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THE VOICE OF THE MOLYBDENUM INDUSTRY

Life Cycle Inventory of Molybdenum Products for Metallurgical Applications

Summary Report 2024

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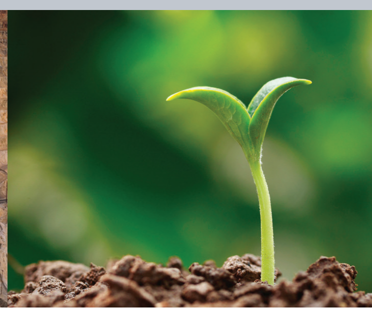

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SECTION 1: INTRODUCTION AND GOAL

Introduction & Background

For over 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 metallurgical molybdenum products. In 2008, 2018, and again in 2024, IMOA has updated the LCI study, with each update increasing Mo production representativeness and enhancing data quality with current facility and background data. These updates also ensure consistency with other metals production LCAs by sharing common methodological approaches using an industry-wide metal and minerals LCA methodology guidance document.

This study underwent an external peer-review process, confirming adherence to the International Standards Organization (ISO) 14040 and 14044 standards on LCA.[1]

Consistency with other Metals LCAs

This study uses LCA methodology and approaches summarized in a 2016 LCA guidance document geared toward the metals and minerals industry, produced and published under a multi-organizational effort that included ten metal commodities, including IMOA, the International Council on Mining and Metals (ICMM), Eurometaux, and Euromines.[2] Over the past two years, the 2016 guidelines have been revisited and updated. Because IMOA actively participates on the multi-metals LCA guidance committee, this study ensures continued consistency with other metals and with the guidelines. This multi-metals work is referred to in this report as "LCA harmonization document" or "Berger (2024)". [3,4]

Goal and High-level Scope

The aim of this study is to develop updated LCI profiles for the intermediate molybdenum products covered by the previous IMOA LCIs:

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

The LCIs are cradle-to-gate, which encompass the processes that include extracting resources from the earth through to the point at which the molybdenum products are ready for shipment to customers, including packaging. The LCIs have 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 any current or new methods highlighted in the harmonization document. The study results are intended to be incorporated into LCA databases for use by LCA practitioners and researchers to calculate potential impacts of molybdenum containing products using appropriate Life Cycle Impact Assessment (LCIA) methodologies. Since this study is cradle-to-gate and therefore not a full LCA that looks at molybdenum's use in applications, the results in this study are not intended to support comparative assertions made publicly available. These results are intended to be used as a

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[1] ISO 14044:2006/Amd1:2017/Amd2:2020, Environmental management – Life cycle assessment – Requirements and guidelines – Amendment 2; ISO 14040:2006/Amd1:2020, the International Standard of the International Standardization Organization, Environmental management.

[2] Santero, N., & Hendry, J. (2016). Harmonization of LCA methodologies for the metal and mining industry. International Journal of Life Cycle Assessment. (Santero, 2016)

[3] The Harmonization update was carried out by Prof. Dr. Markus Berger, University of Twente, on behalf of ICMM.

[4] Berger M: Harmonized calculations methods for product carbon footprints and life cycle assessments in the mining and metals industry. The International Journal of Life Cycle Assessment (2026): https://doi.org/10.1007/s11367-026-02596-2

feedstock material to 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 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);
- Benchmark their own results against the industry-wide averages and measure their own progress;
- Use sustainability/life cycle thinking or LCA as a part of their product and company marketing;
- Enhance their environmental reputation by reporting information and/or milestones in company literature (e.g., websites; Annual Reports; Environmental or Sustainability reports; GRI submissions, etc.); and
- Use as direct input to updating the LCIs of molybdenum chemicals.

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 the general use of the data so that results are not misused in any way. Using these reliable and representative data will increase overall data quality in studies and can aid in the dissemination of valid 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 an upstream feedstock input for product carbon footprints of molybdenum-containing products;
- Use as an upstream feedstock input supporting cradle-to-gate 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.

Carbon Footprints of the Products

In addition to LCI results for RMC powder, RMC briquettes, and FeMo, IMOA has made available the cradle-to-gate carbon footprints of each product, plus molybdenite concentrate which has also been increasingly requested. Table 1 presents the carbon footprints and the degree to which they have decreased since the 2018 study.

Table 1 Comparisons of the carbon footprint of 1 kg of each product

Year	Unit	Molybdenite Conc. (~50% Mo)	Tech Oxide (~60% Mo)	Briquette (~59% Mo)	FeMo (~67% Mo)
2024	kg CO_2-eq	2.84	3.79	4.03	7.41
2018	kg CO_2-eq	*not calculated*	4.96	5.04	8.04
% change from 2018		**n/a**	**24% lower**	**20% lower**	**8% lower**

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 also provides the foundational basis for calculating product carbon footprints. 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: [5]

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, internal to company participants, contains results and interpretation. This study adheres to the principles and framework in ISO 14040 as well as the guidelines specified in ISO 14044. 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.

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: [6]

- "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, Sustainability Director at WAP Sustainability Consulting, and the final letter of conformance is found as Appendix 1.

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

[6] ISO 14044:2006, Section 6.1.

SECTION 2: SCOPE DEFINITION AND METHODOLOGY

Molybdenum Products Studied

The following intermediate molybdenum products were updated:

1. Roasted molybdenite concentrates (RMC) in powder form: Also known as “technical grade molybdenum oxide” or “tech oxide”, RMC is added to steel and iron as an alloying agent to increase strength, hardness, electrical conductivity and resistance to corrosion and wear. It is in coarse 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.
2. RMC briquettes: Also known as tech oxide briquettes, RMC briquettes are added to steel and iron as an alloying agent to increase strength, hardness, electrical conductivity and resistance to corrosion and wear.
3. Ferromolybdenum in chip form: Ferromolybdenum is added to steel and iron as an alloying agent to increase strength, hardness, electrical conductivity and resistance to corrosion and wear. Molybdenum content of this product may range from 60 – 75%.

Table 2 Product identifiers and synonyms

Chemical Name	Identifiers	Synonyms
Molybdenum Disulfide	For roasting: CAS No. 1309-56-4 EC No. 215-172-4	Molybdenite concentrate Unroasted molybdenite concentrate UMC Moly concs Mo (IV) disulfide Mo disulfide Moly sulfide
Molybdenum Sulfide, (MoS_2), roasted	CAS No. 86089-09-0 EC No. 289-178-0	Roasted molybdenite concentrate Roasted moly concs RMC Technical grade moly oxide Tech oxide
Molybdenum Sulfide, (MoS_2), roasted, briquette form	CAS No. 86090-09-0 EC No. 289-178-0	Roasted molybdenite concentrate, briquette form RMC briquettes Tech oxide briquettes
Ferromolybdenum	CAS No. 11121-95-2 EC No. 304-589-8	FeMo Ferromoly

Primary data were collected from facilities, so the production processes, material and energy inputs, and process outputs are current and relevant. 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.

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 cradle-to-gate production of three molybdenum products. Since these do not have defined end-uses as a cradle-to-grave study would have, their results are normalized to a declared unit. For this study, the declared unit is **one kilogram of molybdenum in each product**. The results provided to data requestors are as **one kilogram of each product**, accounting for the industry-average Mo content for 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.

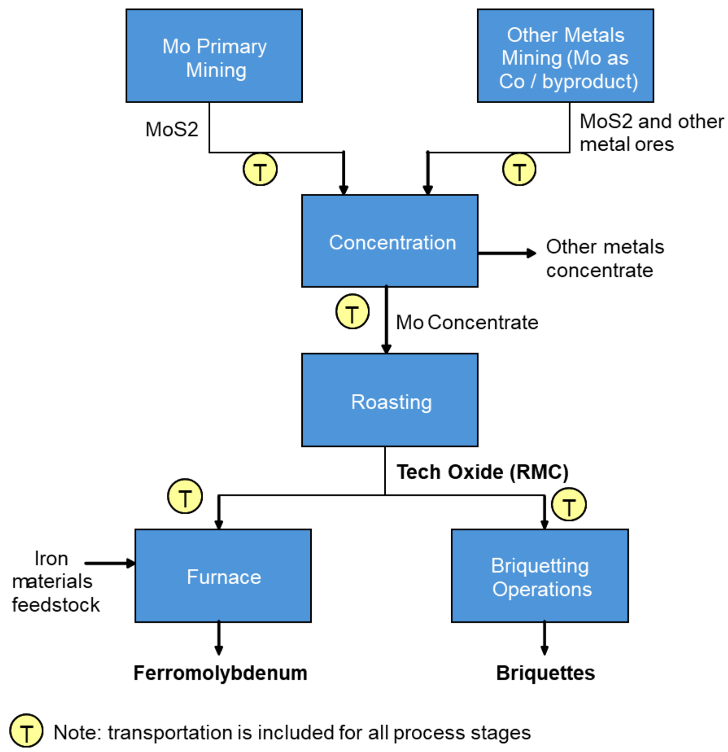


Figure 1 Overall metallurgical Mo LCI system boundary

Cut-off Criteria

<u>Cut-off Criteria Goal</u>

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, meaning 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

Packaging of the finished product is included in the system boundaries since it is part of the delivered product. Transportation of the finished product from the shipping dock to a customer is not included, since downstream producers, such as stainless steel manufactures, capture this data in their own material transportation data.

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 remain aggregated in the production process.

Data Used and LCA Software

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. The LCA for Experts Software System for Life Cycle Engineering was used to model the systems.[7] Measures were made to use the best data available at the time of the study. If there was a choice between two data sets, the better quality data is applied (i.e., the more recent, more representative technologically or geographically….). The secondary data sources are as follows:

- The LCA for Experts database was used for country-specific energy, transportation, most of the material inputs, and some end-of-life disposition datasets;

[7] Sphera, LCA for Experts Software System for Life Cycle Engineering plus the LCA for Experts Database, 1992-2024 (previously named GaBi).

- The EcoInvent database[8] was used for some energy data, some material inputs; and some of the end-of-life disposition datasets;
- For material inputs not available in commercial or public LCA databases, bibliographic, publicly-available sources like LCA studies and journal articles were used (when available);
- As necessary, engineer calculations were made;
- Electricity grids specific to each country or region were applied.

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.

Raw Materials (Resources) Category

The elementary inflows in the results tables are the natural resources extracted from the earth in the "cradle-to-gate" system of metallurgical molybdenum production. These are flows that have been traced to their elementary condition and are aggregated from energy and other materials used or consumed in the system (i.e., intermediate materials, transportation of those materials to the sites, electricity to manufacture, etc.). It is for this reason that process consumables, electricity, fuels, and intermediate molybdenum inputs reported by facilities do not appear in the inventory results.

Some of these inputs may seem not as applicable specifically to molybdenum production. For example, "coal (in ground)" 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. The list of the raw materials inputs included in the results is below.

Table 3 Raw materials inputs

Raw Materials (units in kilograms)
Hard Coal (resource)
Iron (Fe, resource)
Limestone (Calcium carbonate)
Molybdenum (in ground)
Natural Gas (resource)
Crude Oil (resource)

[8] Ecoinvent Centre, ecoinvent data v3.9.1 (Dübendorf: Swiss Centre for Life Cycle Inventories, 2023), www.ecoinvent.org, retrieved within SimaPro.

Uranium (U, ore)
Total freshwater consumed
Lignite (resource)

Air Emissions and Water Effluents

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/or the emissions to air that are found in background data sets within LCA for Experts.

Table 4 Air emissions

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

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/or the effluents found in background data sets within LCA for Experts.

Table 5 Water effluents

Water Effluents (units in kilograms)	
Aluminum (Al3+)	Mercury (Hg+, Hg++)
Ammonia (NH_4+, NH_3, as N)	Molybdenum (Mo II, Mo III, Mo IV, Mo V, Mo VI)
Biological Oxygen Demand (BOD)	Nickel (Ni++, Ni3+)
Chemical oxygen demand (COD)	Nitrate (NO_3-)
Cadmium (Cd++)	Nitrogenous Matter (unspecified, as N)
Chlorides (Cl-)	Oils (unspecified)
Chromium (total)	PAH, unspecified
Arsenic (As)	Phosphate
Copper (Cu+, Cu++)	Phosphorus (P)
Cyanide (CN-)	Silicon Dioxide (SiO_2)
Fluorides (F-)	Sulfate (SO_4--)
Iron (Fe++, Fe3+)	Suspended Matter (unspecified)
Lead (Pb++, Pb4+)	Zinc (Zn++)
Manganese (Mn II, Mn IV, Mn VII)	

Waste/Solid Material Category

LCA databases have evolved over time, and are now more comprehensive, with data sets that cover the actual processing of waste. With a preference for modeling the waste categories instead of keeping them as outflows that require more processing, all wastes in the system have been modeled as their post-treatment fates. For example: non-hazardous waste that is landfilled has been modeled using a non-hazardous waste landfill data set; solvents have been modeled as incinerated (with or without energy recovery, depending on the reported waste), etc. The two waste categories that are reported in the inventory results are waste rock (overburden from mining) and tailings (the slurry product resulting when ore is concentrated). *It should be noted that no additional burden should be attributed to these downstream, as every effort was made to collect emissions from tailings and other facility operations, from facilities themselves*.

Other Reported Categories

Impact Assessment

While the main scope of this study is to produce a cradle-to-gate LCI with no further calculation of inventory flows into impact categories, Global Warming Potential (GWP), also known as the carbon footprint, has been calculated. The carbon footprint is highly relevant in the current environmental and sustainability reporting arena, so it is appropriate to include this metric for IMOA and its members to provide to customers or other interested parties.

The GWP factors used come from the International Panel on Climate Change (IPCC) Sixth Assessment Report (AR6),[9] and GWP is calculated using the entire inventory output from the systems, not just the few reported greenhouse gas (GHG) emissions in Table 4 (i.e., carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)).

Energy Accounting

The energy values represent a quantification of the total energy in the system. **Total primary energy** includes all energy-related inputs to processes in the system, taking into account embodied or feedstock energy (i.e., in lubricating oil and hydrocarbons in plastic packaging materials) and fuel energy (i.e., process energy, transportation energy, etc.). Total energy is further broken down into **non-renewable energy** and **renewable energy**. Non-renewable energy includes sources like crude oil, natural gas, coal, and uranium and examples of renewable sources include hydropower, wind power, and biomass.

Energy losses from the electricity grid, boilers, and equipment are taken into account in the model. Energy is calculated as net calorific value (NCV) or the lower heat value in megajoules (MJ). It should be noted that the energy itself is not part of the inventory of inputs and outputs. Rather, it measures the (used or potential) energy in the system.

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 make in an LCA, since it is not always a clear allocation basis. ISO succinctly explains the step-wise approach to allocation:[10]

[9] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

[10] ISO 14044:2006, Section 4.3.4.2.

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 Specific to this Study

Molybdenum may occur by itself in ore or with copper (and possibly other metals) in multi-metal ores. In the latter case, since allocation cannot be avoided, the copper and molybdenum, as coproducts, need to be appropriately modeled. The allocation rules used in this study follow the guidelines outlined according to the metals LCA harmonization update.[11] Similar to Santero (2016), the update makes an important distinction between metal coproducts produced from mining through concentration, and metal coproducts produced in the downstream processing (i.e., roasting, other molybdenum conversion processes), discussed below.

Metal coproducts from mining through concentration

Metal coproduct allocation procedure is recommended as follows:

- If possible, the allocation should be avoided by subdividing the production of concentrates into individual production routes.
- If this is not feasible, the mass of the total extracted metal content shall be used as the basis for allocating the environmental burden of the mine and concentration to the co-produced concentrates.

Allocation by mass of the total metal content recovered at the concentration stage has been applied, since it a) considers the production of all metals, and, importantly, b) **acknowledges that often the ore(s) go through the same process chains until the co-produced concentrates are separated**.” This approach is carried over from Santero (2016), which provided the rationale that “mass is a consistent physical property of the metal and allows for a geographic and temporal consistency…”. Finally, 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 time period that the LCI data are being utilized.

Metal coproducts after concentration

Pyro- and hydrometallurgical refinery operations have more complex allocation-type choices to make, as these operations often produce multiple metals and non-metal containing coproducts as well as waste streams that contain valuable metals that are either sold/recovered or else treated as a waste product. Berger (2024) proposes to first determine whether the output from a process is a “coproduct” or “waste,” and then model it appropriately. The following recommendations are made for metal coproducts in processes occurring after concentration:

- If allocation cannot be avoided, economic allocation shall be used as the default option.
- The market price of co-products (averaged over the past 10 years to consider price volatility) shall be used to allocate the environmental burden to co-products. If the

[11] ICMM internal document. Referred to as Berger (2024).

difference in the co-products' market prices is below 10%, mass allocation can be used for simplification.

Non-metal coproducts within the whole system
For non-metal coproducts that may otherwise be produced by way of their conventional means, system expansion by substitution is performed, consistent with Berger (2024). System expansion avoids coproduct allocation. This method subtracts out production of that amount of the non-metal coproduct(s) from the system, using the conventional or alternate production technique of the coproducts. The molybdenum system therefore gets credit for offsetting an alternate, conventionally produced, product, yet the impacts of the generation of the coproducts stay in the molybdenum system.

Coproduct Allocation Summary

Modeling the coproducts is summarized as follows, when allocation cannot be avoided:

- Mass allocation is used for the metal coproducts for mining and concentration, on the basis of total metal content recovered in the concentrates.
- Economic allocation is used for the metal coproducts in post-concentration processes, on the basis of total metal content.
- System expansion is used for non-metal coproducts.

SECTION 3: DATA COLLECTION

Reference Year

The reference year for this study is 2022, which was the most current year of available production data that is also most representative of the facilities' production practices. A small percent of 2015 facility data was used, after confirmation with the facilities that no significant changes in their technology or production were made since then.

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 2.

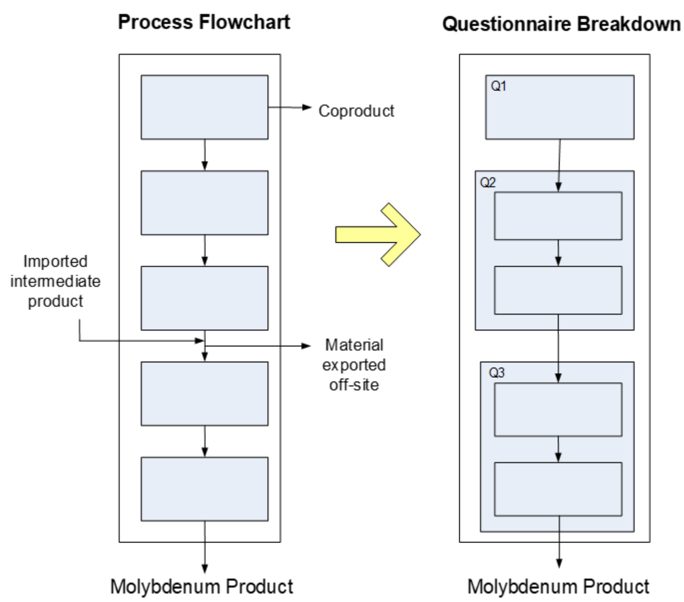


Figure 2 Flowchart-to-questionnaires

Following this methodology, each main unit process stage represented a black box, with the exception of concentration which sometimes required more subdivision (described in more detail in the Concentration modeling section, page 18).

Questionnaires

Data were collected in Microsoft Excel-based questionnaires, with each defined black box representing one unit process. Each unit process spreadsheet included all inputs, outputs, and transportation of materials to the plants. A Spanish language version of the Excel-based Questionnaire and the User Guide were provided for facilities in Spanish-speaking countries to enable full clarity of the questionnaire.

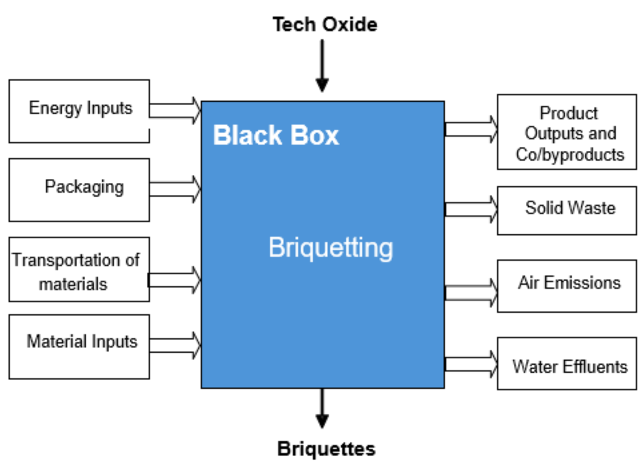


Figure 3 Questionnaire overview

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. Where companies indicated using renewable fuels, we investigated the situation. In many cases, it was found that contractual instruments such as Renewable Energy Certificates (RECs) were used, which could lower facilities' fossil CO_2 emissions. Per ISO 14067 guidelines, documentation was requested and received to ensure that the RECs were a) assigned to the facility, b) were current for the reporting year and continue to be current, and c) are retired after "use".[12]

Concentration (Process A)	Units	Quantity	Data Quality			Transport of Materials to the Site	
			SOURCE	TYPE	YEAR	Distance to site (km or mi)	Mode (truck, train...)
Electricity							
Steam (from off-site)							
Compressed Air							
Other questions:							
Do you purchase any special electricity (such as green electricity) that is not part of the regional electricity grid? If yes, please explain. Yes __ / No __	Answer:						
Do you purchase carbon offsets of any kind? If yes, please explain. Yes __ / No __	Answer:						
Natural Gas							
Propane							
Fuel Oil							
Recycled oil							
Diesel Oil							
Gasoline							
Coal							

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 was reported, so recirculated water was not included. Note also in the figure below that the distances

[12] ISO 14067:2018(E) Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification, Sec. 6.4.9.4.

and modes of transport of the raw materials (also intermediate molybdenum inputs, and purchased fuels) were reported.

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

If the data point is this:	Provide this:
1) Value for the year 2022 (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). 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 information in Table 6 for full clarity of the value.

Waste and Materials Not Recovered

Any material that was 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 reported so the waste could be modeled appropriately.

SITE DATA (black box)	Roasting	Units	Quantity	Data Quality: SOURCE	TYPE	YEAR		
Outflows							Distance off-site	Fate of waste
Solid Waste:	Used oils, used lubricants							
If waste was reported as wet, provid	Lab waste							
the % moisture.	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 differ from coproducts in that they do not have a marketable value. Recovered materials were reported as the following:

- Recycled as a closed loop material: reused/recycled within the same process from where it came. Modeling included only the net of this material's use.
- 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 as an input into the next process without production burdens.
- Reused/recovered/recycled completely outside the boundary of this study. If the recovered material leaves the boundary of this study to be recycled or used by another entity, it leaves without burden, including its transportation away from the facility.

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 could be collected as its own black box or as part of one of the main unit processes. For example, data for the WWTP in Figure 8 was collected separately to accommodate both concentration and roasting wastewater (noting the specific %s provided by a facility). In Figure 9, the roaster is the only process using the sulfur dioxide scrubber, so all data for the scrubber/ sulfuric acid production plant could be collected with the roasting questionnaire.

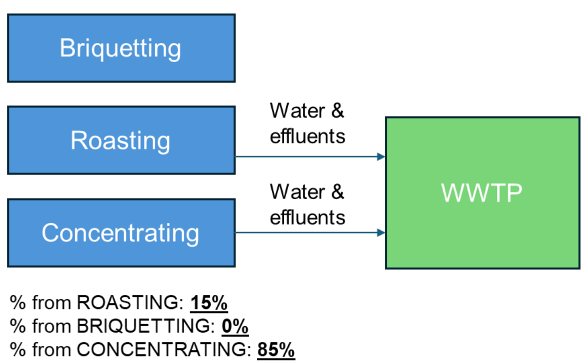


Figure 8 Utilities serving multiple areas of a plant

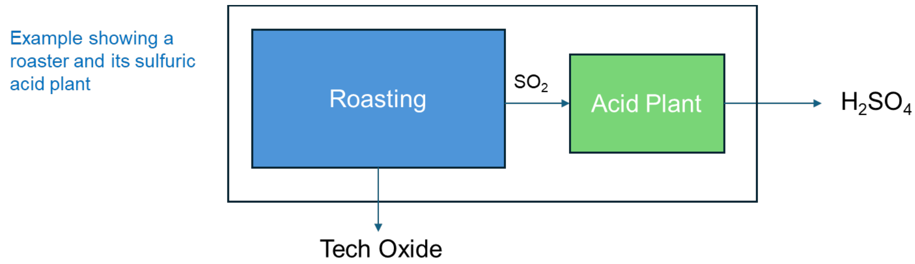


Figure 9 Utilities serving single areas of a plant

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 that were 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 immateriality.

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 and the black box encompasses all mining operations such as overburden removal, blasting, and ore loading and transport. While some operations consider crushing and 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 was averaged on a weighted basis for all of the mining facilities without distinction between the underground and open pit mining, or primary or byproduct mining, in the final results.

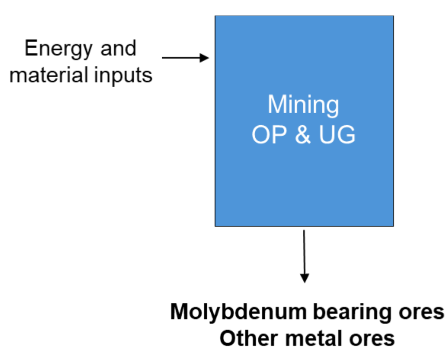


Figure 10 Mining system boundaries

Modeling Coproducts
As described earlier, coproduct allocation was carried out based on the mass of the metals found in the final concentrates. This was done in order to account for not the *potential* yield of the metal (i.e., the measured ore grade) but what was actually recovered at concentration.

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 LCA for Experts 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). Depending on the molybdenum bearing ores, some facilities may produce both copper and molybdenum concentrate, while others may produce only molybdenum concentrate. In the former case, there is often shared ore processing followed by molybdenum-only processing. These are shown below.

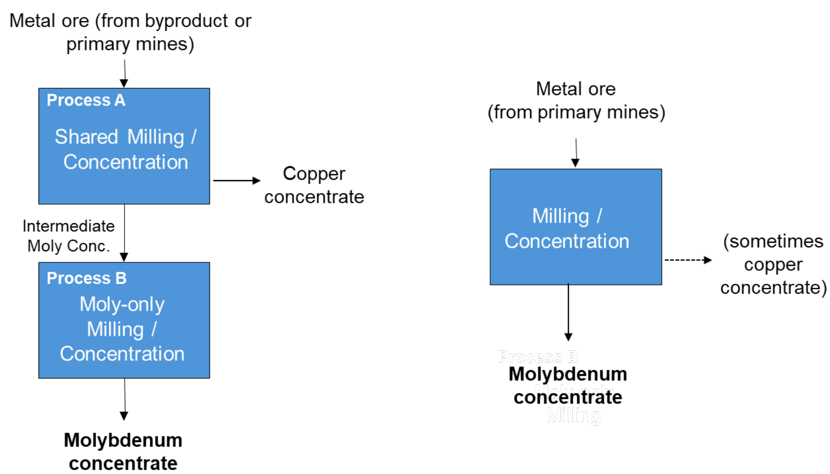


Figure 11 Concentration system boundaries

Data Collection
As shown above, the concentrates may be produced 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 Questionnaire Forms</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 generally 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.

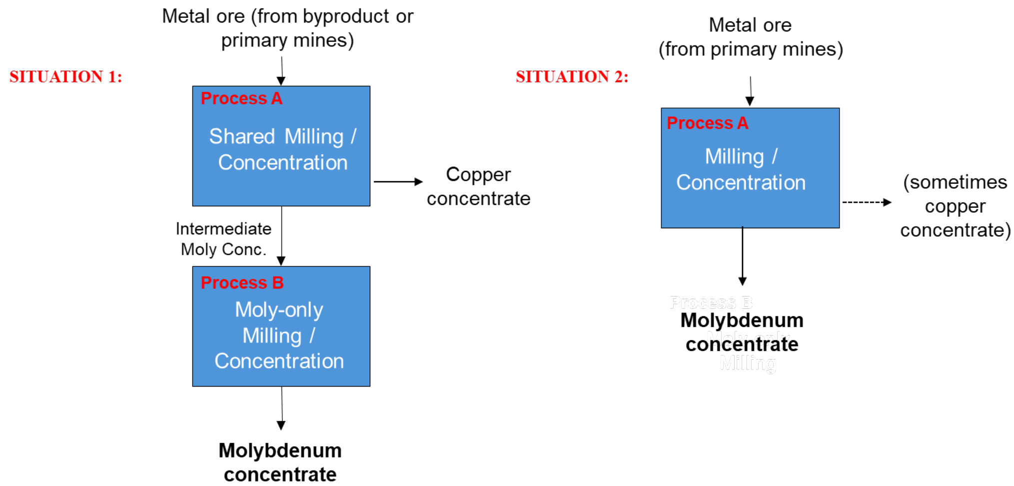


Figure 12 Concentration data collection situations

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 generally 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, when 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 if and when data were available.

Roasting Process

Roasting is a pyrometallurgical process that converts the molybdenite concentrate into technical grade molybdic oxide as a final product to be shipped to customers or as an intermediate product to be further transformed into briquettes or ferromolybdenum. Because the ore is naturally sulfur-rich, many plants include SOx abatement technologies that produce marketable sulfuric acid. This non-metal coproduct has been modeled using system expansion, the preferred approach for non-metal coproducts. Roasting is shown in Figure 13.

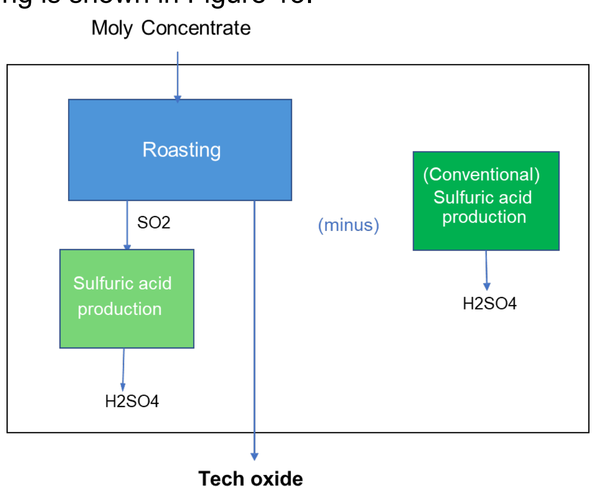


Figure 13 Roasting system boundaries

Briquetting

Briquetting includes the processes starting at the delivery of the tech oxide to the briquetting plant through the formation of briquettes until the point of delivery to a customer. Briquettes are pressed as either cylinders or pillows after application of a binder, typically an ammonium-based product. 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 of iron sources, to the point of delivery of the finished ferromolybdenum to customers. Figure 15 presents the ferromolybdenum system.

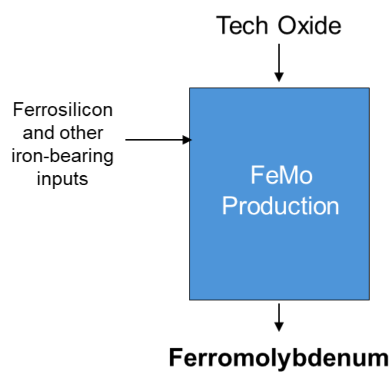


Figure 15 Ferromolybdenum system boundaries

Data Aggregation

Preliminary Questionnaire Check

After questionnaires were returned to Four Elements, they were checked for overall completeness, from both a quantitative and qualitative perspective. Four Elements 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 plus/minus 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. Where RECs were identified, their validity was confirmed;
- 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 Returned Questionnaires

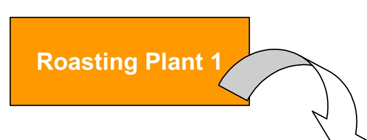
A typical questionnaire that was sent to each of a participating company's facility had one or more data black boxes plus black boxes for on-site utilities. For example:

Site Information for Questionnaire Data	
Site Name and location:	
Products Produced and Utilities:	Molybdenum ore Copper and moly concentrates Roasting WWTP

Figure 16 High level facility information

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;
5. Companies were again contacted for discrepancies on the basis of 1 kg of output. Values were confirmed or modified.
6. Data Summary Sheets (DSSs) were ready to be compiled using the normalized site data (Figure 17).



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 Preparation for the DSS

Compilation of the Summary Sheets for Validation

This section describes each DSS component shown in Table 7.

Table 7 Blank DSS

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							

<u>Weighted Average and "Averaging Type"</u>

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.

<u>Minimum and Maximum Values</u>

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 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.

<u>Number of Sites, Percent of Total Sites</u>

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).

<u>Comments</u>

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.

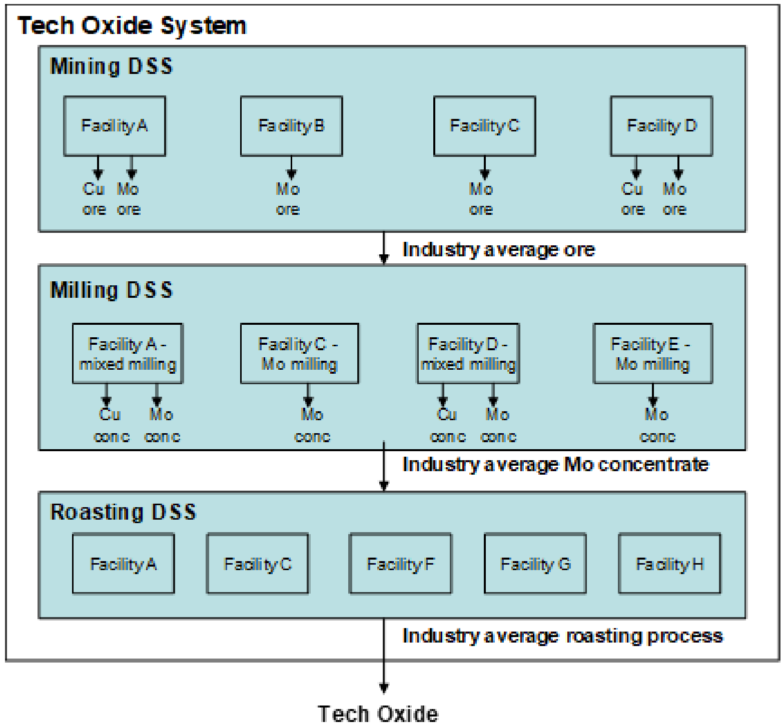


Figure 18 Horizontal and vertical aggregation of data sets

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 were applied.[13] In the internal LCI Report, DQ ratings as defined in the WRI Product Standard were assigned to more detailed aspects of the study.[14] These ranged from "Very Good" for the facility data, and "Very Good to Good" for most of the background data.

Representativeness

Geographical Representation

The primary molybdenum data collected and modeled for this study comes from 11 IMOA member companies, an increase of three companies from 2018, and represents approximately 24% of total global molybdenum produced and 50% of global production minus China, Mongolia, and CIS.[15] Plant data come from North and South America, Europe, and Asia.

Temporal Representation

Considered the most complete and accessible data at the time of collection, 2022 was chosen as the reference year to represent current energy and material usage, technologies, and general plant design. Facilities provided 2022 data. One company used their 2015 copper LCA data.

[13] ISO 14044 Section 4.2.3.6.

[14] 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"

[15] Data from IMOA (April 2024).

Technological Representation

The primary data collected on the metallurgical production processes are assumed to be representative of current technology and plants. For any of the facilities submitting older data, detailed questions were sent, to ensure that their technology and processes are still considered current. Technological coverage for the background data may include industry averages, weighted averages, best available technology, and/or worst operating unit.

Completeness

ISO 14044 defines completeness as the "percentage of flow that is measured or estimated."[16] 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. This goal was met as more companies did participate. In order to protect the confidentiality of the participants, a quantitative analysis on completeness for each unit process stage could not be performed. Using the WRI Product Standard for data quality, completeness is Good to Very Good.

Consistency

Consistency is a qualitative understanding of how uniformly the study methodology is applied to the various components of the study. This measure of quality 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 multi-metal LCA Harmonization effort, ensuring, where applicable, consistency with other metals' LCAs 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 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

<u>Data Quality Indicators</u>

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. 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);

[16] ISO 14044:2006, Section 4.2.3.6.

- 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. Users were given precise instructions to fill out the air emissions and water effluents sections of the questionnaire (Table 6). This approach was helpful in assessing 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 if they have access to the same or similar databases/data sets.

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. the cut-off criteria analysis revealed that the inputs well exceeded the cut-off criteria goal of 99%.

SECTION 6: 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

Policymakers, customers, and researchers reply on LCA for valuable environmental information on product systems. It should be borne in mind that the LCA, like any other scientific or quantitative study, has limitations. In all LCA studies there is an inherent margin of error due to various limitations such as imperfections and unavailability of some relevant data. 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.

That said, this LCI study is considered to be the most comprehensive, current record of environmental inflows and outflows associated with the production of molybdenum products for metallurgical applications, and it should be the go-to source for the LCI of these products.

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 lost 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. Traditional Risk Assessment is better and more appropriate for assessing site-specific risk and toxicity. IMOA (www.imoa.info) has a comprehensive library of technical studies addressing these very issues.

SECTION 7: CONCLUSIONS

This report represents the completed ISO 14040/14044-compliant LCI – IMOA's fourth 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 appropriate modeling of coproducts. It helped pave an early path toward performing metals LCAs using sensible, albeit possibly less sophisticated approaches back then. The metals industry has indeed come a long way.

Published in 2016 and with a new update in progress, the multi-metals LCA Harmonization work provides guidance on the LCA methodology-related challenges many metals face. IMOA has utilized the latest updates of the Harmonization guidelines to ensure that this LCI is aligned with the other metals' LCI/LCAs and has applied the most sensible LCA practices – extremely important given the myriad of current and future LCAs relying on these input data. IMOA continues to educate its member companies and stakeholders about some of the challenging issues encountered in LCA and will continue to lead through active industry participation. IMOA intends to continue to perform updates every five years, or potentially more frequently, to keep the results current.

APPENDIX 1: PEER REVIEW 14044 CONFORMANCE LETTER

WAP SUSTAINABILITY CONSULTING

To: International Molybdenum Association October 10, 2024

From: James Salazar, WAP Sustainability

Re: Review of Life Cycle Inventory of Metallurgical Molybdenum Products: Update Study

WAP Sustainability was recently contracted to provide a third-party review for the LCI study: *Life Cycle Inventory of Metallurgical Molybdenum Products: Update Study –* Prepared by Four Elements Consulting LLC. We have thus reviewed the study against the requirements for LCI studies within ISO 14044:2006 to ensure conformance with ISO 14040:2006 and ISO 14044:2006.

WAP Sustainability first developed a review matrix document that incorporated all of the requirements for LCI studies within ISO 14044:2006 – excluding those requirements pertaining to the life cycle impact assessment and comparative assertions as these did not apply in this case.

WAP then provided comments on an initial draft of the study that did not include results. These comments were incorporated into the document as it was completed. We have now reviewed a complete draft of the study and found the study to be in conformance with all requirements. No further changes are required.

The completed review matrix is attached to this letter. The revised and completed LCI study, dated October 10, 2024, thus conforms to the requirements of the referenced standards.

Sincerely,

Director, WAP Sustainability
Phone: 250.306.0638 Email: james@wapsustainability.com
Attachments [1]

Prepared for

THE VOICE OF THE MOLYBDENUM INDUSTRY

International Molybdenum Association
454-458 Chiswick High Road
London, W4 5TT, United Kingdom
Email: info@imoa.info
www.imoa.info

By

Four Elements Consulting, LLC
1619 22nd Avenue East
Seattle, WA 98112, USA
Email: anne@fourelementsllc.com
www.fourelementsllc.com