires further processing to separate the copper and nickel sulphides. The matte is first cooled and crushed prior to isolation and extraction of the copper sulphide, which is sent to a copper refinery, through leaching and solution purification. Cobalt is also removed during this purification stage through solvent extraction and sent for cobalt refinement (electrowinning). The nickel product is then either cast into anodes and refined through electrolysis or, more commonly, roasted to produce nickel oxide granules (~75% Ni). The NiO granulates are either sold to stainless steel and low-alloy steel manufacturers directly or, more commonly, are reduction roasted to produce marketable nickel metal of purity 93-95% ('Tonimet 95') or 97.0-97.2% ('Tonimet 97').

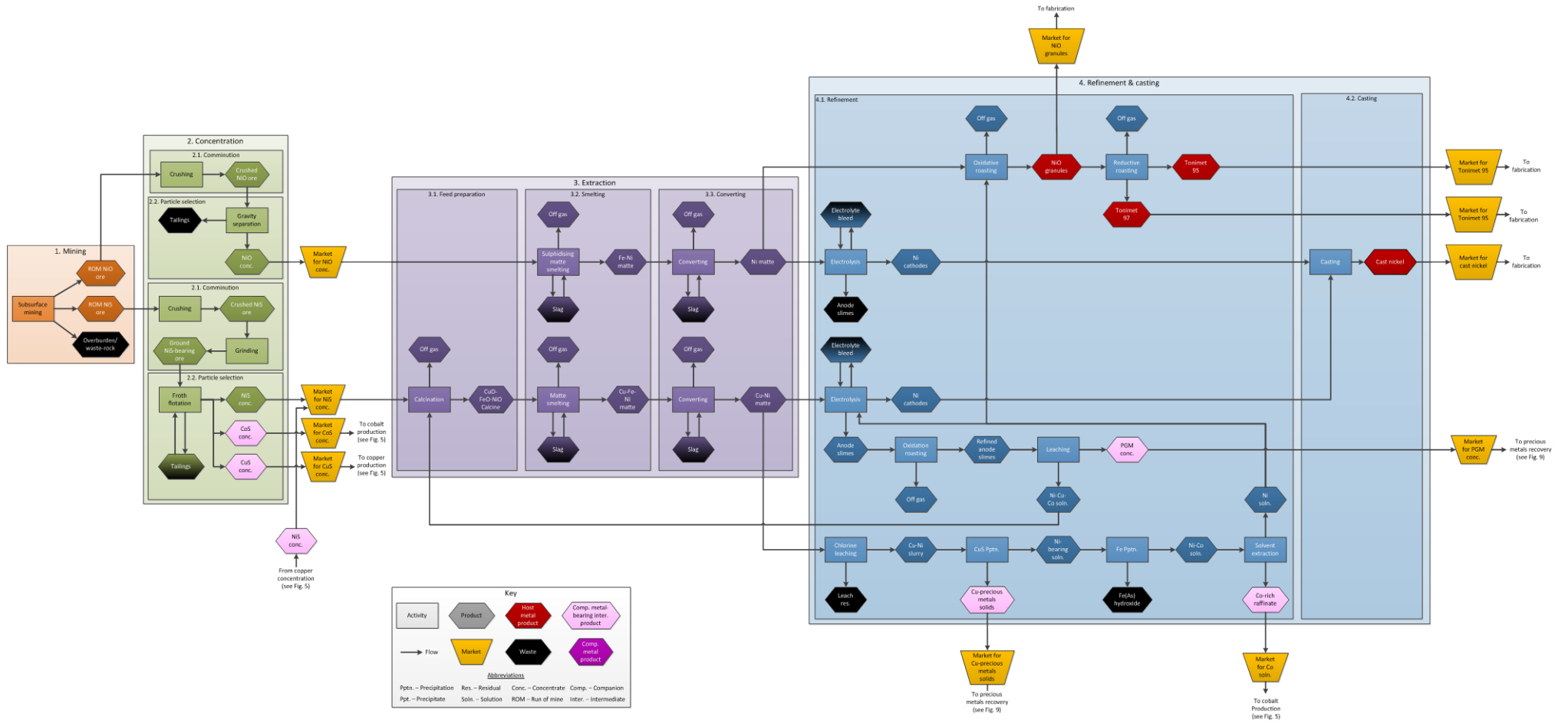


Figure 8. Schematic of the nickel primary production LCI data model.

Copper-nickel matte produced from nickel sulphide ores mined in Russia (the Norilsk-Talnakh region of northern Siberia) often contains appreciable quantities of gold, silver, and platinum group metals (PGMs). The precious metals are recovered from anode slimes produced during electrorefining of the matte. The anode slimes are purified through oxidative roasting and leaching, to remove the nickel-copper content, which is returned to the nickel extraction stage. The precious metals concentrate product is then sent to a precious metals recovery plant (Crundwell *et al.*, 2011; see Figure 9).

4.6.2.3. *Zinc sulphide mineral concentrate*

Zinc sulphide mineral concentrate produced as a by-product of the mineral concentration stage of copper primary production is sold to zinc producers for metal extraction and refinement. Zinc production may follow a hydrometallurgical or pyrometallurgical processing route. Both of these routes have been included in the model, presented in Figure 10, which was developed based on the description of the zinc primary production system in the *Kirk-Othmer Encyclopedia of Chemical Technology* (2014). For both processing routes, the zinc sulphide mineral concentrate is typically first oxidised by roasting to yield zinc oxide calcine and a sulphur-rich off gas, which is sent to a sulphuric acid plant (see Figure 6).

For the pyrometallurgical route, the zinc oxide calcine is blended with metallurgical coke and pelletised before being charged into a sintering machine. The sintering process yields the following products: flue dust, which is returned to the sintering machine; off gas, which is sent to a sulphuric acid plant (see Figure 6); and zinc oxide sinter. The sinter is then charged into a shaft furnace where it is smelted based on the Imperial smelting process. The Imperial smelting process yields the following products: flue dust, which is recirculated to the sintering furnace; off gas, from which zinc is recovered in the condenser; crude lead base bullion, which is sent for refining; zinc, which is separated from the lead through progressive cooling and is either cast into marketable ingots or is sent for further refining. Zinc smelter residues (i.e. flue dust, slag, and off gas) often contain appreciable quantities of indium and germanium. Where concentrations of these metals are high enough, the smelter residues are sent to specialist plants for metals recovery (as an example, the schematic for the production process of indium recovered from zinc smelter flue dusts is presented in Figure 11).

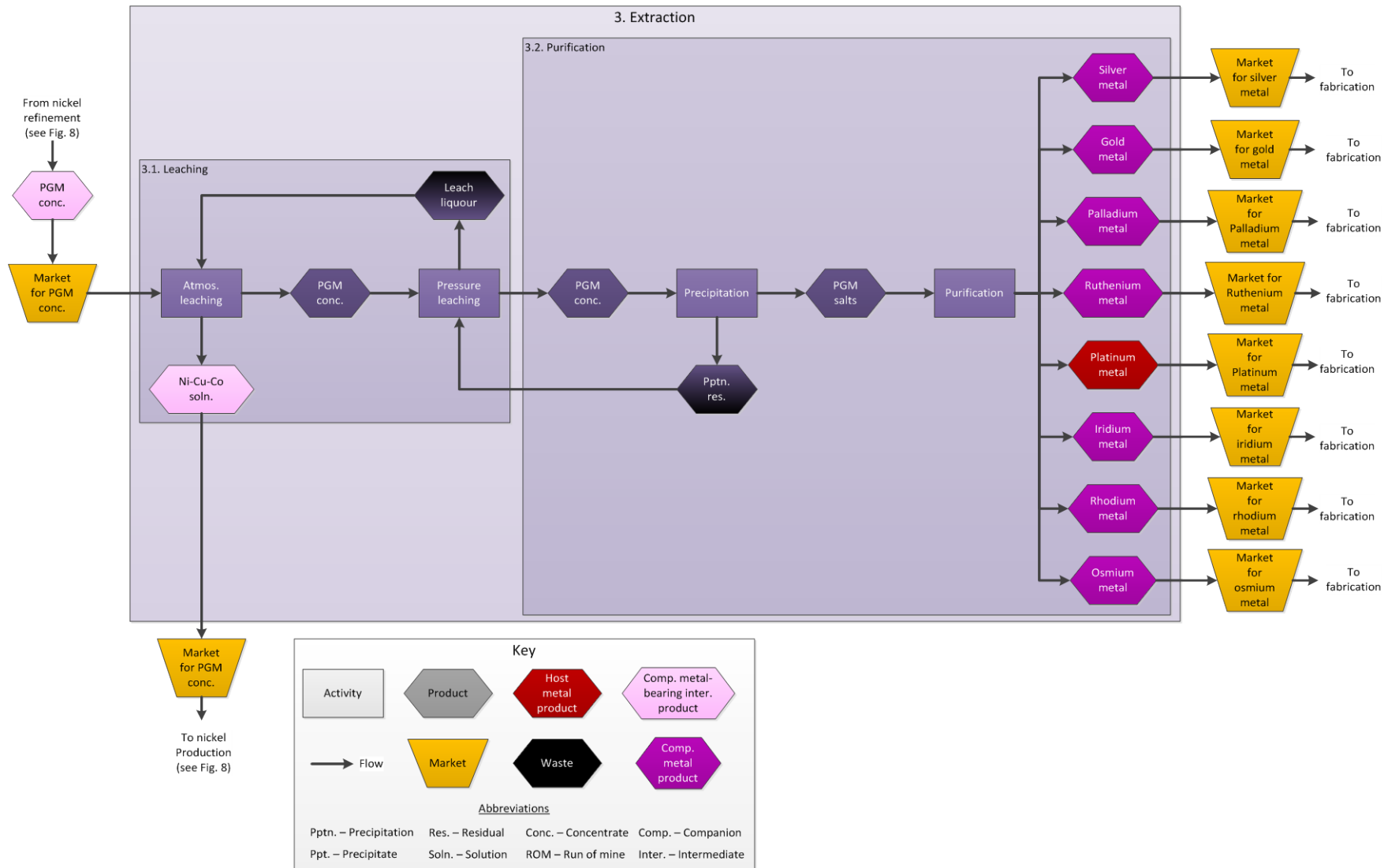


Figure 9. Schematic of the LCI data model for the production of PGMs at a precious metals recovery plant.

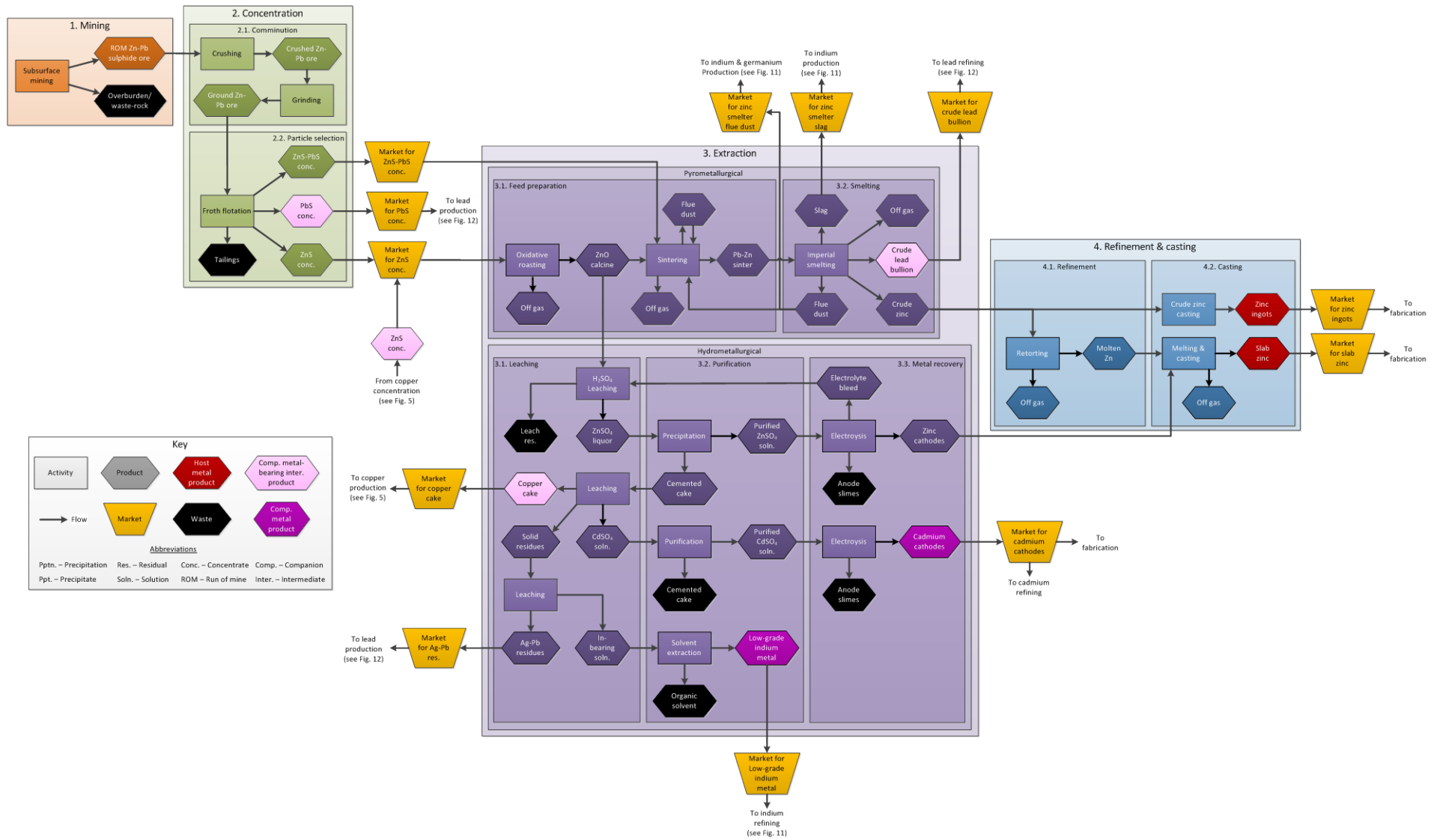


Figure 10. Schematic of the zinc primary production LCI data model.

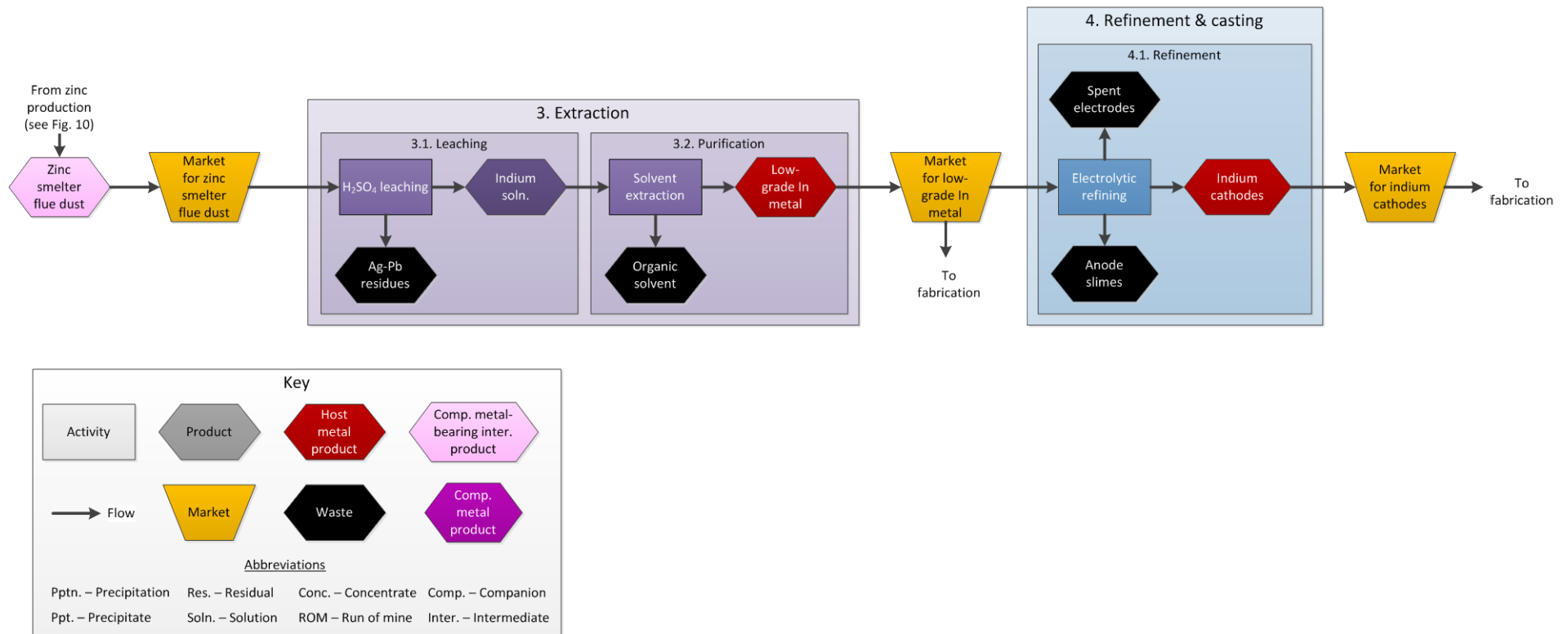


Figure 11. Schematic of the indium primary production LCI data model.

For the hydrometallurgical route, the crude zinc oxide calcine is first leached in dilute sulphuric acid to solubilise the zinc, which is sent for purification. Zinc ferrite, which is formed during the roasting of zinc sulphide, does not dissolve in this step and is subsequently extracted from the leach residue using strong sulphuric acid. The dezincd leach residue may contain a number of valuable metals, including (*inter alia*) lead, silver, gold, germanium, gallium, and indium, which are recovered following further processing. The leached zinc sulphate solute is purified through a highly plant-specific precipitation and cementation process. Metal hydrous oxides are first precipitated from the solution. Other metal impurities are removed from the solution through cementation with zinc dust. Metals that are nobler than zinc are then displaced in their elemental form through and metals that are more electropositive are reduced as salts. Cadmium is extracted from the cemented cake product containing the various metal impurities through a multi-stage leaching and cementation process (Aparajith *et al.*, 2010). The cementation cake is first leached in dilute sulphuric acid to separate cadmium, which dissolves into the liquid phase. The leach residue contains 25-60% Cu, which is filtered and sold on to copper producers for metals recovery. The leach residue also contains indium, which is leached and subsequently purified through solvent extraction to produce low-grade indium metal. The leached cadmium sulphate liquor is filtered and the filtrate purified at elevated pH in an alkali medium. Cadmium is then electrowon from the purified cadmium sulphate electrolyte and sold to fabricators as high quality cadmium cathodes. The purified zinc sulphate solution is electrolysed, with zinc recovered at the cathode. Cathode zinc is melted and cast into marketable slabs of high grade zinc and sold to fabricators.

4.6.2.4. *Lead sulphide mineral concentrate*

Lead sulphide mineral concentrate produced as a by-product of the mineral concentration stage of copper primary production is sold to lead producers for metal extraction and refinement. The lead primary production LCI system model, illustrated in Figure 12, follows a typical pyrometallurgical processing route as described in the *Kirk-Othmer Encyclopedia of Chemical Technology* (2014). Lead sulphide mineral concentrate is predominantly smelted using sinter-blast or Imperial smelting furnace technology.

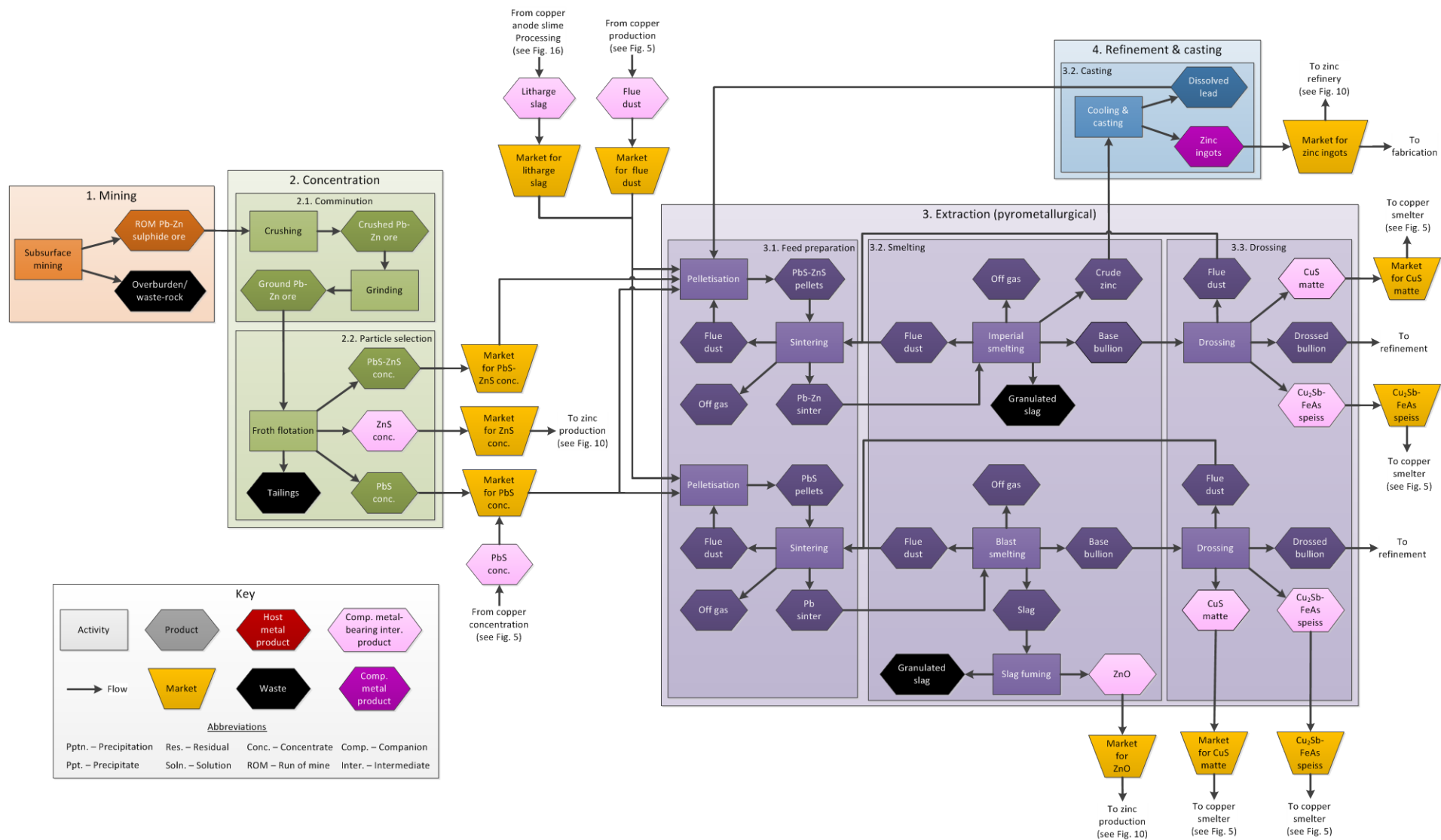


Figure 12. Schematic of the lead primary production LCI data model.

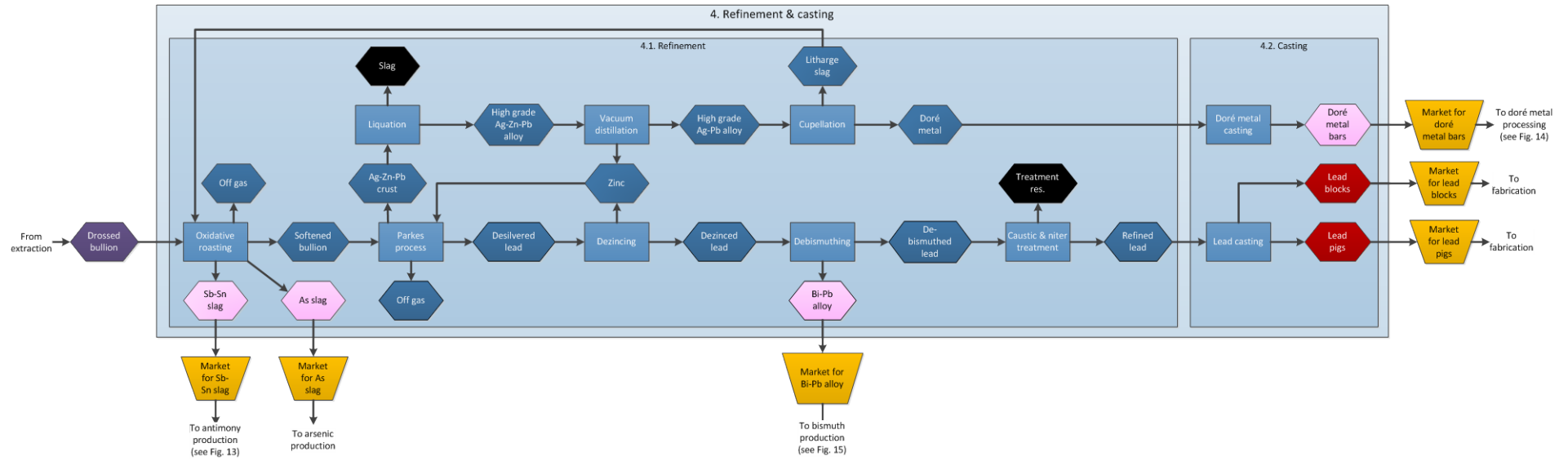


Figure 12 (cont.). Schematic of the lead primary production LCI data model.

With sinter-blast furnace technology, the lead concentrate is blended with (*inter alia*) smelter by-products, returned sinter, and flue dust, pelletised, and charged into a sintering machine. This sinter is then charged into a blast furnace to reduce the lead and other metal oxides to metals and separate the gangue into a molten slag. The products of the lead blast furnace smelting process include: flue dust, which is recirculated to the sintering furnace; off gas, which is sent to a sulphuric acid plant (see Figure 6); slag, from which zinc oxide is recovered through slag fuming; crude lead bullion, which is sent for refining; and a copper- and iron-rich speiss and matte, each of which are sent to a copper smelter for metals recovery. Imperial smelting furnace technology is used to process complex mixed zinc-lead ores, residues, and metal scrap. The charge for the shaft smelting furnace is a pelletised blend of (*inter alia*) mixed zinc- lead concentrates and scrap, metallurgical coke, smelter by-products, and flux. The Imperial smelting process yields the following products: flue dust, from which thallium is recovered prior to being recirculated to the sintering furnace; off gas, from which zinc is recovered in the condenser; crude lead base bullion; zinc, which is separated from the lead through progressive cooling and is cast into ingots.

Base bullion must be refined to increase its purity prior to commercial sale. The first stage of refining is ‘softening’, in which the base bullion is charged into a kettle for oxidative roasting. Molten caustic and molten lead are pumped into a reagent cylinder, which is submerged into the kettle. Arsenic and tin are first selectively skimmed off as sodium arsenate and sodium stannate, respectively, antimony is then removed as sodium antimonite, to leave a softened lead oxide. The sodium arsenate and sodium stannate slag is further processed through leaching and precipitation to produce calcium arsenate, calcium stannate, and a sodium hydroxide solution, which is returned to the leaching step. The sodium antimonite is sent to a special metals refinery to recover antimony, indium, and tellurium (see, for example, Figure 13). The softened lead oxide still contains a number of other impurities, such as silver, gold, bismuth, copper, PGMs, and tellurium. To remove noble metals, such as silver, gold, and PGMs, and residual copper, the softened lead is treated through the Parkes (‘desilvering’) process. Gold, silver, and precious metals are recovered from the Parkes crust as high grade doré metal through a sequential process of liquation, vacuum distillation and cupel treatment.

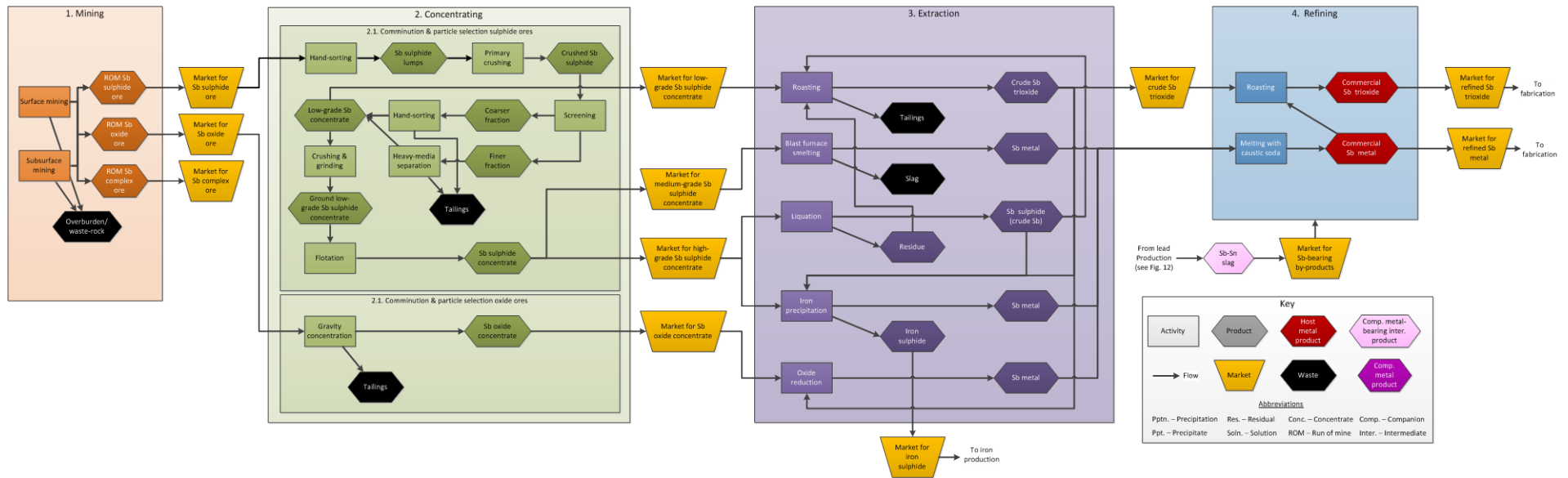


Figure 13. Schematic of the antimony primary production LCI data model.

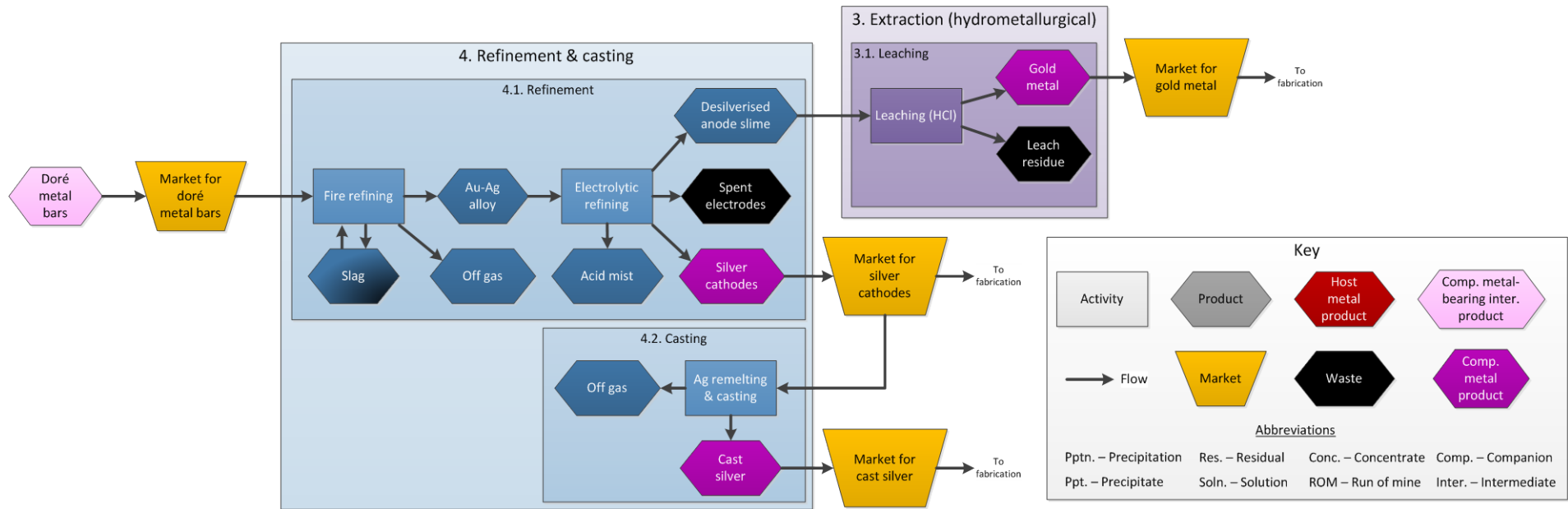


Figure 14. Schematic of the doré metal processing LCI data model.

Chloride and litharge slags formed during liquation and cupellation are, respectively, removed for treatment or returned to the reverberatory furnace, whilst zinc recovered during vacuum distillation is returned to the desilvering process. The doré metal is cast into marketable bars that are sold to precious metals refineries (see Figure 14). The desilvered lead then undergoes a dezincing process, which is accomplished through vacuum distillation or oxidation with caustic soda, to remove zinc, a portion of which is returned to the desilvering process. Bismuth is removed from the dezincing lead using either the Betterton-Kroll or Betts process. Demismuthing is here modelled based on the Betterton-Kroll process, which is used to recover ~90 of bismuth metal produced globally (Polmear *et al.*, 1998). The dezincing lead is charged into a debismuthing kettle. As the charge is heated, a bismuth-enriched dross forms and is skimmed off to blocks and sent to a bismuth recovery plant (see Figure 15). The molten debismuthed lead is then treated with caustic and niter to remove calcium and magnesium in the dross and is cast into marketable 45 kg pigs or one and two tonne blocks.

4.6.2.5. *Copper-cobalt sulphide mineral concentrate*

Around 35 of the global mine production of cobalt comes as a by-product from copper mining (Nassar *et al.*, 2015). The most important source being sedimentary copper ore deposits in the Copperbelt region of the Democratic Republic of the Congo and Zambia (Crundwell *et al.*, 2011). As illustrated in Figure 5, once mined (generally through open-pit mining methods), the ROM ore is crushed and finely ground and the sulphides are separated through bulk flotation using frothers to yield a copper-cobalt sulphide mineral concentrate. The concentrate is then leached with dilute sulphuric acid as a reductant to produce a copper-cobalt sulphate solution, from which a cobalt-rich raffinate is separated through solvent extraction. The marketed product, cobalt hydroxide, is then precipitated from the raffinate with sulphur dioxide, air, and lime. The copper -loaded organic solvent produced during the solvent extraction step is electrolysed in electrowinning cells to produce high purity copper cathodes, which are sold on to fabricators directly or after first being cast into commercial shapes.

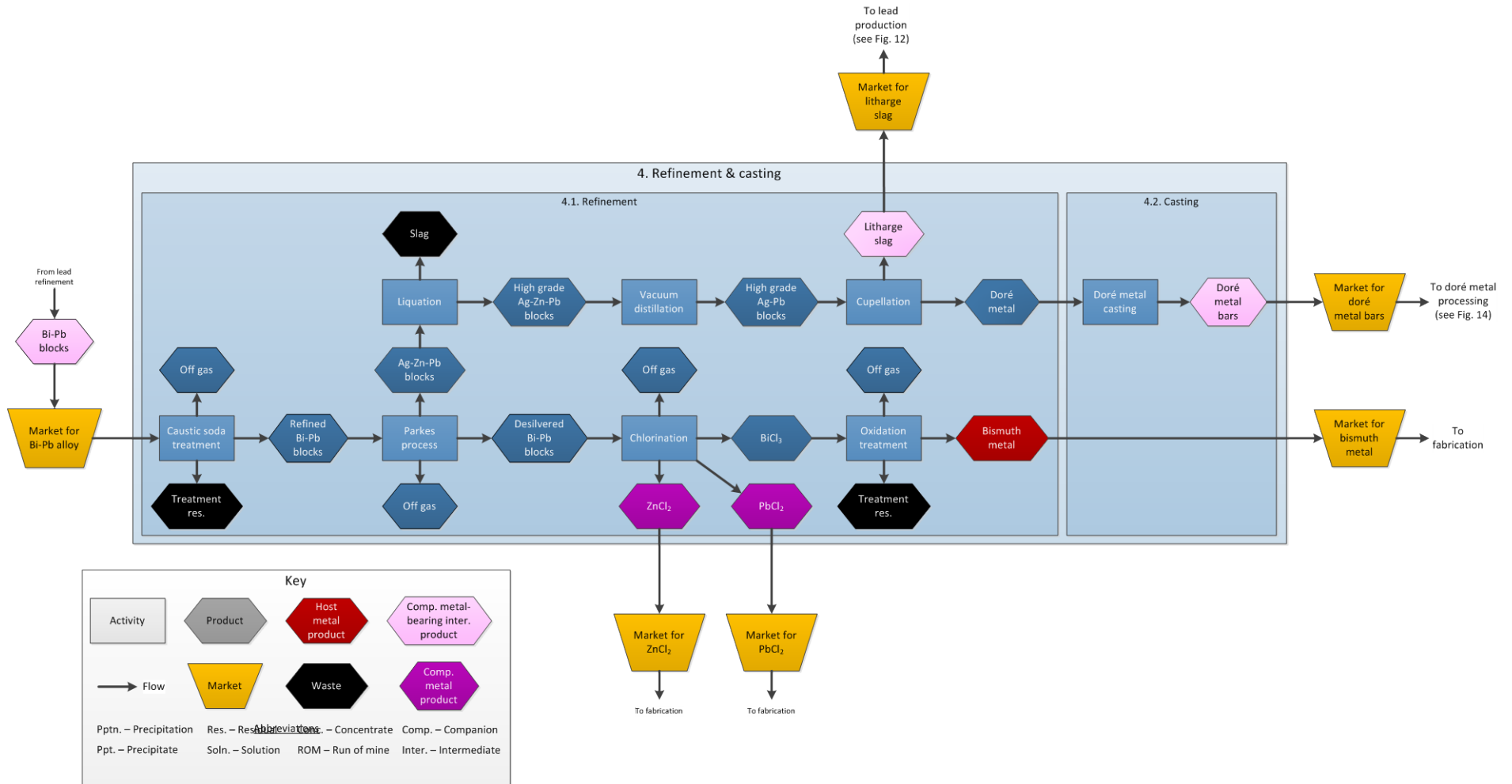


Figure 15. Schematic of the bismuth primary production LCI data model.

4.6.3. *Copper matte conversion flue dust*

Around 9 of the global mine production of bismuth comes as a by-product from copper production. Antimony, arsenic, and thallium may also be recovered as by-products of the copper smelting and converting process. The principle portion of the bismuth, antimony, arsenic, and thallium in copper sulphide ores follow the copper into the matte following smelting. During the conversion of the matte to blister copper, most of these elements, along with lead, are fumed off and collected in the dust collection ('baghouse') or gas treatment ('Cottrell system') system. The collected flue dust is sent to lead producers where the metals are recovered during the lead refinement process (see Section 4.6.2.4).

4.6.4. *Copper electrorefining anode slimes*

Gold, silver, selenium, and tellurium are all produced in marketable forms through the processing copper electrorefining anode slimes, an intermediate product of the copper electrorefining activity. For gold and silver, around 12 and 24 percent of global mine production is as a by-product of copper production, respectively, whilst it's around 90 for both selenium and tellurium (Nassar *et al.*, 2015).

Anode slimes can be processed through a variety of pyro-, pyro-hydro-, or hydrometallurgical routes. The processing method used here, as presented in Figure 16, is based on a pyro-hydrometallurgical route, as described by Hait *et al.* (2009) and Chen *et al.* (2015), and comprises several principle stages:

1. Anode slimes are first leached in sulphuric acid to separate copper and tellurium in the form Cu_2Te . Tellurium is then extracted from this leach solution through precipitation with a copper shot.
2. The leach solid then undergoes a sulphatising or oxidising roast (depending on feed composition) to yield an anode slime calcine and an off gas containing selenium in the form SeO_2 and various impurities, including copper in the form CuS_4 . The selenium is separated from the copper and other impurities through dilute acid or water leaching.
3. The decoppered, deselenised roasting product is smelted to separate impurities (e.g. Cu, Se, Sb, Bi, Te, and Ni), which enter into the slag, from the Pb-Au-Ag alloy product, known as 'doré' metal, which is refined based on the process shown in Figure 14.

4.6.5. Copper electrorefining electrolyte bleed

During electrowinning of copper electrorefining electrolyte bleed, bismuth, antimony, and arsenic are electrolytically reduced at the cathode and deposit as a 'black sludge'. Due to a lack of information available pertaining to the recovery of these metals from copper electrorefining electrolyte, this recovery pathway has not been included in the modelled system.

4.7. Dataset requirements

Based on the proposed LCI data model and the above description of the copper primary production system, we have developed a list of datasets would need to be newly compiled or updated (as listed in Table 18). For each dataset, the corresponding datasets in the existing ecoinvent database is listed, along with an indication of the action required to complete the update.

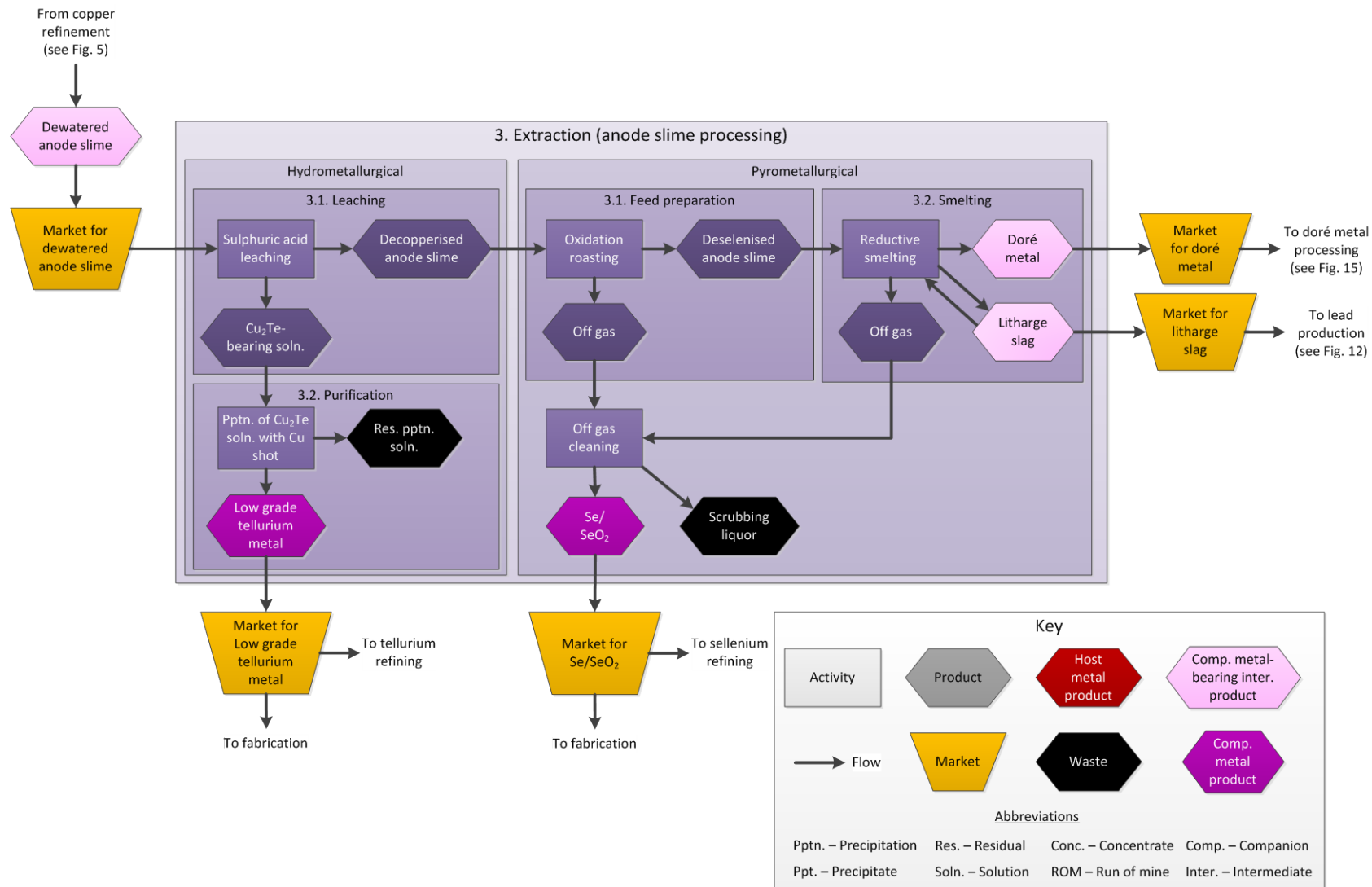


Figure 16. Schematic of the dewatered copper electrorefining anode slime processing LCI data model.

Table 18. Required datasets for the primary production of copper and its companion metals based on the new LCI data model.

For each new dataset, the corresponding dataset from the ecoinvent database is listed along with an indication of the action required for the revision.

Dataset required for update				Corresponding existing dataset				Action required ^a
System	Process stage(s)	Activity dataset name	Reference product name	System	Process stage(s)	Activity dataset name	Reference product name	
Copper	Mining	copper-nickel sulphide ore mine operation	run of mine copper-nickel sulphide ore	Copper ^b	Mining, concentration	copper mine operation	copper concentrate	D, U
Copper	Mining	copper-zinc sulphide ore mine operation	run of mine copper-zinc sulphide ore					N
Copper	Mining	copper-molybdenite ore mine operation	run of mine copper-molybdenite ore	Copper ^a	Mining, concentration	copper mine operation	molybdenite	D, U
Copper	Mining	copper-cobalt sulphide ore mine operation	run of mine copper-cobalt sulphide ore					N
Copper	Mining	copper-lead-zinc sulphide ore mine operation	run of mine copper-lead-zinc sulphide ore					N
Copper	Mining	copper oxide ore mine operation	run of mine copper oxide ore	Copper ^a	Mining, concentration	copper mine operation	copper concentrate	D, U
Copper	Concentration	copper sulphide mineral concentrate production	copper sulphide mineral concentrate	Copper ^a	Mining, concentration	copper mine operation	copper concentrate	D, U
Copper	Concentration	copper sulphide-cobalt sulphide mineral concentrate production	copper sulphide-cobalt sulphide mineral concentrate	Copper ^a	Mining, concentration	copper mine operation	copper concentrate	D, U
Copper	Concentration	copper oxide mineral concentrate production	copper oxide mineral concentrate	Copper ^a	Mining, concentration	copper mine operation	copper concentrate	D, U
Copper	Extraction	copper cathodes production, from copper sulphide-cobalt sulphide mineral concentrate	copper cathodes, from copper sulphide-cobalt sulphide mineral concentrate					N
Copper	Extraction	blister copper production	blister copper	Copper ^a	Extraction	copper production, blister-copper	copper, blister-copper	R, U
Copper	Extraction	brass production	brass	Copper ^a	Extraction	brass production	brass	R, U
Copper	Extraction	bronze production	bronze	Copper ^a	Extraction	bronze production	bronze	R, U

Dataset required for update				Corresponding existing dataset				Action required ^a
System	Process stage(s)	Activity dataset name	Reference product name	System	Process stage(s)	Activity dataset name	Reference product name	
Copper	Extraction	brazing solder production, cadmium free	brazing solver, cadmium free	Copper ^a	Extraction	brazing solder production, cadmium free	brazing solver, cadmium free	R, U
Copper	Extraction	copper cathode production, from hydrometallurgical process route	copper cathode, from hydrometallurgical process route	Copper ^a	Mining, concentration, extraction	copper production, solvent-extraction electro-winning	copper, from solvent-extraction electro-winning	D, U
Copper	Refining	copper cathode production, from pyrometallurgical process route	copper cathode, from pyrometallurgical process route	Copper ^a	Refining	electrolytic refining of primary copper	copper, cathode	R, U
Copper	Refining	anode slime, from copper electrorefining stockpiling	anode slime, from copper electrorefining stockpile	Copper ^a	Refining	anode slime, silver and tellurium containing stockpiling	anode slime, silver and tellurium containing stockpiling	R, U
Copper	Extraction	processing of anode slime, from copper electrorefining	doré metal	Copper ^a	Extraction	processing of anode slime, primary copper production	"copper telluride cement	U
Copper	Refining	casting, brass	casting, brass	Copper ^a	Refining	silver"		R, U
Copper	Refining	casting, bronze	casting, bronze	Copper ^a	Refining	casting, brass	casting, brass	R, U
Molybdenum	Mining	molybdenite ore mine operation	run of mine molybdenite ore	Copper ^a	Mining, concentration	copper mine operation	molybdenite	D, U
Molybdenum	Concentration	molybdenite concentration production	molybdenite concentration	Copper ^a	Mining, concentration	copper mine operation	molybdenite	D, U
Molybdenum	Extraction	molybdenum trioxide production	molybdenum trioxide	Copper ^a	Extraction	molybdenum trioxide production	molybdenum trioxide	D, U
Molybdenum	Extraction	ferro molybdenum production	ferro molybdenum					N

Dataset required for update				Corresponding existing dataset				Action required ^a
System	Process stage(s)	Activity dataset name	Reference product name	System	Process stage(s)	Activity dataset name	Reference product name	
Tellurium	Extraction, refining	tellurium production, semiconductor-grade	tellurium, semiconductor-grade	Copper ^a	Extraction, refining	tellurium production, semiconductor-grade	tellurium, semiconductor-grade	R, U
Gold	Extraction, refining	processing of doré metal	gold	Copper ^a	Extraction	processing of anode slime, primary copper production	copper telluride cement; cement	U
Selenium	Extraction, refining	selenium production, from selenium-rich off gas	selenium					N
Silver	Extraction, refining	silver production	silver	Silver-gold	Mining, concentration, extraction, refining	Silver-gold mine operation with refinery	silver	D, U
Nickel	Extraction	nickel matte production, low copper content	nickel matte, low copper content	Nickel	Extraction; refining	smelting and refining of nickel ore	nickel, 99.5	D, U
Nickel	Extraction	nickel matte production, high copper content	nickel matte, high copper content	Nickel	Extraction; refining	smelting and refining of nickel ore	nickel, 99.5	D, U
Nickel	Refining	nickel cathode production, from electrolysis	nickel cathode	Nickel	Extraction; refining	smelting and refining of nickel ore	nickel, 99.5	D, U
Nickel	Refining	nickel cathode production, hydrometallurgical process route	nickel cathode	Nickel	Extraction; refining	smelting and refining of nickel ore	nickel, 99.5	D, U
Nickel	Refining	anode slime stockpiling, from nickel electrorefining	anode slime, from copper electrorefining stockpile	Copper ^a	Refining	anode slime, silver and tellurium containing stockpiling	anode slime, silver and tellurium containing stockpiling	D, U

Dataset required for update				Corresponding existing dataset				Action required ^a
System	Process stage(s)	Activity dataset name	Reference product name	System	Process stage(s)	Activity dataset name	Reference product name	
Nickel	Extraction	processing of anode slime, from nickel electrorefining	platinum group metals concentrate					N
Platinum group metals (PGM)	Extraction, refining	processing of platinum group metals concentrate	Palladium/platinum	Platinum group metals (PGM)	Mining; concentration; extraction; refining	platinum group metal mine operation, ore with high palladium content	platinum	D, U
Lead	Extraction	drossed lead bullion production, from imperial smelting technology	drossed lead bullion, from imperial smelting technology					N
Lead	Extraction	drossed lead bullion production, from sinter-blast technology	drossed lead bullion, from sinter-blast technology	Zinc-lead	Extraction, refining	primary lead production from concentrate	lead	D, U
Lead	Refining	lead pigs production	lead pigs	Zinc-lead	Extraction, refining	primary lead production from concentrate	lead	D, U
Arsenic	Extraction	arsenic production	arsenic					N
Antimony	Extraction, refining	antimony production	antimony					N
Bismuth	Extraction, refining	bismuth production	bismuth					N
Zinc	Extraction	crude zinc production	crude zinc					N
Zinc	Extraction	zinc cathode production	zinc cathode	Zinc-lead	Extraction, refining	primary zinc production from concentrate	zinc	D, U
Zinc	Refining	zinc ingot production	zinc ingot	Zinc-lead	Extraction, refining	primary zinc production from concentrate	zinc	D, U

Dataset required for update				Corresponding existing dataset				Action required ^a
System	Process stage(s)	Activity dataset name	Reference product name	System	Process stage(s)	Activity dataset name	Reference product name	
Zinc	Refining	slab zinc production	slab zinc	Zinc-lead	Extraction, refining	primary zinc production from concentrate	zinc	D, U
Indium	Extraction, refining	indium production	indium					N
Cadmium	Extraction, refining	cadmium production	cadmium					N
Germanium	Extraction, refining	germanium production	germanium					N
Rhenium	Extraction, refining	rhenium production	rhenium					N
Thallium	Extraction, refining	thallium production	thallium					N

^a D, disaggregate dataset by process stage/activity; N, new dataset to be created; R, retain existing dataset; U, update data.

^b Complete system name from Classen *et al.*, (2009): “Copper, molybdenum & Telluride and silver containing byproducts”.

5. Outlook/next steps

5.1. Introduction

Based on the above described generic metals primary production LCI data model, developed during Phase 2 of this project, an estimation of the further work to be completed in (the upcoming) Phase 3 (i.e. to establish all these new and/or updated datasets of the primary production of critical and scarce metals in the ecoinvent database) is given in the following section. The following project steps can be distinguished:

1. Finalisation of the LCI data modelling strategy
2. LCI data collection
3. Establishment of ecoinvent-compatible datasets and submission of generated datasets for review by the editorial board
4. Finalisation and publication of LCI datasets in ecoinvent version 3.x.

Whilst the last two steps are rather straight forward (i.e. follow, in principle, the general rules given by ecoinvent for submission and publication of new inventory data), the first two steps are specific to this project and are therefore described in more detail below.

5.2. Definition of actual modelling strategy

As described in Section 3 (i.e. the description of the generic metals primary production LCI data model) and shown in the various figures presented in Section 4 from the Cu chain used as an exemplary case study, the here developed approach is based on a repetition of similar processing methods along the various processing stages (but used for different inputs, and thus resulting also in different output flows) all along the four principle processing stages that are distinguished here – i.e. mining, concentration, extraction, and refinement and casting, respectively. To integrate these various processing stages into the inventory data, the following three strategies (listed in descending order of preference) are currently envisaged:

- (i) establishment of **parameterised models** for the various processing methods, which are then used within the process chains of the various metals.
- (ii) establishment of a **separate (processing) dataset** containing the processing method-specific activity data (e.g. its energy input) that is linked as an input to all metal-related transformation processes that make use of this specific processing method.
- (iii) establishment of **individual datasets** for the various metals, not taking into account any synergies for a specific processing method among various metals.

The actual choice of the strategy will depend on the feasibility of such parametrized models for these different processing methods mentioned above. The feasibility of such an approach is dependent on data availability and, from a practical perspective, the viability of such a model. To this end, we will consult with experts to discuss the feasibility of the proposed modelling strategy.

5.3. *LCI data collection*

In the next step, the actual data collection for the compilation of these LCI data on scarce and critical metals will be undertaken. This will be based on information available in scientific literature, databases, and company reports, on expert opinion, and/or on best estimates.

An important aspect of this step is the linking with the already existing primary metal production datasets within the ecoinvent database, which is necessary to ensure continuity for users of this important database. These linking activities are related, but not limited to the following aspects and issues:

- Existing datasets will be aggregated/disaggregated in order to harmonise the respective production chains according to the four principle processing stages that are distinguished here – i.e. mining, concentration, extraction, and refinement and casting.
- By-production process chains so far not (or only partly) included in the ecoinvent database will be included in the host metal production datasets.
- For metals whose primary production is currently not covered in the ecoinvent database and that for which 20 or more are mined as a main product on a global level, the generation of new datasets will be required.

Furthermore, data collection synergies may exist with the Sustainable Recycling Industries (SRI) project, a project that is funded by SECO and jointly implemented by Empa, the World Resources Forum (WRF), andecoinvent. One of the objectives of the SRI project is the creation of “reliable, consistent and transparent regionalised LCI datasets” (<http://sustainable-recycling.org/life-cycle-inventories-overview/>); objective of the component directed byecoinvent that is working in generating regionalized LCI data in South American countries (Brazil, Colombia, Peru, Bolivia, Chile), South Africa and India.

6. References

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7. Annexes

Annex 1

Table A1. Overview of companionship, applications, co-elements, and compounds produced as primary for identified critical and scarce metals.

Name	Companionship (Nassar et al. 2014)		Applications	Co-elements ^a	Compounds produced as primary	Source(s)
	% of global production as by-product (ca. 2008)	Host metals (where applicable)				
GROUP I						
Boron	0	Salt/soda ash (0.2), Potash/Li (0.1)	Glass, insulation (27), glass (24), frits and ceramics (14), agriculture (13), chemicals (7), metallurgy (5), construction materials (4), industrial fluids (2), detergents (1), flame retardants (1), other (2)	None	B ₂ O ₃ , H ₃ BO ₃	EC, 2014a Graedel <i>et al.</i> , 2015b USGS, 2015
Chromium	2	Pt (2)	For USA in 2012: Stainless steel (88), steel (9), superalloys (2), other (1)	None	ferrochromium, Na ₂ Cr ₂ O ₇	EC, 2014a Graedel <i>et al.</i> , 2015b Nuss <i>et al.</i> , 2014 USGS, 2015
Mercury	10	Au-Ag, Zn, Cu, Pb (breakdown not available)	Artisanal & small-scale gold mining (21), vinyl chloride monomer production catalyst (20), chlorine-caustic soda manufacturing (13), dental (10), batteries (10), measuring & control devices (9) electrical & electronic devices (5), lighting (4), other (8)	Ag, Au, possibly others (small share of total production is co-produced)		Graedel <i>et al.</i> , 2015b USGS, 2015
Lithium	52	K (potash)	Batteries (25), ceramics and glass (18), lubricating greases (12), pharmaceuticals and polymers (7), air conditioning (6), primary aluminium production (4), continuous casting (3), other (25)		Li ₂ CO ₃	EC, 2014b
Magnesium	<5	K (potash)	For Europe in 2012: Aluminium alloys (40), magnesium die-casting (39), steel desulphurization (12) nodular cast iron (1), others (8)	None		EC, 2014a Graedel <i>et al.</i> , 2015b
Silicon	0		In 2010: Aluminium alloys (45), silicone and silane chemicals (35), solar PV (12), semiconductors (3), other (5)	None	ferrosilicon	EC, 2014a USGS, 2015

Name	Companionality (Nassar et al. 2014)		Applications	Co-elements ^a	Compounds produced as primary	Source(s)
Beryllium	11	Feldspar, spodumene, mica (breakdown not available)	For Europe: Mech. Eq. (25), Electronic equipment and domestic appliances (20), Electronics and IT (20), Road transport (15), Aircraft, shipbuilding and trains (10), metals (3)	None		EC, 2014a Graedel <i>et al.</i> , 2015b USGS, 2015
Strontium	0		For USA: Pyrotechnics and signals (30), ferrite magnets (30), alloys (10), pigments and fillers (10), electrolytic Zn prod (10), others (10)	None	SrCO ₃	Graedel <i>et al.</i> , 2015b USGS, 2015
GROUP II						
Titanium	0		For USA in 2012: Paint (56), plastic (27), paper (9), welding rod coatings and manufacturing carbides, chemicals and metal (5), others (3)	None	TiO ₂	EC, 2014b Graedel <i>et al.</i> , 2015b USGS, 2015
Zirconium	100	Ti	Ceramics (64), refractory (18), foundry moulds (14), others (4)	Ti	ZrSiO ₄ , ZrO ₂	EC, 2014b Graedel <i>et al.</i> , 2015b USGS, 2015
Hafnium	100	Ti (100) and, specifically, as a portion of the Zr extracted	In 2011: Super alloys for turbine blades (45), nuclear control rods (13), plasma cutting tips (13), optical coatings (11), catalysts (7), CVD targets (7), special steels (3), electronics (1)	Zr		EC, 2014b
Tantalum	28	Sn slag (15), Nb (13)	Capacitors (40), superalloys (21), sputtering targets (12), mill products (11), carbides (10), chemicals (6)	Nb		EC, 2014b USGS, 2015
Niobium	2	Ta, Sn (breakdown not available)	Steel alloys (83), superalloys (8), chemical industry (3), others (6)	Ta (not always)	ferroniobium	EC, 2014a USGS, 2015
Iron						
Cerium	73	Fe (67), Ti (3), Y (2), Sm (1), La and Sn (<1)	In 2011: Polishing (36), metallurgy (19), autocatalysts (13), glass (12), phosphors (4), batteries (3), other catalysts (3), fluid cracking catalysts (2), ceramics (1), other (8)	(Y), La, Pr, Nd, (Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu)	CeO ₂	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015 USGS, 2015

Name	Companionality (Nassar et al. 2014)	Applications	Co-elements ^a	Compounds produced as primary	Source(s)	
Europium	100	Fe (35), Ce (24), Y (19), Sm (15), La (7), Ti (1), Sn (<1)	Phosphors (96), other (4)	Y, La, Ce, Pr, Nd, Sm, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	Eu ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Gadolinium	100	Y (38), Fe (21), Sm (16), Ce (14), La (10), Ti (1), Sn (<1)	Magnets (35), metallurgy (28), phosphors (23), other (14)	Y, La, Ce, Pr, Nd, Sm, Eu, Tb, Dy, Ho, Er, Tm, Yb, Lu	Gd ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Lanthanum	93	Fe (50), Ce (27), Sm (7), Y (6), Ti (2), Sn (<1)	Fluid cracking catalysts (44), batteries (26), metallurgy (10), glass (5), polishing (2), phosphors (2), ceramics (1), autocatalysts (1), other (9)	(Y), Ce, Pr, Nd, (Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu)	La ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Neodymium	100	Fe (57), Ce (18), Sm (9), La (7), Y (7), Ti (2), Sn (<1)	Magnets (89), ceramics (5), metallurgy (2), autocatalysts (2), glass (1), phosphors (1)	(Y), La, Ce, Pr, (Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu)	Nd ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Praseodymium	100	Fe (61), Ce (17), Sm (8), Y (7), La (6), Ti (2), Sn (<1)	Magnets (73), phosphors (12), ceramics (7), metallurgy (4), polishing (2), other (2)	(Y), La, Ce, Nd, (Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu)	Pr ₆ O ₁₁	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Samarium	82	Fe (24), Ce (23), Y (22), La (12), Ti (1), Sn (<1)	Magnets (97), metallurgy (1), other (3)	Y, La, Ce, Pr, Nd, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	Sm ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Dysprosium	100	Y(61), Sm (16), Ce (12), La (6), Fe (4), Ti (1), and Sn (<1)	Magnets (98), others (2)	Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Ho, Er, Tm, Yb, Lu	Dy ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Erbium	100	Y (66), Sm (16), Ce (10), La (6), Ti (2), Sn (<1)	Glass (72), phosphors (25), other (3)	Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Tm, Yb, Lu	Er ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015

Name	Companionality (Nassar et al. 2014)		Applications	Co-elements ^a	Compounds produced as primary	Source(s)
Holmium	100	Y (64), Sm (15), Ce (11), Ti (6), La (5), Sn (<1)	Pigments, magnets, lasers and nuclear	Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Er, Tm, Yb, Lu	Ho ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Lutetium	100	Y (62), Sm (18), Ce (10), La (7), Ti (4)	Phosphors, PET detectors, glass	Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb	Lu ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Terbium	100	Y (44), Fe (19), Sm (16), Ce (13), La (7), Ti and Sn (<1)	Phosphors (71), magnets (24), other (5)	Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Ho, Er, Tm, Yb, Lu	Tb ₄ O ₇	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Thulium	100	Y (64), Sm (16), Ce (12), La (6), Ti (2)	None	Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb, Lu	Tm ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Yttrium	29	Sm (13), Ce (9), La (5), Fe (3), Ti and Sn (<1)	Phosphors (79), ceramics (21)	La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	Y ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Ytterbium	100	Y (68), Sm (14), Ce (13), La (5), Ti (1)	Fibre optics, lasers, photovoltaics, stress gages	Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Lu	Yb ₂ O ₃	BGS, 2011 EC, 2014a Nassar <i>et al.</i> , 2015
Scandium	100	Fe, Sn, W, U (breakdown not available)	Aluminium alloys (85), Lighting (10), Fuel cells (5)			EC, 2014b
Aluminium						
Gallium	100	Al (vast majority), Zn (minor quantities)	NdFeB magnets (29), GaAs integrated circuits (21), GaAs/GaP LEDs (15), CIGS PV (4), GaN LEDs (4)	None		Løvik <i>et al.</i> , 2015 USGS, 2015

Name	Companionality (Nassar et al. 2014)		Applications	Co-elements ^a	Compounds produced as primary	Source(s)
Vanadium	82	Fe slag (62), alumina (12), spent catalysts (7), U residues (1)	In 2013: China (52), South Africa (27), Russia (19), USA (1), Australia (1)	None	ferrovanadium	EC, 2014b USGS, 2015
Tin	3	Zn (2), Ta (0.4), Cu (0.1)	Electronic solder (45), industrial solder (9), tinfoil (16), chemicals (15), brazing (5), float glass (2), others (9)	None		EC, 2014b USGS, 2015
Uranium						
Silver	71	Zn/Pb (36.5), Cu (23.5), Au (10.4), Other (0.5)	In 2013: Electrical and electronics (19), jewellery (15), coins and medals (11), photography (6), brazing and solder (6), PV (5), silverware (5), ethylene oxide industry (2), others (15), net investment (16)	Zn (37), Cu (21), Au (13)		EC, 2014b USGS, 2015
Indium	100	Zn (80), Sn (15), Cu (5)	In 2011: Flat panel displays (56), solders (10), PV (8), thermal interface materials (6), batteries (5), alloys/compounds (4), compound semiconductors and LEDs (3), other (8)			EC, 2014a USGS, 2015
GROUP III						
Nickel						
Copper						
Zinc						
Lead						
Molybdenum	46	Cu (46)	Engineering steels (35), stainless steel (25), tool and high speed steel (11), chemicals (10), cast iron (8), superalloys (6), molybdenum metal (6)	Cu (not always)	ferromolybdenum	EC, 2014b Graedel <i>et al.</i> , 2015a
Antimony	80	Pb (40), Ag (16), W (12), Sn (8), Au (4)	In 2011: Flame retardants (43), lead-acid batteries (32), lead alloys (14), plastics (6), glass, ceramics and other (5)		Sb ₂ O ₃	EC, 2014a
Cobalt	85	Ni (50), Cu (35), Pt, Pd, As (minor quantities)	In 2011: Batteries (30), superalloys (19), carbides and diamond tooling (13), catalysts (9), pigments (9), magnets (7), steel alloys (5), others (8)	Ni (55), Cu (35), others (10)	CoO, Co(OH) ₂	EC, 2014a
Cadmium	100	Zn (100)	NiCd batteries (86), pigments (9), coatings (4), alloys, PV, stabilizers and others (1)			USGS, 2015

Name	Companionality (Nassar et al. 2014)		Applications	Co-elements ^a	Compounds produced as primary	Source(s)
Gold	14	Cu (12), Zn (1), Ag (0.5), Pt (0.4), Ni (0.1)	Jewelry (82), electroics (13), dental (2), other (3)			EC, 2014b
Tellurium	100	Cu (>90), Pb and Bi (<10)	In 2011: PV (40), thermo-electric (30), metallurgy (15), rubber applications (5), other (10)			EC, 2014b
Palladium	97	Ni (53), Pt (44)	In 2012: Autocatalysts (75), electrical (10), chemical (5), medical (4), jewellery (4), other (2)	Pt, Ru, Rh, Os, Ir, Cu, Ni		EC, 2014a
Platinum	16	Ni (15.8), Pd (0.3)	In 2012: Autocatalysts (68), jewellery (10), chemical ind (6), medical ind (5), petroleum ind (1), glass ind (1), electrical ind (1), other (8)	Pd, Ru, Rh, Os, Ir, Cu, Ni		EC, 2014a
Rhenium	100	Cu-Mo (71), Cu (29)	In 2011: Aerospace superalloys (63), gas turbine superalloys (13), catalysts (9), automobiles (5), tools (2), oil/gas (2), other (7)			EC, 2014b USGS, 2015
Rhodium	100	Pt (85), Ni (15)	In 2011: Autocatalysts (80), chemical (9), glass (4), electrical (1), other (7)	Pt, Pd, Ru, Os, Ir, Cu, Ni		EC, 2014a EC, 2014b USGS, 2015
Silver	71	Zn/Pb (36.5), Cu (23.5), Au (10.4), Other (0.5)	In 2011: Electrical and electronics (19), jewellery (15), coins and medals (11), photography (6), brazing and solder (6), PV (5), silverware (5), ethylene oxide industry (2), others (15), net investment (16)	Zn (37), Cu (21), Au (13)		EC, 2014a EC, 2014b
Indium	100	Zn (80), Sn (15), Cu (5)	In 2011: Flat panel displays (56), solders (10), PV (8), thermal interface materials (6), batteries (5), alloys/compounds (4), compound semiconductors and LEDs (3), other (8)			EC, 2014a USGS, 2015
Tin	3	Zn (2), Ta (0.4), Cu (0.1)	Electronic solder (45), industrial solder (9), tinsplate (16), chemicals (15), brazz (5), float glass (2), others (9)	None		EC, 2014b USGS, 2015
Tungsten	5	Sn (majority), Mo (minor quantities)	Cemented carbides (60), fabricated products (17), alloy steels (13), superalloys (6), tungsten alloys (4)	None	Ammonium paratungsten, FeSiW	EC, 2014a USGS, 2015

Name	Companionality (Nassar et al. 2014)		Applications	Co-elements ^a	Compounds produced as primary	Source(s)
Arsenic	92	Cu, Pb, Co, Au, Sn, Zn (breakdown not available)	Wood preservation and pesticides (68), semiconductor devices (7), Cu alloys (7), other (18)	None	As ₂ O ₃	Graedel <i>et al.</i> , 2015a Hanusch <i>et al.</i> , 1997 USGS, 2015
Bismuth	90	Pb (54), W (13.5), Cu (9), Sn (9), Mo (4.5)	Solders, wires, safety fuses, molded products (35), metallurgical additives (35), pharmaceuticals and chemicals (28), other (2)			Graedel <i>et al.</i> , 2015a USGS, 2015
Selenium	100	Cu (~90), Ni/Zn/Ag/Hg/Pb (~10)	Metallurgy (40), glass manufacturing (25), agriculture (10), chemicals and pigments (10), electronics (10), other (5)	None		EC, 2014b USGS, 2015
Germanium	100	Zn (60), coal fly ash (40)	Fibre optics (30), infrared optics (25), polymerization catalysts (25), electronics and solar electric (15), other (5)			EC, 2014a
Ruthenium	100	Pt (>95), Ni (<5)	In 2012: Electrical (57), electro-chemical (20), chemical (12), other (11)	Pt, Pd, Rh, Os, Ir, Cu, Ni		EC, 2014a
Thallium	100	Cu, Pb, Zn (breakdown not available)	Cardiovascular imaging, gamma radiation detection equipment, high temperature superconductors for wireless com filters, lenses, prisms and windows for infrared detection and transmission equipment, thallium-arsenic-selenium crystal filters for light diffraction in acousto-optical measuring devices, alloying element in mercury for low temperature measurement			USGS, 2015
Iridium	100	Pt (>95), Ni (<5)	Electrical (57), electro-chemical (20), chemical (12), other (11)	Pt, Pd, Ru, Rh, Os, Cu, Ni		EC, 2014a
Osmium	100	Pt (majority), Ni (minor quantities)		Pt, Pd, Ru, Rh, Ir, Cu, Ni		EC, 2014a

^a Similar or unknown economic importance.

Note that row colours correspond to the coverage of the metal inecoinvent as follows: red, not covered; orange, partially covered; and green, covered.

Annex 2

Table A2. Metals primary production datasets currently available in the ecoinvent database.

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
Aluminium	Mining	Infrastructure	mine construction, bauxite	mine infrastructure, bauxite	1998	2015	GLO	
Aluminium	Mining	Infrastructure	recultivation, bauxite mine	recultivation, bauxite mine	1998	2015	GLO	
Aluminium	Mining	Transforming	bauxite mine operation	bauxite, without water	2010	2015	GLO	Average bauxite mining technology world-wide (open mining)
Aluminium	Concentration; extraction	Infrastructure	aluminium hydroxide factory construction	aluminium hydroxide factory	2002	2015	RER; RoW	
Aluminium	Concentration; extraction	Transforming	aluminium hydroxide production	aluminium hydroxide	2012	2015	GLO	Average technology for the global aluminium industry.
Aluminium	Concentration; extraction	Infrastructure	aluminium oxide factory construction	aluminium oxide factory	2002	2015	RER; RoW	
Aluminium	Concentration; extraction	Transforming	aluminium oxide production	aluminium oxide	2012	2015	GLO	Average technology for the aluminium produced globally.
Aluminium	Extraction	Transforming	anode production, paste, for aluminium electrolysis	anode, paste, for aluminium electrolysis	2010	2015	CA-QC	
Aluminium	Extraction	Transforming	anode production, prebake, for aluminium electrolysis	anode, prebake, for aluminium electrolysis	2012	2015	CA-QC; RoW	
Aluminium	Extraction	Infrastructure	aluminium electrolysis facility construction	aluminium electrolysis facility	2002	2015	CA-QC; CN; IAI Area 1; IAI Area 2, without Quebec; IAI Area 3; IAI Area 4&5 without China; IAI Area 8; IAI, EU27 & EFTA; IAI Area, Europe outside EU & EFTA; UN-	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
							OCEANIA	
Aluminium	Extraction	Transforming	cathode production, for aluminium electrolysis	cathode, for aluminium electrolysis	1995	2015	RER; RoW	Average technology for the aluminium consumed in Europe (85% pre baked, 15% Söderberg)
Aluminium	Extraction; refining	Transforming	aluminium production, primary, liquid prebake	aluminium, primary, liquid	2012	2015	CA-QC; CN; IAI Area 1; IAI Area 2, without Quebec; IAI Area 3; IAI Area 4&5 without China; IAI Area 8; IAI, EU27 & EFTA; IAI Area, Europe outside EU & ETFA; UN-OCEANIA	
Aluminium	Extraction; refining	Transforming	aluminium production, primary, ingot	aluminium, primary, ingot	2012	2015	CA-QC; CN; IAI Area 1; IAI Area 2, without Quebec; IAI Area 3; IAI Area 4&5 without China; IAI Area 8; IAI, EU27 & EFTA; IAI Area, Europe outside EU & ETFA; UN-OCEANIA	
Aluminium	Extraction; refining	Transforming	aluminium production, primary, liquid, Söderberg	aluminium primary, liquid	2012	2015	CA-QC; CN; IAI Area 1; IAI Area 2, without Quebec; IAI Area 3; IAI Area 4&5 without China; IAI Area 8; IAI, EU27 & EFTA; IAI Area, Europe outside EU & ETFA; UN-OCEANIA	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
Iron & steel	Mining	Transforming	iron mine operation, crude ore, 46% Fe	iron ore, crude ore, 46% Fe	1999	2000	GLO	Open pit mining
Iron & steel	Mining	Infrastructure	reclamation, iron mine	reclamation, iron mine	2000	2000	GLO	Reclamation of open pit mines
Iron & steel	Mining	Infrastructure	mine construction, iron	mine construction, iron	2000	2000	GLO	Open pit mining
Iron & steel	Concentration	Transforming	iron mine beneficiation to 65% Fe	iron ore, beneficiated, 65% Fe	1998	2000	CA-QC	Milling & mechanical sorting
Iron & steel	Extraction	Transforming	sinter production, iron	sinter, iron	1999	2002	GLO	Continuous travelling grate
Iron & steel	Extraction	Transforming	iron pellet production	iron pellet	1999	2002	CA-QC; RoW	Strate grate and grate kiln process
Iron & steel	Extraction	Transforming	pig iron production	pig iron	1999	2002	GLO	Blast furnace
Copper ^a	Mining; concentration	Transforming	copper mine operation	copper concentrate	1994	2015	AU; RAS; RER; RLA; RNA; RoW	70% open pit and 30% underground
Copper	Mining; concentration	Transforming	copper mine operation	molybdenite	1994	2015	AU; RAS; RER; RLA; RNA; RoW	70% open pit and 30% underground
Copper	Mining, concentration, extraction, refining	Transforming	gold-silver-zinc-lead-copper mine operation and refining	copper	2004	2015	SE; RoW	Open pit mining; comminution; leaching in dilute cyanide soln.
Copper	Extraction; refining	Transforming	copper production, primary	copper	1994	2015	AU; RAS; RER; RLA; RNA; RoW	reverberatory furnace 23.7%; flash smelting furnaces 60.7%; other 6.2%.; SX-EW 9.4%
Copper	Extraction	Transforming	copper production, blister-copper	copper, blister-copper	1994	2015	RER; RoW	reverberatory furnace 6.2%; flash smelting furnaces 76%; other 17.8%
Copper	Mining; concentration;	Transforming	copper production, solvent-extraction electro-winning	copper, from solvent-extraction electro-winning	1994	2015	GLO	Mining: same as "copper mine operation"; concentration: leaching;

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	extraction							extraction: cementation and electrowinning
Copper	Mining; concentration; extraction	Transforming	copper production, solvent-extraction electro-winning	sulphuric acid	1994	2015	GLO	
Copper	Refinement & casting	Transforming	electrolytic refining of primary copper	copper, cathode	1994	2015	GLO	Electrorefining
Copper	Refinement & casting	Transforming	electrolytic refining of primary copper	anode slime, silver and tellurium containing, from primary copper production	1994	2015	GLO	Electrorefining
Copper	Refinement & casting	Transforming	anode slime, silver and tellurium containing stockpiling	anode slime, silver and tellurium containing stockpiling	2005	2015	US; RoW	
Copper	Extraction	Transforming	processing of anode slime, primary copper production	copper telluride cement	2000	2015	GLO	Leaching; pptn. of copper telluride on copper choppings; melting of residues; Moebius electrolysis of residues
Copper	Extraction	Transforming	processing of anode slime, primary copper production	silver	2000	2015	GLO	Leaching; pptn. of copper telluride on copper choppings; melting of residues; Moebius electrolysis of residues
Copper	Extraction	Transforming	brass production	brass	2000	2015	CH; RoW	
Copper	Extraction	Transforming	bronze production	bronze	2000	2015	CH; RoW	
Copper	Extraction	Transforming	brazing solder production, cadmium free	brazing solver, cadmium free	2000	2015	CH; RoW	
Copper	Refinement & casting	Transforming	casting, brass	casting, brass	1996	2015	CH; RoW	Melting of alloy; casting into ingots
Copper	Refinement & casting	Transforming	casting, bronze	casting, bronze	1996	2015	CH; RoW	Melting of alloy; casting into ingots
Copper	Mining; concentration	Transforming	molybdenite mine operation	copper concentrate	1994	2015	GLO	Mining: 70% open pit and 30% underground;

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	on							concentration: grinding; gravity separation; flotation with lime and frothing reagents
Copper	Mining; concentration	Transforming	molybdenite mine operation	molybdenite	1994	2015	GLO	70% open pit and 30% underground
Copper	Extraction; refining	Transforming	tellurium production, semiconductor-grade	tellurium, semiconductor-grade	1992	2015	CA-QC; RoW	70% open pit and 30% underground
Copper	Extraction	Transforming	molybdenum production	molybdenum	2000	2015	RER; RoW	A mix of 80% hydrometallurgical and 20% pyrometallurgical production of zinc used as proxy
Copper	Extraction	Transforming	molybdenum trioxide production	molybdenum trioxide	2008	2015	GLO	Blast furnace used as proxy
Nickel	Mining, concentration, extraction, refining	Transforming	nickel mine operation, sulfidic ore	nickel, 99.5%	1994	2015	GLO	Mining: underground & disposal of overburden; concentration: flotation with lime and reagents & disposal of tailings; extraction: pyro (roasting, smelting, & converting); refinement: electrolysis
Nickel	Mining, concentration, extraction, refining	Transforming	nickel mine operation, sulfidic ore	copper	1994	2015	GLO	Mining: underground & disposal of overburden; concentration: flotation with lime and reagents & disposal of tailings; extraction: pyro (roasting, smelting, & converting); refinement: electrolysis
Nickel	Mining, concentration	Transforming	nickel mine operation, sulfidic ore	ammonium sulfate, as N	1994	2015	GLO	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	on, extraction, refining							
Nickel	Mining, concentration, extraction, refining	Transforming	nickel mine operation, sulfidic ore	sulfuric acid	1994	2015	GLO	
Nickel	Mining, concentration, extraction, refining	Transforming	ferronickel production, 25% Ni	ferronickel, 25% Ni	1994	2015	GLO	Mining: open pit (inc disposal of overburden); concentration: comminution only (inc disposal of tailings); extraction: drying (dehydration via calcination in rotary kiln), smelting (electric arc); refinement:
Nickel	Mining, concentration, extraction, refining	Treatment	treatment of nickel smelter slag, residual material landfill	nickel smelter slag	1994	2015	CH; RoW	Residual waste landfill
Nickel	Extraction; refining	Transforming	smelting and refining of nickel ore	ammonium sulfate, as N	2010	2015	GLO	
Nickel	Extraction; refining	Transforming	smelting and refining of nickel ore	copper	2010	2015	GLO	extraction: pyro (roasting, smelting, & converting); refinement: electrolysis
Nickel	Extraction; refining	Transforming	smelting and refining of nickel ore	nickel, 99.5%	2010	2015	GLO	extraction: pyro (roasting, smelting, & converting); refinement: electrolysis
Nickel	Extraction; refining	Transforming	smelting and refining of nickel ore	sulfuric acid	2010	2015	GLO	
Nickel	Extraction; refining	Transforming	smelting and refining of nickel ore	steam, in chemical industry	2010	2015	GLO	
Nickel	Mining; concentration	Transforming	mining and beneficiation of nickel ore	nickel ore, beneficiated, 16%	2010	2015	CA-QC; RoW	Mining: underground; concentration: unknown

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	on							
Platinum group metals (PGM)	Mining, concentration, extraction, refining	Transforming	platinum group metal mine operation, ore with high palladium content	copper	1995	2015	RU	Mining: underground; concentration: comminution (grinding), gravity separation, flotation; extraction: pyro (roasting, smelting, converting)
Platinum group metals (PGM)	Mining, concentration, extraction, refining	Transforming	platinum group metal mine operation, ore with high palladium content	nickel, 99.5%	1995	2015	RU	Mining: underground; concentration: comminution (grinding), gravity separation, flotation; extraction: pyro (roasting, smelting, converting)
Platinum group metals (PGM)	Mining, concentration, extraction, refining	Transforming	platinum group metal mine operation, ore with high palladium content	palladium	1995	2015	RU	Mining: underground; concentration: comminution (grinding), gravity separation, flotation; extraction: pyro (roasting, smelting, converting)
Platinum group metals (PGM)	Mining, concentration, extraction, refining	Transforming	platinum group metal mine operation, ore with high palladium content	platinum	1995	2015	RU	Mining: underground; concentration: comminution (grinding), gravity separation, flotation; extraction: pyro (roasting, smelting, converting)
Platinum group metals (PGM)	Mining, concentration, extraction, refining	Transforming	platinum group metal mine operation, ore with high palladium content	rhodium	1995	2015	RU	Mining: underground; concentration: comminution (grinding), gravity separation, flotation; extraction: pyro (roasting, smelting, converting)
Platinum group metals (PGM)	Mining, concentration, extraction,	Transforming	platinum group metal mine operation, ore with high rhodium content	copper	1995	2015	ZA	Mining: underground; concentration: comminution (grinding), gravity separation, flotation;

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	refining							extraction: pyro (roasting, smelting, converting)
Platinum group metals (PGM)	Mining, concentration, extraction, refining	Transforming	platinum group metal mine operation, ore with high rhodium content	nickel, 99.5%	1995	2015	ZA	Mining: underground; concentration: comminution (grinding), gravity separation, flotation; extraction: pyro (roasting, smelting, converting)
Platinum group metals (PGM)	Mining, concentration, extraction, refining	Transforming	platinum group metal mine operation, ore with high rhodium content	palladium	1995	2015	ZA	Mining: underground; concentration: comminution (grinding), gravity separation, flotation; extraction: pyro (roasting, smelting, converting)
Platinum group metals (PGM)	Mining, concentration, extraction, refining	Transforming	platinum group metal mine operation, ore with high rhodium content	platinum	1995	2015	ZA	Mining: underground; concentration: comminution (grinding), gravity separation, flotation; extraction: pyro (roasting, smelting, converting)
Platinum group metals (PGM)	Mining, concentration, extraction, refining	Transforming	platinum group metal mine operation, ore with high rhodium content	rhodium	1995	2015	ZA	Mining: underground; concentration: comminution (grinding), gravity separation, flotation; extraction: pyro (roasting, smelting, converting)
Chromium	Mining; concentration	Transforming	chromite ore concentrate production	chromite ore concentrate	1994	2015	GLO	Mining: 21% open pit, 79% underground; concentration: comminution, gravity separation
Chromium	Extraction	Transforming	chromium production	chromium	1994	2015	RER; RoW	75% aluminothermic process, 25% electrolysis of dissolved ferrochromium
Chromium	Extraction	Transforming	ferrochromium	ferrochromium, high-carbon,	1994	2015	GLO	Direct reduction of chromite

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
			production, high-carbon, 68% Cr	68% Cr				ores with carbon in three-phase submerged arc furnaces. 50% ordinary technology, 50% new processes like Outokumpu, Showa Denko, Krupp-CODIR & plasma furnace
Manganese	Mining; concentration	Transforming	manganese concentrate production	manganese concentrate	1994	2015	GLO	Mining: 70% open pit, 30% underground; concentration: comminution, gravity separation
Manganese	Extraction	Transforming	ferromanganese production, high-coal, 74.5% Mn	ferromanganese, high-coal, 74.5% Mn	1994	2015	RER; RoW	blast furnaces (20%), electric arc furnaces without flux (27%), electric arc furnaces with calcareous flux (53%)
Manganese	Extraction; refining	Transforming	manganese production	manganese	2003	2015	RER; RoW	electrolysis (25%), electrothermic processes (75%).
Antimony	Mining; concentration	Transforming	stibnite mine operation, 70% stibnite	stibnite ore, 70% stibnite	1994	2015	CA-QC; CN; RoW	
Antimony		Transforming	antimony production	antimony	1994	2015	CN; RoW	
Tellurium	Extraction; refining	Transforming	tellurium production, semiconductor-grade	tellurium, semiconductor-grade	1992	2015	CA-QC, RoW	
Zinc-lead	Mining, concentration	Transforming	Zinc-lead mine operation	lead concentrate	1994	2015	GLO	
Zinc-lead	Mining, concentration	Transforming	Zinc-lead mine operation	zinc concentrate	1994	2015	GLO	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	on							
Zinc-lead	Extraction, refining	Transforming	primary lead production from concentrate	crust from Parkes process for lead production	2005	2015	CA-QC, RoW	sintering, smelting (blast furnace)
Zinc-lead	Extraction, refining	Transforming	primary lead production from concentrate	lead	2005	2015	CA-QC, RoW	sintering, smelting (blast furnace)
Zinc-lead	Extraction, refining	Transforming	primary lead production from concentrate	sulfuric acid	2005	2015	CA-QC, RoW	
Zinc-lead	Extraction, refining	Transforming	primary zinc production from concentrate	cadmium sludge from zinc electrolysis	2003	2015	CA-QC, RoW	roasting (fluidised bed), leaching, precipitation, electrolysis
Zinc-lead	Extraction, refining	Transforming	primary zinc production from concentrate	copper cake	2003	2015	CA-QC, RoW	roasting (fluidised bed), leaching, precipitation, electrolysis
Zinc-lead	Extraction, refining	Transforming	primary zinc production from concentrate	indium rich leaching residues	2003	2015	CA-QC, RoW	roasting (fluidised bed), leaching, precipitation, electrolysis
Zinc-lead	Extraction, refining	Transforming	primary zinc production from concentrate	sulfur dioxide, liquid	2003	2015	CA-QC, RoW	The sulphur dioxide is then converted to sulphuric acid in a conventional recovery system (converted and absorbing tower)
Zinc-lead	Extraction, refining	Transforming	primary zinc production from concentrate	sulfuric acid	2003	2015	CA-QC, RoW	The sulphur dioxide is then converted to sulphuric acid in a conventional recovery system (converted and absorbing tower)
Zinc-lead	Extraction, refining	Transforming	primary zinc production from concentrate	zinc	2003	2015	CA-QC, RoW	roasting (fluidised bed), leaching, precipitation, electrolysis
Zinc-lead	Extraction, refining	Transforming	indium production	indium	2000	2015	RER, RoW	leaching, solvent extraction, precipitation, electrefining
Zinc-lead	Extraction, refining	Transforming	cadmium sludge from zinc electrolysis stockpiling	cadmium sludge from zinc electrolysis	2012	2015	US; RoW	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
Gold-silver-zinc-lead-copper	Mining, concentration, extraction, refining	Transforming	Gold-silver-zinc-lead-copper mine operation and refining	copper	2000	2006	SE, RoW	mining: open pit; concentration: comminution, leaching; extraction: drying (autoclave), roasting, electrowinning, smelting (gold)
Gold-silver-zinc-lead-copper	Mining, concentration, extraction, refining	Transforming	Gold-silver-zinc-lead-copper mine operation and refining	gold	2000	2006	SE, RoW	mining: open pit; concentration: comminution, leaching; extraction: drying (autoclave), roasting, electrowinning, smelting (gold)
Gold-silver-zinc-lead-copper	Mining, concentration, extraction, refining	Transforming	Gold-silver-zinc-lead-copper mine operation and refining	lead	2000	2006	SE, RoW	mining: open pit; concentration: comminution, leaching; extraction: drying (autoclave), roasting, electrowinning, smelting (gold)
Gold-silver-zinc-lead-copper	Mining, concentration, extraction, refining	Transforming	Gold-silver-zinc-lead-copper mine operation and refining	silver	2000	2006	SE, RoW	mining: open pit; concentration: comminution, leaching; extraction: drying (autoclave), roasting, electrowinning, smelting (gold)
Gold-silver-zinc-lead-copper	Mining, concentration, extraction, refining	Transforming	Gold-silver-zinc-lead-copper mine operation and refining	zinc	2000	2006	SE, RoW	mining: open pit; concentration: comminution, leaching; extraction: drying (autoclave), roasting, electrowinning, smelting (gold)
Gold-silver	Mining, concentration, extraction, refining	Transforming	Gold-silver mine operation with refinery	gold	2004	2015	CA-QC, PE, PG, RoW	mining: open pit; concentration: comminution, leaching; extraction: electrolysis
Gold-silver	Mining,	Transforming	Gold-silver mine	silver	2004	2015	CA-QC, PE, PG,	mining: open pit;

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	concentration, extraction, refining		operation with refinery				RoW	concentration: comminution, leaching; extraction: electrolysis
Silver-gold	Mining, concentration, extraction, refining	Transforming	Silver-gold mine operation with refinery	gold	2004	2015	CA-QC, PE, PG, RoW	mining: open pit; concentration: comminution, leaching; extraction: electrolysis
Silver-gold	Mining, concentration, extraction, refining	Transforming	Silver-gold mine operation with refinery	silver	2004	2015	CA-QC, PE, PG, RoW	mining: open pit; concentration: comminution, leaching; extraction: electrolysis
Gold	Mining, concentration, extraction, refining	Transforming	Gold production	gold	2001	2015	AU, CA, RoW, TZ, US, ZA	mining: open pit; concentration: comminution, leaching; solvent extraction; electrolysis
Gallium	Extraction, refining	Transforming	gallium production, semiconductor-grade	gallium, semiconductor-grade	1999	2015	GLO	hydrometallurgical processes (Rhône-Poulenc-Process)
Cadmium		Market	primary zinc production from concentrate	cadmium sludge from zinc electrolysis	2011	2015	CA-QC, RoW	
Tantalum	Mining, concentration, extraction, refining	Transforming	tantalum production, powder, capacitor-grade	tantalum, powder, capacitor-grade	2000	2015	GLO	Mining: open pit; concentration: unknown; reduction in multiple hearth furnace or rotary kiln
Tin	Mining,	Transforming	tin production	tin	1996	2015	RER, RoW	Data relate to an assumed tin

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	concentration, extraction, refining							production
Magnesium	Extraction, refining	Transforming	magnesium production, electrolysis	chlorine, liquid	2011	2015	IL, RoW	electrochemical process
Magnesium	Extraction, refining	Transforming	magnesium production, electrolysis	magnesium	2011	2015	IL, RoW	electrochemical process
Magnesium	Extraction, refining	Transforming	magnesium production, electrolysis	potassium chloride	2011	2015	IL, RoW	electrochemical process
Magnesium	Extraction, refining	Transforming	magnesium production, pigeon process	magnesium	2011	2015	CN	calcination, grinding, briquetting, reduction, refining
Magnesium	Refining	Transforming	magnesium-alloy production, AZ91	magnesium-alloy, AZ91	1998	2015	RER, RoW	unknown
Magnesium	Refining	Transforming	magnesium-alloy production, AZ91, diecasting	magnesium-alloy, AZ91, diecast	1998	2015	RER, RoW	unknown
Indium		Market	primary zinc production from concentrate	indium rich leaching residues	1994	2015	RER, RoW	
Indium		Market	molybdenum production	indium rich leaching residues	2000	2015	RER, RoW	
Titanium	Mining, concentration, extraction, refining	Transforming	titanium production, primary	titanium, primary	2004	2015	GLO	
Titanium	Mining, concentration, extraction,	Transforming	titanium production, primary, triple melt	titanium, primary, triple melt	2004	2015	GLO	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	refining							
Titanium	Mining, concentration, extraction, refining	Transforming	titanium dioxide production, chloride process	titanium dioxide	2005	2015	RER, RoW	
Titanium	Mining, concentration, extraction, refining	Transforming	titanium dioxide production, sulfate process	titanium dioxide	2005	2015	RER, RoW	
Titanium	Mining, concentration, extraction, refining	Transforming	titanium tetrachloride production	titanium tetrachloride	2004	2015	GLO	
Titanium	Mining, concentration, extraction, refining	Transforming	titanium zinc plate production, without pre-weathering	titanium zinc plate, without pre-weathering	1997	2015	DE, RoW	
Zirconium	Mining, concentration, extraction, refining	Transforming	zirconium oxide production	zirconium oxide	2000	2015	AU, RoW	
Rare earth metals	Mining, concentration, extraction, refining	Transforming	rare earth oxides production from bastnäsite concentrate	cerium concentrate, 60% cerium oxide	2000	2015	CN, RoW	
Rare earth metals	Mining, concentration	Transforming	rare earth oxides production from	lanthanum oxide	2000	2015	CN, RoW	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	on, extraction, refining		bastnäsite concentrate					
Rare earth metals	Mining, concentration, extraction, refining	Transforming	rare earth oxides production from bastnäsite concentrate	neodymium oxide	2000	2015	CN, RoW	
Rare earth metals	Mining, concentration, extraction, refining	Transforming	rare earth oxides production from bastnäsite concentrate	praseodymium oxide	2000	2015	CN, RoW	
Rare earth metals	Mining, concentration, extraction, refining	Transforming	rare earth oxides production from bastnäsite concentrate	samarium europium gadolinium concentrate, 94% rare earth oxide	2000	2015	CN, RoW	
Uranium	Mining, concentration, extraction, refining	Transforming	uranium production, centrifuge, enriched 3.0%	uranium, enriched 3.0%, per separative work unit	1993	2015	CN, DE, GB, NL, RU	
Uranium	Mining, concentration, extraction, refining	Transforming	uranium production, diffusion, enriched 3.0%	uranium, enriched 3.0%, per separative work unit	1980	2015	FR, US, RoW	
Uranium	Mining, concentration, extraction, refining	Transforming	uranium fuel element production, enriched 3.0%, for light water reactor	uranium, enriched 3.0%, in fuel element for light water reactor	1980	2015	US, RoW	
Uranium	Mining,	Transforming	uranium fuel element	uranium, enriched 3.8%, in	1980	2015	CH, CN, FR, US,	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	concentration, extraction, refining		production, enriched 3.8%, for light water reactor	fuel element for light water reactor			RoW	
Boron	Mining, concentration, extraction, refining	Transforming	calcium borates production	calcium borates	2000	2015	TR, RoW	
Boron	Mining, concentration, extraction, refining	Transforming	sodium borates production	sodium borates	2000	2015	US, RoW	
Boron	Mining, concentration, extraction, refining	Transforming	boric acid production, anhydrous, powder	boric acid, anhydrous, powder	2000	2015	RER, RoW	
Boron	Mining, concentration, extraction, refining	Transforming	boric oxide production	boric oxide	2000	2015	GLO	
Boron	Mining, concentration, extraction, refining	Transforming	boron carbide production	boron carbide	2000	2015	GLO	
Boron	Mining, concentration, extraction, refining	Transforming	boron trifluoride production	boron trifluoride	2000	2015	GLO	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
Boron	Mining, concentration, extraction, refining	Transforming	borax production	borax	2000	2015	RER, RoW	
Mercury	Mining, concentration, extraction, refining	Transforming	mercury production	mercury	2000	2015	GLO	
Lithium	Mining, concentration, extraction, refining	Transforming	lithium brine inspissation	lithium brine, 6.7 % Li	2009	2015	GLO	
Lithium	Mining, concentration, extraction, refining	Transforming	lithium carbonate production, from concentrated brine	lithium carbonate	2009	2015	GLO	
Lithium	Mining, concentration, extraction, refining	Transforming	lithium chloride production	lithium chloride	2000	2015	GLO	
Lithium	Mining, concentration, extraction, refining	Transforming	lithium fluoride production	lithium fluoride	2009	2015	CN, RoW	
Lithium	Mining, concentration, extraction, refining	Transforming	lithium hexafluorophosphate production	lithium hexafluorophosphate	2009	2015	CN, RoW	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	extraction, refining							
Lithium	Mining, concentration, extraction, refining	Transforming	lithium hydroxide production	lithium hydroxide	2000	2015	GLO	
Lithium	Mining, concentration, extraction, refining	Transforming	lithium hydroxide production	lime	2000	2015	GLO	
Lithium	Mining, concentration, extraction, refining	Transforming	lithium manganese oxide production	lithium manganese oxide	2009	2015	GLO	
Silicon	Mining, concentration, extraction, refining	Transforming	silicon hydrochloration	silicon tetrachloride	2000	2015	GLO	
Silicon	Mining, concentration, extraction, refining	Transforming	silicon production, electronics grade	silicon tetrachloride	1992	2015	DE, RoW	
Silicon	Mining, concentration, extraction, refining	Transforming	silicon production, electronics grade	silicon, electronics grade	1992	2015	DE, RoW	
Silicon	Mining, concentration	Transforming	silicon production, electronics grade	silicon, solar grade	1992	2015	DE, RoW	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	on, extraction, refining							
Silicon	Mining, concentration, extraction, refining	Transforming	silicon production, metallurgical grade	silicon, metallurgical grade	2000	2015	NO, RoW	
Silicon	Mining, concentration, extraction, refining	Transforming	silicon production, multi-Si, casted	silicon, multi-Si, casted	1997	2015	CA-QG, RER, RoW	
Silicon	Mining, concentration, extraction, refining	Transforming	silicon production, single crystal, Czochralski process, electronics	silicon, single crystal, Czochralski process, electronics	1992	2015	RER, RoW	
Silicon	Mining, concentration, extraction, refining	Transforming	silicon production, single crystal, Czochralski process, photovoltaics	silicon, single crystal, Czochralski process, photovoltaics	1992	2015	RER, RoW	
Silicon	Mining, concentration, extraction, refining	Transforming	silicon production, solar grade, modified Siemens process	silicon, solar grade	2004	2015	RER, RoW	
Silicon	Mining, concentration, extraction, refining	Transforming	silicon tetrachloride production	carbon monoxide	1986	2015	GLO	
Silicon	Mining, concentration, extraction, refining	Transforming	silicon tetrachloride production	silicon tetrachloride	1986	2015	GLO	

System	Processes covered	Dataset category	Activity dataset name	Ref. product name	Start year	End year	Geography	Technology level
	extraction, refining							
Cobalt	Mining, concentration, extraction, refining	Transforming	cobalt production	cobalt	2000	2015	GLO	

^a Refers to the “copper, molybdenum & Telluride and silver containing by-products” system.