# Life Cycle Inventory of Molybdenum Products for Metallurgical Applications: Update Study

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# Summary Report
2018

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# SECTION 1: INTRODUCTION AND GOAL

## Introduction & Background

For nearly two decades, the non-ferrous and ferrous metals industries have adopted Life Cycle Assessment (LCA) as a powerful and comprehensive environmental tool to supply environmental information to customers, help identify areas of process improvement, and measure environmental performance. As one of the earliest adopters of LCA within the metals industry, in 2000 the International Molybdenum Association (IMOA) completed a Life Cycle Inventory (LCI) for three molybdenum products for metallurgical applications. In 2008 and again in 2018, IMOA updated the LCI to increase Mo production representativeness and further improve the data quality with current facility and background data. Most notably, the 2018 update ensured consistency with other metals groups using a metal and minerals LCA methodology guidance document.

## Harmonization of Metals LCAs

In 2014, a 'Harmonization of LCA Methodologies for Metals' guidance document geared toward the metals and minerals industry was published under a multi-organizational effort that included ten metal commodities including IMOA, the International Council on Mining and Metals, Eurometaux, and Euromines. The Harmonization Document was produced to order to lay out a set of recommendations for producing consistent LCIs and LCAs across the metals industry and to enhance public awareness about metal-specific issues around LCA best practice. The importance of having a consistent approach across the metals and minerals industry was also being driven by an increase in the life cycle based initiatives of governments and regulators, the end-use market sectors, civil society, multi-lateral organizations, and material specifiers. This industry-wide effort came at a time when strict adherence to high quality data – notably primary data within five years of age – was becoming a requirement for government programs e.g. the EU Product Environmental Footprint (PEF) initiative.

## Goal and High-level Scope

The aim of this study is to develop updated LCI data profiles for the intermediate molybdenum products for metallurgical applications, as covered by the previous LCIs:

a) Roasted molybdenite concentrates (RMC), also known as "technical grade molybdenum oxide" or "tech oxide", in powder form
b) RMC in briquette form
c) Ferromolybdenum (FeMo)

The LCIs are cradle-to-gate, encompassing the processes that include resource extraction from the earth through to the point at which the molybdenum products are ready for shipment to customers, including packaging. The LCIs are based on current data on process technologies, energy and materials consumed, and environmental outputs. They take into account methodological issues that have evolved since the original LCI, and incorporate current or new methods highlighted in the Harmonization Document. The geographical scope is global production minus China; with plant data submitted from North and South America, Europe, and Asia. The study results are intended to be incorporated into LCA databases and will be used by LCA practitioners and researchers to calculate potential impacts of molybdenum-containing products using appropriate Life Cycle Impact Assessment methodologies. Since this study is cradle-to-gate and therefore not a full LCA that looks at molybdenum use in applications, the study results are not intended to support comparative assertions disclosed to the public. The results are intended to be used as feedstock material into downstream LCA studies that could be used for making comparative assertions, provided those studies comply with the ISO 14044 requirements on comparative assertions.

## Intended Applications for Data Requestors

The LCI results will be provided to qualifying individuals, defined here as people or organizations who demonstrate enough familiarity with LCA and how to use the study results, to guard against their misuse. Using reliable and representative data will increase overall data quality in studies and can aid in the dissemination of positive environmental messages with regard to molybdenum-containing products. Uses of these data for the metallurgical industries (e.g. stainless steel producers), researchers, LCA consultants, industry groups, and marketers may include:

- Support research of molybdenum feedstocks and molybdenum-containing products;
- Use as upstream feedstock input for cradle-to-gate LCIs and cradle-to-grave LCAs of molybdenum-containing products;
- Use to assess current and new molybdenum-containing technologies;
- Use as an input and to support high quality data requirements of policy requirements, i.e., Product Environmental Footprints (PEFs); and
- Use to support public facing Environmental Product Declarations (EPDs) and other LCAs.

## Intended Applications for IMOA and their Members

IMOA and its participating members can use the study to:

- Provide current information to stakeholders to support the sales and marketing of molybdenum products;
- Answer requests for environmental information (e.g., carbon footprint data requests by customers);
- Benchmark their own results against industry-wide averages, and to measure their own progress;
- Use sustainability/life cycle thinking or LCA as a part of their product and company marketing;
- Enhance their environmental image by reporting information and/or milestones in company literature (e.g. websites; Annual Reports; Environmental or Sustainability reports; Global Reporting Initiative submissions); and
- Use as direct input to updating the LCIs of molybdenum chemicals, which are also a part of IMOA's overall LCI program.

## Peer Review

This update study has undergone an external peer review to ensure credibility and objectivity of the data and results as well as conformance with the International Organization for Standardization (ISO) standards on LCA. The critical review process ensured the following: [1]

- "the methods used to carry out the LCA are consistent with this International Standard,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent."

The peer review was led by James Salazar, Principal of Coldstream Consulting Ltd., based out of British Columbia, Canada.

[1] ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines, Section 6.1.

# Life Cycle Assessment Defined

Life Cycle Assessment (LCA) has become one of the most valuable environmental tools for assessing the environmental footprint of a product or process because it provides quantitative and scientific analyses of the environmental impacts of products and their associated industrial systems. LCA evaluates all stages of a products' life cycle, which include extraction of raw materials, manufacturing, transport and use of products, and end-of-life management (e.g., recycling, reuse, and/or disposal). ISO developed principles and a framework for conducting LCA, and the four main parts of an LCA defined in this framework include: [2]

1. Goal and Scope definition: specifying the reason for conducting the study, intended use of study results, intended audience, system boundaries, data requirements, and study limitations.
2. Life Cycle Inventory (LCI): collecting, validating and aggregating input and output data to quantify material use, energy use, environmental discharges, and waste associated with each life cycle stage.
3. Life Cycle Impact Assessment (LCIA): using impact categories, category indicators, characterization models, equivalency factors, and weighting values to translate an inventory into potential impact on human health and the environment.
4. Interpretation: assessing whether results are in line with project goals, providing an unbiased summary of results, defining significant impacts, and recommending methods for reducing material use and environmental burdens.

This update study covers the first two parts of the LCA framework, i.e., goal and scope defining, and the LCI process. The main report, which is internal to company participants, interprets the results. This study adheres to ISO 14044 principles, framework and guidelines. It aims to meet the essential requirements formalized by the ISO, specifically:

- The project aims at taking an inventory of the environmental inflows and outflows associated with the cradle-to-gate production of a product;
- The goal and scope of the project are precisely defined at the beginning of the project;
- Assumptions are clearly stated, and the methodology is as transparent as allowed with protection of confidential data;
- System boundaries, functional unit, and allocation rules are rigorously defined and described;
- Pertinent data are collected and their quality is rigorously assessed; and
- Reporting requirements are stated.

[2] ISO 14040:2006, the International Standard of the International Standardization Organization, Environmental management. Life cycle assessment. Principles and framework.

# SECTION 2: SCOPE DEFINITION AND METHODOLOGY

This section presents the project scope and describes the general methodology used. Additional details related to the methodology and the life cycle stages are presented in the Modeling section.

## Molybdenum Products Studied

The following intermediate molybdenum products were updated:
1. RMC, also known as technical grade molybdic oxide ("tech oxide") and "molybdenum sulfide ($MoS_2$), roasted", in powder form;
2. RMC in briquette form; and
3. Ferromolybdenum lumps.

Primary data were collected from facilities, so the production processes, material and energy inputs, and facility outputs are current. The molybdenum products studied are "average" to the industry, and not "typical". Studying an average product enables the span of technologies and material inputs to be taken into account in the analysis, yet specific characteristics of *actual* products are lost (i.e., actual product density, molybdenum content, etc.). Thus, the resulting product accounts for components of the whole industry, which is a critical aspect of the goal of the study.

Transportation of upstream materials and energy to the facilities are accounted for, but transportation of the finished product from the shipping dock to a customer is not, as downstream producers, such as stainless steel manufacturers, capture this data in their own material transportation data.

## Functional and Declared Units

To conduct an effective LCI under ISO guidelines, all flows within the system boundaries must be normalized to a functional unit or declared unit. The functional unit describes the function of a product or process system, allowing the comparison of different industrial systems performing the same function or assessing a product in a contextual basis. A declared unit does not need to have a function associated with it. This study looks at the production of three molybdenum products. Since these, without their defined end-uses, do not have a function, their results are normalized to a declared unit. For this study, the declared unit is **one kilogram of molybdenum in each product studied**, i.e. one kilogram of molybdenum in the tech oxide, the briquette, and the ferromolybdenum. The results provided to data requestors are as **one kilogram of each product.**

## System Boundaries

### General Process Overview

This study covers five major unit processes that have been defined for metallurgical molybdenum production, listed below and presented in the Modeling section:

1. Mining, including both primary (Mo ores) and byproduct mines (Mo and Cu ores);
2. Concentration, including milling;
3. Roasting into tech oxide;
4. Briquette production; and
5. Ferromolybdenum production.

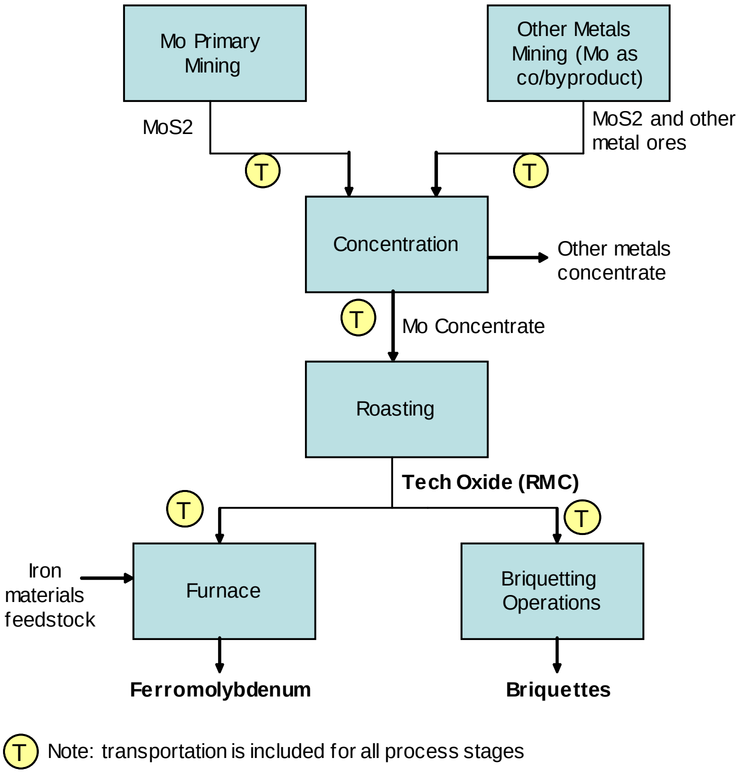


**Figure 1: Overall metallurgical Mo LCI system boundary**

## Cut-off Criteria

### Cut-off Criteria Goal

In LCA, a cut-off criteria is defined for the selection of materials and processes to be included in the system boundaries. Only the first of the decision rules defined by ISO, i.e., cut-off based on mass criteria, was used, implying that materials and processes included in the system were chosen based upon their contribution by mass to the production processes. A cut-off criterion of 99.5 percent of the mass of inputs was used to determine the inputs and outputs of each unit process stage.

### Attaining the Cut-off Criteria Goal

In order to attain this cut-off goal, the facility questionnaires contained pre-defined lists of key inputs expected for each specific process. Additional space was provided to encourage the site staff to fill in any additional inputs that fit within the mass criteria threshold. Three guidelines were used to help collect as many of the inputs as possible to reach at least 99%:

- Facilities should report all fuel inputs;
- Facilities should report inputs that have a high purchase price. A high price may signify a high raw material cost and the possible use of scarce natural resources, numerous manufacturing processes potentially reflecting high energy consumption, or both; and
- Facilities should report environmentally relevant inputs or materials that may potentially be toxic.

## Final Product Packaging

In the original study, packaging of final products was included as a sensitivity analysis. The sensitivity analysis demonstrated packaging to be negligible. Nonetheless, packaging is included as part of the main results since it is part of the delivered product.

### Exclusion of Data from the System Boundaries

Two elements of the life cycle have been excluded from the system boundaries: capital equipment and human-related activities. This is standard practice for most LCAs and the reasons are described briefly below.

**Capital Equipment**

In LCA system boundary defining, one might include capital equipment such as the production and transportation of concrete and steel for facility infrastructure. However, capital equipment is generally excluded since its contribution to the overall life cycle is small. Exceptions to this are materials that may be considered capital equipment yet need to be replaced over the course of a year. For the metallurgical industry these include mining truck tires and steel consumables in the milling process, such as liners and crushing/grinding media.

**Human Involvement**

Flows that are not directly related to industrial activities are not taken into account, such as cafeteria inflows and waste, restroom operations, and driving to and from work. These specific flows related to people and offices are not unique to molybdenum production. Flows attributable to people and offices in the plant which may be difficult to separate from production process flows, such as electricity, are usually small in comparison to the production process flows, so are left aggregated in the production process.

## Data Used

Both primary data (collected from the manufacturers) and secondary data (publicly-available, literature sources) can be used for LCAs, and it is common to see a mix of both data types. For this study, primary data for the five defined unit processes were used. Secondary data were used as the background data for the Mo product model, including fuel use, material and reagent inputs, ancillary inputs, and transportation of materials to the plants. The most up-to-date data sets from the Gabi database[3] were used, and the EcoInvent database[4] was used where no materials were available in Gabi. Utilizing the most currently available data, especially from well-known and accepted databases, enhances the quality of the study and increases its transparency, reliability, and confidence level.

## Data Categories

### Choosing Inventory Flows

LCA methodology proposes to consider, at the onset of the study, the environmental inventory and impact flows that will most likely receive subsequent attention. While keeping the breadth of the life cycle approach, setting priorities in terms of data collection and relevant industry flows helps to focus the project and ease the subsequent use of data in decision-making.

### Molybdenum LCI Data Categories and Inventory Flows

The inflows and outflows presented in the results have been identified using the following criteria:

- The flows relevant to the molybdenum industry, including environmental policies and priorities around molybdenum mining and processing facilities; and/or
- The flows identified by downstream data users, such as the stainless steel industry for the LCI and LCA work on its stainless steel products.
- Common flows related to energy and fuel use.

The next sections outline and describe the list of inputs and outputs included in the study.

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[3] thinkstep AG, GaBi Software-System and Database for Life Cycle Engineering 1992-2018.

[4] Ecoinvent Centre, Ecoinvent data v3 (Dübendorf: Swiss Centre for Life Cycle Inventories, 2017), retrieved from: www.ecoinvent.org.

## Elementary Input Flows

The energy and materials reported in the questionnaires have been traced to their elementary condition (i.e., they are generated after full aggregation of upstream data with downstream data), and are called raw materials in the results. It is for this reason that the consumables, fuels, and intermediate molybdenum inputs reported by facilities do not show up in the LCI results.

**Table 1: Raw materials inputs**

| **Elementary inputs (units in kilograms)** |
|---|
| Hard Coal (resource) |
| Iron (Fe, resource) |
| Limestone (Calcium carbonate) |
| Molybdenum (in ground) |
| Natural Gas (resource) |
| Crude Oil (resource) |
| Uranium (U, ore) |
| Total net water consumption |
| Lignite (resource) |

## Air Emission Category

**Table 2: Air emissions**

| **Air Emissions (units in kilograms)** |
|---|
| Ammonia ($NH_3$) |
| Carbon Dioxide ($CO_2$, fossil) |
| Carbon Monoxide (CO) |
| Hydrogen Chloride (HCl) |
| Hydrogen Cyanide (HCN) |
| Hydrogen Sulfide ($H_2S$) |
| Hydrogen Fluoride (HF) |
| Copper (Cu) |
| Lead (Pb) |
| Mercury (Hg) |
| Methane ($CH_4$) |
| Molybdenum (Mo) |
| Nitrogen Dioxide ($NO_2$) |
| Nitrogen Oxides (NOx as $NO_2$) |
| Nitrous Oxide ($N_2O$) |
| Particulates (unspecified) |
| Sulfur Dioxide ($SO_2$) |
| Zinc (Zn) |
| Non-methane VOC (unspecified) |

## Water Effluent Category

**Table 3: Water effluents**

| **Water Effluents (units in kilograms)** |
|---|
| Aluminum (Al3+) |
| Ammonia ($NH_4$+, $NH_3$, as N) |
| Biological Oxygen Demand (BOD) |
| Chemical oxygen demand (COD) |
| Cadmium (Cd++) |
| Chlorides (Cl-) |
| Chromium (total) |
| Arsenic (As) |

| |
|---|
| Copper (Cu+, Cu++) |
| Cyanide (CN-) |
| Fluorides (F-) |
| Iron (Fe++, Fe3+) |
| Lead (Pb++, Pb4+) |
| Manganese (Mn II, Mn IV, Mn VII) |
| Mercury (Hg+, Hg++) |
| Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI) |
| Nickel (Ni++, Ni3+) |
| Nitrate ($NO_3$-) |
| Nitrogenous Matter (unspecified, as N) |
| Oils (unspecified) |
| PAH, unspecified |
| Phosphate |
| Phosphorus (P) |
| Silicon Dioxide ($SiO_2$) |
| Sulfate ($SO_4$--) |
| Suspended Matter (unspecified) |
| Zinc (Zn++) |

## Waste/Solid Material Category

The waste categories reported in the results have evolved since the original study. In the earlier studies, waste types collected from facilities were reported in the inventory results as the reported waste types, with the intent for users of the data to link end-of-life data sets for final "disposition". The 2018 included processing of waste in the model. For example: non-hazardous waste that is landfilled is modeled using a non-hazardous landfill data set, solvents are modeled as incinerated (with or without energy recovery, depending on the reported waste), etc. The waste category, characterized as "Deposited Material", is **Waste Rock** (overburden from mining) and **Tailings** (the slurry product resulting when ore is concentrated). **Note: no additional burden should be attributed to these flows, as waste rock has no inherent burdens, and any emissions from tailings, such as effluent data, have been reported by facilities within the facility questionnaires.**

**Table 4: Deposited Material**

| **Deposited Material (units in kilograms)** |
|---|
| Waste Rock |
| Tailings |

## Energy Accounting

The energy values represent a quantification of the total energy in the system. Total Energy, called "Energy Resources" includes all energy-related inputs to processes in the system, taking into account embodied, or feedstock, energy (i.e., in lubricating oil and packaging materials) and fuel energy (i.e., process energy, transportation energy, etc.). The model also accounts for energy losses from the electricity grid, boilers, and equipment. Energy Resources is further broken down into non-renewable (i.e., fossil fuels) and renewable (i.e., solar, wind, biomass…) energy. There is no double-counting here – these flows are expressing energy resources in terms of energy in the system while the fossil fuel related elementary inputs are expressed as kg of those resources extracted from the ground.

**Table 5: Energy**

| **Energy (units in megajoules (MJ))** |
|---|
| Energy resources |
| Non-renewable energy |
| Renewable energy |

# Allocation

## Introduction to Co-products and the Allocation Procedure

Many industrial processes produce multiple useful outputs which are referred to as co-products. In LCA, the functional unit generally focuses on one main product, and co-product(s) are modeled with other product systems. This makes it necessary for multiple output systems to be divided into more than one process, fairly distributing the environmental inflows and outflows of the multiple output process between the main product and various coproducts. This is referred to as "allocation".

When allocation is required, the key to robust modeling is to determine (a) which are the co-products that need to be allocated, and (b) on what basis should the allocation be made (e.g., on a weight basis, value basis, etc.). This is typically one of the more difficult methodological decisions to answer in an LCA, since it is not always a clear allocation basis. ISO succinctly explains the step-wise approach to allocation:[5]

1. Wherever possible, allocation should be avoided by (a) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these subprocesses, or (b) expanding the product system to include the additional functions related to the co-products.
2. Where allocation cannot be avoided, the system inputs and outputs should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; (i.e., they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system).
3. Where physical relationship alone cannot be established or used as the basis for allocation the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, environmental input and output data might be allocated between co-products in proportion to the economic value of the products.

## Allocation Decisions Made for this Study

**Metal Coproducts**. Molybdenum may occur by itself in ore or with copper and potentially other metals in multi-metal ores. In the latter case, since allocation cannot be avoided, the copper and molybdenum and other metals, as coproducts, need to be appropriately modeled. The molybdenum LCIs follow the approach outlined and recommended in Table 4 of the Harmonization Document. That is, for base metals, the preferred method is to use mass allocation for the coproducts, on the basis of the total metal output.[6] The choice of mass allocation is reasonable: "Mass is a consistent physical property of the metal and allows for a geographic and temporal consistency…" (Harmonization Document, Table 4). Furthermore, the mass of outputs remains relatively constant over a number of years, while economic allocation (market value) may fluctuate considerably in a short period of time, leading to LCA results that may not always be representative of the system or the date that the LCI data are being utilized. For the molybdenum study, the allocation percentage used was based on the mass of metals in the final concentrates. The allocation percentage is thus carried upstream through to the mining process as shown in Figure 3, to account for the *actual* metal recovered at the concentration process, not the *potential* metal found in the ore (i.e., grade of Mo in the ore).

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[5] ISO 14044:2006, Section 4.3.4.2.

[6] Informally defined in PE (2014), base metals are those that have relatively low economic value, relative to precious metals.

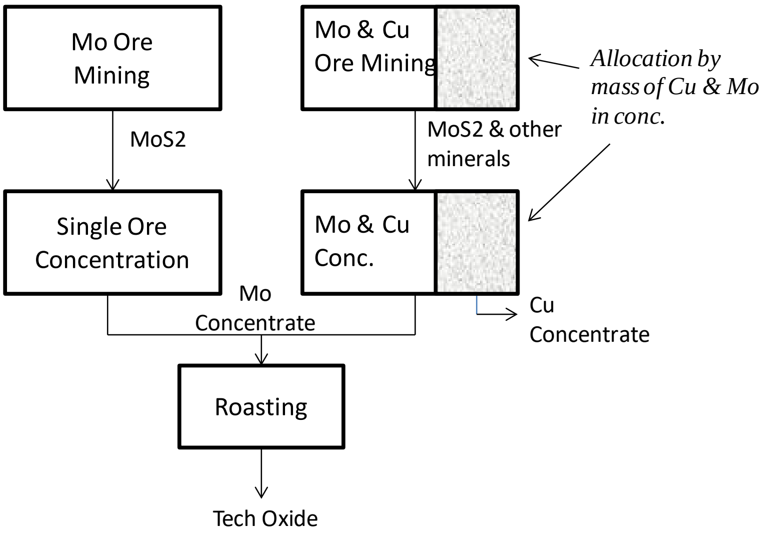



**Figure 2: Metallurgical molybdenum LCI mass allocation schematic**

**Non-metal coproducts**. For non-metal coproducts that may otherwise be produced by way of alternate means, system expansion by substitution was done. This method subtracts out the non-metal coproduct from the system using the conventional or an alternate production technique of the coproduct, making the assumption that the production associated with molybdenum processes has offset that alternative production. System expansion avoids coproduct allocation. See ISO (2006) or the Harmonization Document for a general discussion on handling coproducts in metals LCA.

# SECTION 3: DATA COLLECTION

## Reference Year and Data Years Collected

The reference year for this study is 2016, or the most current year of available production data that is also most representative of the facilities' production practices. In the few cases where 2016 data was not representative of a facility's usual production, for reasons such as periodic shut-downs or other factors that could have produced unusually low volumes for that year, facilities provided 2015 data. Some 2012 facility data, used for a Copper LCA, were used.

## Process Stage Grouping in Black Boxes

The goal of this study was to collect current, representative data to produce a balance sheet of the environmental flows to and from the environment. The ISO standards recommend a black box approach to data collection so that the highest level of data is generated and all inflows and outflows to a product system are included. While the highest level of a process is ideal for the black box, there are factors that require a process to be broken down into smaller boxes. These are:

- **Existence of co-products:** The mere fact that co-products are produced during the process (especially if they do not fall out near the end of the process) means that this process must be broken down to the point at which the co-product is produced.
- **Existence of imports or exports in integrated facilities**: If any intermediate material is transported off-site to be processed elsewhere, or an intermediate product comes onto the site to be processed further, then the two processes would have to be separated since the tonnage of product coming into the facility does not equal the tonnage leaving the facility.

- **Different level of plant integration**: Less-integrated facilities may not be averaged with fully integrated facilities.

These three possibilities are presented in Figure 3.

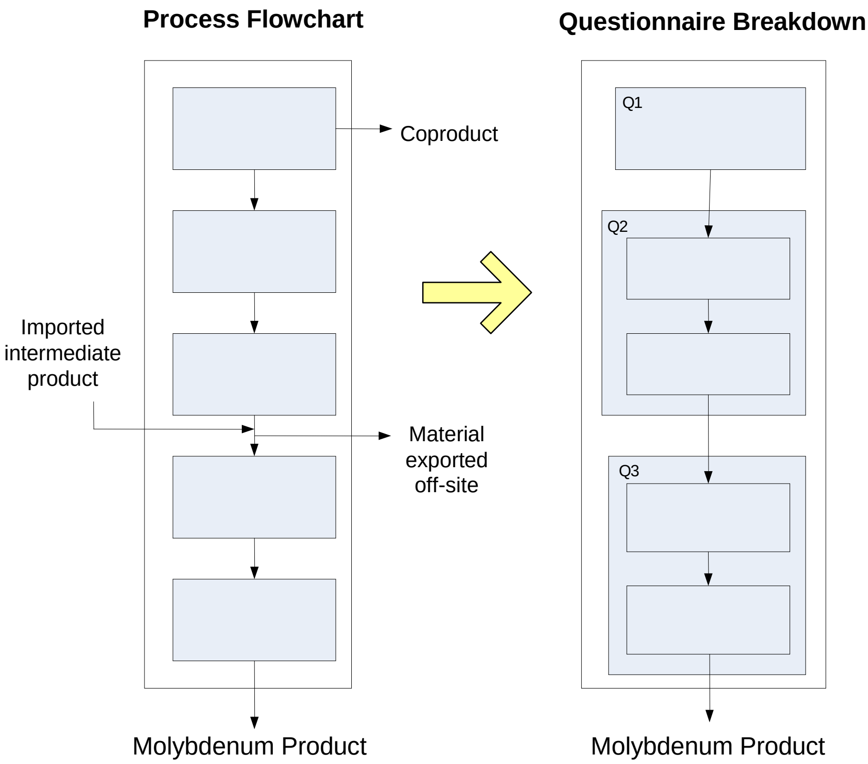



**Figure 3: Flowchart-to-questionnaires**

Following this methodology, each main unit process stage represented a black box, with the exception of concentration which required more subdivision, depending on when coproducts, if any, occur (described in more detail in the Concentration modeling section, page 17).

## Questionnaire for New Data

Data were collected in Microsoft Excel-based questionnaires, with each defined black box representing one unit process. Each unit process spreadsheet included all inputs (e.g., energy and materials), outputs (e.g., products, coproducts, air emissions, water effluents, solid waste, and recovered materials), and transportation of materials to the plants. A Spanish version of the Excel-based questionnaire and a Spanish user guide were provided on an as-needed basis to enable full clarity of the questionnaire.

### Products and Co-products

All products and any co-products were reported for the one-year period, both in total mass and in molybdenum or other metal content (where applicable).

| Concentration (Process A) | Units | Quantity | Data Quality | | |
|---|---|---|---|---|---|
| | | | SOURCE | TYPE | YEAR |
| ***Product*** | | | | | |
| Moly Intermediate Product | | | | | |
| Intermediate Mo Concentrate | | | | | |
| % Moly | | | | | |
| % other metal (name): ____________ | | | | | |
| Co-products (intermediate) | | | | | |
| Other concentrates | | | | | |
| % Copper | | | | | |
| % other metal (name): ____________ | | | | | |
| % other metal (name): ____________ | | | | | |

**Figure 4: Products and coproducts in questionnaire: example**

## Energy Inputs

Quantities of purchased electricity and purchased fuels consumed during the processing or manufacturing of the product were reported.

| Concentration (Process A) | | Units | Quantity | Data Quality | | | Trasport of Materials to the Site | |
|---|---|---|---|---|---|---|---|---|
| | | | | SOURCE | TYPE | YEAR | Distance to site (km or mi) | Mode (truck, train...) |
| **Purchased Energy:** | Electricity | | | | | | | |
| | Steam (from off-site) | | | | | | | |
| | Compressed Air | | | | | | | |
| | Others (please specify) | | | | | | | |
| | | | | | | | | |
| **Purchased Fuels:** Include fuels for mobile equipment | Natural Gas | | | | | | | |
| | Propane | | | | | | | |
| | Fuel Oil | | | | | | | |
| | Recycled oil | | | | | | | |
| | Diesel Oil | | | | | | | |
| | Gasoline | | | | | | | |
| | Coal | | | | | | | |
| | Coke | | | | | | | |
| | Others (please specify) | | | | | | | |
| | | | | | | | | |

**Figure 5: Energy input in questionnaire: example**

## Materials and Other Inputs

Inputs consumed during processing or manufacturing were reported for the year's period. For recycled materials, the percentage of recycled content was specified and modeled accordingly. All known materials that were used in the process were reported, with the goal of 99.5 percent of inputs. For chemicals and reagents, the chemical composition of the compounds were supplied, and the amount was reported in pure terms (e.g., 100 percent of weight) in order to avoid over-reporting the use of that input. Only *net* consumption of process and/or cooling water (e.g., make-up water) was reported. Recycled water, including that recycled within a process, throughout the facility, or outside the facility, were not included.

| SITE DATA (black box) | Briquetting | Units | Quantity | Data Quality | | | Trasport of Materials to the Site | |
|---|---|---|---|---|---|---|---|---|
| | | | | SOURCE | TYPE | YEAR | Distance to site (km or mi) | Mode (truck, train...) |
| If a solution, specify either the concentrated quantity or dilution % (e.g., 10 kg NaOH (50%) or 5 kg NaOH (100%) | Product and process Inputs for **Briquetting** | | | | | | | |
| | Water (process and/or cooling water make-up) | | | | | | | |
| | Binder agent 1 (Type: ________________) | | | | | | | |
| | Binding agent 2 (Type: ________________) | | | | | | | |
| | Ammonia | | | | | | | |
| | Lubricating oil | | | | | | | |
| | Others inputs needed for the process | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |

**Figure 6: Materials input in questionnaire: example**

## Air emissions

Process-related air emissions were reported. In cases where air emissions were not provided in the questionnaires, publicly-available emissions factors were used, especially as they related to fuel combustion related emissions. To ensure the soundness and completeness of the data and to avoid missing data points, facility staff provided the following information for each air emission:

**Table 6: Air data collection**

| | |
|---|---|
| **1) Value for the year 2016 (or closest year available)** | ***Facility data*** |
| **2) "Zero" for values of zero.** | **0** |
| **3) NA if not applicable.** | **NA** |
| **4) ND if no data are available** | **ND** |
| **5) If ND, is it expected to be at the site?** | **Yes/No** |

Efforts were made to report total emissions (fugitive plus stack), but fugitive was not always achievable.

## Water Effluents

Total wastewater and effluents generated by the process were reported. If the facility had an on-site wastewater treatment plant (WWTP), the effluents were reported as levels leaving the WWTP. Water effluents from tailings and the tailings pond were reported if any water leaves the "fence line" of the facility, i.e., leaks or release to groundwater or surface water. Many facilities reported closed-loop, zero-discharge systems. Water effluent data points were collected using the inputs in Table 6 for full clarity of the flow.

## Waste and Materials Not Recovered

Any material not considered a recoverable or recyclable material was reported in its dry form as waste. Fate of the waste (e.g., municipal landfill, non-energy recovery incinerator…) was a required entry so it could be modeled appropriately.

| SITE DATA (black box) | Roasting | Units | Quantity | Data Quality: SOURCE | Data Quality: TYPE | Data Quality: YEAR | Distance off-site | Fate of waste |
|---|---|---|---|---|---|---|---|---|
| *Outflows* | | | | | | | | |
| Solid Waste: | Used oils, used lubricants | | | | | | | |
| If waste was reported as wet, provide the % moisture. | Lab waste | | | | | | | |
| | Slags and ash | | | | | | | |
| | Other waste categories (please specify) | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | Waste from Acid plant or SO2 removal , if applicable | | | | | | | |
| | Used oils, used lubricants | | | | | | | |
| | Lab waste | | | | | | | |
| | Slags and ash | | | | | | | |
| | Residue, sludge (not recycled) | | | | | | | |

**Figure 7: Solid waste in questionnaire: example**

## Recovered Material

Materials recovered included molybdenum-bearing or other materials produced as a byproduct and used in another process on or off the site. Recovered materials were reported as the following:

- Recycled as a closed loop material: reused/recycled within the same process it came from. Modeling included only the net use of this material.

- Reused/recovered/recycled in a molybdenum process within the boundary of this study. The rule for the modeling is as follows: if the material stays within the boundary of this study, it is accounted for in the study, treated either as a coproduct or as a recovered material to be used as an input into another process.

- Reused/recovered/recycled completely outside the boundary of this study. The rule for the modeling is as follows: if the material leaves the boundary of this study, it leaves without burden, including its transportation away from the facility.

## Transportation

The distances and modes of transport of the raw materials, intermediate molybdenum inputs, and purchased fuels were reported and modeled. Transportation of waste shipped away from the site was also included.

## Utilities

The questionnaires requested all of the above input and output data for on-site utilities, such as steam generation plants, sulfur dioxide scrubbers, and WWTPs. Utility data were collected as their own black box or as part of one of the metallurgical processes. For example, data for the WWTP in Figure 8 was collected separately since both mining and concentration send wastewater there, but the roaster is the only process using the sulfur dioxide scrubber, so all data for the scrubber could be collected with the roasting questionnaire (Figure 9).

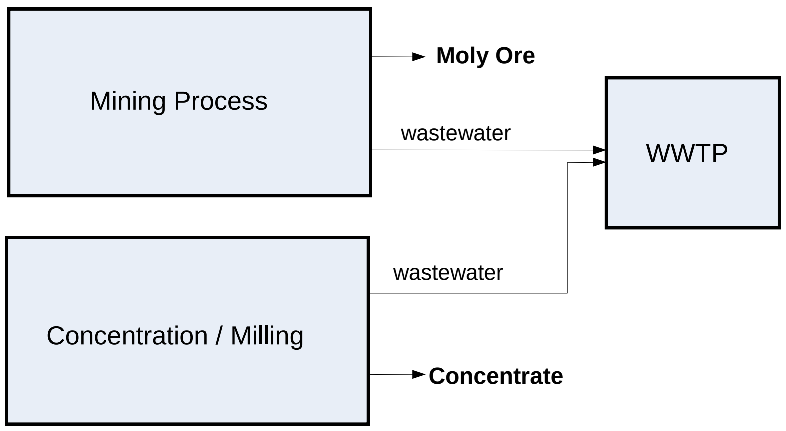



**Figure 8: Utilities in the questionnaire (a)**

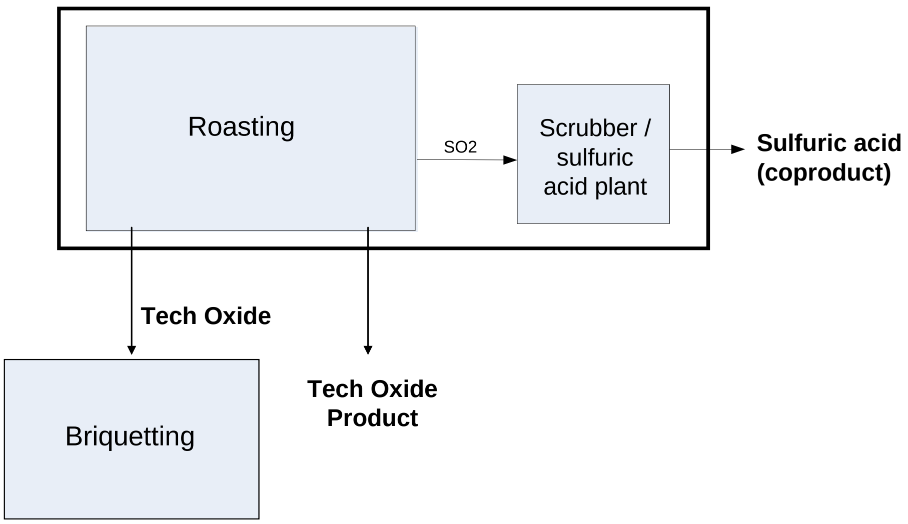



**Figure 9: Utilities in the questionnaire (b)**

### Packaging of the Final Product

Companies reported packaging types used to ship to customers. Based on responses from the questionnaires, the two most common packaging types reported and calculated in the inventories included polypropylene “supersacs”, and 55-gallon steel drums. Other packaging materials such as shrink wrap and pallets were not included due to negligible materiality.

## Data Quality Tracking

To track data quality, the following was reported for each applicable section in the questionnaire:

- Source, i.e., direct plant data or published sources;
- Type, i.e., measured, calculated, averaged, etc.;
- Year of the data.

# SECTION 4: MODELING

## Mining

The mining stage of molybdenum production includes all processes to extract molybdenum and byproduct ore up to the point of delivery to the concentrator. Mining ores containing molybdenum may be carried out by way of underground mining or surface/open pit mining. Data for both mining methods were collected as a black box that encompassed all mining operations such as overburden removal, blasting, and ore loading and transport. While some operations consider grinding to be part of the mining system boundaries, to the best extent possible, this activity was kept with the milling and concentration unit process. Both underground and open pit mining were aggregated together; mining is averaged on a weighted basis for all of the mining facilities, without distinction between the underground / open pit mining, or primary / byproduct mining, in the results.

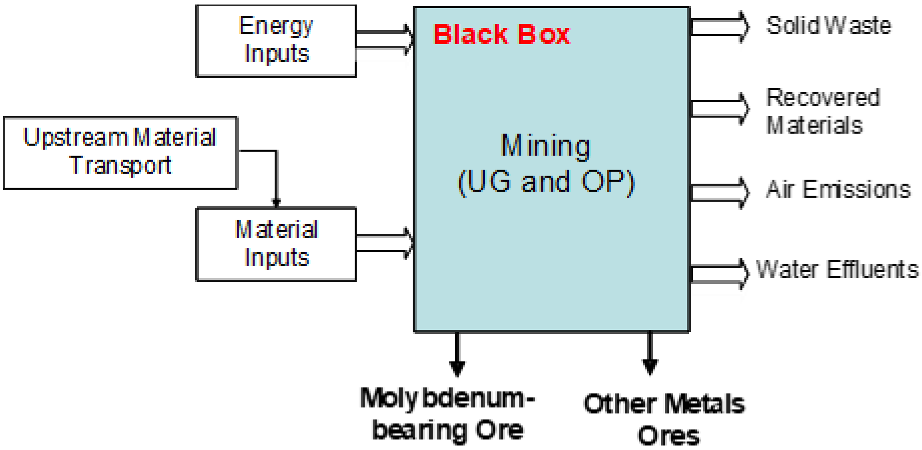



**Figure 10: Mining system boundaries**

### Modeling Coproducts

As introduced earlier, coproduct allocation was carried out based on the mass percentage of metals in the final concentrates. This was done in order to account for what was actually recovered at concentration, not the *potential* yield of the metal (i.e. extracted from the ground).

### Mining Fuels and Air Emissions

Fuels for underground and open pit mining are primarily consumed in mobile equipment. In the questionnaire, the site staff provided data on how the fuel is used, i.e., either in trucks or other equipment, including heavy loaders or for drilling, blasting or hauling machinery. Data sets within Gabi accounted for emissions factors for these applications.

## Concentration

Concentration is the stage at which the ore undergoes crushing, grinding, flotation, and sometimes leaching to obtain a concentrate of over 90% molybdenite. The concentration processes generally start at the primary crusher and continue to the point of delivery of concentrate to the roaster (but not delivery itself). Figure 11 presents an overview of the concentration (milling) system.

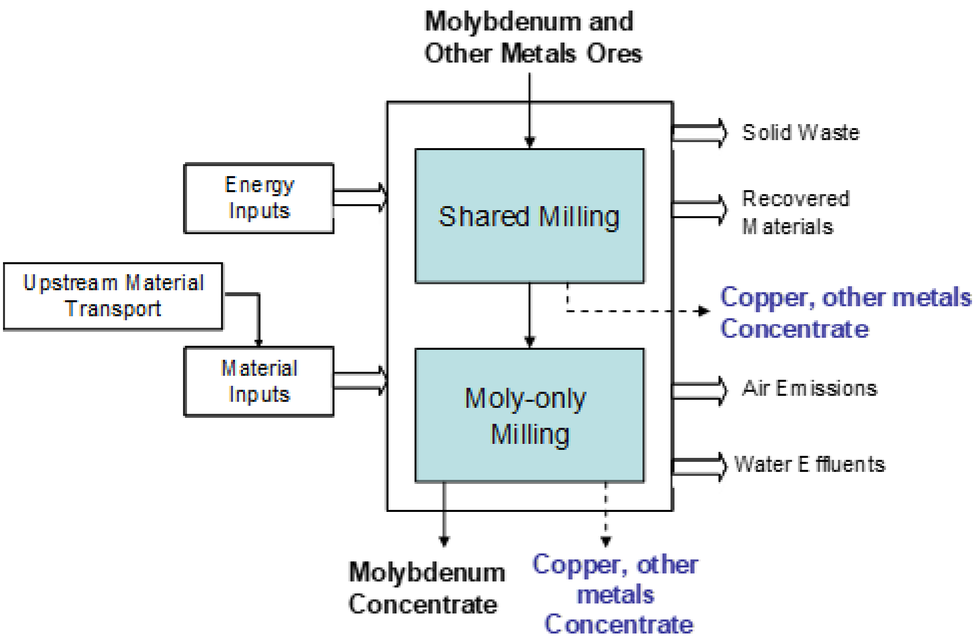



**Figure 11: Concentration system boundaries**

### Data Collection

As shown in Figure 12, concentration processes at some facilities may produce the copper concentrate and molybdenum concentrate at different stages. In order to correctly allocate environmental inflows and outflows to these processes, two situations were defined for data collection and aggregation:

<u>Situation 1: Two Black Boxes / Two Questionnaires</u>
This situation was applied where copper (or other metal) concentrate is produced before the molybdenum concentrate is fully processed. Since subsequent moly-only milling processes may be energy intensive and may consume additional materials, it is necessary to break concentration down into two black boxes, with input and output data collected for both (i.e., Process A box and Process B box in Figure 12).

<u>Situation 2: One Black Box / One Questionnaire</u>
The processes for this situation can be put into one black box since the concentrate(s) that leave the concentration plant are generated at the same time or are all mixed as one concentrate. In this case, only one set of inputs and outputs are collected in one questionnaire.

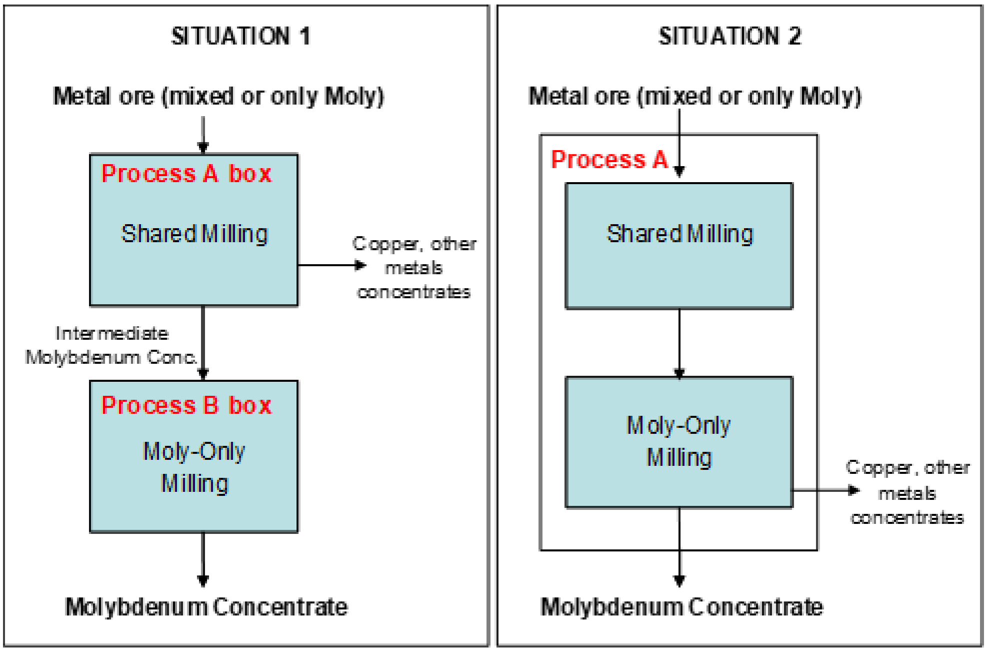



**Figure 12: Concentration data collection situations**

### Modeling Coproducts

For Situation 1 in Figure 12, an allocation based on the metal mass in the concentrates was applied to the products from shared concentration (i.e., copper concentrate and the intermediate molybdenum concentrate), and no allocation was made on the moly-only concentration.  For Situation 2, an allocation based on the metal mass of the concentrates produced in the Process A box was made if applicable.

### Tailings Effluents

Tailings effluents were reported based on the surface water effluents released from tailings piles for the year the data were reported. More explicitly: if water is leaving the “fence line” of the facility then the concentration of effluents were reported.

## Roasting Process

Roasting is a pyrometallurgical process that converts the molybdenite concentrate into technical molybdic oxide as a final product (in powder form, going to customers for chemical production, stainless steel production, etc.) or as an intermediate product to be further transformed into briquettes or ferromolybdenum.  Because the material is naturally sulfur-rich, many plants include SOx abatement technologies that produce marketable products such as sulfuric acid. This non-metal coproduct has been modeled using system expansion, the preferred approach set out in the Harmonization document. This modeling choice is justified since data for the more conventional production route for sulfuric acid production is available, and because the often high-quality sulfuric acid from roasting can offset alternative production.[7] Roasting is shown in Figure 13.

[7] For more information, see Table 6 in the Harmonization document.

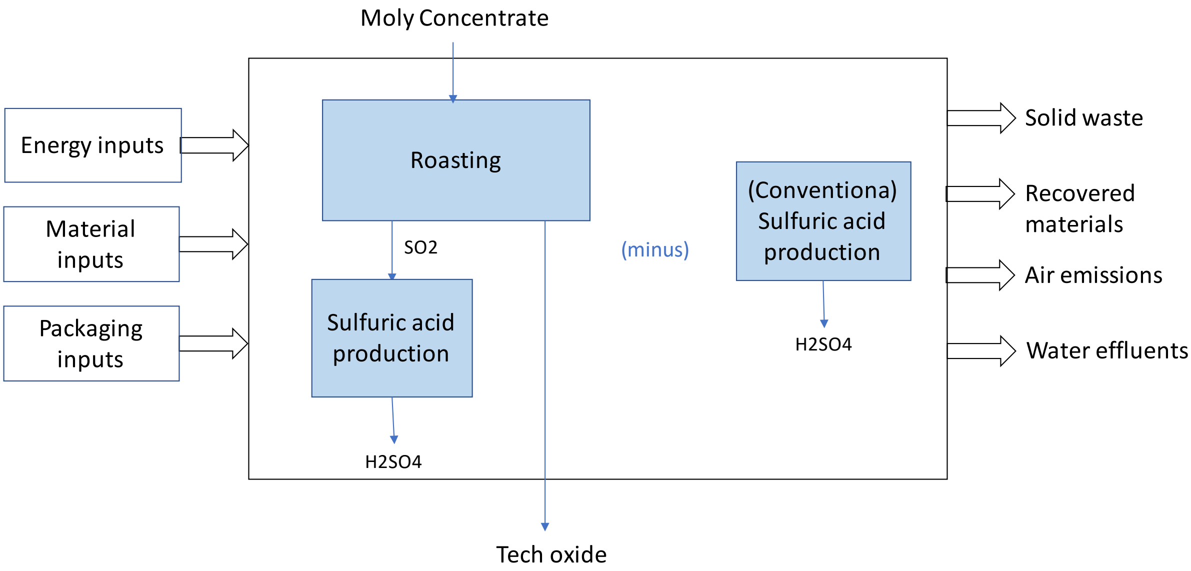



**Figure 13: Roasting system boundaries**

## Briquetting

Briquetting includes the processes starting at the delivery of the tech oxide to the briquetting plant through the formation of briquettes to their point of delivery to a customer. Briquettes are pressed into pillows after application of a binder, typically an ammonium-based product. No coproducts were produced in the briquetting system. Figure 14 presents the briquetting system.

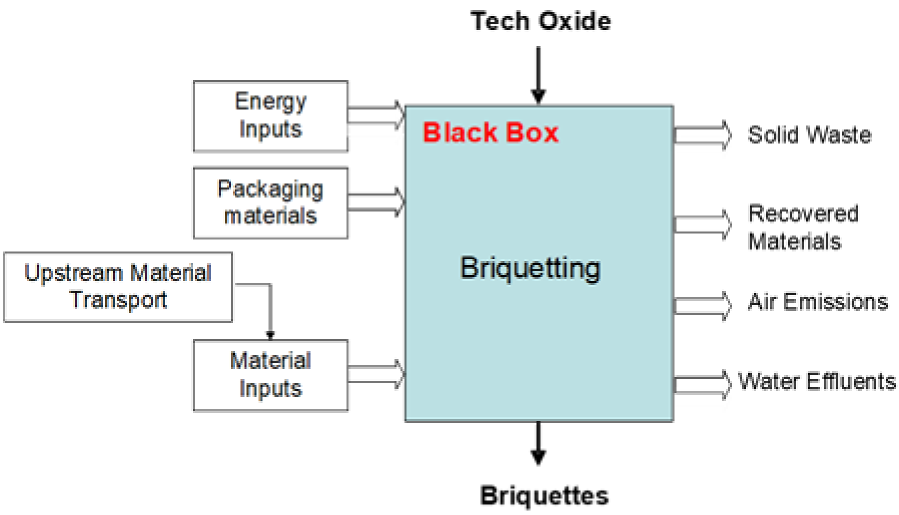



**Figure 14: Briquette system boundaries**

## Ferromolybdenum Production

Ferromolybdenum production includes the processes starting at the delivery of the tech oxide to the ferromolybdenum plant where tech oxide is reduced in the presence the iron sources, to the point of delivery of the finished ferromolybdenum to customers. No coproducts were produced in the ferromolybdenum system. Figure 15 presents the ferromolybdenum system.

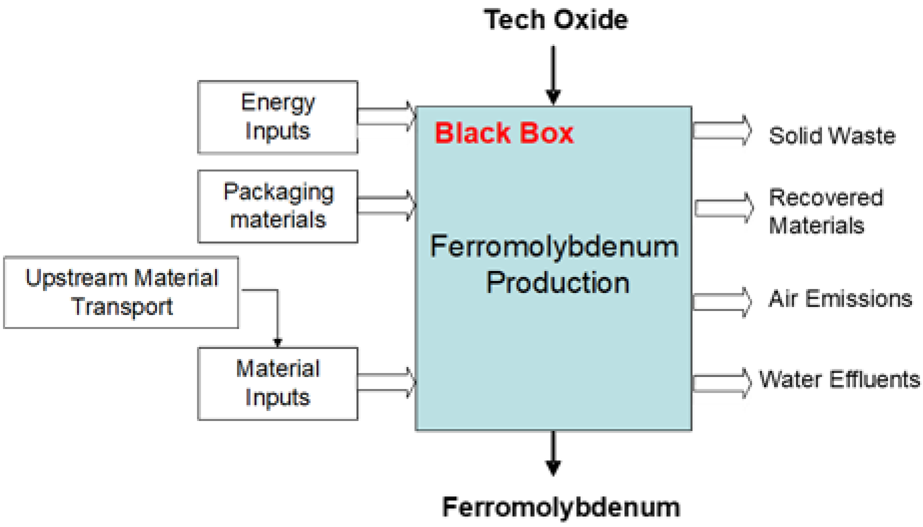



**Figure 15: Ferromolybdenum system boundaries**

# Data Aggregation

## Preliminary Questionnaire Check

As questionnaires were returned to Four Elements LLC, they were checked for overall completeness, from both a quantitative and qualitative perspective. Four Elements LLC worked during this early phase to locate and correct possible discrepancies, errors and data gaps within each data set before aggregating them into data summary sheets (DSSs), the final averaging and aggregating step in the production of the average data set for each unit process stage. Specific checks included the following:

- Data tables, data quality indicator tables, and qualitative questions were checked for completeness;
- A molybdenum balance was calculated for each black box questionnaire to ensure correct balance of molybdenum inputs and products. Where there was an imbalance of greater than +/- 3%, the facility was contacted for verification or explanation;
- Energy sources at each facility were summed into a total energy value in order to compare the energy consumed for like-process stages. Where energy consumption for a facility was not in the same order of magnitude of similar facilities, the facility was contacted for verification of fuel and electricity inputs;
- Utility repartitions were checked to be sure that the contributing processes added to no more than 100%;
- Flows used or recycled internally and/or used in the metallurgical system were subtracted out of the system; and
- Where any gaps in the data or obvious discrepancies were found, the facility was contacted for explanation and data completion.

## Modeling the Questionnaires

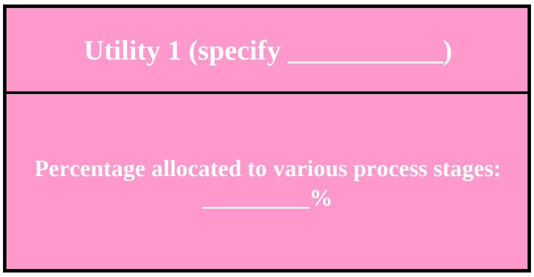
A typical questionnaire that was sent to each of a participating company's facility had one or more data black boxes plus black boxes for on-site utilities. For example:

| Site Information for Questionnaire Data | |
|---|---|
| **Site Name and location:** | |
| **Products Produced and Utilities:** | molybdenum ore<br>copper ore<br>molybdenum concentrate<br>copper concentrate<br>WWTP |

Most questionnaires had any combination of utility data, coproducts to allocate, and recycling loops to model. The following steps were taken to distill this complex relationship into raw data sets for each main unit process stage:

1. Utilities were allocated amongst the applicable processes;
2. Internal-loops were addressed;
3. Co-products and/or recovered materials not used in the molybdenum system were allocated or removed;
4. Raw data sets were normalized on the basis of 1 kg of molybdenum in that unit process' output. The exception is mining, in which the basis is per 1 kg molybdenum recovered in the concentrate; and
5. Data Summary Sheets (DSSs) were prepared from the normalized site data.

**Step 1: Utilities allocated between the products or processes**
The facility staff provided allocation information for the on-site utilities, in a box similar to the one below.




Using this data, all inputs and outputs reported in the utility section were added to the appropriate metallurgical process boxes according to their use in the processes.

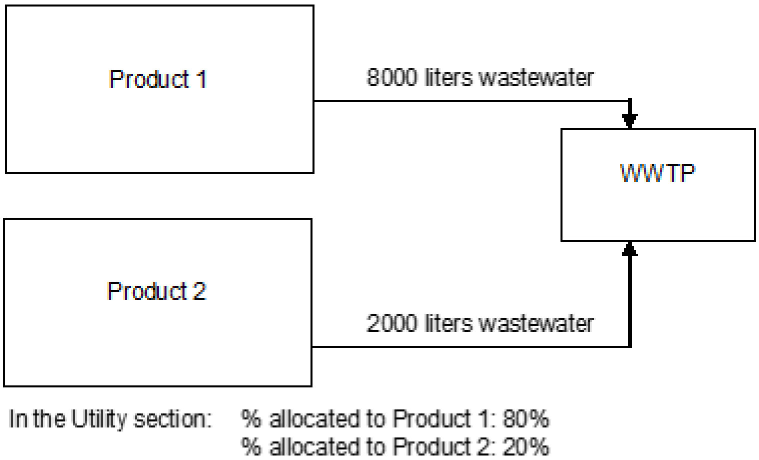
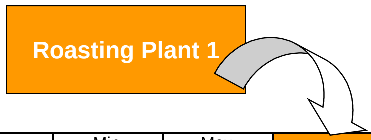



**Figure 16: Allocating utility data**

**Step 2: Treatment of internal loops between metallurgical processes**
Internal loop flows in a facility were subtracted out of each product system as long as the input/output amounts were the same. For example, a facility produces sulfuric acid from the roasting process and sends it to the concentrator. If the output and input amount was the same, it was treated as a closed loop. If the amounts differed, then only the net amount was counted as an inflow to the process or as a coproduct.

**Step 3: Treatment of co-products and/or recovered materials not used in the metallurgical processes**
All co-products and recovered materials were allocated away from the molybdenum systems, following the allocation rules described above.

**Step 4: Final preparation for DSS**
The resulting product inputs and outputs were normalized to one kilogram of molybdenum in the unit process output and are averaged with other products, shown in Figure 17. The next section details the DSSs.




| Tech Oxide Production | | | Weighted Average | Min. Reported Value | Max. Reported Value | Roasting Plant 1 | Roasting Plant 2 | Roasting Plant 3 |
|---|---|---|---|---|---|---|---|---|
| **Moly product** | Tech oxide | kg | | | | | | |
| | Moly in Tech Oxide | kg | | | | | | |
| **Coproducts** | Sulfuric Acid (H2SO4, 100%) | kg | | | | | | |
| | Rhenium | kg | | | | | | |
| | Copper in Cu coproduct | kg | | | | | | |
| **Energy In** | Electricity (from off-site) | kWh | | | | | | |
| | Diesel Oil | kg | | | | | | |
| **Material In** | Total Molybdenum Mass in | kg | | | | | | |
| | Moly In | kg | | | | | | |

**Figure 17: Aggregating questionnaire: step 4**

## Data Summary Sheets for Validation

As demonstrated above, fully aggregated data sets were placed into spreadsheets organized into individual unit processes. Table 7 presents part of a blank DSS, and Appendix 2 contains all unit process stage DSSs except roasting and briquetting.[8] The next sections describe each DSS component.

| Tech Oxide Production per 1 kg Mo | | | Weighted Average | Min. Reported Value | Max. Reported Value | Avg type - Only rpt'd? | # Sites who Reported | % of Sites | Comments |
|---|---|---|---|---|---|---|---|---|---|
| **Moly product** | Tech oxide | kg | | | | | | | |
| | Moly in Tech Oxide | kg | | | | | | | |
| **Coproducts** | Sulfuric Acid (H2SO4, 100%) | kg | | | | | | | |
| | Copper in Cu coproduct | kg | | | | | | | |
| **Energy In** | Electricity (from off-site) | kWh | | | | | | | |
| | Diesel Oil | kg | | | | | | | |

**Table 7: Blank DSS**

### Weighted Average and "Averaging Type"

A weighted average was taken for each unit process inflow and outflow. Two types of weighted averages were made: a weighted average of all of the sites together or a weighted average of only the sites that reported the flow ("*Avg. type – Only rpt'd?*"). The reason for distinguishing this is based on different representation in the industry. "No" to *Only reported* refers to a flow that may not necessarily be found at all of the facilities, such as an obscure reagent. The flow would therefore have to be averaged over all sites since this is an industry average. However, an outflow such as ammonia to air might be expected to be emitted from all briquetting sites, since facilities use ammonia-based products in the process. Therefore, if a briquetting facility does not report ammonia air emissions, then the average method for *only reporting sites* is used: the ammonia is averaged out across only the sites that reported it, so as to not reduce its industry representation.

An average was made over all sites for materials and energy in and the solid materials out of a unit process. Air and water outflows that were *expected* to be released were averaged for only the sites that reported data for them.

### Minimum and Maximum Values

Minimum and maximum data values provided the variability of each data category as a means of checking the precision of the data. Outliers were double-checked by the site staff to

[8] While all unit process stages had more than three physical facilities contributing data, the roasting and briquetting DSSs could not be shared since two companies contributed their multi-facility data.

determine whether they were valid and should be included in the average, and any number that could not be explained or validated was removed from the data set. Besides their use in identifying data deficiencies or outliers, there was no statistical or quantitative check for a margin of error.

**Number of Sites, Percent of Total Sites**
The number of sites that reported data and the percent of total sites that reported data provided an indication of data gaps (for such flows as air emissions and water effluents) as well as an indication of how representative that specific flow is in the industry (for flows like materials and energy).

**Comments**
The comment section provided explanation where necessary, including stating which material input flows were not included in the model due to lack of available data.

### Final Aggregation of Data to Produce the LCI

Figure 18 presents the overall process by which the individual data sets of each unit process are aggregated horizontally to produce one weighted average data set, which is then linked to the next unit process stage. In the figure, the mining, milling, and roasting are linked together in the LCA software to produce the LCI results for tech oxide.

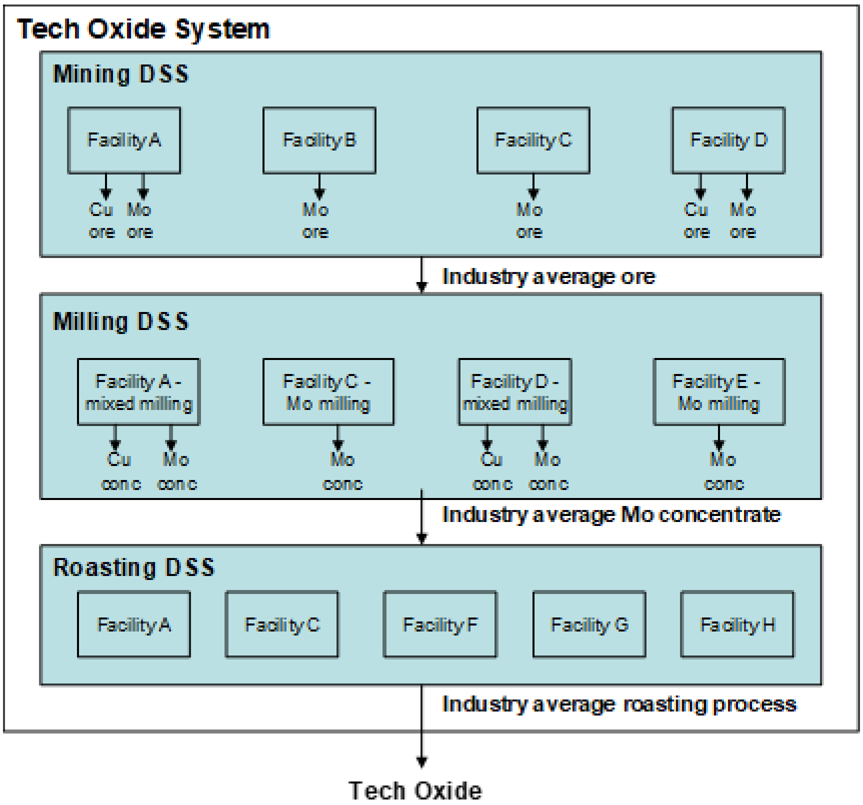



**Figure 17: Horizontal and vertical aggregation of data sets**

## Background Data

Background data, which are the data sets making up the production and modeling of energy and electricity use, transportation, and material inputs is almost always from secondary sources and may cover a broad range of technologies, time periods, and geographical locations. The use of secondary data is normal and necessary in an LCI, but measures are made to use the best data that are available at the time of the study. If there is a choice between two data sets, the better quality data is used (more recent, more representative technologically or geographically….). The secondary data sources are as follows:

- The Gabi database[9] was used for country-specific energy, transportation, and most of the material inputs;
- The EcoInvent database[10] was used for some energy data, some material inputs; and most of the end-of-life disposition datasets;
- Bibliographic, publicly-available sources like LCA studies and journal articles; and
- Engineer calculations made for material inputs not available in commercial or public LCA databases or external LCA studies. These were used in conjunction with Gabi background data.

Electricity grids specific to each country or region were applied. The table overleaf presents the locations of the participating facilities and the most recent electricity grid mix data available (data source provided).

[9] thinkstep AG, GaBi Software-System and Database for Life Cycle Engineering 1992-2018.

[10] Ecoinvent Centre, Ecoinvent data v3 (Dübendorf: Swiss Centre for Life Cycle Inventories, 2017), retrieved from: www.ecoinvent.org.

**Table 8: Electricity grid mixes for each region**

| | Peru | Mexico | Chile SIC | Chile SING | Netherlands | Belgium | UK | Austria | Japan | AZ, US | IA, US | UT, US | PA, US | CO, US |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PE (2013) | EIA (2008) | Codelco (2017) | Codelco (2017) | ts (2014) | ts (2014) | ts (2014) | ts (2014) | ts (2014) | eGRID (2016) | eGRID (2016) | eGRID (2016) | eGRID (2016) | eGRID (2016) |
| **Hard coal** | 1.8 | 8.0 | 27.5 | 77.0 | 31.4 | 6.1 | 30.1 | 7.5 | 33.5 | 29.5 | 52.8 | 22.5 | 17.7 | 51.5 |
| **NG** | 39.5 | 50.0 | 0.0 | 10.0 | 49.9 | 26.7 | 29.7 | 8.3 | 40.4 | 39.8 | 6.8 | 15.6 | 38.2 | 20.2 |
| **HFO** | 6.0 | 19.0 | | | 1.9 | 0.3 | 0.5 | 0.9 | 11.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.0 |
| **Biomass** | 1.2 | 0.3 | 4.3 | 0.0 | 2.0 | 3.6 | 4.1 | 5.3 | 2.8 | 0.4 | 1.3 | 1.3 | 1.9 | 0.3 |
| **Biogas** | | | | | 1.0 | 1.3 | 2.4 | 0.9 | | | | | | |
| **Hydro** | 51.6 | 16.0 | 39.0 | 0.0 | 0.1 | 2.1 | 2.6 | 68.5 | 8.4 | 3.5 | 5.0 | 47.2 | 0.9 | 12.1 |
| **Wind** | | | 5.3 | 3.0 | 5.6 | 6.4 | 9.5 | 5.9 | 0.5 | 1.2 | 21.1 | 8.6 | 1.0 | 15.1 |
| **Photovoltaic** | | | 4.3 | 8.0 | 0.8 | 4.0 | 1.2 | 1.2 | 2.4 | 2.8 | 0.0 | 0.5 | 0.4 | 0.8 |
| **Waste** | | | 0.0 | 1.0 | 3.4 | 2.9 | 1.2 | 1.5 | 0.6 | | | | | |
| **LNG** | | | 18.5 | 0.0 | | | | | | | | | | |
| **Diesel** | | | 1.1 | 1.0 | | | | | | | | | | |
| **Nuclear** | | 4.0 | | | 4.0 | 46.6 | 18.8 | | | 19.5 | 12.8 | 3.4 | 39.7 | 0.0 |
| **Geothermal** | | 2.7 | | | | | | | 0.3 | 3.2 | 0.0 | 0.7 | 0.0 | 0.0 |
| **Total -->** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** |

## SECTION 5: DATA QUALITY EVALUATION

Evaluation of data quality is important not only to understand the reliability of the data, but also to properly interpret and/or use the results. The data quality elements in ISO 14044[11] were applied, and in the main, internal LCI Report for participating companies, DQ ratings as defined in the WRI Product Standard[12] were assigned to more detailed aspects of the study. These ranged from Very Good for the facility data, and Very Good to Good for most of the background data.

### Representativeness

#### Geographical Representation

Primary data from facilities around the world were collected to represent the molybdenum industry. Data was submitted by eight IMOA member companies and represents approximately 30% of total global molybdenum produced, and 46% of global production minus China.[13]

#### Temporal Representation

Considered the most complete and accessible data at the time of collection, 2016 data was the reference year, i.e., the data year chosen to represent current energy and material usage, technologies, and general plant design. Facilities provided 2016 (or 2015) data. Two companies used their 2012 copper LCA data. A summary of the data years for total molybdenum produced and processed is provided in Table 9.

**Table 9 Molybdenum production quantities represented in this LCI**

| | 2016 | 2015 | 2012 |
|---|---|---|---|
| **Mining** | 23% | 24% | 53% |
| **Milling/Concentration** | 21% | 27% | 52% |
| **Roasting** | 68% | 32% | 0% |
| **Briquetting** | 59% | 41% | 0% |
| **FeMo Production** | 56% | 44% | 0% |

#### Technological Representation

Technological coverage, or the technology mix, may include weighted average of the actual process mix, best available technology, or worst operating unit. The primary data collected on the metallurgical production processes are assumed to be representative of current technology and plants. Detailed questions were sent to copper/molybdenum production facilities who participated in the 2012 copper LCA study to ensure that their technology from 2012 remains current.

### Completeness

ISO 14044 defines completeness as the "percentage of flow that is measured or estimated."[14] One of the goals of the study was to increase the number of participants and include as many facilities as possible for the most representative LCI of these products. Even though we met this goal and more companies participated, a quantitative analysis on completeness for each unit process stage could not be performed in order to protect the confidentiality of the participants. Using the WRI Product Standard for data quality, completeness is Good to Very Good.

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[11] ISO 14044 Section 4.2.3.6.

[12] World Resources Institute and World Business Council for Sustainable Development, September 2011, Table 8.2 Sample scoring criteria for performing a qualitative data quality assessment. See http://www.ghgprotocol.org/product-standard. Ratings are "Very Good", "Good", "Fair", and "Poor"

[13] Data from IMOA (March 2018).

[14] ISO 14044:2006, Section 4.2.3.6.

## Consistency

Consistency is a qualitative understanding of how uniformly the study methodology is applied to the various components of the study. This quality of measure is one of the most important aspects for such a large-scale study with many facilities and questionnaires involved. Consistency was applied in two fundamental ways: 1) consistency with the Harmonization Document, ensuring, where applicable, consistency with other metals' LCA and LCIs; and 2) consistency with the previous metallurgical molybdenum LCI studies, including ensuring that:

- The previous methodologies and study approaches not covered by the Harmonization Document were applied except where scope has changed or data have evolved;
- The same fundamental data categories were used and their information was collected in questionnaires;
- The questionnaires requested the same qualitative and quantitative data; and
- The same modeling approach was applied.

### Data Collection Consistency

Consistency was maintained in the handling of questionnaires in order for the many individuals completing them to provide appropriate data in the appropriate manner. The questionnaires were distributed in electronic format with User Guide instructions on what type and form of data were needed, how data points should be reported, and how the data points were obtained. When questions arose, Four Elements LLC communicated directly with the sites to resolve issues. When completed questionnaires were returned and rigorous data checking was completed, the data was linked to DSSs for further data processing and checking. This process was treated in the same, consistent manner for all questionnaires. With a common approach to data collection from the sites, communication with the sites, and data handling, overall consistency in the work was maintained.

### Data Checking Consistency

**Data Quality Indicators**

The questionnaire included qualitative data quality indicators, including information on the time span of the reported data, the source of the data, and the type of data. Data source refers to where each data point originated. For example, the facility staff specified whether the data point came from the plant itself or from another source (other sites, published emissions, etc.). Data type refers to how each data point was obtained. Facility staff specified whether the data point was:

- Measured (e.g., electricity meter);
- Estimated (i.e., estimation had been established based on approximations, like transportation distance);
- Calculated (i.e., using emissions factors, mass balance, etc); or
- Shared or apportioned (i.e., data for two processes are estimated).

**Data Availability and Data Gaps**

Particular attention was given to identify areas of the questionnaire that could potentially have data gaps, such as unknown or unmeasured air emissions and water effluents. Users were given specific instructions to fill out the air emissions and water effluents sections of the questionnaire (page 13). This was done to ensure that any blank cell in the questionnaire was not misinterpreted or misrepresented in the data set. This approach was used especially to assess whether the emission should be averaged over all of the sites or across only the sites that reported that data.

## Reproducibility

Reproducibility is the qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reported in the study. The modeling and methodology are transparent enough such that an independent practitioner could reproduce the results.

## Precision and Reliability

Precision is the measure of the variability of the data values for each data category expressed. The minimum and maximum data values provided in the DSSs provide the variance of the data points. Using the WRI Product Standard for data quality, reliability is Very Good since all data that have been provided by molybdenum production facilities have been based on direct facility, utility, and sales records.

### Cut-off Criteria Analysis

Upstream material inputs to the unit processes were assessed in terms of availability of information on production data that could be included in the study. Inputs of fuel (used for energy) and net water used were not included in this count. As is shown in Table 10, the inputs well exceeded the cut-off criteria goal of 99%, with the exception of FeMo production, which almost made the cutoff goal. It should be noted that a goal of 99% is ambitious, going well beyond the more often-seen cut-off criterion of 95%.

**Table 10: Cut-off criteria analysis**

| | % Included | Comments |
|---|---|---|
| Mining | 100.00% | |
| Milling / Beneficiation | 99.99% | Specialized chemicals whose trade names could not be traced (and general chemical families could not be included due to lack of data). |
| Roasting | 99.84% | No data for some small amounts of chemicals used |
| Briquette Production | 100.00% | |
| FeMo Production | 98.60% | No data for some small amounts of chemicals used |

# SECTION 6: EXPLANATION OF RESULTS FLOWS

The inventory tables consist of elementary inflows, elementary outflows, and energy measures.

### Elementary Flows from the Earth (Inflows)

The elementary inflows in the tables are the natural resources extracted from the earth in the “cradle-to-gate” system of metallurgical molybdenum production. These inputs have been derived from energy and other materials used or consumed in the system (i.e., raw materials, distribution of the raw materials, manufacture, etc.). Some of these inputs may seem not so immediately relatable to molybdenum production, but the explanation is that they come from energy or other upstream materials in the process. “Coal (in ground)”, for example, comes from coal usage in electric utilities. Iron comes from upstream materials, such as steel balls consumed during milling and ferrous materials used in the ferromolybdenum process. Limestone is used as a material in itself or as a scrubbing agent in electric utilities upstream. Uranium ore in the inventory indicates an amount of nuclear energy supplying the electricity grid.

### Elementary Outflows

**Air Emissions**

Air emissions represent the air pollutants that have been emitted in the cradle-to-gate processes of each product. These may include air emissions data reported in the questionnaires and emissions to air that are found in background data sets within Gabi and Ecoinvent. The non-methane volatile organic compounds (VOCs) category is more general in nature and encompasses many subcategories or flows which have been identified in upstream data sets. This category was compiled using the output list of non-methane VOCs.

#### Water Effluents

Water effluents contain the water related emissions released to water in the cradle-to-gate processes of each product. These may include water effluents reported directly in the facility questionnaires and effluents found in background data sets within Gabi and Ecoinvent.

#### Deposited Materials

As mentioned earlier, waste categories reported in the questionnaires have been modeled with their end-of-life fates. The categories found in the results, presented for accounting purposes, are as "deposited materials" the waste rock from mining and tailings from the milling/concentrating operations.

### Energy

Energy includes **total primary energy,** further broken down into **Non-renewable energy** and **renewable energy**. Non-renewable energy represents fossil-related energy sources, and renewable energy comes from renewable sources. Hydropower and biomass are examples of renewable sources of energy. Natural gas, coal, and nuclear fuel are examples of non-renewable energy sources. Energy is presented in Megajoules. It should be noted that the energy is not part of the inventory of inputs and outputs itself, but more a measure of the amount of energy used within the systems.

### Understanding the Flows – Relativity of the Numbers

The reader should be reminded of the relativity of the inflows and outflows found in the LCI tables. For example, some flows are in the order of 10E-8 or smaller. They are still counted in the system but they are very small. Thus, results can be misleading unless the user takes into account the numerical values of the results.

The reader should also be reminded that some of the inputs and outflows may not be intuitive to the product systems studied, but are present as a result of upstream production of materials or other background data. For example, uranium ore is due to the nuclear electricity used in the grid.

## SECTION 7: LIMITATIONS

Of vital importance to any study and especially for results interpretation is the reliability and consistency of the calculations made. The study limitations should be stated and understood so that the results are not interpreted without acknowledging what assumptions and data may be affecting the results.

### General Use

This LCI is considered to be the most comprehensive, current record of environmental inflows and outflows associated with the production of metallurgical molybdenum products. However, it should be borne in mind that LCA, like any other scientific or quantitative study, has limitations and is a far from perfect tool for assessing exact environmental impacts and attributes associated with product systems. There is always inherently going to be some margin of error in the results. LCAs and LCIs are based on models in a software using datasets of varying quality. Data sets often cover a broad range of technologies, time periods, and geographical locations, increasing the uncertainty of the results. The exclusion and/or unavailability of potentially relevant data could also increase the uncertainty.

LCI results used as-is or calculated into potential environmental impacts (e.g., global warming potential, acidification potential, etc.) should not be considered to be the only source of environmental information should claims or assertions be made on the environmental performance of the product. The results should not be considered sufficient for optimization of environmental performance at manufacturing plants, since the black box approach to data collection is used and specific unit process information is not singularly identifiable within the results.

### Site Specificity

LCI and LCA in general are not site-specific. The normalization of emissions from the system unit processes to one reference flow or declared unit (e.g., a kilogram of molybdenum in a product) erases all spatial and temporal characteristics, which are needed to assess local environmental impacts. Therefore, the study should not be used to assess local issues associated with the production of molybdenum products, such as potential exposure to workers. Furthermore, LCI does not account for threshold-driven impacts such as human- and eco-toxicity, so the data contained in this study should not be extrapolated for human- or eco-toxicity impact assessments. The user is urged to read more about the limitations of human- and eco-toxicity related impact assessment categories in the Harmonization Document.[15] Traditional Risk Assessment is usually an appropriate tool for assessing site-specific risk, and IMOA (www.imoa.info) has a comprehensive library of technical studies addressing these very issues.

## SECTION 8: CONCLUSIONS

This report represents the completed ISO 14040/14044-compliant Life Cycle Inventory – IMOA's third major update on molybdenum products for metallurgical applications. IMOA has conducted LCIs on tech oxide, molybdenum briquettes, and ferromolybdenum since 2000. Being one of the first metals associations to perform an industry-wide LCI/LCA study, IMOA wound its way through the complex web of modeling industry-average products including the modeling of coproducts. It helped pave an early path toward performing metals LCAs using sensible, albeit possibly rudimentary, approaches. The metals industry has indeed come a long way. Published in 2014, the Harmonization Document provides guidance on the LCA methodology-related challenges many metals face. IMOA utilized the Guidance for this update to ensure that this LCI is aligned with the other metals' LCI/LCAs and applies the most sensible LCA practices – extremely important given the myriad of current and future LCAs relying on these input data. IMOA continues to elucidate and enhance awareness with its member companies and stakeholders about some of the challenging issues encountered in LCA and will continue to lead through active industry participation.

[15] Harmonization document, Sec. 5.1 for broad discussion of impact categories, and Sec. 5.2.2 for discussion of impact categories not recommended.