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Material Flow and Supply Chain Assessment of Rechargeable Aluminum Batteries

KAUST Energy Transition Program

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Abstract

The increasing deployment of electrochemical energy storage has intensified interest in battery chemistries that rely on abundant, recyclable, and geographically diverse materials. Rechargeable aluminum batteries are one potential alternative to conventional lithium-ion batteries due to the abundance of aluminum, its established industrial supply chain, and its high recyclability. However, evaluating the scalability of an aluminum battery requires consideration of the complete material system rather than aluminum alone.

This study investigates the material flows and supply-chain characteristics of a non-aqueous rechargeable aluminum battery using an aluminum anode and a Mo_6S_8 Chevrel-phase cathode. The assessment focuses primarily on aluminum, molybdenum, and sulfur and combines literature review, material flow analysis, global production data, geographic production mapping, recycling analysis, and a preliminary supply-chain bottleneck assessment.

A quantitative material flow analysis was developed for the aluminum pathway from bauxite production through alumina refining, primary aluminum production, downstream applications, and end-of-life recovery. Geographic production maps were developed for bauxite, alumina, primary aluminum, molybdenum, and sulfur. The analysis shows that geographic concentration changes significantly along the aluminum supply chain, with downstream alumina refining and primary aluminum production more concentrated than bauxite extraction. A preliminary weighted bottleneck assessment classified aluminum as low risk, sulfur as moderate risk, and molybdenum as high risk within the adopted screening framework, identifying molybdenum as the principal raw-material concern among the materials assessed. Significant data gaps were identified for battery-grade aluminum foil allocation and, more importantly, for industrial-scale Mo_6S_8 production, material allocation, and recycling. The results demonstrate that replacing conventional lithium-ion materials with an aluminum-based chemistry changes the nature of supply-chain risk rather than eliminating it.

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1 Introduction

1.1 Battery Materials and the Energy Transition

The transition toward low-carbon energy systems is increasing the deployment of electrochemical energy storage across transportation, stationary storage, and other applications. As battery deployment increases, attention must be given not only to electrochemical performance but also to the material requirements associated with large-scale manufacturing.

Lithium-ion batteries currently dominate many battery applications. Their continued expansion requires substantial quantities of materials such as lithium, graphite, nickel, cobalt, manganese, copper, and aluminum, although the exact material requirements depend strongly on the battery chemistry. These materials have different geological availability, geographic production distributions, processing requirements, recycling pathways, and exposure to geopolitical or market risks.

Consequently, the scalability of a battery technology cannot be evaluated solely on the basis of energy density, cycle life, or other electrochemical characteristics. The availability and movement of materials through mining, refining, manufacturing, use, and end-of-life stages must also be considered [9].

1.2 Motivation for Alternative Battery Chemistries

Alternative battery chemistries can potentially reduce dependence on some of the materials associated with conventional lithium-ion batteries. However, material substitution does not necessarily eliminate supply-chain risk. Instead, replacing one chemistry with another may transfer dependence from one group of materials and processes to another.

This motivates a supply-chain assessment of emerging battery technologies before large-scale commercialization. Such an assessment can identify whether a proposed chemistry relies on geographically concentrated materials, by-product commodities, immature manufacturing processes, or poorly developed recycling pathways.

Rechargeable aluminum batteries are particularly interesting from this perspective. Aluminum is produced globally at very large scale and is supported by mature mining, refining, smelting, fabrication, and recycling industries. It is also highly recyclable and can be repeatedly remelted and reused [6–9].

From an electrochemical perspective, aluminum is a multivalent metal, with Al^{3+} allowing the transfer of three electrons per ion. However, the high charge density of Al^{3+} also creates significant challenges for reversible transport and intercalation in cathode materials. The feasibility of an aluminum battery therefore depends not only on aluminum but also on the cathode and electrolyte systems used [1, 2].

1.3 Battery Chemistry Investigated

The battery system considered in this study is a non-aqueous rechargeable aluminum battery using aluminum metal as the negative electrode and Mo_6S_8 Chevrel phase as the positive electrode material.

Chevrel-phase compounds contain an open framework capable of accommodating guest ions and have been investigated as host materials for multivalent-ion batteries. Mo_6S_8 has been demonstrated experimentally and theoretically as a host material for Al^{3+} insertion, making it a relevant cathode candidate for rechargeable aluminum batteries [1, 2].

From a supply-chain perspective, however, the use of Mo_6S_8 introduces additional material dependencies beyond aluminum. In particular, production of the cathode requires molybdenum

and sulfur, while its synthesis introduces processing steps that are considerably less mature than the established industrial aluminum supply chain [3].

The investigated material system therefore provides a useful case study for determining whether an aluminum-based battery reduces material supply-chain constraints or instead shifts potential bottlenecks toward different materials and manufacturing processes.

1.4 Aim and Scope

The objective of this study is to assess the material flows and supply-chain characteristics associated with the investigated rechargeable aluminum battery.

The analysis focuses primarily on aluminum, molybdenum, and sulfur. The main objectives are to:

1. identify the principal material and processing pathways associated with the battery;
2. quantify material flows where sufficiently reliable industrial data are available;
3. evaluate the geographic concentration of key material production;
4. examine recycling and end-of-life pathways;
5. identify potential material and processing bottlenecks; and
6. identify major data gaps that currently limit a complete quantitative MFA.

The study is primarily a material flow and supply-chain assessment. Detailed electrochemical performance comparison, life-cycle assessment, and techno-economic analysis are outside the present scope and are considered potential extensions of the work.

2 Background and Related Work

2.1 Rechargeable Aluminum Batteries

Rechargeable aluminum batteries have been investigated using a range of electrode and electrolyte systems. The choice of cathode strongly influences the electrochemical mechanism and the materials required by the battery.

Although aluminum offers attractive theoretical properties, practical rechargeable aluminum batteries remain considerably less technologically mature than established lithium-ion batteries. The high charge density of Al^{3+} presents challenges for reversible ion transport and the development of suitable host materials [1, 2].

2.2 Chevrel-Phase Cathodes

Mo_6S_8 belongs to the Chevrel-phase family of molybdenum chalcogenides. Its structure contains interconnected sites capable of hosting guest ions and has been investigated extensively in multivalent battery research [1–3].

The ability of the Chevrel structure to accommodate multivalent ions makes it scientifically interesting for aluminum storage. However, the high charge density of Al^{3+} can lead to strong interactions with the host lattice and sluggish solid-state diffusion. Consequently, Mo_6S_8-based aluminum systems remain predominantly at the research stage [1, 2].

From the perspective of this project, Mo_6S_8 is particularly important because it introduces molybdenum and sulfur into the battery supply chain. Any potential advantage associated with replacing lithium-ion battery materials must therefore be evaluated against the availability and supply risks of these materials.

2.3 Aluminum Production

Primary aluminum production begins with bauxite mining. Bauxite is processed using the Bayer process to produce alumina, Al_2O_3. Alumina is subsequently converted into metallic aluminum through the Hall–Héroult electrolytic process [8, 11].

Primary aluminum can then undergo casting, rolling, extrusion, and other fabrication processes depending on its final application. Battery applications requiring thin aluminum foil introduce additional rolling and quality requirements [12].

The aluminum industry also has a well-developed secondary production pathway. Aluminum scrap can be collected, sorted, remelted, and returned to productive use. Recycling therefore represents an important component of the aluminum material cycle [7–9].

2.4 Molybdenum Production

Molybdenum is commonly obtained from molybdenite-containing ores. It can be produced from primary molybdenum mines or recovered as a by-product of other mining operations, particularly copper production [4].

Molybdenite is typically recovered through mineral-processing operations such as flotation before further conversion into processed molybdenum products. The dependence of a significant portion of molybdenum production on other mining industries is important from a supply-chain perspective because supply may not respond independently to changes in molybdenum demand [4].

2.5 Sulfur Production

Modern sulfur production differs from conventional mineral extraction because substantial quantities are recovered as a by-product during oil and natural-gas processing and refining. Removal of sulfur-containing compounds from fossil fuels produces elemental sulfur that subsequently supplies numerous industrial applications [5].

This means that sulfur is produced at large scale and across several countries, but its supply is structurally connected to the operation of other industries. By-product dependence is therefore an important consideration even where geographic production concentration is relatively low [5].

3 Methodology

3.1 Overall Assessment Framework

The methodology combines supply-chain mapping, literature review, material flow analysis, geographic production assessment, recycling analysis, and weighted bottleneck assessment.

The first step was to identify the major materials required for the investigated battery and trace their upstream production pathways. The analysis was then divided into three main material branches: aluminum, molybdenum, and sulfur.

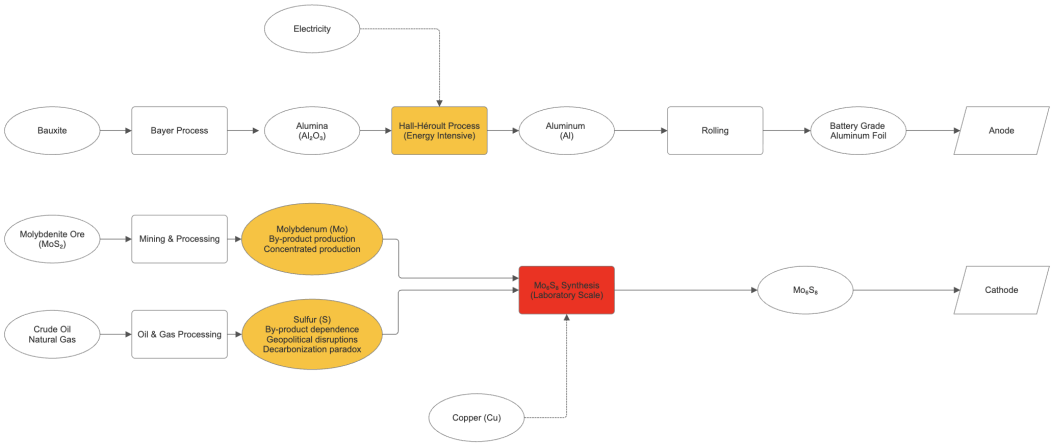


Figure 1 Material supply-chain framework for the investigated Al–Mo_6S_8 battery. Yellow stages indicate identified supply-chain concerns, while red indicates a major bottleneck or limited industrial maturity.

The aluminum pathway could be quantified in the greatest detail because it is supported by a mature global industry and relatively extensive statistical data. Molybdenum and sulfur could be quantified upstream, but the transition from these commodities to battery-specific Mo_6S_8 production was limited by data availability.

3.2 Data Collection

Country-level production data were collected primarily from the U.S. Geological Survey Mineral Commodity Summaries. Production estimates for 2024 were used where available to provide a consistent basis for comparison [6].

Academic literature was used to characterize processing routes, material relationships, recycling, molybdenum production, sulfur supply, Chevrel-phase synthesis, and battery supply chains. Institutional and industry sources were used where relevant data were not available in academic publications, particularly for aluminum recycling statistics.

Data were assessed according to their definitions before being incorporated into the MFA. Particular attention was given to recycling terminology because collection rate, recycling efficiency rate, recycling input rate, and process recovery efficiency represent different quantities and should not be treated interchangeably [7, 8]. The treatment of system boundaries, assumptions, and data gaps was informed by established aluminum MFA studies [9, 10].

3.3 Aluminum Material Flow Analysis

The aluminum MFA follows the pathway:

Bauxite → Alumina → Primary Aluminum → Rolled Aluminum → Battery Pathway → End of Life → Secondary Aluminum.

Global bauxite mine production in 2024 was used as the upstream reference flow [6]. Conversion through the refining and smelting stages was estimated using industry material relationships reported by the International Aluminium Institute (IAI). As a general industry relationship, approximately 4–6 tonnes of bauxite are required to produce 2 tonnes of alumina, which subsequently produce approximately 1 tonne of primary aluminum. The exact material requirement varies according to ore quality and operating conditions [11].

The MFA was constructed as a mass-flow model rather than as a representation of a single physical production facility. Consequently, reductions in mass between stages should not

automatically be interpreted as recoverable process losses. In particular, the reduction from bauxite to alumina primarily represents removal of the non-alumina fraction of the ore during Bayer refining, while the reduction from alumina to metallic aluminum reflects the removal of oxygen during Hall–Héroult electrolysis in addition to process-related material losses.

The rolling stage was included to represent fabrication of primary aluminum into thin aluminum products. Rolling and associated fabrication generate process scrap, much of which can potentially be returned to the aluminum production cycle [12].

A major uncertainty occurs when the global aluminum flow is allocated to battery-grade foil. Aluminum is used in numerous sectors, and a reliable global value describing the fraction of primary aluminum specifically allocated to foil for the investigated rechargeable aluminum battery technology could not be identified. The downstream battery pathway is therefore treated as a scenario rather than as an estimate of actual current global aluminum-battery production.

For the end-of-life stage, the global aluminum Recycling Efficiency Rate (RER) reported by the International Aluminium Institute was adopted. The RER describes the proportion of aluminum available for recycling that is recovered. A global RER of 76% was applied to the modeled end-of-life flow, while the remaining 24% was represented as unrecovered material [7, 8].

3.4 Geographic Production Assessment

Country-level production maps were developed for five materials or processing stages:

1. bauxite mine production;
2. alumina refinery production;
3. primary aluminum smelter production;
4. molybdenum mine production; and
5. sulfur production.

All maps use 2024 production estimates from the USGS and a common visualization format to allow comparison of geographic concentration [6].

Production concentration was also evaluated using the share associated with the largest producer and, where relevant, the three largest producing countries.

3.5 Bottleneck Assessment

A preliminary weighted supply-chain risk assessment was developed to compare the principal raw materials considered in the study. Five criteria were selected: resource availability risk, production concentration, by-product dependence, geopolitical risk, and raw-material production maturity. The criteria were assigned weights of 15%, 25%, 20%, 15%, and 25%, respectively. Greater weight was assigned to production concentration and production maturity because these factors were considered particularly relevant to the ability of a material supply chain to respond to potential future scale-up. The criteria and weights are summarized in Table 1.

Each criterion was assigned a score from 1 to 3, where 1 indicates low risk, 2 indicates moderate risk, and 3 indicates high risk. The overall supply-chain risk score was calculated using the weighted sum

$$R = \sum_i w_i s_i, \tag{1}$$

where w_i represents the weight assigned to criterion i and s_i represents its corresponding risk score.

The final scores were classified as follows:

Table 1 Criteria and weights used in the supply-chain risk assessment.

Criterion	Weight
Resource availability risk	15%
Production concentration	25%
By-product dependence	20%
Geopolitical risk	15%
Raw-material production maturity	25%

- 1.00–1.66: Low risk;
- 1.67–2.33: Moderate risk; and
- 2.34–3.00: High risk.

Scores were assigned based on the production and resource data, geographic concentration analysis, literature evidence on by-product dependence, and the maturity of the corresponding industrial production pathways. Because the framework is intended as a preliminary screening assessment, the scores represent comparative judgments based on the available evidence rather than standardized criticality thresholds and should not be interpreted as absolute measures of global material criticality.

The production-maturity criterion refers specifically to the upstream production of aluminum, molybdenum, and sulfur. Manufacturing maturity of the Mo_6S_8 cathode is considered separately because Mo_6S_8 is a manufactured compound rather than a mined raw material.

4 Results

4.1 Aluminum Material Flow Analysis

The aluminum pathway was the most completely quantifiable component of the battery supply chain.

Global bauxite mine production in 2024 was approximately 450 million tonnes. As the material moves through Bayer refining and Hall–Héroult smelting, the mass flow decreases substantially. This reduction reflects the composition of bauxite, the removal of non-aluminum components during refining, and the conversion of alumina into metallic aluminum.

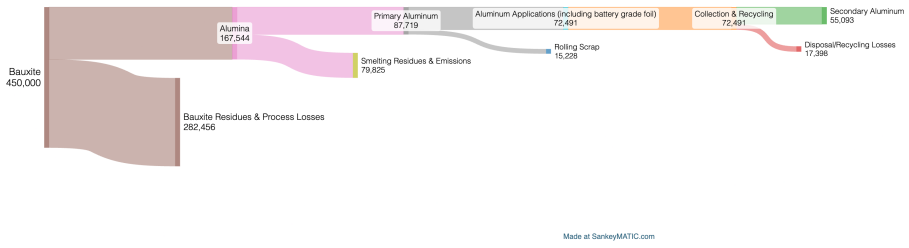


Figure 2 Global aluminum material flow analysis based on 2024 production data. The downstream battery pathway represents a scenario because a reliable global allocation to battery-grade aluminum foil was not identified.

The modeled pathway results in approximately 72,491 kt of aluminum entering the downstream application stage.

This quantity should not be interpreted as actual global aluminum consumption by batteries.

Aluminum is used across transportation, construction, packaging, electrical systems, machinery, and many other applications. Because no defensible global allocation factor for battery-grade aluminum foil associated with the investigated technology was identified, the downstream battery pathway represents a scenario used to investigate subsequent material recovery.

Applying the global Recycling Efficiency Rate of 76% to the modeled end-of-life flow results in approximately 55,093 kt of recovered secondary aluminum and approximately 17,398 kt of unrecovered aluminum.

The MFA therefore demonstrates both the strong upstream data availability for aluminum and the increasing uncertainty that appears when a global commodity flow is allocated to a specific emerging battery application.

4.2 Geographic Distribution of Bauxite Production

Bauxite production is concentrated among several major producers. Guinea, Australia, and China are the three largest producers and together account for approximately 71.8% of global production. Guinea represents approximately 28.9% of global bauxite production, while Australia and China also contribute substantial shares [6].

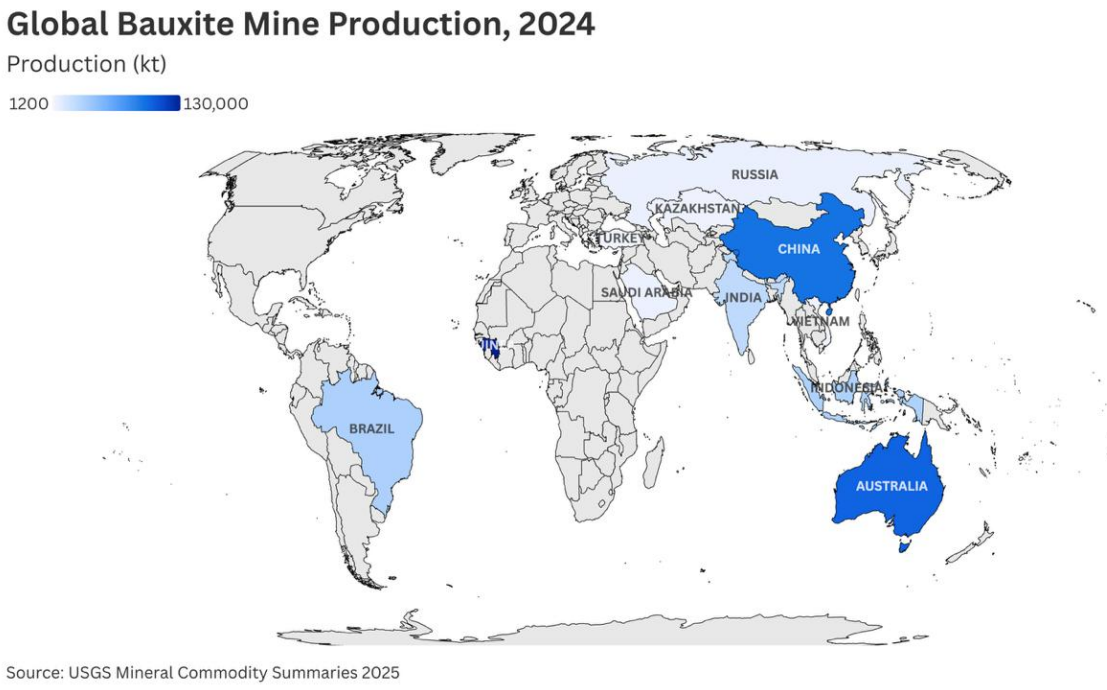


Figure 3 Global bauxite mine production by country, 2024.

Although the top three countries represent a large fraction of production, no single producer dominates the bauxite market to the same extent observed at some downstream processing stages.

4.3 Geographic Distribution of Alumina Production

The geographic distribution changes substantially when moving from bauxite extraction to alumina refining. China becomes the dominant alumina-producing country, while Australia remains another major producer [6]. This indicates that processing capacity is more geographically concentrated than the underlying mineral extraction stage.

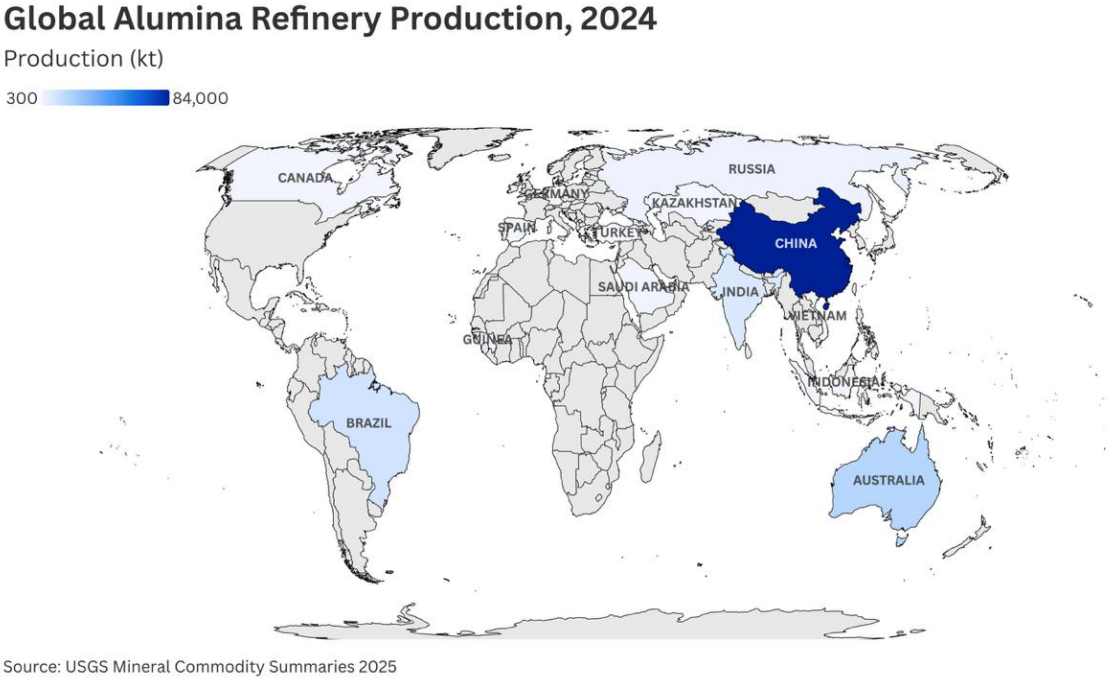


Figure 4 Global alumina refinery production by country, 2024.

This result demonstrates the importance of distinguishing geological availability from processing capacity when evaluating supply-chain risk.

4.4 Geographic Distribution of Primary Aluminum Production

Primary aluminum production remains strongly concentrated in China [6].

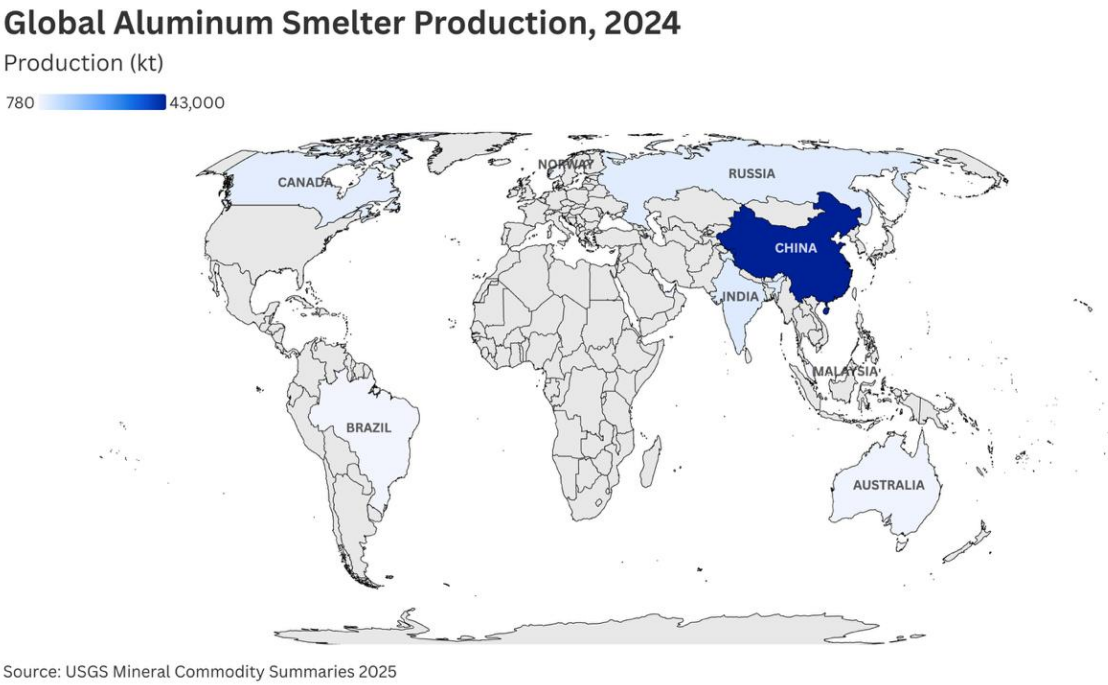


Figure 5 Global primary aluminum smelter production by country, 2024.

The progression from bauxite to alumina and finally primary aluminum shows that geographic concentration changes along the supply chain. Aluminum may have a broad resource base, but downstream refining and smelting capacity represents a more concentrated part of the system.

This observation was incorporated into the bottleneck assessment by assigning aluminum a moderate rather than low production-concentration score.

4.5 Geographic Distribution of Molybdenum Production

Molybdenum production is also geographically concentrated. China is the largest producer, accounting for approximately 42% of global production. Peru and Chile are also major producers, and the three largest producing countries together account for approximately 73% of global output [6].

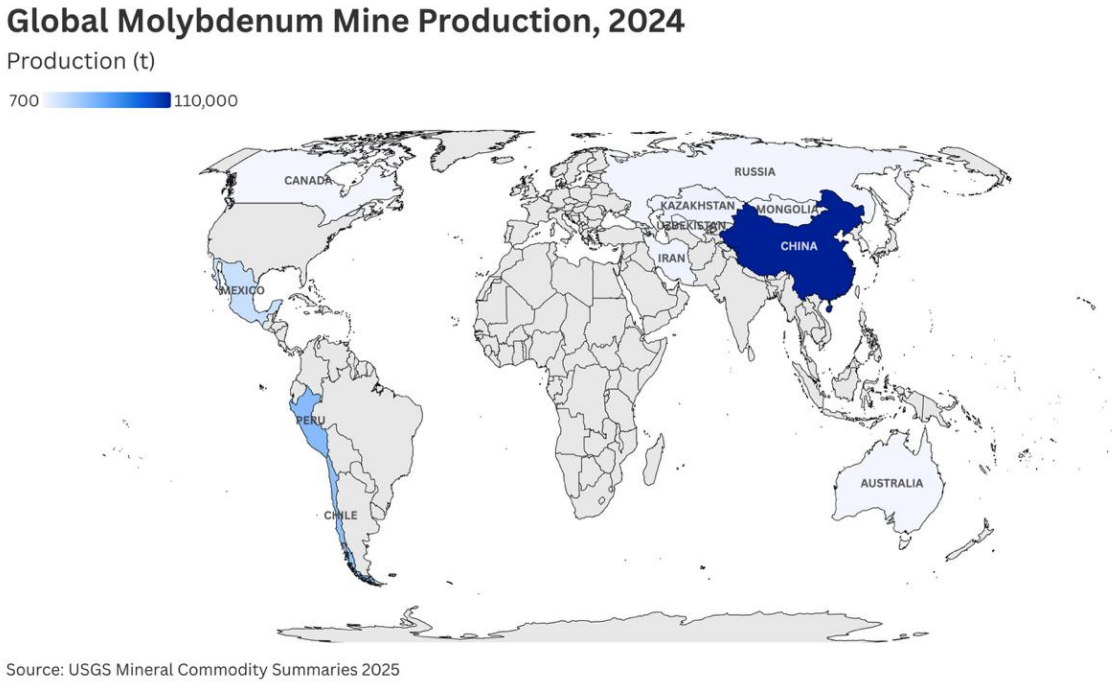


Figure 6 Global molybdenum mine production by country, 2024.

Geographic concentration is particularly relevant because molybdenum is the principal metallic component of the Mo_6S_8 cathode. In addition, molybdenum can be recovered as a by-product of other mining operations, particularly copper production, further increasing potential supply-chain exposure [4].

4.6 Geographic Distribution of Sulfur Production

Sulfur production is more geographically distributed than molybdenum production. Major producers include China, the United States, Russia, Saudi Arabia, the United Arab Emirates, and several other countries [6].

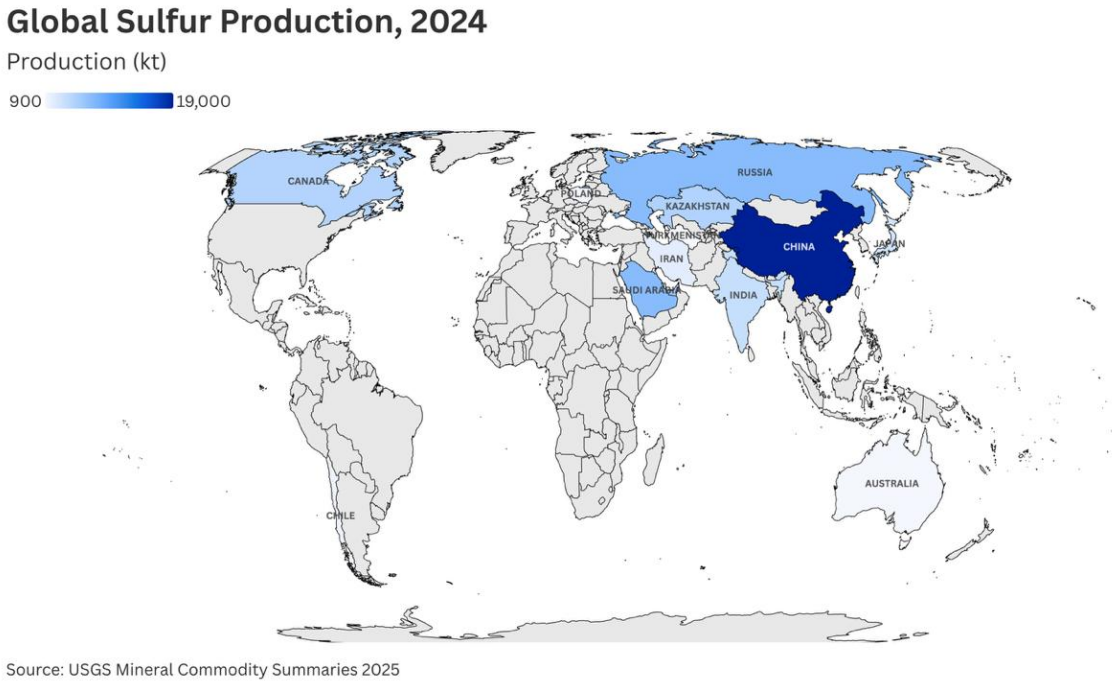


Figure 7 Global sulfur production by country, 2024.

The geographic distribution suggests lower concentration risk than molybdenum. However, much modern sulfur production originates from oil and gas processing and refining. The primary supply concern for sulfur is therefore structural dependence on other industries rather than geographic concentration alone [5].

4.7 Comparison of Geographic Concentration

Comparison of the five production maps demonstrates that geographic concentration varies considerably between materials and between successive stages of the aluminum supply chain.

Bauxite production is shared among several major producers, with Guinea, Australia, and China collectively accounting for approximately 72% of global mine production. Geographic concentration becomes more pronounced downstream, as China becomes the dominant producer of both alumina and primary aluminum.

Molybdenum also exhibits substantial production concentration. China accounts for approximately 42% of global mine production, while China, Peru, and Chile collectively account for approximately 73%. Sulfur production is distributed across a broader group of countries and therefore exhibits lower geographic concentration than molybdenum [6].

These results demonstrate that resource availability and production concentration represent different dimensions of supply risk. A material may have a large global resource base while still depending on geographically concentrated processing capacity. This distinction is particularly important for aluminum, where concentration increases substantially between bauxite extraction and downstream refining and smelting.

4.8 Supply-Chain Bottleneck Assessment

The weighted bottleneck assessment produced distinct risk profiles for the three principal materials, as shown in Table 2.

Aluminum received an overall score of 1.25 and was classified as low supply risk. Its high

Table 2 Preliminary supply-chain bottleneck assessment.

Criterion	Weight	Aluminum	Molybdenum	Sulfur
Resource availability risk	15%	1	2	1
Production concentration	25%	2	3	2
By-product dependence	20%	1	3	3
Geopolitical risk	15%	1	3	2
Raw-material production maturity	25%	1	1	1
Overall score		**1.25**	**2.35**	**1.80**
Classification		**Low**	**High**	**Moderate**

resource availability, established industrial infrastructure, and mature recycling system reduce its overall risk. Nevertheless, the geographic maps indicate meaningful concentration in alumina refining and primary aluminum production.

Sulfur received an overall score of 1.80 and was classified as moderate risk. Its geographic production is comparatively distributed, but by-product dependence increases its supply-chain exposure.

Molybdenum received the highest overall score of 2.35, placing it in the high-risk category. Its score reflects the combined effects of production concentration, by-product dependence, and geopolitical exposure.

Within the materials assessed, molybdenum therefore emerges as the most significant potential raw-material bottleneck for the investigated Al–Mo_6S_8 battery.

4.9 Comparison with Lithium-Ion Battery Supply Chains

The material dependencies of the investigated Al–Mo_6S_8 system were compared qualitatively with NMC and LFP lithium-ion battery supply chains. The comparison is intended to identify differences in material dependency and supply-chain maturity rather than to compare electrochemical performance, environmental impact, or cost.

Factor	**Al - Mo_6S_8**	**NMC**	**LFP**
Anode	Aluminum	Graphite	Graphite
Cathode materials	Mo, S	Li, Ni, Co, Mn	Li, Fe, P
Main material concern	Molybdenum	Co, Ni, Li, graphite	Li, graphite
By-product dependence	Mo & S	Co	Lower
Manufacturing maturity	Very low	Very high	Very high
Supply-chain infrastructure	Developing / not established at scale	Established	Established
Recycling infrastructure	Not established	Commercial	Commercial

Table 3 Qualitative comparison of the Al–Mo_6S_8, NMC, and LFP battery supply chains.

NMC batteries rely on graphite anodes and cathode materials containing lithium, nickel, cobalt, and manganese. LFP batteries avoid nickel and cobalt in the cathode but retain dependence on lithium and graphite. Both chemistries are supported by established commercial cell-manufacturing supply chains and developing commercial recycling infrastructure.

The investigated Al–Mo_6S_8 system replaces these principal active electrode dependencies with aluminum at the negative electrode and molybdenum and sulfur in the positive electrode. This substitution therefore changes rather than eliminates material supply-chain exposure. In the present bottleneck assessment, molybdenum represents the most significant raw-material concern.

A further distinction is technological maturity. NMC and LFP batteries are commercially established and benefit from large-scale manufacturing infrastructure. In contrast, an equivalent industrial supply chain for Mo_6S_8 cathode production and Al–Mo_6S_8 battery manufacturing has not yet been established at comparable scale.

The comparison therefore illustrates that the potential supply-chain benefits of an alternative battery chemistry should be evaluated across the complete material system. Removing dependence on established battery materials can introduce new resource, processing, manufacturing, and recycling constraints elsewhere in the supply chain.

4.10 Data Gaps

One of the most significant results of the study is the identification of gaps in the quantitative material supply chain.

For aluminum, the main downstream uncertainty is the allocation of primary aluminum to battery-grade foil for the investigated technology. Upstream aluminum production is extensively documented, but a reliable global battery-specific allocation factor was not identified.

For molybdenum and sulfur, global production and geographic data are available, but no reliable allocation factors were identified describing the quantities directed specifically toward Mo_6S_8 production.

The largest data gap occurs at the Chevrel-phase stage. Academic literature provides information on Mo_6S_8 synthesis, structure, and electrochemical behavior, but reliable data were not identified for global commercial production volumes, industrial manufacturing yields, or established end-of-life recovery [1, 3].

Reliable quantitative data are therefore strongest for upstream commodities and become increasingly limited toward battery-specific processes. Rather than assigning speculative flows to these stages, the missing quantities were retained as explicit gaps in the MFA.

5 Discussion

The principal finding of this study is that the supply-chain implications of a rechargeable aluminum battery cannot be inferred from the abundance of aluminum alone. The investigated chemistry replaces several material dependencies associated with conventional lithium-ion batteries, but simultaneously introduces different constraints associated with molybdenum, sulfur, and the production of the Mo_6S_8 cathode.

Aluminum itself presents a comparatively favorable upstream supply profile. Bauxite resources are large, primary aluminum is produced at substantial global scale, and an established recycling industry provides a significant secondary material pathway [6, 7]. These characteristics contribute to the low overall aluminum risk score obtained in the preliminary bottleneck assessment.

However, the geographic analysis demonstrates that geological availability and industrial supply concentration are not equivalent. Bauxite extraction is distributed among several major

producers, whereas alumina refining and primary aluminum smelting are substantially more concentrated. The aluminum supply chain therefore becomes more geographically concentrated as material moves downstream. This supports treating production concentration as a meaningful supply-chain consideration even where the underlying raw material is abundant.

Molybdenum presents a different risk profile. Its production is more geographically concentrated and a significant portion is recovered alongside other mineral commodities [4, 6]. By-product dependence can reduce the responsiveness of supply because production decisions may be influenced by the economics and demand of the host commodity rather than molybdenum alone. When combined with geographic and geopolitical concentration, these characteristics make molybdenum the most significant raw-material concern identified in the present assessment.

Sulfur illustrates another form of supply dependence. Its production is geographically more distributed than molybdenum, but much of the modern sulfur supply is recovered during fossil-fuel processing. Consequently, sulfur availability is linked to activity in industries outside the battery supply chain. This dependence may become increasingly relevant as global energy systems move away from fossil fuels [5].

The comparison with NMC and LFP further demonstrates that material substitution should be interpreted as a redistribution of supply-chain dependencies rather than their complete removal. The Al–Mo_6S_8 chemistry avoids several principal active electrode materials used in conventional lithium-ion batteries, but it introduces molybdenum dependence and a substantially less mature cathode-manufacturing pathway.

Technological maturity also has an important effect on the ability to perform a quantitative MFA. Mature commodity industries such as aluminum generate extensive production, processing, and recycling statistics. In contrast, the literature on Mo_6S_8 primarily describes material synthesis and electrochemical behavior at research scale [1, 3]. Industrial production volumes, manufacturing yields, process losses, and recycling flows are not reported with comparable detail.

The inability to quantify the complete Mo_6S_8 pathway is therefore not only a methodological limitation but also an indication of the current development stage of the technology. If Al–Mo_6S_8 batteries progress toward commercialization, improved industrial data will be required to determine whether the raw-material and manufacturing constraints identified in this study remain significant at larger scale.

6 Limitations and Future Work

The main limitation of the present analysis is the availability of battery-specific industrial data. Upstream production of aluminum, molybdenum, and sulfur is relatively well documented, but data availability decreases substantially as the analysis moves toward the specific Al–Mo_6S_8 battery supply chain.

For aluminum, the main uncertainty is the allocation of primary aluminum to battery-grade foil for the investigated technology. A reliable global allocation factor could not be identified, and the downstream aluminum pathway in the MFA was therefore treated as a scenario rather than an estimate of current battery-sector consumption.

A larger data gap exists for the Mo_6S_8 cathode. Although global molybdenum and sulfur production can be quantified, reliable information describing the quantities allocated specifically to Mo_6S_8 production was not identified. Industrial-scale production volumes, manufacturing yields, process losses, and established recycling flows for Mo_6S_8 are also limited.

The weighted bottleneck assessment represents a preliminary screening framework rather than a comprehensive material-criticality assessment. Its results depend on the selected criteria, weights, and categorical scores. Future work could therefore include sensitivity analysis and

additional indicators such as trade dependence, market concentration, substitutability, and price volatility.

The first priority for extending the MFA should be obtaining more representative downstream data for battery-grade aluminum foil and industrial Chevrel-phase manufacturing. The recycling assessment should also be extended from aluminum to the complete battery system, including molybdenum recovery and treatment of other battery components.

A comparative life-cycle assessment could subsequently evaluate the environmental impacts of Al–Mo_6S_8 batteries relative to established lithium-ion chemistries such as NMC and LFP. A techno-economic assessment could similarly examine material costs, processing requirements, manufacturing costs, and scale-up economics. Both analyses would become considerably more meaningful once representative industrial-scale data for Chevrel-phase production are available.

7 Conclusion

This study assessed the material flows and supply-chain characteristics of a rechargeable aluminum battery using an aluminum anode and a Mo_6S_8 Chevrel-phase cathode. The analysis combined supply-chain mapping, material flow analysis, global production data, geographic concentration mapping, recycling assessment, and a preliminary weighted bottleneck analysis.

The aluminum pathway could be quantified in considerably greater detail than the cathode pathway because of its mature industrial supply chain and extensive statistical data. The analysis also demonstrated that geographic concentration changes along the aluminum value chain: bauxite extraction is distributed among several major producers, while alumina refining and primary aluminum smelting are substantially more concentrated.

The bottleneck assessment classified aluminum as low risk, sulfur as moderate risk, and molybdenum as high risk within the adopted screening framework. Molybdenum therefore emerged as the principal raw-material concern for the investigated chemistry. In addition, the limited availability of industrial-scale Mo_6S_8 production and recycling data represents an important technology-level constraint.

Overall, the study shows that shifting from conventional lithium-ion materials to an Al–Mo_6S_8 chemistry does not eliminate supply-chain constraints; it redistributes them. Aluminum itself appears comparatively favorable from a resource availability and recycling perspective, while molybdenum supply and the maturity of Chevrel-phase manufacturing become more important potential constraints. Future evaluation of the technology should therefore consider the complete battery material system rather than aluminum availability alone.

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