BMAC Battery Metals Association of Canada

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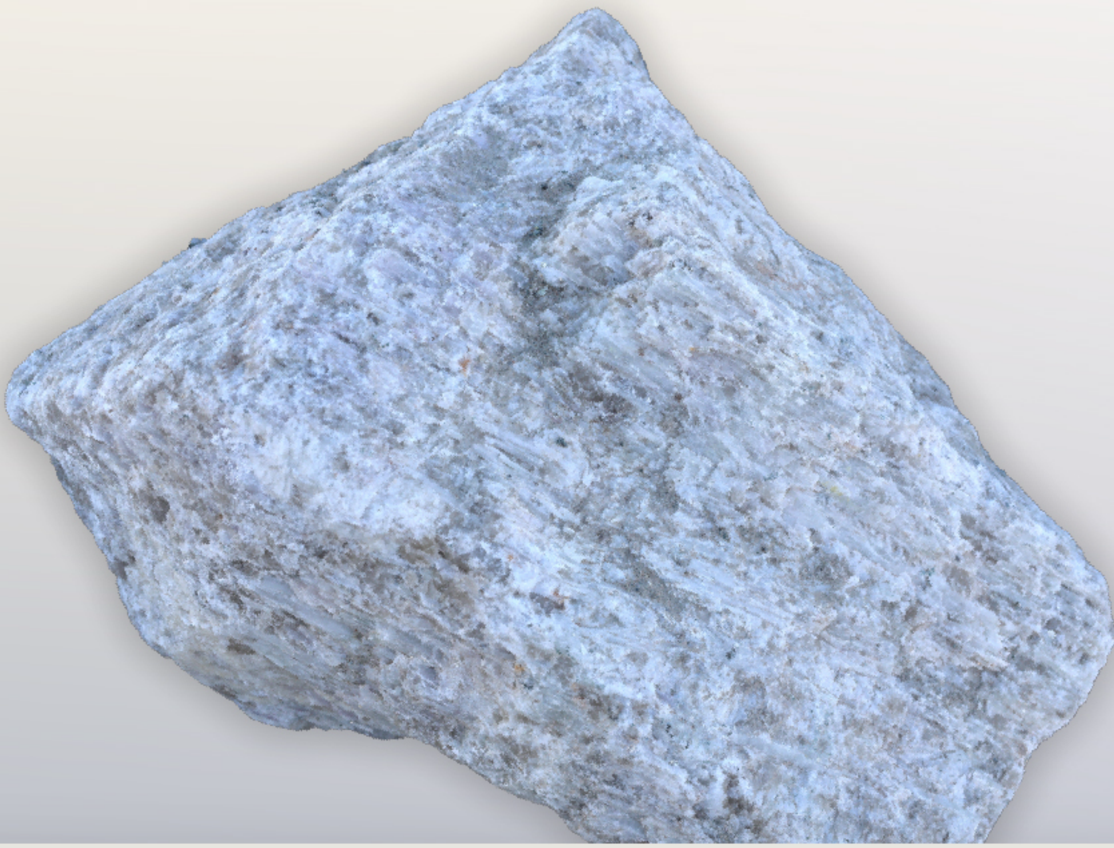
FOCUS ON

LITHIUM



FROM

ROCKS

TO

POWER

Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, & Beyond

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From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond

Focus on Lithium

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About Us

BMAC | Battery Metals Association of Canada

The Battery Metals Association of Canada (BMAC) is a national non-profit association of industry participants and champions from across all segments of the battery metals value chain. From mining to specialty chemical refining, manufacturing, end use and recycling, BMAC is focused on coordinating and connecting the segments of this value chain, ensuring Canada captures the economic potential of the sector and is able to attain its electrification targets. Together, our members collaborate to accelerate the development of the battery metals ecosystem in Canada.

The Transition Accelerator | L'Accélérateur de transition

The Transition Accelerator drives projects, partnerships, and strategies to ensure Canada is competitive in a carbon-neutral world. We're harnessing the global shift towards clean growth to secure permanent jobs, abundant energy, and strong regional economies across the country. We work with 300+ partner organizations to build out pathways to a prosperous low-carbon economy and avoid costly dead-ends along the way. By connecting systems-level thinking with real-world analysis, we're enabling a more affordable, competitive, and resilient future for all Canadians.

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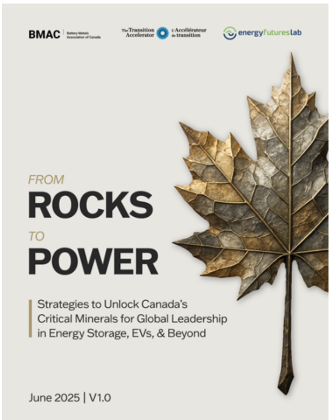
The Energy Futures Lab is an award-winning, Alberta-based not-for-profit that brings together a diverse network of innovators, influencers, and system actors from across Canada's energy landscape. Established in 2015, the Lab was created to address growing polarization around Canada's energy transition and respond to its most pressing challenges.

Through trusted leadership and creating non-partisan spaces for collaboration, the Lab convenes stakeholders and Rights and Title Holders to generate and test innovative, enduring solutions to complex, system-level issues. By empowering communities and change-makers to work across divides, the Lab fosters the conditions for meaningful progress toward a shared vision of a resilient and sustainable energy future.

About This Report



This chapter is part of a larger report, *From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond*. The full report identifies clear, investable priorities in eight minerals, each of them critical to building resilient EV and energy storage value chains. By looking at specific opportunities and providing detailed justifications for its recommendations, *From Rocks to Power* offers a way out of our perpetual planning cycle and towards a new momentum for Canada's critical minerals sector—and our future economic prosperity.

Read the full report here »

Additional chapters are available for download below:

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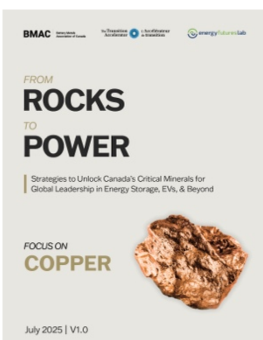

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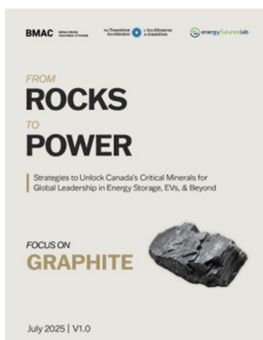

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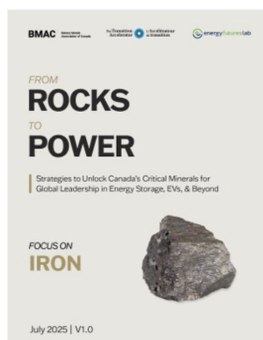

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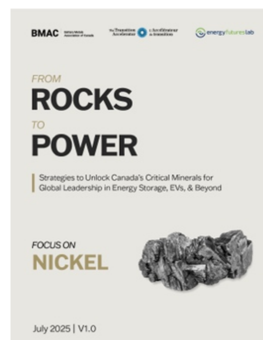

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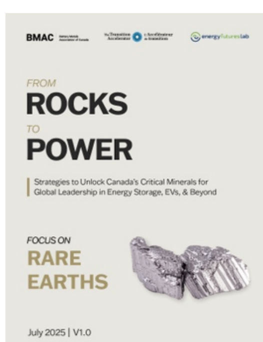
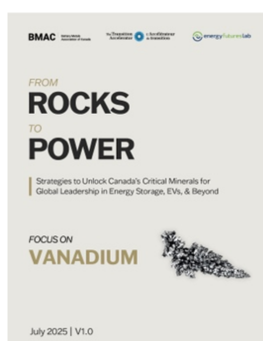


Vanadium »



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Lithium

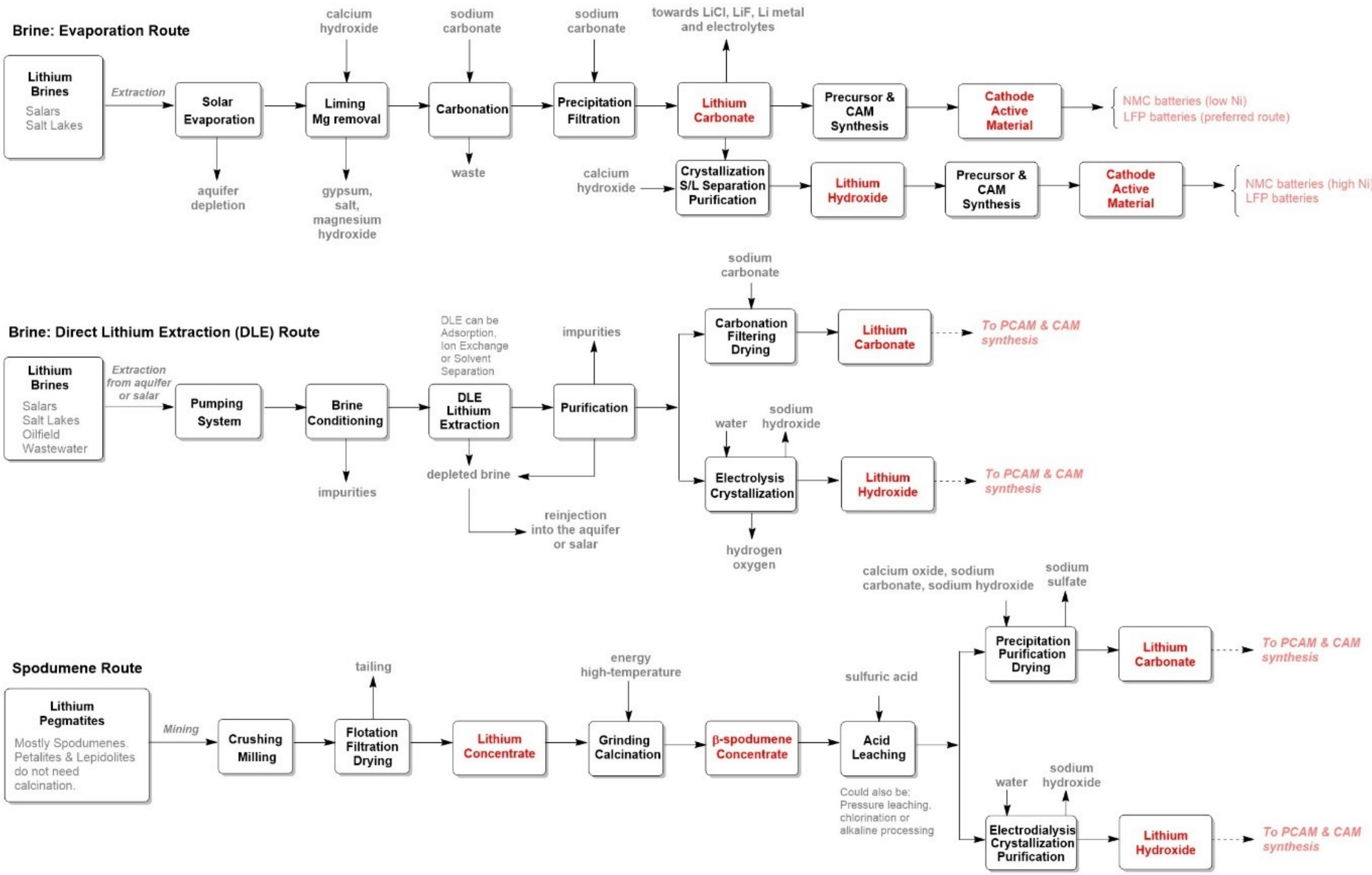


Figure 1 Simplified Lithium Flowsheet: Brine evaporation, DLE and spodumene routes

1 The Canadian Strategy for Lithium

1.1 Lithium in Canada

Table 1 Non-exhaustive selection of operational and future lithium extraction and processing projects in Canada

Operational Lithium Extraction Sites				
Project Name	**Company**	**Province**	**Type**	**Status**
North American Lithium	Sayona + Piedmont	QC	Spodumene	Operational
Tanco	Sinomine	MB	Tantalum, Cesium, Spodumene	Operational
Selection of Future Lithium Extraction Projects				
Project Name	**Company**	**Province**	**Type**	**Status**
Boardwalk*	LithiumBank	AB	Brine	PEA 2024
Clearwater*	E3 Lithium	AB	Brine	PFS 2024
Prairie Lithium*	Arizona Lithium	SK	Brine	PFS 2023
Yellowknife	Li-FT	NWT	Spodumene	MRE 2024
Snow Lake	Snow Lake Lithium	MB	Spodumene	PEA 2023
PAK	Frontier Lithium + Mitsubishi	ON	Spodumene	PFS 2023
Separation Rapids	SCR Sibelco NV + Avalon	ON	Petalite, Lepidolite	PEA 2018
Georgia Lake	RockTech	ON	Spodumene	PFS 2022
Seymour Lake	Green Technology Metals	ON	Spodumene	PEA 2023
James Bay	Rio Tinto (Arcadium)	QC	Spodumene	FS 2021
Rose Lithium-Tantalum Project	Critical Elements Lithium Corp	QC	Spodumene	FS 2023
Whabouchi	Rio Tinto (Nemaska) + Investissement QC	QC	Spodumene	PFS 2023
Moblan	Sayona + Investissement Quebec	QC	Spodumene	DFS 2024
*Note: most DLE brine projects are coupled with processing steps to lithium carbonate or hydroxide				
Selection of Future Lithium Refining Projects				
Project Name	**Company**	**Province**	**Type**	**Start**
Sayona Converter	Sayona + Piedmont	QC	Li_2CO_3	2026
Bécancour Converter	Rio Tinto (Nemaska) + Investissement QC	QC	LiOH	2026
Red Rock Converter	RockTech	ON	LiOH	2026
Thunder Bay Converter	Avalon Advanced Materials	ON	LiOH + Li_2CO_3	2026
Thunder Bay Converter	Green Technology Metals	ON	LiOH	2026
Frontier Lithium Converter	Frontier Lithium + Mitsubishi	ON	LiOH + Li_2CO_3	2026

Canada ranks 6th in lithium reserves and 8th in resources globally, but despite being the 7th producer worldwide, its production is still relatively low, representing only 0.4% of global output in 2022.[1,2] The resources are non-conventional brines, such as oilfield brines, industrial wastewaters in Alberta and Saskatchewan, and spodumenes in Manitoba, Ontario, and Quebec.

Around 36 major lithium extraction projects are in Canada, and only two are currently operational and producing lithium concentrates from spodumene.

The Tanco Mine in Manitoba, a Chinese-owned operation by Sinomine, specializes in tantalum and cesium extraction. However, small spodumenes have been mined and concentrated since 2021 before being sent to China.[3,4] Additionally, several early-stage pegmatite mining projects are being developed in Manitoba, notably by Grid Metals Corp. for Donner Lake and Falcon West,[5] and around Snow Lake by Snow Lake Lithium and Foremost Lithium.[6,7]

The North American Lithium Mine in QC, a pegmatite mine that previously specialized in spodumene concentrate for Chinese refineries, opened in 2018 and went bankrupt one year later. The new Joint Venture ownership, comprising Sayona Mining (Australia) and Piedmont Lithium (U.S.), has restarted the mine. It produced the first tonnes of spodumene concentrate in March 2023.[8] So far, it is the only hard rock mine focusing exclusively on lithium in Canada. The joint venture is also planning two mines in the same region, Authier and Tansim, to form a lithium hub in Abitibi-Témiscamingue. A second hub is projected at Eeyou Istchee James Bay, with the Moblan and Lac-Albert projects. Plans to develop a lithium hydroxide/lithium carbonate refinery in Quebec are also underway.[9] Neighbouring spodumene projects in Northern Quebec, such as **James Bay Lithium**, owned by Allkem (AU),[10,11] or the **Rose lithium-tantalum** project, owned by Critical Elements (CA), are also in motion.[12,13]

The Whabouchi Mine in Quebec, run by Nemaska Lithium, produced spodumene concentrate from 2017–19. After maintenance and bankruptcy, it has found new ownership by the Livent (briefly Arcadium Lithium, and now Rio Tinto) and the government of Quebec, which plan to restart the mine and build a lithium hydroxide processing plant in Bécancour, Quebec.[14,15] Nemaska Lithium and Livent have agreed to supply Ford with LiOH for its EV batteries for 11 years.[16]

The company**, E3 Lithium in Alberta,** has been running an advanced project in the Clearwater Area to pump lithium from oilfield brine pools through a proprietary ion-exchange DLE technique and process it further to LiOH. Similarly, **LithiumBank** is developing several DLE projects in Alberta and Saskatchewan and projects to refine it to LiOH as well. Using a licensed DLE technology from Go2Lithium, they recently opened a DLE pilot plant in Calgary.[17] Other projects include Neolithica or Highwood Oil. DLE could be a fast and clean method to obtain lithium, but Smart Prosperity and the CPAWS warn about such projects' uncertain upstream environmental costs.[18,19]

Natural Resources Canada recently invested around $9 million in **Saltworks Technologies Inc.** and **NORAM Electrolysis Systems Inc.** (NESI), two companies developing midstream solutions for lithium processing.[20] The first one is designing systems to refine DLE-extracted LiCl from brine sources or Li_2SO_4 from spodumene sources into either Li_2CO_3 or LiOH,[21] while the latter specializes in developing electrochemical processes and electrolyzers for refining LiCl to LiOH.[22]

Northwestern Ontario has attracted several hard-rock lithium mining projects,[23] and a LiOH processing plant in Thunder Bay, ON, is planned by Avalon Advanced Materials.[24] The Critical Minerals Infrastructure Fund (CMIF) announced in October 2024 a $13.8 million funding for critical minerals development in Northern Ontario. This investment would notably support road and bridge upgrades for Green TM Resources Canada's Armstrong lithium mine, road access for Rock Tech Lithium's Georgia Lake lithium mine, Indigenous Engagement, and road and electricity infrastructure for Frontier Lithium's Pakeagama Lithium mine.[25]

In February and March 2025, several rounds of federal funding announcements by the CMIF were released to support various lithium projects across Canada. The Moblan, Rose Lithium Tantalum, and the Renard Mine were beneficiary projects in Québec, while E3 Lithium's Clearwater Project received additional funds in Alberta. The Fort Alexander Indian Band, operating as Sagkeeng First Nation, also received a CMIF -Indigenous Grant to support community engagement sessions related to the Donner Lithium mining project in Manitoba.

1.2 Target

Our 2022 report, 'Roadmap for Canada's Battery Value Chain,' established the following objectives for lithium. Due to the competitive landscape in North America and the multiplication of lithium projects worldwide, Canada should aim for 10% of the North American EV market as a baseline, possibly increasing to 12.5% as a stretch goal.

The original report planned on 25 ktpa of lithium carbonate equivalent (LCE) per DLE project, but the more conservative 15 ktpa assumption has been updated. Spodumene mining projects can have a more sizeable capacity, with the example of operating North American Lithium mine having the nameplate capacity to produce up to 30 ktpa of LCE. James Bay or Whabouchi have a significantly higher capacity.

Table 2 Lithium Targets

Lithium Mandated Benchmark (10% of 2030 North American Market)		
	2030	**2040**
Lithium (ktpa LCE)	57	114
Projects needed (DLE)	4	8

1.3 Scenario Outline

Canada has the potential to develop domestic capacity in Direct Lithium Extraction (DLE) in Alberta and Saskatchewan while also providing local spodumene feed for cathode manufacturing in Ontario and Québec. This strategic move will bolster the country's position in the global lithium market and enhance its domestic supply chain for lithium-ion batteries.

- In Saskatchewan and Alberta, developing lithium brine DLE projects should be the priority. This approach involves integrating these extraction projects with a chemical processing and DLE research hub to foster innovation, scaling and efficiency. Establishing a Cathode Active Material (CAM) and Precursor Cathode Active Material (pCAM) plant in the west, such as Alberta or British Columbia, will further strengthen the local supply chain and add value. By aligning these initiatives with a clean energy strategy, Canada can ensure that the extraction and processing methods are environmentally sustainable.

- In Québec and Ontario, ramping up spodumene extraction is crucial due to the regions' rich spodumene deposits, the many existing projects, and the benefits of clean energy grids. Strengthening the projected Bécancour lithium hydroxide processing and pCAM/CAM production hub in Québec will enhance its capacity to transform spodumene concentrates into battery cathodes. Integrating this processing hub with a spodumene processing research centre will drive technological advancements, making extraction and processing methods more efficient and sustainable.

1.4 Signature Projects

- Develop direct lithium extraction (DLE) operations and lithium brine processing projects in the West, especially in Saskatchewan and Alberta
- Strengthen the existing and projected spodumene mining and lithium processing projects in Québec and Ontario
- Establish a DLE research hub in the West to facilitate the scaling up and deployment of this technology, similar to the Alberta Oil Sands Technology and Research Authority (AOSTRA) model.
- Similarly, a spodumene processing research hub in Québec should be developed.
- Build a pCAM/CAM processing hub in the West and strengthen the projected one in Québec.

1.5 Strategic Priorities

- **Chemical Processing Pathways & pCAM/CAM Plant Hubs:**
    - **Identifying suitable chemical intermediates,** such as LiOH or Li_2CO_3, is critical in lithium-ion battery production. The choice between these two will depend on the specific battery technology used. Therefore, off-takers, battery manufacturers, and OEMs must clearly define their preferences and requirements for these intermediates. This will ensure the optimal compatibility and performance of the batteries.
    - **A source-dependant chemical intermediate:** Depending on the chosen chemical processing methods, spodumene is typically more suited for conversion into lithium hydroxide (LiOH). At the same time, brine sources are generally more appropriate for producing lithium carbonate (Li_2CO_3). This distinction is essential for optimizing the extraction and processing routes for different types of lithium resources.
    - **A hub-and-spoke system:** The lithium industry could significantly benefit from adopting a hub-and-spoke system for the later stages of chemical processing,

such as precursor cathode active material (pCAM) and cathode active material (CAM) manufacturing. This system allows for centralized processing facilities (hubs) that receive raw materials from various smaller extraction sites (spokes), enhancing efficiency and reducing costs.

  - **Strengthen existing processing hub projects:** The Bécancour/Vallée de la Transition Énergétique initiative in Quebec serves as an exemplary model for such a hub-and-spoke system in the lithium industry. Strengthening this initiative in Eastern Canada while developing similar hubs in Western Canada, such as Alberta, could provide balanced and widespread processing capabilities across the country.
  - **Strategic location:** It is essential to consider the strategic location of pCAM and CAM plant hubs near battery manufacturing facilities. This proximity ensures that the processed lithium intermediates can be quickly and efficiently converted into final battery products, minimizing transportation costs and time delays.
  - **Process optimization:** Optimizing the input of water, chemicals, heat, and reagents is crucial for efficiently operating these midstream processing plants. Careful planning and resource management can lead to significant cost savings and environmental benefits.
  - **Mutualize DLE processing?** An alternative strategy could involve centralizing lithium processing from various Direct Lithium Extraction (DLE) operations by cutting off the in-site flow earlier.
    - For instance, producing lithium chloride (LiCl) concentrates on-site before transporting them to a centralized hub for further processing could be a viable option.
    - This approach would require exploring the technical pathways and determining the most effective points at which to cut off in-site DLE processes. However, this might present challenges regarding recycling heat and water and managing waste efficiently.
- **Clean Energy Strategy:**
  - **A clean energy strategy for critical minerals operations:** Canada urgently needs to develop a comprehensive clean energy strategy for producing lithium and other critical minerals. This strategy should focus on reducing the carbon footprint of extraction and processing activities, promoting electrification and sustainable practices, and ensuring long-term energy security.
  - **Collaboration and partnerships:** There are numerous opportunities to synergize with other industries to decarbonize the energy grid broadly. Establishing interprovincial partnerships can facilitate sharing resources and technologies, enhancing the overall effectiveness of clean energy initiatives.
  - **Utilize CCUS for fossil fuel-driven operations:** The deployment of Carbon Capture, Utilization, and Storage (CCUS) technologies should be prioritized,

especially if natural gas is used in the production processes. This can significantly reduce greenhouse gas emissions and make the industry more sustainable.
    - **Alberta's deregulated grid:** Alberta holds a distinct advantage due to its deregulated grid, which can provide more flexible and cost-effective energy solutions for lithium production and other critical mineral projects.
    - **A balanced approach:** While advancing a clean energy strategy is essential, ensuring that this effort does not delay the development and implementation of critical mineral projects is also important. Balancing environmental goals with industry needs is vital to maintaining momentum in the sector.
- **Developing Synergies:**
    - Valuing chemical waste and byproducts from the lithium industry can lower operational costs and strengthen synergies with other industries. For instance, finding secondary uses for these byproducts can create additional revenue streams and reduce waste.
    - **Value sulfur byproducts:** Sour brine aquifers, which contain hydrogen sulfide (H_2S), can produce sulfuric acid (H_2SO_4), a valuable chemical for various industrial applications. Consolidating such initiatives in regions like Alberta can enhance the economic viability of lithium extraction while providing essential chemicals for other industries.
    - **Reusing captured carbon for lithium processing steps:** Implementing Carbon Capture Utilization (CCU) technologies can further enhance the sustainability of DLE processes. For example, if natural gas is used in DLE operations, capturing and converting the resulting CO_2 into soda ash (Na_2CO_3) can facilitate the production of lithium carbonate (Li_2CO_3) later in the process.
    - **Water and heat management:** Finding value-added applications for fresh water and waste heat is an overarching challenge that needs to be addressed. Efficiently managing these resources can significantly improve the sustainability and profitability of lithium extraction and processing operations.
    - **Intersectoral approach:** Developing a complementary approach with other sectors, such as oil and gas, agriculture, and petrochemicals, can create cross-industry opportunities. Rather than competing for resources, industries can collaborate to maximize the benefits and efficiencies of their operations.

- **Research & Development:**
    - **A national lithium R&D strategy:** Incorporating lithium firms into a national Research and Development (R&D) strategy is essential for maintaining long-term industry competitiveness. This includes fostering innovation and developing new technologies to improve extraction and processing methods.
    - **Water optimization:** Recycling water is critical to sustainable lithium production. Efforts should focus on minimizing makeup water usage, optimizing

water treatment technologies, and maximizing water reuse to reduce environmental impact.
    - **DLE research hub:** Direct Lithium Extraction (DLE) presents a significant opportunity to establish a demonstration fund similar to the Alberta Oil Sands Technology and Research Authority (AOSTRA) model. This could involve setting up a central DLE research centre to foster innovation and development in this field and strengthen the processing technologies for lithium brine resources.
    - **Spodumene treatment research hub:** Establishing a spodumene research hub in Québec and a brine-focused research centre in Alberta can provide balanced research capabilities across different types of lithium resources. This can drive advancements in extraction and processing techniques tailored to each resource type.
    - **Public-private partnerships:** Boosting public-private partnerships is crucial for scaling up DLE processes and integrating them into mainstream production. Collaborative efforts can accelerate the development and commercialization of new technologies.
- **Material Standards:**
    - **Battery-grade lithium standards:** Harmonizing the lithium supply chain for electric vehicle (EV) batteries requires issuing standards and specifications for battery-grade lithium intermediates. Coordination with standards organizations, such as the Canadian Standards Association (CSA) and the Standards Council of Canada (SCC), as well as price reporting agencies, OEMs, and battery manufacturers, can ensure consistency and quality.
    - **Build on existing international initiatives:** By leveraging existing initiatives, such as the ISO/TC 333 lithium committee of the SCC or the Battery Passport project from the Global Battery Alliance (GBA), a solid framework can be established for these standards.
    - **Leverage Canada's ESG strength:** Incorporating Environmental, Social, and Governance (ESG) performance standards into the material specifications can highlight the value of Canadian lithium producers, emphasizing their commitment to sustainable and responsible practices.

    - **The right ESG metrics:** Water usage and recycling metrics should be included in the ESG performance standards. This can drive improvements in resource management and environmental stewardship within the lithium industry.
- **Regulatory Certainty:**
    - **A distinct regulation for DLE operations:** Developing a brine-specific type of regulation is necessary, as the existing NI 43-101 standards are not well-suited to the unique characteristics and timelines of brine projects. While a complete overhaul of these standards is not required, targeted adjustments can provide the necessary framework.

    - **A methodological standard:** Standardizing NI 43-101 procedures and methodologies for lithium projects can offer clear guidelines for companies, reducing uncertainty and ensuring consistency across the industry.
    - **Addressing provincial regulation gaps:** It is crucial to ensure a comprehensive regulatory framework exists in all provinces, including British Columbia. Addressing gaps in provincial regulations can align standards and practices across the country, fostering a more cohesive industry environment.
    - **Favour brownfield projects:** Accelerating timelines for brownfield projects can favour the development of DLE operations. Streamlining regulatory processes for these sites can reduce delays and facilitate faster project implementation.
- **Protection from Price Volatility and Secure Off-Taker:**
    - **Price stability:** Facilitating stability and certainty in the lithium market through government procurement contracts, contracts for differences, government-guaranteed future purchases of locally sourced critical minerals, or buffer stock mechanisms can provide a safety net for producers. These measures can help mitigate the risks associated with price volatility.
    - **Maintain competitiveness:** It is essential to ensure that price contracts or protection mechanisms do not significantly increase the cost of lithium products. Balancing cost management with market stability is vital to maintaining competitiveness.
    - **Coordination with the United States:** There is an opportunity to coordinate with the United States to enforce these mechanisms. Cross-border collaboration can enhance market stability and provide a unified approach to managing price volatility in the North American lithium market.

2 Lithium: A Universal Charge Carrier Needed for Lithium-Ion Battery Cathodes, Electrolytes and Beyond

2.1 General Properties

Lithium is a silvery-white alkali metal, notable for being the lightest and having the lowest density among metals. While it reacts similarly to sodium, it is less reactive with oxygen and water but still highly flammable, necessitating storage in mineral oil to prevent reactions with air, including nitrogen.[26] Lithium doesn't exist in elemental form; it is primarily sourced from pegmatite rocks with lithium silicates or brines containing lithium chloride.[27] As for its electrochemical properties, it has excellent electrical conductivity and elemental lithium Li and its cation Li^+ form a couple with one of the strongest reduction potentials ($E° = -3.040$ V), meaning that elemental lithium has a strong tendency to lose one electron to become a positive ion Li^+.[28] This phenomenon can be reversible, and because lithium has a low molar mass/density and is easily extracted, it became an element of choice for energy storage.[29,30] Beyond batteries, lithium compounds are used in glass and ceramics, lubricating greases, soaps, continuous casting, cement, pharmaceuticals, polymers, air treatment, and nuclear applications. Lithium is classified as a critical mineral by several countries and international organizations,[31–39] and the U.S. Department of Energy anticipates its status to remain critical from 2025 to 2035.[40]

Figure 2 Examples of applications for lithium materials

Lithium was discovered in Sweden by José Bonifácio de Andrada e Silva and recognized as a new element in 1817 by Johan August Arfvedson and Berzelius. Initially used in alloys during World War I, such as for Scleron and Bahnmetall, industrial production began in Germany in 1923, and the U.S. in 1929.[41] During World War II, lithium hydride was used to generate hydrogen for rescue balloons, as well as for aircraft equipment. Lithium's use then expanded into industrial lubricants as lithium stearates have all-purpose temperature-resistant grease quality, and lithium salts were used as bipolar disorder treatment as early as 1949. As the U.S.

atomic and nuclear programme developed in the 1950s, so did the demand for lithium, as it can be used as shielding material, a cooling medium, a molten salt solvent or even as a material for thermonuclear weapons.[41–43] Many operations were discontinued in the 1960s – Quebec briefly produced lithium carbonate between 1960 and 1964, but new applications for lithium as an additive for glass, ceramics, and alloy metal subsequently increased. Production is now growing and concentrated in Australia, Chile, China and Argentina after the booming demand following the lithium-ion battery revolution. Lithium refining is mainly processed in China and Chile.

Plants readily absorb lithium, but it is not a nutrient and has variable tolerance in different species. Lithium is also present in trace amounts in most vertebrates, including 2 mg on average in humans.[42] As previously stated, lithium salts can be used as mood stabilizers due to their similarity to sodium ions, with a safe dosage for bipolar disorder treatment being 150–500 mg of lithium carbonate per day. However, lithium can cause mild poisoning at 10 mg/L and be lethal at 20 mg/L, and it has been linked to altered thyroid function and reproductive hazards.[41] Lithium oxides, hydroxide and carbonate are harmful caustic bases, and lithium hydroxide can cause caustic burns.[43] The French Agency for Food, Environmental and Occupational Health and Safety has proposed that lithium carbonate, chloride, and hydroxide be classified as hazardous to fertility and fetal development in 2019.[44,45] Lithium hydride LiH is especially hazardous because of its reactivity and the release of large volumes of hydrogen. Due to their extreme reactivity, organolithium compounds and lithium metal are prone to spontaneous ignition and need special handling. Finally, lithium hexafluorophosphate $LiPF_6$, a significant electrolyte used for lithium batteries used in batteries, can release toxic hydrofluoric acid HF and POF_3 upon contact with water.

2.2 Role in Energy Storage

Contrarily to copper or nickel, crucial across a wide range of low-carbon technologies, lithium's primary use in clean technology is for energy storage and batteries. Lithium is used across all Li-ion technologies, regardless of the cathode composition, thus including the most popular technologies, such as NMC or LFP. Lithium can be found in two parts of the cell during fabrication: As part of the cathode active material ($LiMO_2$, with M = Ni, Mn or Co for NMC; or $LiFePO_4$ for LFP) and inside the electrolyte (usually as $LiPF_6$, $LiBF_4$, $LiAsF_6$ or $LiClO_4$ salts dissolved in an organic solvent such as ethylene carbonate, dimethyl carbonate and diethyl carbonate).

The role of lithium is to store energy by converting electrical current into chemical energy when the battery is charged and to release that energy by converting chemical energy back to an electrical current when the battery is discharged during utilization. During the charge, the cathode active material is oxidized and releases lithium ions Li^+ through the electrolyte. After passing through the separating membrane, those ions get stored between the graphite sheets of the anode by insertion and combine with the electrons of the charging current to form LiC_6. During the discharge, *i.e.* when the battery produces electricity, the LiC_6 material at the anode will naturally release lithium ions and electrons. The ions will return to the cathode to form the original cathode active material. At the same time, the electrons can be used as a source of electricity to power an external circuit, such as a motor.[46]

Lithium ions are used as charge carriers, able to store and carry the energy of the current. Lithium excels at this, as it has a significant negative redox potential and has low molar and volumic mass, thus providing a high energy density and voltage.[47] The excellent reversibility of the lithium insertion is linked to a longer cycle life, which depends on specifically designed cathode and anode materials. The IEA estimates that there is, on average, 8.9 kg of lithium/electric vehicle.[48]

2.3 A Brief History of the Development of Lithium-Ion Batteries

Historically, while secondary (rechargeable) battery technologies were dominated by technologies such as lead-acid, nickel-cadmium or nickel–metal hydride, Stanley Whittingham, an Exxon employee, developed a new battery type in 1977 with lithium metal as an anode, a mixture of organic solvent and lithium salt $LiPF_6$ as an electrolyte and finally, titanium sulfide TiS_2 as a cathode. This new technology instantly doubled the specific energy of rechargeable batteries. However, several safety problems reoccurred, notably battery explosions due to the formation of lithium dendrites, which created a problematic short circuit.[49]

Several improvements, such as John Goodenough's replacement of TiS_2 by cobalt dioxide CoO_2 for the cathode in 1979 and the use of carbon (petroleum coke) as an anode, as Akira Yoshino found in 1985, gave rise to the safer lithium-ion technology. Commercialized by Sony in 1991, the first Li-ion rechargeable battery used lithium in the cathode, this time, with lithium cobalt oxide $LiCoO_2$ as the active material, while the anode used coke, and the electrolyte was a mixture of propylene carbonate and $LiPF_6$. This first li-ion battery is designated as lithium cobalt oxide LCO. Continuous advances in this battery type marked the following decades by improving electrolytes and optimizing electrode formulation and chemistry.

The Li-ion battery family now includes different types of cathodes: NMC (lithium nickel manganese cobalt oxide), NCA (lithium nickel cobalt aluminum oxide), NCMA (Lithium nickel cobalt manganese aluminum oxide), LMO (lithium manganese oxide), LFP (lithium iron phosphate), as well as different types of anodes such as graphite, hard carbon, tin/cobalt, LTO (lithium titanate) and silicon/carbon. Whittingham, Yoshino and Goodenough shared the 2019 Nobel Prize in Chemistry for their groundbreaking contributions.

2.4 Substitutes

For ceramics and glasses, sodium and potassium fluxes can be used at the cost of lower performance. Sodium can also replace lithium for primary aluminum production and continuous casting, and boron, glass, and polymer fibres can substitute aluminum–lithium alloys. Other aluminum, calcium, and polyurea formulations can be used instead of lithium for greases.[50] While some promising advancements in the battery field, such as solid-state batteries, still rely on lithium,[51] finding substitutes means using a completely different charge carrier. Previously widespread lead-acid and nickel-based batteries such as nickel-cadmium or nickel–metal hydride can substitute lithium batteries, but performances would significantly suffer. Future chemistries such as sodium-ion batteries will potentially be able to mitigate the demand for lithium for light vehicles or bulkier iron-air batteries for energy storage systems coupled with renewable power sources.[40,52]

2.5 Supply and Demand

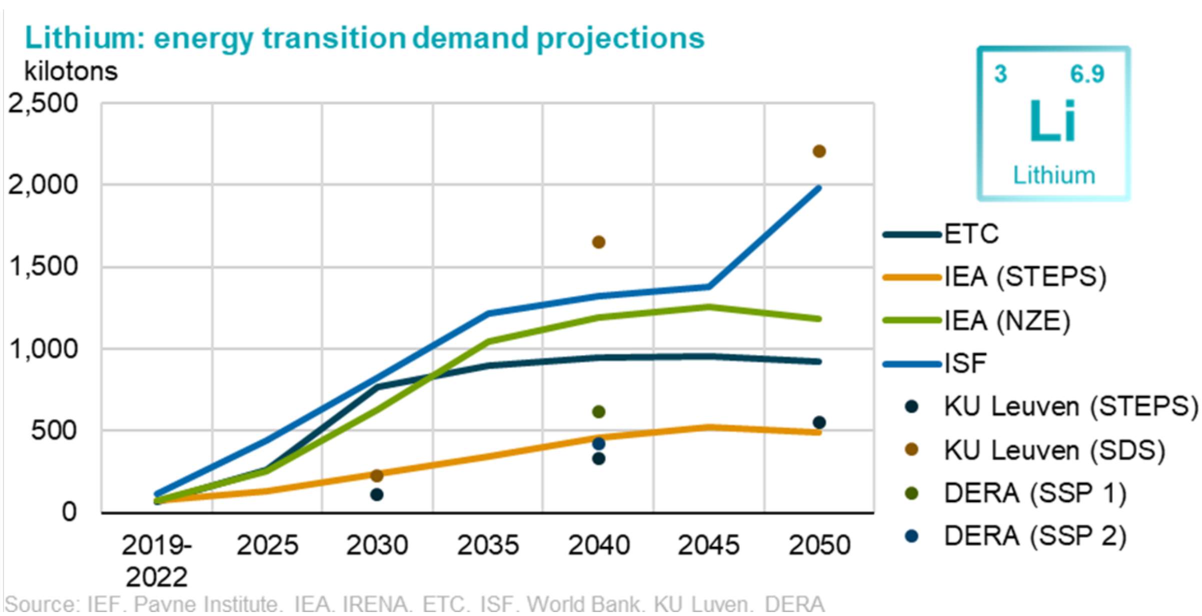


Figure 3 Lithium demand projections to 2050 according to various energy transition scenarios[53]

The 2022 refined lithium demand accounted for 0.72 million tonnes of lithium carbonate equivalent (LCE), and McKinsey calculated it will reach 3.06 million tonnes of LCE by 2030, while another optimistic electric-vehicle adoption scenario led by the same consulting company estimated that it could reach 3.8 million tonnes of LCE in 2030.[54,55] McKinsey, Benchmark Mineral Intelligence, UBS and the Energy Transition Commission agreed that a supply gap is highly probable if potential production capacity is not fully developed in the coming years.[52,55–57] Batteries mainly drive this growing demand, as they might represent 95% of lithium demand in 2030, compared to 74% in 2021 and only 59% in 2017.[1,26] Indeed, the whole lithium economy is booming. The 2022 market size of lithium has already increased 6.7 times its 2017 value, while demand has tripled.[58] Meanwhile, lithium prices have become highly volatile. They first saw a dramatic increase in 2020–22 before undergoing a collapse in 2023: Between January and April 2023, lithium carbonate prices in China dropped by over 60%, whereas those in Europe decreased by 20%. This was primarily due to destocking across the battery supply chain and the emergence of new mining projects, which lowered short-term demand for lithium.[58] Lithium exploration also saw a 90% spending increase in 2022, strongly driven by Canada and Australia.[58] The average observed lead time for lithium mining projects is relatively short compared to other critical minerals, taking only four years in Australia and seven years in South America.

3 The Lithium Flowsheet: Salt Brines or Hard-Rock Spodumenes?

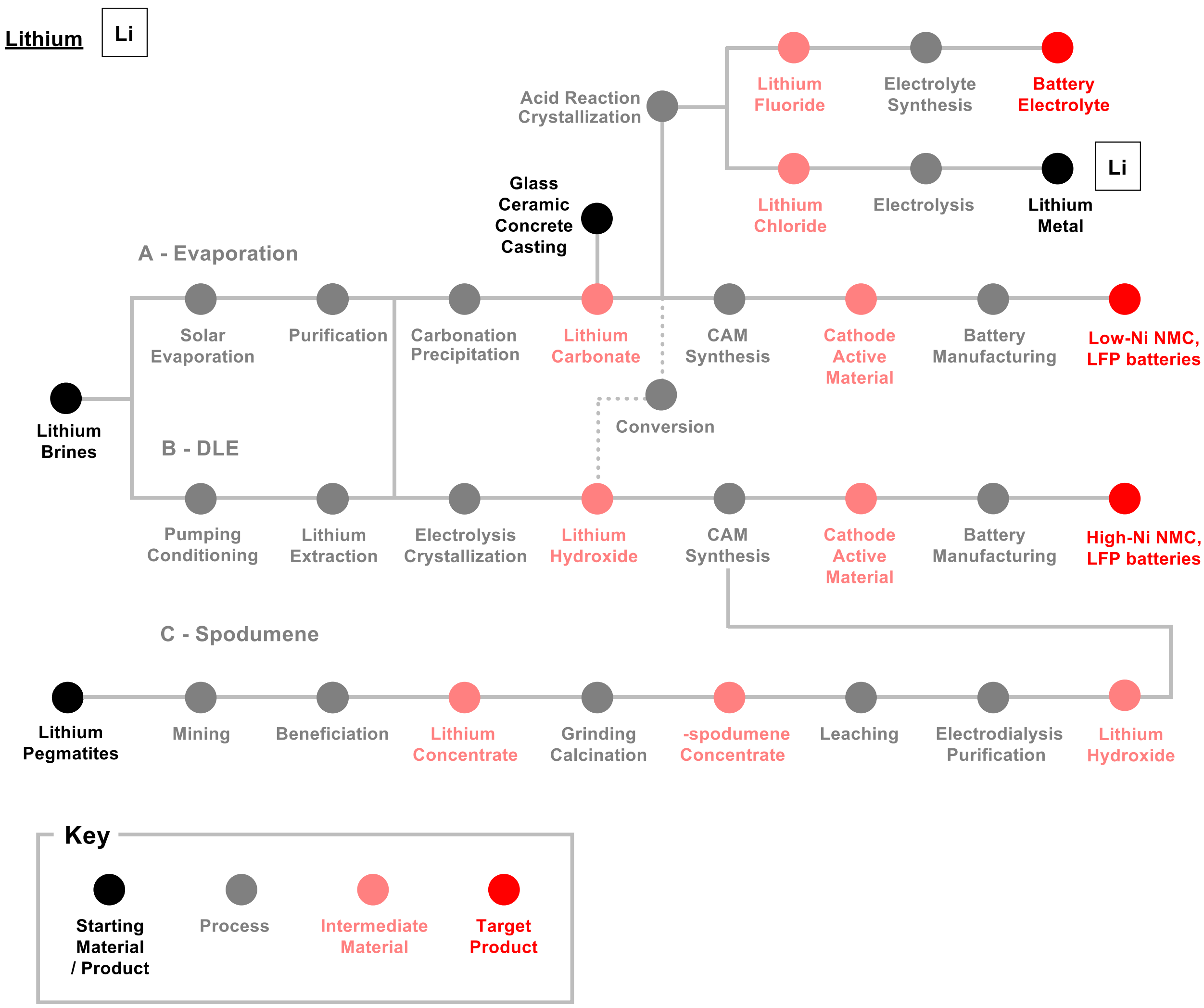


Figure 4 Simplified flowsheet of the lithium value chain

3.1 Lithium Ores, Production and Reserves

3.1.1 Type of Lithium Resources and Availability

Lithium is ranked as the 32–33rd most abundant element in Earth's crust, with a mean content of approximately 20 ppm (g/tonne).[42] This makes lithium a relatively widely distributed resource compared with lead (16 ppm in Earth's crust) or zinc (1 ppm).[43] Seawater also contains lithium, with an average concentration of 0.18 ppm,[50] but exploitation of such resources could be challenging. As such, lithium is not considered to be scarce, but concerns rely more on how the supply could meet the future demand driven by the EV market and how fast production capacity can expand.[59–62]

Exploitable lithium resources are classified into **hard-rock ores** and **brine pools**. Lithium is also present in a third minor category in the form of volcano-sedimentary deposits as hectorite $Na_{0.33}(Mg,Li)_3Si_4O_{10}(F,OH)_2$ in **clays**, but no commercial operation is yet active. Plans to develop mining of clay stones are underway in Nevada and Mexico.[63–67] It is estimated that lithium brine deposits make up around 66% of resources, while pegmatites represent 26% and clay only 8%.[68]

Pegmatites, coarse-grained igneous rocks, are a key hard-rock source of lithium, with granitic pegmatites being the last part of a magma body to crystallize, forming large crystals. The most crucial lithium ore mineral in pegmatites is **spodumene** $LiAlSi_2O_6$, which, after heating to around 1000ºC, converts to β-spodumene suitable for chemical reactions. Spodumene is found in Western Australia, North Carolina, Quebec, Manitoba, Western China, the DRC, and Brazil. Another essential mineral is **petalite** $LiAlSi_4O_{10}$, which also converts to β-spodumene and is found in Zimbabwe, Namibia, Brazil, Australia, and Manitoba. While mica minerals like **lepidolite** $K(Li,Al)_3(Al,Si)_4O_{10}(F,OH)_2$ or **amblygonite** $(Li,Na)AlPO_4(F,OH)$ were previously used for lithium extraction, they are now less popular due to high fluorine content. Only spodumene and petalite in pegmatites hold significant economic importance.[41,43]

The second important source of lithium, in the form of lithium chloride LiCl, is found in **brine pools** due to the natural leaching of lithium-containing rocks and/or evaporation processes. High concentrations of LiCl can be found in high-altitude salars (salt lakes) in Chile, Argentina, Bolivia, China, and Nevada. Typically, high concentrations of sodium, potassium, and magnesium are associated with lithium-rich brine sources. It is essential to note that a high magnesium-to-lithium ratio can render the project economically unviable.[41] Brine is pumped from underground and then concentrated by solar evaporation in large, shallow ponds.

Alternative **non-conventional brine sources**, including underground oilfield waters and geothermal sources, could be exploited. Oilfield brines typically contain less lithium concentration than salars. However, after pumping this brine back onto the surface, direct lithium extraction techniques (DLE) would allow for efficient separation of lithium before the remaining brine can be pumped down into the aquifer.[69] This represents a significant opportunity for territories where the oil gas industry is already implanted, such as Texas, Arkansas, Alberta and Saskatchewan.[18,19,70,71] Finally, geothermal brine exploitation is planned at the Salton Sea in California.[72,73] Those projects could rely on low-carbon geothermal energy to extract lithium, thus potentially leading to negative CO_2 intensities.

3.1.2 International Lithium Production, Reserves and Resources

Table 3 Estimated reserves & mined production of lithium by country in tonnes

Country	Li production in 2022[a] (in tonnes)	Country	Li Reserves in 2024[a] (in tonnes)
United States	N/A[b]	Portugal	60,000
Portugal	380	Zimbabwe	310,000
Canada	**520**	Brazil	390,000
Zimbabwe	1,030	**Canada**	**930,000**
Brazil	2,630	United States	1,100,000
Argentina	6,590	Other countries	2,800,000
China	22,600	China	3,000,000
Chile	38,000	Argentina	3,600,000
Australia	74,700	Australia	6,200,000
Other countries	/	Chile	9,300,000
World total (rounded)	**146,000**	**World total (rounded)**	**28,000,000**

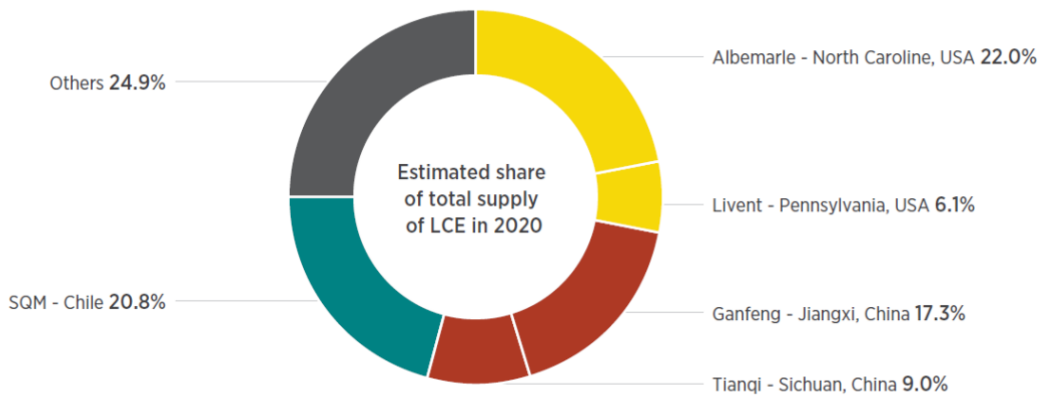
[a]Data from the 2024 U.S. Geological Survey,[2] NRCan's dataset differs slightly.[1]
[b]U.S. Production numbers are withheld from world total to avoid disclosing proprietary data.

Table 4 Estimated resources of lithium in 2024 by country in tonnes

Country	Estimated Li resources in 2024[a,b] (tonnes)	Country	Estimated Li resources in 2024[a,b] (tonnes)
Kazakhstan	50,000	Serbia	1,200,000
Austria	60,000	Czechia	1,300,000
Finland	68,000	Mexico	1,700,000
Ghana	200,000	**Canada**	**3,000,000**
Namibia	230,000	DRC	3,000,000
Portugal	270,000	Germany	3,800,000
Spain	320,000	China	6,800,000
Zimbabwe	690,000	Australia	8,700,000
Brazil	800,000	Chile	11,000,000
Mali	890,000	United States	14,000,000
Peru	1,000,000	Argentina	22,000,000
Russia	1,000,000	Bolivia	23,000,000
		World total (rounded)	**105,000,000**

[a]Data from the 2024 U.S. Geological Survey.[2]
[b]Resources encompass a large quantity of minerals identified with reasonable certainty but have not proven economically viable for extraction yet. Reserves are a portion of the resources demonstrated to be legally and financially extractable.

According to the U.S. Geological Survey, Australia, Chile, China, and Argentina are responsible for 97% of the estimated worldwide lithium production in 2022.[2] It is also worth noting that only five companies accounted for approximately 75% of the 2020 global lithium supply and that only 16 mines accounted for most of the world lithium production in 2022.[57] The historical lead from the 80s of Chilean brines for lithium production was supplanted in 2017 by Australian spodumenes. This transition followed the changes in the EV market: as the demand for lithium rose, so did its price, making energy-intensive mining of hard-rock ores more economically viable. Additionally, the increased demand for high-nickel Li-ion cathodes supported increased spodumene production, as it is easier to produce the LiOH required for high-nickel chemistries from hard-rock ores than from brine.



Source: Palandrani, 2020.

Figure 5 Lithium supply by company in 2020[57]

3.1.2.1 Australia, the Current Lithium Spodumene Superpower

Australia has recently become the first global lithium producer due to its exploitation of spodumene deposits. Domestic production tripled from 2016 to 2017, drastically increasing lithium world production by 74%. Australia hosts at least six significant mining sites, including the Greenbushes mine, which produced 1,350,000 tonnes of spodumene concentrates in 2022.[74] Other significant operations include, by order of importance, Pilgangoora, Mount Marion, Mount Cattlin, Wodgina, Finniss Lithium and Bald Hill. Although more than half of the world's lithium is mined in Australia, 96% is exported to China for refining.[75,76] However, Albermarle, a global lithium giant already owning Greenbushes and Wodgina mines, is developing a lithium hydroxide plant in Kemerton to process spodumene concentrates from its mines. This refinery's announced capacity will be 100,000 tonnes of LiOH per annum.[77,78] Spodumene operations in Australia are considered the world's most energy-intensive and GHG-emitting lithium processes. However, they would also potentially have one of the world's lowest production costs for LiOH.[55,79–81]

3.1.2.2 Chile, Leading the Global Brine Extraction

Chile was the world's second lithium producer in 2022, the top exporter of Li_2CO_3 and the second exporter of LiOH in 2019. Two companies, Sociedad Química y Minera (SQM) and Albemarle, currently have the most extensive brine operations in the world in the Salar de Atacama, in desertic Northern Chile. SQM also holds Li_2CO_3 and LiOH plants near Antofagasta, and BYD has planned a $290 million LFP cathode factory in the same region.[82] Both companies have permission from the government to mine lithium until 2030 (SQM) and 2043 (Albermarle), but plans are underway to create a state-owned lithium company to renegotiate license agreements and boost the state's influence on new joint ventures. As such, lithium is crucial to Chile's economy, accounting for almost 10% of GDP; however, the industry still lacks more advanced refining capacities and value-added products. At the same time, social and ethical aspects could be improved. Ongoing issues include protests by Mapuche indigenous people against new lithium projects, the topic of a fairer redistribution of wealth generated from lithium production, and a particular concern for water resources.[50] SQM has been particularly under scrutiny recently.[50,83] Chile's lithium remains the least carbon-emitting on the planet thanks to the solar evaporation process.[80,84–86]

3.1.2.3 The Other Cornerstones of the Lithium Triangle: Argentina & Bolivia

Three countries currently hold the most significant lithium resources (53%) and reserves (46% for Chile and Argentina only) in the world: Chile, Argentina, and Bolivia—but aside from Chile, Argentina and Bolivia have different socio-political and economic contexts, with more difficulties and delays for Bolivia, while Argentina's lithium industry is on the rise. Indeed, Chilean estimation forecasted that Argentina's lithium production would outpace Chile's by 2035.[87] In 2022, two large projects were running in Argentina, one in Sales de Jujuy, operated by Allkem (merging with Rio Tinto after being Arcadium Lithium), and the Fénix site operated by Livent (also Arcadium Lithium) in the Salar del Hombre Muerto. The first uses solar evaporation in ponds and refines concentrates to Li_2CO_3 since 2014,[88] while the latter uses DLE with a selective adsorption plant to produce Li_2CO_3 and LiCl.[89,90] Due to a pro-market approach, Argentina has attracted around 49 mining projects at different stages, and current production could triple this year depending on the challenges DLE technologies face.[91,92] Meanwhile, Bolivia's impressive resources at the Salar de Uyuni remain untapped. The Bolivian government had previously limited foreign investment, and local opposition to mining had delayed the development of any tangible projects. In conjunction with the government, the state-owned company Yacimientos de Litio Bolivianos (YLB) has only yielded poor results, despite an investment of $800 million. The current government shifted gears and called for DLE proposals led by foreign companies to develop the sector.[93–95] As such, a consortium led by CATL, a major Chinese battery manufacturer, signed a $1 billion contract in November 2024 to develop two lithium projects in Bolivia. Meanwhile, Russian company Uranium One signed a contract in September 2024 to construct a 14,000 tpa plant.[96]

3.2 Processing

China currently dominates the lithium refining capacities like rare earth, cobalt, nickel, graphite and copper. In 2019, the IEA estimated that 59% of refined lithium was processed in China, while 29% was processed in Chile.[48] In the future, 49% of planned refining lithium projects for 2023–30 are located in China, 16% in Argentina, 11% in Australia and 9% in Chile.[58] Projections for 2030 by the IEA indicate that the geographic concentration of refining facilities will slowly diversify.[97]

3.2.1 Evaporation: The Traditional Brine Processing Technology

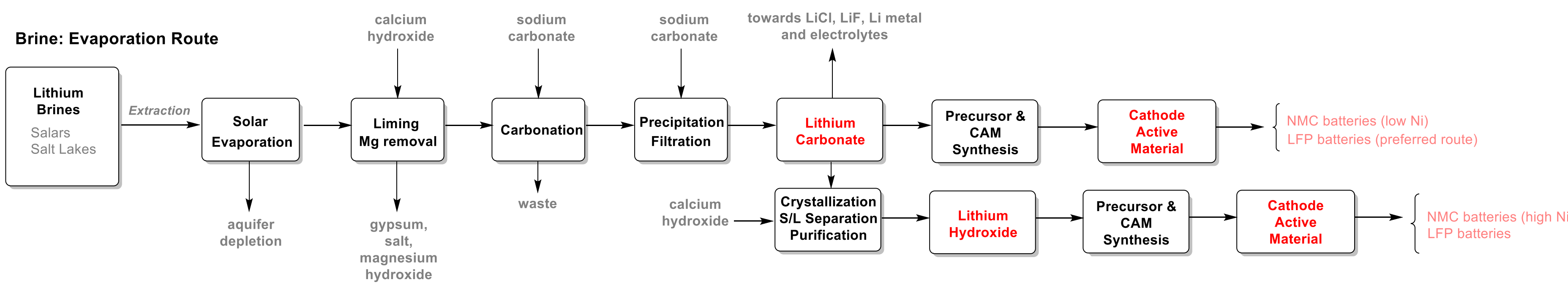


Figure 6 Brine evaporation flowsheet

Lithium brines from salt lakes and aquifers, notably from Chilean sources, are traditionally refined to lithium carbonate Li_2CO_3 through a solar evaporation system comprising multiple large ponds. Lithium extraction processes used are site-specific and depend on several factors, such as the lithium content of the source, the concentration of calcium and magnesium, the presence of impurities, the evaporation rate and other climatic and local meteorological conditions. The Mg/Li ratio is particularly critical to the economic viability of brine processing, as too much magnesium can affect purification costs. The primary method is called the *lime soda evaporation process*.

The brine water is pumped from several meters under the surface of the Atacama salt lakes and placed in a series of solar ponds for evaporation. Some calcium chloride can be added to remove sulfate ions as precipitated gypsum $CaSO_4$. As the water volume decreases and depending on the concentration, certain byproduct salts crystallize first (halite NaCl), and some can be repurposed for fertilizers (sylvite/potash KCl, sylvinite KCl·NaCl, kainite $KCl \cdot MgSO_4 \cdot 3H_2O$, carnallite $MgCl_2 \cdot KCl \cdot 6H_2O$, *etc.*). To maintain consistent volumes, every pond is routinely harvested for precipitated salts. The evaporation and crystallization process is slow and takes 12–18 months, yielding a concentrated yellowish solution comprising 6% lithium chloride brine LiCl.

This concentrated brine is then purified by a liquid-liquid extraction process using kerosene, alcohol, and sodium hydroxide to reduce boron levels. It is then treated with lime $Ca(OH)_2$ to remove magnesium by precipitating magnesium hydroxide $Mg(OH)_2$ and soda ash Na_2CO_3 to remove calcium by precipitating calcium carbonate $CaCO_3$. After filtration, the purified LiCl solution is carbonated with Na_2CO_3 to produce lithium carbonate Li_2CO_3, which is filtered, dried, and milled to form a compact powder.[26,41,43] Other operational concurrent methods to the *Atacama process* exist, such as the *Silver Peak or Lithium Americas Corp. processes* in Cauchari-Olaroz in Argentina. Still, all necessitate long solar evaporation time and yield Li_2CO_3.

All solar evaporation processes are more economical than the hard rock process and do not require as much energy input. They also do not need a wide variety of chemicals used as reagents. However, the pumping, evaporation, purification, and water-demanding processes in areas where water is already scarce can be an environmental liability. Besides the depletion of local aquifers and the large amount of solid waste produced, the evaporation rate is weather-dependent and requires a lot of time.

Li_2CO_3 can be a precursor for cathode active materials for Li-ion batteries. However, it is more suitable for LFP or low-nickel NMC batteries, as cathode production for higher nickel-content batteries would necessitate a higher temperature if sourced from Li_2CO_3, thus making this step more energy-intensive and less economically viable. $LiOH \cdot H_2O$ is therefore favoured over Li_2CO_3 for high-nickel NMC batteries, a technology capturing market shares and is thought to supplant the less efficient low-nickel NMCs.[57,98] Nevertheless, Li_2CO_3 can be converted into $LiOH \cdot H_2O$ through an energy-demanding causticization/crystallization extra step.[99]

Other than cathode applications, Li_2CO_3 is still an essential key chemical intermediate: it can be converted to lithium fluoride LiF and further processed to electrolytes such as lithium hexafluorophosphate $LiPF_6$, or it can be transformed to LiCl and then lithium metal.

3.2.2 Direct Lithium Extraction: The Novel Brine Process

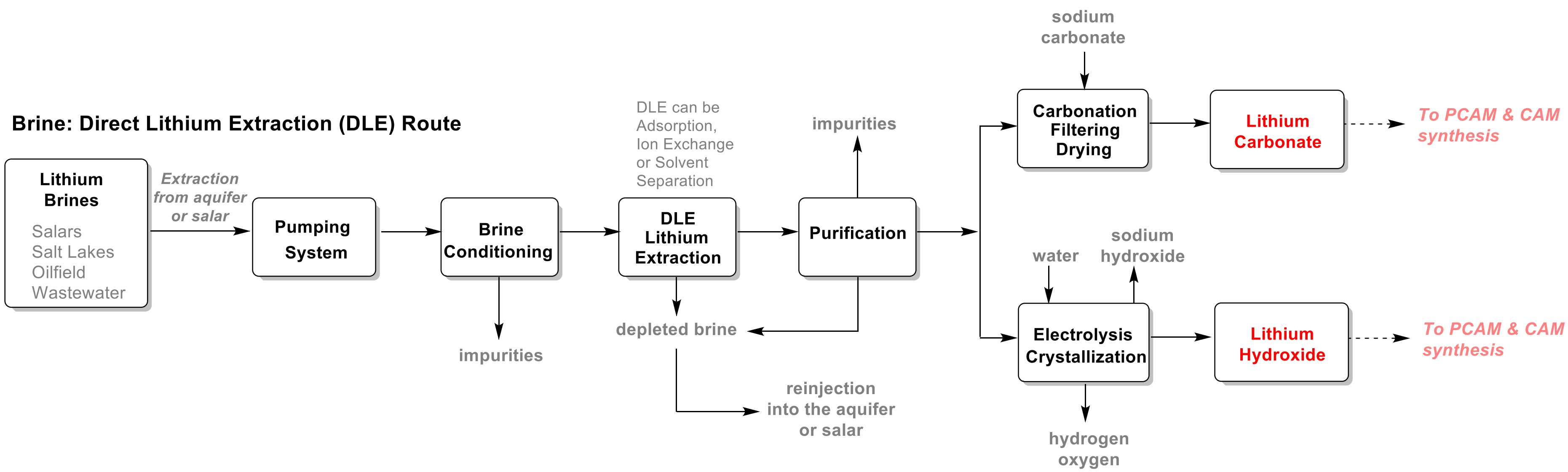


Figure 7 Direct Lithium Extraction flowsheet

Direct Lithium Extraction techniques, or DLE, are another promising methodology for treating lithium brine sources. Instead of using primarily solar evaporation and removing impurities through crystallization to isolate lithium chloride, as in the usual pond evaporation process, DLE extracts lithium ions or lithium chloride from the pumped brine using chemical or physico-chemical processes. The lithium-depleted brine solution can be reinjected inside the source.

This strategy has numerous advantages compared to pond evaporation: it would shorten production times from extraction to production from years to hours or days, it would improve the lithium recovery rate, it has lower land area requirements, it is not weather-dependent, and it consumes less water. In terms of costs, the capex of developing a DLE operation can be slightly more expensive than a solar evaporation site but within the same range, while the OPEX can be lower. As solar evaporation virtually consumes free energy from the sun, it has an energy advantage over DLEs, but both techniques are less emission-intensive than spodumene processing.[90]

So far, only a handful of operational DLE sites are active: the Fénix site in Argentina at the Salar del Hombre Muerto, operated by Livent/Arcadium Lithium and using a US proprietary adsorption technology, and three sites in China using SunResin, a Chinese-owned adsorption technology. Several DLE sites are projected in Canada, such as Lithium Bank, E3 Lithium and Arizona Lithium in Alberta and Saskatchewan.

Several extraction methodologies exist to selectively separate lithium from the brine solution, such as adsorption, ion exchange (IX), solvent extraction, chromatography, or membrane separation.

So far, all operational DLE sites opted for the adsorption strategy. Adsorption is a simple process that captures the wanted molecules, here lithium chloride, from the brine in interstices created by an adsorbent resin with specific characteristics (porosity, structure, pore size, *etc.*), and later water treatment can remove it from the adsorbent. Adsorption is a process already routinely used for water treatment, pharmaceuticals or hydrometallurgy, but its adaptation to lithium extraction is only used in Argentina and China.

For instance, the Fénix site in Argentina is based on a 1995 technology, using a flow of brine through several adsorption columns packed with gibbsite $\gamma\text{-}Al(OH)_3 \cdot nH_2O \cdot LiCl$. A freshwater flow from the neighbouring Los Patos/Trapiche aquifers is then used to strip the lithium off the columns. However, contrary to the novel projected DLE operations, short solar evaporation steps in ponds are still necessary before and after the adsorption stage (**Figure 5.3.5**). Similarly to the evaporation process, a final carbonation step using Na_2CO_3 in the concentrated LiCl solution will precipitate Li_2CO_3 as a product. The system runs on fossil-fuel energy, with steam generation driven by natural gas and the electricity generator running on diesel and natural gas.[41] Despite these limitations, the Fénix site showed the way for a commercially successful semi-continuous DLE operation, producing 22,500 tonnes of lithium carbonate equivalent each year.

Direct Lithium Extraction Flowsheet

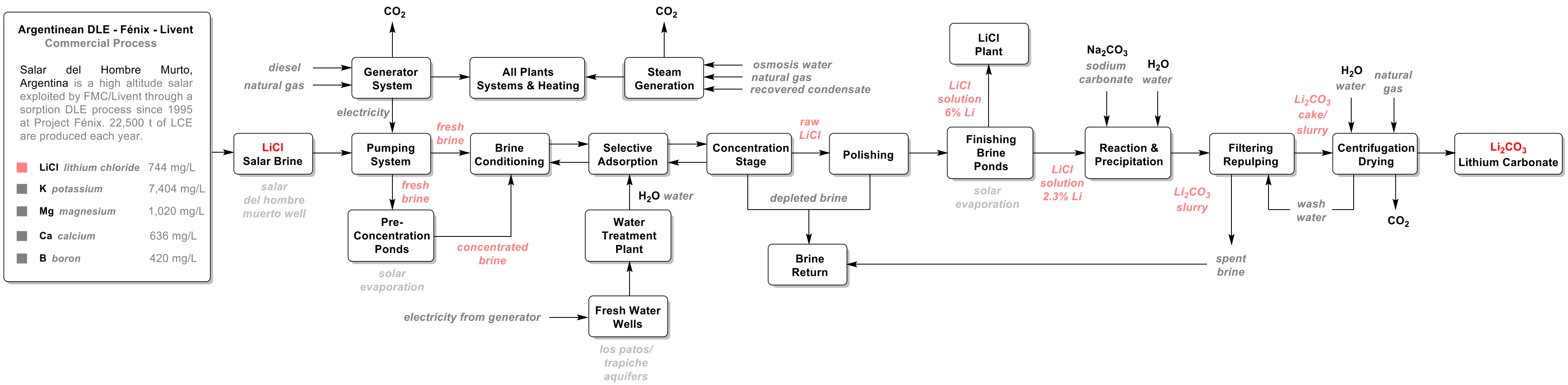


Figure 8 The DLE/Evaporation flowsheet of Project Fénix in Argentina

Ion exchange materials replace ions with different ions of the exact electrical charges. In this case, the lithium brine solution stream will have its lithium ions substituted by hydrogen ions when passing through the sieve-like ion exchange material. A subsequent acidic wash will release the lithium ions and store the hydrogen ions once again. This process is highly selective and could process low-concentration brine sources. Still, the ion-exchange material requires a large quantity of acid and base and a relatively high upfront cost. Ion exchange processes are already used commercially for the refining of several metals, such as gold, tungsten and uranium, and demonstration-scale ion exchange processes are tested for nickel, cobalt and scandium.

Finally, another possible DLE method is solvent extraction. By mixing the lithium brine with an organic solution, usually kerosene as a solvent and extractant molecules, lithium can selectively migrate towards the organic solution while leaving the impurities and other ions, such as sodium and magnesium, in the original brine solution. This method can achieve a high lithium concentration and has the advantage of having low opex cost and no requirement for an additional concentration step, as IX and adsorption might need. However, it might be less suited to brine sources with a higher impurity content, and using organic solvent and chemical reagents could pose logistical and environmental hazards.

3.2.3 Spodumene Processing

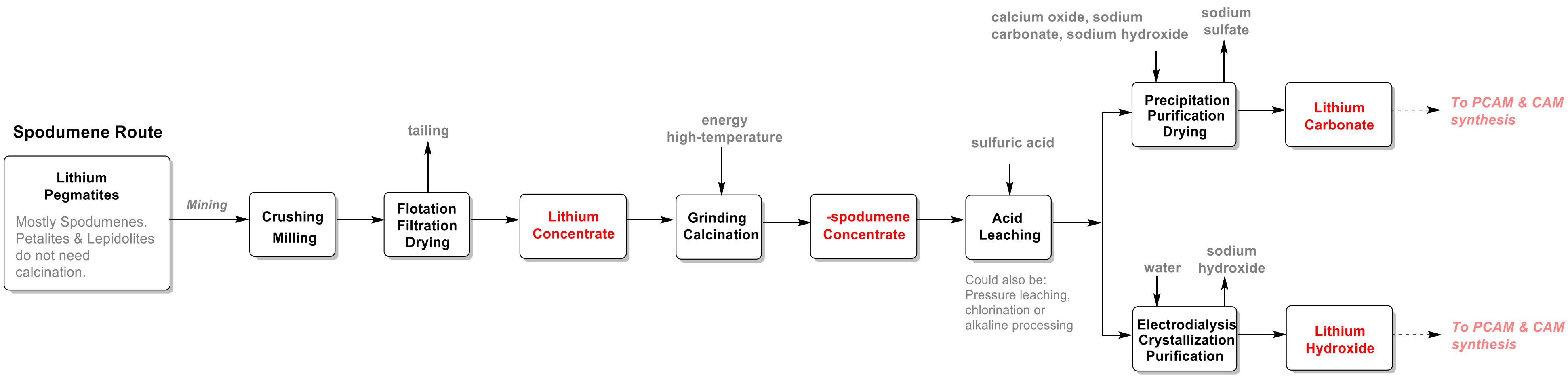


Figure 9 Flowsheet of spodumene processing

After extraction through quarrying or in an open pit mine, hard-rock lithium ore is first treated by separating the parent rock from the lithium-bearing minerals, such as spodumene, through comminution and beneficiation.[26,41,43] First, multistage steps of crushing, grinding, and milling transform the ore into a fine powder, which is then sent to a flotation process. Flotation agents such as fatty acids or sulfonated oils form foam: quartz, feldspar and mica minerals are trapped in the foam, while spodumene floats off and iron is removed magnetically. After drying and filtration, a spodumene concentrate product of approximately 6% Li_2O concentration is obtained.

This spodumene concentrate mainly consists of α-spodumene, one of the three polymorphs of spodumene and the only naturally occurring one. However, α-spodumene is not treatable through leaching. Therefore, it must be converted to a more reactive β-spodumene form through pretreatment before further treatment and chemical processes. This pretreatment, also known as decrepitation or calcination, usually requires 1,000–1,100°C heating for 4 hours in a brick-lined rotary kiln. The kiln is traditionally heated by gas, oil or coal, but electric heating is possible. This calcination step is unnecessary if the initially mined ore is lepidolite, amblygonite or zinnwaldite.

The β-spodumene concentrate obtained after calcination then undergoes a chemical treatment to convert it to a more readily soluble lithium salt. Several processing pathways exist: the acid, alkaline, and chlorine processes.

The first process, and the most extensively used, goes through the roasting of β-spodumene concentrates in the presence of sulfuric acid at 250°C in a small rotary furnace or through a heated conveyor belt. Acid digestion takes around 1 hour with an 85% yield for lithium recovery, producing lithium sulfate salts Li_2SO_4 and insoluble ore residues. A leaching step with hot water dissolves these lithium salts, and several precipitation and filtration steps in combination with the addition of lime slurry and soda ensure the removal of impurities such as aluminum salts, iron oxides, magnesium hydroxide, silicates, or multivalent cations. The purified lithium solution is concentrated through an ion exchange process or evaporation.

At this step, the purified and concentrated lithium sulfate solution can be treated to yield either lithium carbonate Li_2CO_3 or lithium hydroxide monohydrate $LiOH \cdot H_2O$. Li_2CO_3 is obtained by carbonating the solution by adding soda ash Na_2CO_3 at 90–100°C and subsequent centrifugation, washing, and drying. The main by-product of this process is aqueous sodium sulfate Na_2SO_4. As for $LiOH \cdot H_2O$, it can be produced through the causticization of the lithium sulfate solution using soda NaOH and a later crystallization step, yielding sodium sulfate as a byproduct as well. This is the leading industrial pathway for lithium hydroxide production used in China.

Otherwise, an electrodialysis step can bypass the use of NaOH to convert the lithium sulfate solution to $LiOH \cdot H_2O$, which is purified after recompression, crystallization, filtration and drying. Nemaska Lithium in Quebec developed this step, but it requires an important amount of electricity.

Alternatively, β-spodumene concentrates can be treated with limestone or soda ash *via* the alkaline process to yield either Li_2CO_3 or $LiOH \cdot H_2O$. Finally, lithium concentrates can also be treated with calcium chloride $CaCl_2$ at 700°C through chlorination, producing lithium chloride LiCl.

3.2.4 Comparison of the Lithium Processing Routes

The routes toward Li-ion battery production from lithium mining are quite diverse between hard-rock spodumene and brine and lithium carbonate and hydroxide intermediates. The scale is different: 750 tonnes of brine or 250 tonnes of lithium ores are necessary to produce 1 tonne of battery-grade lithium.[100]

Despite this, several life cycle assessments agree that using Chilean brines to produce lithium intermediates and batteries is, so far, the least emitting mainstream route. Indeed, a 2020 study by Minviro focusing on lithium hydroxide showed that lithium from Chilean brine with home-extraction and refining emitted 5 $tCO_2/tLiOH \cdot H_2O$, but emissions rose to 8 $tCO_2/tLiOH \cdot H_2O$ for Argentinean brine with extraction and carbonation in Argentina and conversion to lithium hydroxide in the U.S., while GHG dramatically increased to 15 $tCO_2/tLiOH \cdot H_2O$ for Australian spodumene with refining in China.[84]

Another report published in 2021 by the Argonne Institute quantified both lithium carbonate and hydroxide emissions from Chilean brine sources and Australian spodumenes: Evaporation of brine to lithium concentrate only gave very negligible emission, while the production of carbonate from concentrate gave 2.7–3.1 tCO_2e/tLi_2CO_3, which rose to 6.9–7.3 tCO_2e /$tLiOH \cdot H_2O$ for hydroxide. Australian spodumene extraction and concentration, due to the high energy required for hard-rock mining and crushing, already releases ~0.42 $tCO_2e/t_{spodumene}$, and the following refining steps released 20.4 tCO_2e/tLi_2CO_3 for lithium carbonate, and 15.7 $tCO_2e/tLiOH \cdot H_2O$ for lithium hydroxide.[79]

Both LCAs identified the same sustainability challenges: the spodumene-focused industry is highly emissive due to energy-consuming mining and concentrating steps and high temperatures required for the following refining, most usually occurring in China where coal is used for the necessary heat and steam, and the local electrical grid is highly emissive. Extraction from different minerals, such as petalite or lepidolite, would potentially emit even more GHGs.[80] Switching from fossil fuels to low-carbon and renewable energy would decrease the footprint of this spodumene ore route. The brine route is notably less demanding in fossil fuels, except for Argentinean brines, where the direct lithium extraction (DLE) technique relies on a large quantity of natural gas for heating. Cleaner energy and newer optimized DLE processes could solve this problem.

Additionally, making LiOH from brine is more than twice as much carbon-emitting as making Li_2CO_3 directly due to the energy-intense additional causticization (using $Ca(OH)_2$) and crystallization steps needed to convert brine-obtained Li_2CO_3 to LiOH. Another key finding is that ore and brine routes require a high quantity of water in regions where water is scarce: More than 50% of the global lithium production volume is located in areas with extreme water stress.[48,85] However, the brine route would still require less freshwater.[86]

Finally, closing the loop and recycling lithium from batteries would improve sustainability. Nevertheless, the end-of-life recycling rates and recycled content rates for lithium are currently meagre (<1%),[101] Although battery recycling will be a secondary source of lithium, recovery is still a challenge because of the high energy required. The future capacity increase of recycling plants able to treat the black mass through hydrometallurgy will probably increase this recycling rate, but presumably not to game-changing levels (6% in 2030).[54]

Endnotes

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