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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

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- Saskatchewan Research Council (SRC)
- Sherritt International Corporation
- Teck Resources Limited
- VRB Energy Inc.
- Worley Consulting Insights

About Us

BMAC

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

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.

Energy Futures Lab

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.

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Executive Summary

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This report aims to lay the analytical groundwork for mineral-specific strategies to secure Canada's place in the global value chain for electric vehicles. Although the current list by the federal government accounts for 34 minerals, only eight critical minerals and materials were selected for the present study: Copper, graphite, iron, lithium, nickel, phosphate, rare earths (counted as one, although it is a subset of seventeen different elements), and vanadium. This selection allows a deeper dive into specific and strategic minerals we believe are essential for the EV value chain in Canada. Indeed, those selected critical minerals all have integral roles in the EV supply chain, whether for battery materials, motors and magnets, electricity and current transmission or energy storage in a broader sense.

One of the main contributions of this report is to collect and synthesize industry knowledge specific to each of the eight minerals. This adds a much-needed level of specificity to current policy discussions, which tend to speak of 'critical minerals' as a monolith. This report illuminates mineral-specific market dynamics, material flowsheets, and Canadian strengths in the various supply chains by convening industry experts in a series of workshops. The longer-term contribution of this exercise is catalyzing the creation of a coalition of industry actors, from upstream and downstream in each of these supply chains, who are pursuing the common goal of capitalizing on Canada's critical mineral opportunity.

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The report translated this overall goal into specific targets for four specific battery metal strategies as a starting point: lithium, nickel, graphite, and rare earth. A priority flagged for future research was expanding this metal-specific analysis to other critical minerals essential for Canada's battery value chain. This report undertakes this task by articulating detailed strategies for eight critical minerals.

The Eight Critical Minerals and Materials Investigated in This Report

Copper is necessary for all electrification efforts linked to the energy transition, whether it is for producing, transporting, or using electricity: it is in electrical wires, generators, transformers, inverters, electrical motors, *etc.* For EVs, it is used in wiring, in the electric motor, and as a current collector in the battery. It is also essential for the charging infrastructure.

Graphite is essential for anode material across Li-ion battery technologies. Although it can be doped with silicon to enhance its properties, it is mainly used for its ability to reversibly store lithium-ion in a stable manner, while being relatively low-cost and abundant.

Lithium is essential as a small, light, and efficient energy carrier in all lithium battery technologies. The storage and release of lithium ions allow for the storage and usage of electrical current in an optimized manner. It is specifically used as a material for cathode and electrolyte.

Although **iron** is abundant and primarily used for steels and alloys, our attention focused on the iron precursors used for lithium-iron-phosphate (LFP) battery cathodes. These can include pure iron powders or iron sulfate. High-purity iron ore was added to the federal critical minerals list in 2021.

Nickel is primarily used for stainless steel, but it is also a vital part of the nickel-manganese-cobalt (NMC) battery cathodes, a type of high-performance and long-range Li-ion battery. Although it can be substituted for LFP batteries, nickel-based batteries are expected to remain a significant part of the battery mix in the years to come, especially in North America. The trend has also seen an increase in the nickel ratio of NMC batteries.

Phosphate is mainly used for the fertilizer industry. However, phosphate and, ultimately, its transformation to battery-grade purified phosphoric acid supply can be the bottleneck for LFP battery cathode fabrication. Thus, it is essential for the lithium-iron-phosphate battery industry, a technology that allows for cheaper, safer and better cycling energy storage than LFP, at the cost of lower performances. Phosphorus in general was added to the federal critical mineral list in 2024.

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Although **vanadium** alloys can be used for specialty steels in the car industry, vanadium is not used in EV batteries per se, but vanadium flow batteries have shown the potential to be long-lasting stationary energy storage solutions. Several opportunities exist in Canada, from titanomagnetite to oil sands and carnotite deposits.

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Table 1.1.1 Summary of Canada's global rank in reserve, extraction and processing for the selected critical minerals, as well as a comparison between the 2022 extraction and the mandated benchmark target to reach in 2030

Critical Mineral	**Copper**	**Graphite**	**Iron**	**Lithium**	**Nickel**	**Phosphate**	**REE**	**Vanadium**
Role Canada	Current	NMC + LFP Anode	LFP cathode	NMC+LFP cathode, electrolyte	NMC cathode	LFP cathode	Permanent Magnets	Flow battery
Global Reserve Rank[a]	13th	9th	7th	6th	7th	*18th	10th	/
Global Extraction Rank[a]	12th	7th	7th	7th	6th	None	None	None
Global Processing Rank[a]	16th	None	15th (steel)	None	4th	None	None	1 refinery
2022 Extraction in tonnes[a,b] (% world)	520,000 (2.4%)	13,000 (0.8%)	41,400,000 (2.7%)	520 (0.4%)	143,000 (4.4%)	0	0	0
2030 Target (tonnes)[b,c]	75,000	223,000 (raw graphite)	38,000	11,000	37,000	80,000 (85% PPA)	/	/

*Data from the 2016 *Yearly Mineral Commodity Summary of the* U.S. Geological Survey.

[a] Data mostly from the: U.S. Geological Survey, *Yearly Mineral Commodity Summary*, 2024; and also from NRCan, 2024; IEA, 2024.

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[c] Original and updated targets from: A Roadmap for Canada's Battery Value Chain. Transition Accelerator, Battery Metals Association of Canada, Accelerate, Energy Futures Lab. The target is to build an EV supply chain replicating Canada's 10% share of North American automotive manufacturing. The numbers represent the additional capacity of the selected critical minerals to bring online by 2030 in tonnes per annum.

Summary of Findings

Building Canada's Leadership in Copper Metallurgy and Expanding Copper Mining

Copper is a cornerstone material for the transition to EVs and the broader clean energy economy. To ensure Canada captures its share of the North American EV market—10% as a baseline, with a potential leadership target of 35% by 2030—Canada must address declining copper processing capacity and maximize its resource potential. While British Columbia (BC) holds significant untapped copper reserves, the country lacks the metallurgical infrastructure to process these resources at scale.

- **Accelerate Near-Term Copper Production:** Advance life extensions and expansions of current copper mining operations while supporting the implementation of mining projects in development, especially in BC, and expand concentrate production.
- **Boost the Midstream Segment by Building a New Metallurgical Plant:** There is already enough copper concentrate produced in British Columbia to justify the operation of a new copper smelter, provided that we ignore the selling agreements already in place to sell Canadian copper concentrates to Asian smelters. Building a new pyrometallurgical plant in BC, taking feed from the existing mines, projected ones, and scrap would advance the Canadian copper supply chain. If the social mandate does not allow it, supporting R&D and optimizing viable hydrometallurgical operations of copper sulfide should be pursued. Scaling existing operations, such as the Horne smelter and Montreal copper refinery, should also be supported.

Positioning Canada as a North American Leader in Graphite Anodes

Canada has the resources and industrial capacity to become the primary North American supplier of coated spherical purified graphite (CSPG) for EV battery anodes. By advancing natural graphite mining, establishing processing hubs, and diversifying into synthetic graphite, Canada can secure its role in the critical minerals supply chain while driving economic growth and innovation. A bullish scenario can be considered. This strategy focuses on:

- **Expanding Natural Graphite Mining:** Prioritize mining and shaping/milling projects in Québec and British Columbia, leveraging the provinces' rich deposits and industrial infrastructure. The projects in Québec are more advanced and should be supported and reinforced, while the ones in BC need a boost to develop more rapidly.
- **Developing Coating Hubs and Anode Material Plants:** Establish coating and anode production hubs in Québec and British Columbia, supported by partnerships with international companies that possess the expertise and intellectual property for anode manufacturing technology.

- **Advance Synthetic Graphite in Alberta:** Build a synthetic graphite processing facility in Alberta's Industrial Heartland, utilizing existing petrochemical infrastructure.
- **Explore Alternative Graphite Sources:** bioresources such as the pyrolysis of forestry industry wood waste can be converted into graphite, and natural gas can be transformed into hydrogen and graphite through a pre-combustion carbon capture system. Such alternatives should be supported through R&D and scaled locally.

Canada Should Scale Innovative and Cleaner Processes to Incorporate its Iron Products into EV Cathodes

Canada already has significant operations in high-purity iron ore mining and steelmaking, and the mandated benchmark quantity of supplementary iron necessary for LFP cathode manufacturing is likely not a bottleneck. However, iron sulfate is traditionally the chemical intermediate necessary to produce precursors to LFP cathodes. Canada can encourage iron sulfate production from steel mills, but above all, it should support the commercial viability and scaling of new pCAM and CAM processes using iron powder or iron oxide to bypass iron sulfate and avoid controversial sodium sulfate waste issues.

- **Produce Iron Sulfate from Existing Steel Mills:** The pickling step in steel mills necessitates the treatment of steel with sulfuric acid; this is an opportunity to produce iron sulfate as a byproduct to sell for pCAM/CAM LFP cathode makers.
- **Leverage Canada's Iron Products and Support Clean Cathode Manufacturing Processes:** NanoOne has developed cleaner processes to use iron powder or iron oxide with other precursors to produce CAM in one pot and avoid sulfate salt issues. These initiatives should be supported to ensure commercial viability and scaling, as they can boost competitiveness and increase social mandate against Chinese CAM processes. Rio Tinto's RTIT plant in Quebec already produces pure iron powder as a by-product of its titanium operation.

Advancing Lithium Spodumene and Brine in Canada

To secure 10–12.5% of the North American EV market, Canada must capitalize on its abundant lithium resources and establish a robust, integrated supply chain. With increasing global competition and new lithium projects emerging worldwide, Canada should not aim for a bolder scenario but can distinguish itself by focusing on both natural and direct lithium extraction (DLE), sustainable processing, and advanced manufacturing capabilities.

- **Direct Lithium Extraction (DLE) in Western Canada:** Prioritize lithium brine extraction in Saskatchewan and Alberta, integrating these operations with a dedicated DLE research hub to advance innovation, de-risk and scale DLE operations, modelled on the Alberta Oil Sands Technology and Research Authority (AOSTRA). Building a Cathode Active Material (CAM) and Precursor Cathode Active Material (pCAM) facility in Alberta or British Columbia would further enhance the region's role in the battery value chain.

- **Spodumene Mining and Processing in Québec and Ontario**: Ramp up spodumene extraction to take advantage of rich and large deposits and existing projects. Strengthen the Bécancour lithium hydroxide processing hub in Québec to convert spodumene into battery-grade materials. Support one lithium hydroxide plant project in the Thunder Bay area to take feed from the Western Ontario spodumene projects. Establish a spodumene processing research centre to drive technological efficiency and sustainability.

Canada Should Spearhead Nickel Production and Processing for EV Batteries in North America

Canada has the opportunity to become a leading supplier of nickel for the North American electric vehicle market. With significantly larger nickel resources than the U.S., Canada should aim for a leadership scenario, capturing up to 35% of the 2030 market share, well above the 10% baseline goal. Achieving this target requires scaling up domestic mining and processing capacity while building integrated supply chains for battery-grade nickel products.

- **Expand Nickel Mining and Processing**: Strengthen existing nickel mining operations and processing capacity by expanding and modernizing capacities in Newfoundland and Labrador, Québec, Ontario, and Alberta. Advance 3–4 large-scale mining projects to produce 35–40 ktpa of elemental nickel each, ensuring a steady supply of battery-grade materials.
- **Develop Long-Term Processing Capacity in British Columbia:** Establish a large nickel metallurgical facility in BC capable of producing nickel sulfate ($NiSO_4$), nickel metal, or precursor cathode active materials (pCAM). Integrate black mass recycling to support future battery circularity, complementing feedstock from imported laterite precipitates and domestic sulfide ores.
- **Leverage Imported Feedstocks in the Short Term:** Use imported mixed hydroxide precipitates (MHP), mixed sulfide precipitates (MSP), or matte as interim feedstocks to scale up domestic processing capabilities to nickel sulfate or pCAM.

Leveraging Canada's Igneous Phosphate Deposits to Lead Purified Phosphoric Acid Production and LFP Batteries

Canada can potentially play a pivotal role in the North American transition to lithium iron phosphate (LFP) battery production by scaling up domestic supply chains for battery-grade phosphoric acid (PPA). PPA production capacity is thought to be a global bottleneck for LFP cathode material production. However, Canada's rare igneous deposits make it particularly suitable for developing PPA. This scenario requires developing new phosphate extraction projects and phosphoric acid processing capacity.

- **Accelerate Phosphate Mining Development:** Launch 3–4 phosphate mining projects across Québec, British Columbia, and Ontario. Prioritize igneous phosphate deposits for cathode material (battery-grade PPA) due to their suitability for high-purity processing while reserving sedimentary deposits primarily for fertilizer use in the short term (MGA).
- **Build Purified Phosphoric Acid Processing Hubs:** Establish two processing hubs to produce merchant-grade phosphoric Acid (MGA) and Purified Phosphoric Acid (PPA). The one in Québec should focus on converting local igneous deposits into PPA for pCAM and CAM applications. The one in Western provinces (Alberta or BC) should handle regional feedstocks for fertilizer use and support a potential Western Canada's LFP supply chain.

Building Canada's Rare Earth Element (REE) Supply Chain and Magnet Manufacturing Capacity

To establish a leadership position in the growing market for rare earth elements (REEs), Canada should focus on developing a centralized processing and magnet manufacturing hub, which could be built around the SRC's initiatives in Saskatchewan. This strategy ensures alignment with global supply chain demands while leveraging Canada's resource base and technological expertise. A phased approach is critical, balancing immediate actions with long-term development, and a high level of coordination will be needed to establish this nascent domestic supply chain from the start.

- **Short-Term Reinforcement of Midstream REE Processing:** Import monazite concentrates and other REE-rich waste materials to maximize the production of individual rare earth oxides (REOs). Leverage existing Canadian facilities, such as the Saskatchewan Research Council (SRC) processing facility and Canadian IP, such as Ucore's technology, to refine REOs and establish a robust processing foundation.
- **Establish Magnet Manufacturing**: Use domestically processed REOs to build metalmaking, magnet manufacturing and magnetic powder production facilities. Build partnerships with material manufacturers, EV motor producers, and OEMs to secure off-take agreements and ensure a reliable, customer-driven supply chain.
- **Develop Mining Capacities in the Medium Term:** Ramp up mining capacities by opening 3–4 REE mines, including projects in the Northwest Territories, BC, Saskatchewan and Québec to provide a consistent supply of high-grade REE concentrates. Maximize economic viability by selling value-added co-products alongside REEs. Ensure the centralized processing facility in Saskatchewan can handle feedstock from domestic mines, reducing dependency on international sources and strengthening the Canadian supply chain.

Unlocking Canada's Potential in Vanadium Recovery and Energy Storage Solutions

Canada has a unique opportunity to establish itself as a global hub for vanadium recovery, processing, and vanadium redox flow battery (VRFB) production. By leveraging existing industrial assets and its proximity to petroleum-based vanadium sources in Alberta, Canada can create a competitive vanadium value chain. This initiative supports the transition to clean energy and strengthens Canada's critical minerals sector.

- **Build Midstream Processing and Manufacturing Capacity:** In the short term, Canada should build vanadium processing and VRFB production capacities in Alberta. Establish a vanadium processing and recovery plant in the Alberta Industrial Heartland or Fort McMurray, and leverage proximity to the oil sands industry for a steady vanadium supply from petroleum residues.
- **Boost Vanadium Recovery from Secondary Sources:** Promote recovery from fly ash from coal and oil-fired power plants in Alberta, Saskatchewan, and the Maritimes. Ensure steady feedstock for the processing facility while reducing industrial waste.
- **Leverage Existing VRFB Assets:** Expand and integrate the capabilities of facilities like Invinity's Vancouver operation, VRB Energy's expertise and Vanadium Corp to jumpstart electrolyte and VRFB manufacturing and domestic deployment, with export opportunities.
- **Expand Primary Vanadium Supply in the Long Term:** Develop vanadium co-production and collaborate with iron, uranium, and aluminum mining operations in resource-rich provinces (BC, SK, QC, NL) to recover vanadium as a co-product. Support the titanomagnetite vanadium mine projects in Quebec. Establish supply chain linkages between vanadium mining, processing, and battery manufacturing to strengthen Canada's critical mineral resilience and value-added production capabilities.

1 Introduction

1.1 Aim and Scope of This Study

1.1.1 The Context of This Report

The Canadian federal government defines critical minerals as minerals with a threatened supply chain while still having a reasonable chance of being produced in Canada. They also need to be either essential to Canada's economic or national security, be required for a transition to a low-carbon and digital economy, or position Canada as a sustainable and strategic partner within global supply chains. The first iteration of the Government of Canada's critical mineral list was proposed in 2021 and subsequently updated in 2024. Both federal and several provincial governments published lists of critical minerals within the framework of a strategy and suite of policies to boost their development.[1–6]

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Global Reserve Rank[a]	13th	9th	7th	6th	7th	*18th	10th	/
Global Extraction Rank[a]	12th	7th	7th	7th	6th	None	None	None
Global Processing Rank[a]	16th	None	15th (steel)	None	4th	None	None	1 refinery
2022 Extraction in tonnes[a,b] (% world)	520,000 (2.4%)	13,000 (0.8%)	41,400,000 (2.7%)	520 (0.4%)	143,000 (4.4%)	0	0	0
2030 Target (tonnes)[b,c]	75,000	223,000 (raw graphite)	38,000	11,000	37,000	80,000 (85% PPA)	/	/

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1.1.3 The Structure of This Report

Each of the eight critical minerals and associated materials is analyzed in a dedicated chapter. The structure of most chapters is designed to be similar and is divided into three different parts: the first one focuses on the Canadian strategy for this specific mineral and material supply chain, the second part explains the general properties and role of this specific mineral, and finally, the third part analyzes the technical flowsheet of this mineral.

Before defining strategies, the first part of each chapter will start by giving an overview of Canada's ranking in the global supply chain. An outline of the mining production, the types of ores that are significant to Canada's provinces, the different domestic processing and refining assets, and the different companies are also given. Additionally, a summary table will be shown at the beginning of this subsection to give a non-exhaustive list of significant domestic projects and operational facilities along the supply chain of interest. A production target, quantifying in kilotonne per annum of the amount of specific critical minerals to produce in Canada is then specified, along with the number of mines and refining facilities needed when possible. The targets are either from our previously released 2022 roadmap or from an updated analysis.[7] A scenario outline will then summarize the most appropriate strategy to fulfill these objectives, and a list of signature projects will illustrate the most essential facilities and infrastructure required, be it new mines, metallurgical plants or refining facilities. A more detailed list of strategic priorities will then complete this strategy, by summarizing actionable policies in short notes organized in categories, such as processing pathways, potential clusters, synergies, R&D, Skills & Education, Collaboration with Government, Strategic Partnerships, Circularity, Infrastructure *etc.*

The second part of each chapter gives general information on the specific critical mineral. Firstly, the general properties and a description of the critical mineral and its associated element are given, along with the main applications they can be used for. A historical summary of its industry and details on the possible toxicity and bioactivity of the element will also be described. A subsequent section will focus on explaining this critical mineral's role in the energy transition, emphasizing energy storage, current transmission, and permanent magnets. All those applications are linked to the EV industry, supply chain, and supporting infrastructure. A short history of how the most important technologies were discovered and scaled will also be given when appropriate. The following section will then show the possible substitutes that can be used instead of this specific critical mineral and what trade-off such an alternative entails. Finally, the ultimate section will describe the global market, with a selection of demand forecasts and projections for the future decades.

The third and final part of each chapter aims to give a technical overview of the flowsheet of this specific mineral along the different value chain segments: from mining, to processing, to advance material manufacturing and battery making. This section aims to give some background knowledge, an overview of technical details and some references to policymakers interested in a specific critical mineral supply chain. First, a brief description of the different types of natural ores, minerals and raw materials available are given. Then, a brief overview of the reserves and mining capabilities worldwide, along with recent production numbers from leading countries, is shown to assess the Canadian situation within a global context properly. Some specific notes about countries or regions of interest are also provided. Finally, the last subsection will focus on the processing pathways that come after mining and extraction until the manufacturing of advanced materials or finished products. Technical details of the major processes taken from scientific literature and various engineering encyclopedias will be given to illustrate the possible routes and material flows. A difference between the main metallurgical routes, such as between pyrometallurgy or hydrometallurgy, and between the different main types of raw material feedstock will be made.

1.2 Approach and Methodology for Critical Minerals Value Chain Analysis

For this project, we followed a structured, multi-stage approach to analyze the critical minerals value chain and formulate actionable strategies. Our methodology was designed to ensure valuable insights, stakeholder engagement, and practical recommendations tailored to Canada's unique natural resources and the specific challenges each commodity or material faces.

The reality faced by the Canadian rare earth industry, a nascent economy heavily dominated by Chinese assets globally, is very different from the difficulties faced by the Canadian nickel or copper industry, which are base metals that Canada has successfully developed throughout their value chains for over a hundred years. Similarly, the challenges and opportunities for opening a midstream chemical or metallurgical plant differ significantly from those for opening an open pit mine. Additionally, each province and region in Canada has a unique economic environment, infrastructure, labour market, electrical grid or regulation.

By acknowledging all those different factors and the complexity of the critical minerals landscape in Canada, we aimed to engage a wide variety of stakeholders throughout the elaboration of this report.

Our methodology comprised four different stages: preliminary analysis, engagement with experts, strategy refining, and final reporting through continuous engagement.

1.2.1 Stage 1: Preliminary Analysis

The first phase focused on establishing a solid understanding of this project's selected eight critical minerals through rigorous preliminary work. This included:

- **Flowsheet Analysis:** A comprehensive mapping of the value chain for each critical mineral, encompassing extraction, refining, manufacturing, and recycling processes. In our context, a flowsheet represented the flow of materials, from the choices of technologies, processes, and chemical intermediaries that exist between the extraction of raw ore; and the manufacturing of batteries, magnets or wires.
- **Global and Domestic Capacity Assessment:** We analyzed mineral reserves, resources, mining activities, and refining capacities in Canada and globally, highlighting Canada's strengths and gaps within the international context.
- **Market Trends and Risks:** Future market demand, potential supply gaps, emerging technologies, and substitutes were evaluated, along with geopolitical risks that could disrupt supply chains.

These findings were distilled into *detailed factsheets* and more concise *pre-read documents* that framed *key questions* to guide stakeholder discussions in subsequent workshop

1.2.2 Stage 2: Expert Engagement and Validation

We organized the first round of workshops to ground our analysis in industry expertise, inviting key stakeholders from the Battery Metals Association of Canada (BMAC) community network and beyond. Two sessions of the first workshop gathered experts from 4 of the 8 selected critical minerals, with the first session focusing on graphite, nickel, lithium and copper, and the second session focusing on rare earths, vanadium, phosphate and iron. The sessions lasted three hours and were conducted online; they were facilitated through videoconferences and interactive boards and maps.

This phase involved:

- **Validation and Review:** Industry experts reviewed and validated our flowsheet analysis, ensuring its accuracy and relevance to the Canadian context.
- **Expert Insights:** by reacting to our key questions within the context of the pre-read documents, industry experts shared their understanding of their sector's challenges while highlighting practical solutions and potential opportunities.
- **Policy Recommendations:** Discussions explored policies and regulations needed to strengthen Canada's critical mineral value chains, including opportunities for innovation and strategic investment.
- **Asset Mapping:** Participants identified key assets across the value chain, from extraction to advanced materials manufacturing and recycling.

The insights from this workshop formed the basis for developing preliminary strategies, or "straw dog strategies," which synthesized stakeholder input into actionable concepts and plans.

1.2.3 Stage 3: Strategy Refinement

In the second workshop, we presented the straw dog strategies to the same group of experts for further refinement. Similarly to stage 2, two sessions of gathering experts from 4 critical minerals each were held. Similarly to stage 2, the first session focused on graphite, nickel, lithium and copper, and the second session focused on rare earths, vanadium, phosphate and iron.

This phase included:

- **Feedback and Revision:** Experts provided detailed feedback on the proposed strategies, revising them to reflect industry realities and priorities.

- **Support Assessment:** A "temperature check" was conducted to assess the level of support for each strategy among participants.

- **Refined Strategies:** This feedback was integrated into a set of more polished and targeted strategies for Canada's critical mineral sectors as output.

1.2.4 Stage 4: Final Reporting and Continuous Engagement

Building on the refined strategies, we developed a comprehensive final report synthesizing our findings and recommendations. This phase included:

- **Blind Spot Analysis:** We identified potential gaps in our analysis and addressed them through additional targeted interviews with other industry experts.
- **Ongoing Stakeholder Engagement:** Continuous dialogue with stakeholders ensured that the final report captured emerging insights and maintained alignment with industry and policy needs.

1.2.5 Stakeholder Participation

The project successfully engaged over 22 companies and organizations over the two workshops and four sessions, representing a diverse cross-section of the critical minerals value chain. Participants included:

- **Industry Scope:** Entities ranged from mining companies and advanced material manufacturers to recycling organizations.
- **Geographic Coverage:** All participating organizations were Canadian-based or operating in Canada, ensuring relevance to national policy and economic objectives.
- **Additional participants:** additional interviews of relevant industry and government experts during stage 4 through the organizing partners' networks and continuous engagement allowed to tackle blind spots and answer clarifying questions.

We recognize that further Indigenous engagement will be essential in the process of moving forward with designing and implementing these strategies. Meaningful Indigenous engagement is a foundational prerequisite for critical mineral development. Specifically, Indigenous peoples must be recognized as 'rights holders', not merely 'stakeholders.' This is reflected in recent legislation at the federal and provincial levels to reflect the United Nations Declaration on the Rights of Indigenous Peoples surrounding free, prior and informed consent.[8] Engagement, early and often, throughout the life of a mining project must be a top priority. As noted by the BC First Nations Energy and Mining Council,[9] "a key purpose of a consent-based approval framework and regulation of mining projects, from staking to permitting to land reclamation and restoration, is to respect and uphold First Nations' self-determination and self-governance, their human rights and to foster fair share benefit agreements between mining proponents and First Nations communities." Capacity-building is key to empowering First Nations to take equity ownership in projects (ex, the Government of Canada's loan guarantee program). For example, the Tahltan Nation has greatly enhanced its living standards *via* partnerships directly with resource developers, leading to housing, mining, and hydropower projects.[10] The capacity to engage in these partnerships with a strong negotiating position was built up over time, bolstered through the mechanism of the community economic development corporation.

1.3 Summary of Findings

Building Canada's Leadership in Copper Metallurgy and Expanding Copper Mining

Copper is a cornerstone material for the transition to EVs and the broader clean energy economy. To ensure Canada captures its share of the North American EV market—10% as a baseline, with a potential leadership target of 35% by 2030—Canada must address declining copper processing capacity and maximize its resource potential. While British Columbia (BC) holds significant untapped copper reserves, the country lacks the metallurgical infrastructure to process these resources at scale.

- **Accelerate Near-Term Copper Production:** Advance life extensions and expansions of current copper mining operations while supporting the implementation of mining projects in development, especially in BC, and expand concentrate production.
- **Boost the Midstream Segment by Building a New Metallurgical Plant:** There is already enough copper concentrate produced in British Columbia to justify the operation of a new copper smelter, provided that we ignore the selling agreements already in place to sell Canadian copper concentrates to Asian smelters. Building a new pyrometallurgical plant in BC, taking feed from the existing mines, projected ones, and scrap would advance the Canadian copper supply chain. If the social mandate does not allow it, supporting R&D and optimizing viable hydrometallurgical operations of copper sulfide should be pursued. Scaling existing operations, such as the Horne smelter and Montreal copper refinery, should also be supported.

Positioning Canada as a North American Leader in Graphite Anodes

Canada has the resources and industrial capacity to become the primary North American supplier of coated spherical purified graphite (CSPG) for EV battery anodes. By advancing natural graphite mining, establishing processing hubs, and diversifying into synthetic graphite, Canada can secure its role in the critical minerals supply chain while driving economic growth and innovation. A bullish scenario can be considered. This strategy focuses on:

- **Expanding Natural Graphite Mining:** Prioritize mining and shaping/milling projects in Québec and British Columbia, leveraging the provinces' rich deposits and industrial infrastructure. The projects in Québec are more advanced and should be supported and reinforced, while the ones in BC need a boost to develop more rapidly.
- **Developing Coating Hubs and Anode Material Plants:** Establish coating and anode production hubs in Québec and British Columbia, supported by

partnerships with international companies that possess the expertise and intellectual property for anode manufacturing technology.

- **Advance Synthetic Graphite in Alberta:** Build a synthetic graphite processing facility in Alberta's Industrial Heartland, utilizing existing petrochemical infrastructure.
- **Explore Alternative Graphite Sources:** bioresources such as the pyrolysis of forestry industry wood waste can be converted into graphite, and natural gas can be transformed into hydrogen and graphite through a pre-combustion carbon capture system. Such alternatives should be supported through R&D and scaled locally.

Canada Should Scale Innovative and Cleaner Processes to Incorporate its Iron Products into EV Cathodes

Canada already has significant operations in high-purity iron ore mining and steelmaking, and the mandated benchmark quantity of supplementary iron necessary for LFP cathode manufacturing is likely not a bottleneck. However, iron sulfate is traditionally the chemical intermediate necessary to produce precursors to LFP cathodes. Canada can encourage iron sulfate production from steel mills, but above all, it should support the commercial viability and scaling of new pCAM and CAM processes using iron powder or iron oxide to bypass iron sulfate and avoid controversial sodium sulfate waste issues.

- **Produce Iron Sulfate from Existing Steel Mills:** The pickling step in steel mills necessitates the treatment of steel with sulfuric acid; this is an opportunity to produce iron sulfate as a byproduct to sell for pCAM/CAM LFP cathode makers.
- **Leverage Canada's Iron Products and Support Clean Cathode Manufacturing Processes:** NanoOne has developed cleaner processes to use iron powder or iron oxide with other precursors to produce CAM in one pot and avoid sulfate salt issues. These initiatives should be supported to ensure commercial viability and scaling, as they can boost competitiveness and increase social mandate against Chinese CAM processes. Rio Tinto's RTIT plant in Quebec already produces pure iron powder as a by-product of its titanium operation.

Advancing Lithium Spodumene and Brine in Canada

To secure 10–12.5% of the North American EV market, Canada must capitalize on its abundant lithium resources and establish a robust, integrated supply chain. With increasing global competition and new lithium projects emerging worldwide, Canada should not aim for a bolder scenario but can distinguish itself by focusing on both natural and direct lithium extraction (DLE), sustainable processing, and advanced manufacturing capabilities.

- **Direct Lithium Extraction (DLE) in Western Canada:** Prioritize lithium brine extraction in Saskatchewan and Alberta, integrating these operations with a dedicated DLE research hub to advance innovation, de-risk and scale DLE operations, modelled on the Alberta Oil Sands Technology and Research Authority (AOSTRA). Building a Cathode Active Material (CAM) and Precursor Cathode Active Material (pCAM) facility in Alberta or British Columbia would further enhance the region's role in the battery value chain.
- **Spodumene Mining and Processing in Québec and Ontario**: Ramp up spodumene extraction to take advantage of rich and large deposits and existing projects. Strengthen the Bécancour lithium hydroxide processing hub in Québec to convert spodumene into battery-grade materials. Support one lithium hydroxide plant project in the Thunder Bay area to take feed from the Western Ontario spodumene projects. Establish a spodumene processing research centre to drive technological efficiency and sustainability.

Canada Should Spearhead Nickel Production and Processing for EV Batteries in North America

Canada has the opportunity to become a leading supplier of nickel for the North American electric vehicle market. With significantly larger nickel resources than the U.S., Canada should aim for a leadership scenario, capturing up to 35% of the 2030 market share, well above the 10% baseline goal. Achieving this target requires scaling up domestic mining and processing capacity while building integrated supply chains for battery-grade nickel products.

- **Expand Nickel Mining and Processing**: Strengthen existing nickel mining operations and processing capacity by expanding and modernizing capacities in Newfoundland and Labrador, Québec, Ontario, and Alberta. Advance 3–4 large-scale mining projects to produce 35–40 ktpa of elemental nickel each, ensuring a steady supply of battery-grade materials.
- **Develop Long-Term Processing Capacity in British Columbia:** Establish a large nickel metallurgical facility in BC capable of producing nickel sulfate ($NiSO_4$), nickel metal, or precursor cathode active materials (pCAM). Integrate black mass recycling to support future battery circularity, complementing feedstock from imported laterite precipitates and domestic sulfide ores.
- **Leverage Imported Feedstocks in the Short Term:** Use imported mixed hydroxide precipitates (MHP), mixed sulfide precipitates (MSP), or matte as interim feedstocks to scale up domestic processing capabilities to nickel sulfate or pCAM.

Leveraging Canada’s Igneous Phosphate Deposits to Lead Purified Phosphoric Acid Production and LFP Batteries

Canada can potentially play a pivotal role in the North American transition to lithium iron phosphate (LFP) battery production by scaling up domestic supply chains for battery-grade phosphoric acid (PPA). PPA production capacity is thought to be a global bottleneck for LFP cathode material production. However, Canada’s rare igneous deposits make it particularly suitable for developing PPA. This scenario requires developing new phosphate extraction projects and phosphoric acid processing capacity.

- **Accelerate Phosphate Mining Development:** Launch 3–4 phosphate mining projects across Québec, British Columbia, and Ontario. Prioritize igneous phosphate deposits for cathode material (battery-grade PPA) due to their suitability for high-purity processing while reserving sedimentary deposits primarily for fertilizer use in the short term (MGA).
- **Build Purified Phosphoric Acid Processing Hubs:** Establish two processing hubs to produce merchant-grade phosphoric Acid (MGA) and Purified Phosphoric Acid (PPA). The one in Québec should focus on converting local igneous deposits into PPA for pCAM and CAM applications. The one in Western provinces (Alberta or BC) should handle regional feedstocks for fertilizer use and support a potential Western Canada's LFP supply chain.

Building Canada’s Rare Earth Element (REE) Supply Chain and Magnet Manufacturing Capacity

To establish a leadership position in the growing market for rare earth elements (REEs), Canada should focus on developing a centralized processing and magnet manufacturing hub, which could be built around the SRC’s initiatives in Saskatchewan. This strategy ensures alignment with global supply chain demands while leveraging Canada's resource base and technological expertise. A phased approach is critical, balancing immediate actions with long-term development, and a high level of coordination will be needed to establish this nascent domestic supply chain from the start.

- **Short-Term Reinforcement of Midstream REE Processing:** Import monazite concentrates and other REE-rich waste materials to maximize the production of individual rare earth oxides (REOs). Leverage existing Canadian facilities, such as the Saskatchewan Research Council (SRC) processing facility and Canadian IP, such as Ucore's technology, to refine REOs and establish a robust processing foundation.
- **Establish Magnet Manufacturing**: Use domestically processed REOs to build metalmaking, magnet manufacturing and magnetic powder production facilities. Build partnerships with material manufacturers, EV motor producers,

and OEMs to secure off-take agreements and ensure a reliable, customer-driven supply chain.

- **Develop Mining Capacities in the Medium Term:** Ramp up mining capacities by opening 3–4 REE mines, including projects in the Northwest Territories, BC, Saskatchewan and Québec to provide a consistent supply of high-grade REE concentrates. Maximize economic viability by selling value-added co-products alongside REEs. Ensure the centralized processing facility in Saskatchewan can handle feedstock from domestic mines, reducing dependency on international sources and strengthening the Canadian supply chain.

Unlocking Canada's Potential in Vanadium Recovery and Energy Storage Solutions

Canada has a unique opportunity to establish itself as a global hub for vanadium recovery, processing, and vanadium redox flow battery (VRFB) production. By leveraging existing industrial assets and its proximity to petroleum-based vanadium sources in Alberta, Canada can create a competitive vanadium value chain. This initiative supports the transition to clean energy and strengthens Canada's critical minerals sector.

- **Build Midstream Processing and Manufacturing Capacity:** In the short term, Canada should build vanadium processing and VRFB production capacities in Alberta. Establish a vanadium processing and recovery plant in the Alberta Industrial Heartland or Fort McMurray, and leverage proximity to the oil sands industry for a steady vanadium supply from petroleum residues.
- **Boost Vanadium Recovery from Secondary Sources:** Promote recovery from fly ash from coal and oil-fired power plants in Alberta, Saskatchewan, and the Maritimes. Ensure steady feedstock for the processing facility while reducing industrial waste.
- **Leverage Existing VRFB Assets:** Expand and integrate the capabilities of facilities like Invinity's Vancouver operation, VRB Energy's expertise and Vanadium Corp to jumpstart electrolyte and VRFB manufacturing and domestic deployment, with export opportunities.
- **Expand Primary Vanadium Supply in the Long Term:** Develop vanadium co-production and collaborate with iron, uranium, and aluminum mining operations in resource-rich provinces (BC, SK, QC, NL) to recover vanadium as a co-product. Support the titanomagnetite vanadium mine projects in Quebec. Establish supply chain linkages between vanadium mining, processing, and battery manufacturing to strengthen Canada's critical mineral resilience and value-added production capabilities.

2 Copper

2.1 The Canadian Strategy for Copper

2.1.1 Copper in Canada

Table 2.1.1 Non-exhaustive selection of operational and future copper extraction and processing projects in Canada

Selection of Operational Copper Extraction Sites

Project Name	Company	Province	Type	Status
Ming Mine	FireFly Metals	NL	Copper Sulfide, Underground	Operational
Kidd Mine	Glencore	ON	Copper Sulfide, Underground	Operational
Sudbury Operations (5 mines)	Vale	ON	Copper/Nickel Sulfide, Underground	Operational
Snow Lake-Lalor Mine	Hudbay	MB	Copper Sulfide, Underground	Operational
Copper Mountain Mine	Hudbay + Mitsubishi	BC	Copper Sulfide, Open Pit	Operational
Gibraltar Mine	Taseko	BC	Copper Sulfide, Open Pit	Operational
Highland Valley Copper Mine	Teck	BC	Copper Sulfide, Open Pit	Operational
Mount Milligan	Centerra Gold	BC	Copper Sulfide, Open Pit	Operational
Mount Polley	Imperial Metals	BC	Copper Sulfide, Open Pit, Underground	Operational
Myra Falls	Trafigura Mining	BC	Copper Sulfide, Underground	Care and Maintenance
New Afton Mine	New Gold	BC	Copper Sulfide, Open Pit, Underground	Operational
Red Chris	Imperial Metals	BC	Copper Sulfide, Open Pit, Underground	Operational

Many nickel deposits contain significant amounts of copper, which is why nickel plants can produce copper concentrates and products. Refer to the nickel chapter for more information.

Selection of Future Copper Extraction Projects

Project Name	Company	Province	Type	Status
Corner Bay Project	Doré Copper Mining Corp	QC	Copper Sulfide, Underground	PEA 2022
Gaspé Copper	Osisko Metals	QC	Copper Sulfide, Open Pit	PEA expected in 2026
Marathon Palladium & Copper Mine	Generation Mining	ON	Copper Sulfide, Open Pit	Amended FS 2024
McIlvenna Bay	Foran	MB	Copper Sulfide, Underground	FS 2022
Berg Project	Surge Copper Corp	BC	Copper Sulfide, Open Pit	PEA 2023
Galore Creek	Newmont + Teck	BC	Copper Sulfide, Open Pit	PFS 2025
KSM	Seabridge Gold	BC	Copper Sulfide, Open Pit, Underground	PFS 2022

Kutcho	Kutcho Copper Corp	BC	Copper Sulfide, Underground	FS 2021
Schaft Creek	Teck + Copper Fox Metals	BC	Copper Sulfide, Open Pit	PFS 2025
Yellowhead	Taseko	BC	Copper Sulfide, Open Pit	FS 2014, Updated 2019
NICO Cobalt-Gold-Bismuth-Copper Mine	Fortune Metals	NT	Copper Sulfide, Open Pit, Underground	Updated FS 2021
Casino	Casino Mining Corp	YT	Copper Sulfide, Open Pit	FS 2022

Selection of Operational and Projected Copper Metallurgical Plants

Project Name	Company	Province	Type	Status
Horne Smelter	Glencore	QC	Pyrometallurgy to copper anode	Operational
Montréal CCR	Glencore	QC	Copper electro-fining plant: Anode to Cathode	Operational
NICO Hydrometallurgical Plant	Fortune Metals	AB	Hydrometallurgy to copper cement	Updated FS underway

In 2022, Canada ranked 12th in global copper production, 16th in refining, and 13th in copper reserves. The 30 operating copper mines located nationwide, mining copper as a primary product or a by-product, mined an estimated 520,000 tonnes of copper in 2022, according to the USGS, or 511,000 tonnes, according to NRCan.[11,12] The Canadian export of copper-based products represented $9.4 billion the same year. Important players in the Canadian copper sector include Teck, Taseko Mines, Hudbay Minerals, Centerra Gold and Glencore.

Around 53% of the 2022 Canadian output came from British Columbia, while operations in Sudbury, Ontario accounted for 31%. The most significant operations are in British Columbia, with the Highland Valley Copper site, Gibraltar, Copper Mountain and Mount Milligan. Most deposits there are of the porphyry type with sulfide ores. Smaller operations exist in Newfoundland and Labrador, Manitoba, and Quebec.

Large copper mining projects have mainly focused on northern British Columbia's Golden Triangle/Copper Corridor. Those projects include Galore Creek, operated by Teck and Newmont; KSM, by Seabridge Gold; Kutcho, by Kutcho Copper Corp; Schaft Creek, by Teck and Copper Fox Metals; and Yellowhead, by Taseko. Casino is another very large mining project situated in Yukon. Foran is developing a copper-zinc mine project called McIlvenna in the Flin Flon greenstone belt but in east Saskatchewan. Finally, another project of interest is Fortune Metal's NICO mining and refinery project: the company plans to mine a deposit of cobalt, bismuth, copper and gold in the Northwest Territories, and refine the concentrates in a hydrometallurgical facility in Alberta's industrial heartland to produce copper cement, on top of cobalt sulfate, bismuth and gold doré.

Canada's only remaining copper metallurgical facility is the Glencore-owned Horne smelter in Rouyn-Noranda, Quebec. The feedstock can be a mixture of copper ores sourced from Glencore's Sudbury operations and scrap. Since 1975, the Noranda reactor plant has been producing a high-grade matte which, since 1988, has been converted in the Noranda continuous converter to blister copper. A sulfuric acid plant is also integrated into the facility.[13] The impure copper anodes are then transported to the CCR refinery in Montreal, the only existing Canadian copper electro-refinery. In addition to refining copper anodes to cathode copper, the plant also produces refined silver, gold, selenium, tellurium, as well as platinum/palladium concentrate.

Table 2.1.2 Canadian mine production of copper contained in concentrates, by province and territory in 2022[12]

Province	**Provisional Production in 2022** (tonne x 10^3)	**Percentage**
British Columbia	270	52.8%
Ontario	159	31.2%
Newfoundland and Labrador	22	4.2%
Manitoba	20	4.0%
Others	40	7.8%
Total	**511**	**100.0%**

2.1.2 Targets

Our previous report, 'Roadmap for Canada's Battery Value Chain,' did not specify objectives for copper. In the present study, we used the same target: Canada reaching 10% of the 2030 North American EV market as a baseline and a potential leader scenario aiming at 35%. The exact vehicle fleet modelling and EV market penetration assumptions were made, this time using estimates of copper content in different EVs from a 2022 S&P analysis.[14] Canada hosts significant resources that can be developed in BC, but the province lacks accompanying metallurgical processing capacity.

Copper Mandated Benchmark (10% of 2030 North American Market)		
	2030	**2040**
Copper (ktpa elemental)	75	153
Copper Leader scenario (35% of 2030 North American Market)		
Copper (ktpa elemental)	263	535

2.1.3 Scenario Outline

Canada already has expertise in copper mining, processing and refining. However, the copper processing rate has declined since the Hudbay Flin Flon smelter closed in 2011. The Kidd Creek copper smelter in Timmins, Ontario, closed one year earlier in 2010. There has been a slow but steady decrease in copper mining output since then. A future scenario for the copper industry in Canada would include accelerating near-term copper production, boosting the midstream segment by integrating BC copper corridor operations in a new metallurgical plant, and developing a longer-term pipeline of mineral supply.

- **Accelerate Near-Term Copper Production:** Advance life extensions and expansions of current copper mining operations while supporting the implementation of mining projects in development, especially in BC, and expand concentrate production.
- **Boost the Midstream Segment by Building a New Metallurgical Plant:** All the copper concentrate produced in British Columbia is shipped overseas, mostly to China, for processing. However, enough copper concentrate is produced in British Columbia to justify the development and operation of a new copper smelter, provided suitable economic conditions can be found to justify such a change. Building a new, clean, pyrometallurgical plant in BC, taking feed from the existing and projected material, plus scrap, would securely advance the Canadian copper supply chain. A cost/benefit analysis would be required. mines, projected ones, and scrap would advance the Canadian copper supply chain. If the social mandate does not allow it, supporting R&D and optimizing viable hydrometallurgical operations of copper sulfide should be pursued. Scaling existing operations, such as the Horne smelter and Montreal copper refinery, should also be supported.

2.1.4 Signature Projects

- Advance life extension and expand current mines and smelter
- Develop several mining projects in BC and YT
- Build a large copper metallurgical facility in BC

2.1.5 Strategic Priorities

Extend and Expand Current Copper Operations:

- **Extend the life** of currently operational copper mines operations in BC, ON & MB.
- **Support the expansion** of currently operational copper mines. The modernization and expansion of Horne smelter in Quebec should also be supported.

Copper Corridor: Develop Mining Operations at Scale in British Columbia:

- **Developing substantial mining operations in British Columbia** could involve establishing a network of mines capable of consistently supplying a local copper smelter or hydrometallurgical plant. The chemical collaboration metallurgical complex described below could be this midstream facility. This long-term strategy would ensure a steady flow of raw materials, foster regional economic growth, and create numerous job opportunities within the mining and processing sectors.
    - Advanced Projects such as Galore Creek, Schaft Creek, Kutcho, KSM or Yellowhead in BC, and Casino in YT should be supported.
- **Fund exploration of copper deposits:** to keep pursuing the discovery of new viable deposits for the long-term supply.

Develop a Copper Metallurgy Plant in British Columbia: Probably a smelter, perhaps a leaching plant, and potentially a mix of both.

The collaboration described here can involve mutualizing industrial processes to handle copper concentrate from various mines sourced locally or even internationally. The goal is to convert these concentrates into copper intermediates, such as matte, blister, cathode, or other forms, within a centralized metallurgical hub. This approach aims to achieve scalability and maximize the economic viability of the operations by pooling resources and optimizing processing techniques.

Identifying the most suitable technological pathways that align with the selected scenario is crucial. These pathways include options like smelters and/or hydrometallurgical plants.

- **Pyrometallurgy:** Smelters are advantageous because they can process various input feeds, including scrap. However, they were often perceived as having significant environmental drawbacks, including releasing greenhouse gases (GHG), sulfur dioxide and other pollutants like metal dust. In 2025, a modern copper smelter can be built with the highest environmental standards; a review of advanced plants in Europe or Japan could testify to this situation. Such a plant would produce sulfuric acid either for the chemical industry or as feedstock necessary for hydrometallurgical operations. Thus, a smelter handling copper concentrates to produce anode copper could be considered in BC. Further electrorefining can be carried out on-site or at a different location, depending on several factors, including access to affordable green electricity.
    - Around 100–200 ktpa minimum of contained copper in feed material is considered convenient for a smelter to reach a viable scale; there is currently available material of this quantity in British Columbia. With the new mines coming online, there is a case for investigating the building of a new copper metallurgical plant in British Columbia.
    - Commercial smelters buying concentrates on the market often sometimes operate on thin margins; an integrated business of owning mines and processing plants could be considered.vA joint venture or cooperation arrangement could also be considered.
    - Finding an off-taker or a market for the sulfuric acid by-product would be required.

    - British Columbia hosted several copper smelters around the turn of the last century, including the Trail region, until WWI.
    - Low Treatment Charges (TCs) and Refining Charges (RCs) can be an issue. In the short term, global copper smelting capacity is under utilized, and many smelters' economic model is to buy copper concentrates on the international market and smelt an agreed number of tonnes according to a TC rate. TCs are predicted to be low in 2025, making short-term viability of copper smelting difficult.[15]
    - If the economic viability and environmental assessment are valid and a social mandate allows it, a smelter project should be advanced in BC.
- **Hydrometallurgy:** In contrast, hydrometallurgy of sulfide ores is tailored to specific mineralogy and requires substantial investment in research and development to be effective. This method also involves high costs for scaling up operations, making it a less flexible but potentially more environmentally friendly option, depending on the leach residue.
    - Hydrometallurgical processing of sulfide ores is technically viable, with options such as pressure oxidation, which Sherritt developed in the 1980s. Dynatec and CESL also pursued research. However, no commercial-scale plant was built. They could potentially operate at a smaller scale than smelters.
    - Hydrometallurgical plants can have significant environmental issues that need careful attention in a new facility. These include safe handling and storage of leach residues and control of liquid effluents. Environmental concerns linked to sulphur dioxide or metal dust are non-existent in this case.
    - Hydrometallurgical plants can cleanly treat high-arsenic copper concentrates. This was previously a limit for pyrometallurgy, but modern smelters can also treat those concentrates, provided correct safeguards are in place.
    - Barriers against hydrometallurgical plants can include an expected lower potential economic viability of operations, lower recovery of precious metals, and the reluctance of industry players to choose this pathway.
    - A technical, economic and environmental trade-off would be required to choose a pathway between pyrometallurgy and hydrometallurgy.
- **Using Both Routes:** A metallurgical complex merging both routes could be an option: smelting ores of various grades and mineralogy while feeding a nearby hydrometallurgical plant with the sulfuric acid necessary for treating some specifically complex ores, perhaps imported.
    - The potential for the processing of concentrates or intermediate materials from outside the country could be examined. This might be interesting for **the processing of high-arsenic ores from overseas**, which could benefit from being treated more sustainably on Canadian territory. This strategy is already in place for other metals, such as nickel intermediate materials from Cuba being treated at the Fort Saskatchewan plant operated by Sherritt.
- **Scrap Intake:** Regardless of the option, scrap should be integrated as a feedstock to promote a higher level of circularity.

- **Clean Power:** If inexpensive and abundant clean electricity is available, a copper refining facility for electrorefining and/or electrowinning can be integrated to produce high-purity copper cathodes.
- **Copper Refining:** An electro refinery (similar to for example, the copper refinery in Montréal) can potentially be built if a smelter is considered. However, it does not need to be co-located with the smelting operation. If the copper processing plant is a leaching process, then an electrowinning operation producing cathode copper will likely be integrated. In both cases, low-cost electricity is advantageous, and electrowinning requires more power per tonne of copper than electrorefining.
- **Copper Cementation:** An alternative route to copper refining could be optimized copper cementation/precipitation from Cu(II) solution. This can theoretically bypass the need for electricity. Cementation is a known process, but it was previously not possible to obtain adequate copper purity without refining. Optimized copper precipitation, such as processes developed by Canadian company Destiny Copper, can reach a high-purity copper powder product. This could support *in situ* leaching in some mines, scrap leaching, and recycling, and it could even potentially become an alternative for copper electrorefining and electrowinning.
- **Brass Mills & Copper Mills:** Should also be integrated to the value chain.

Developing Synergies Between Industries:

- **Producing Sulfuric Acid:** A copper smelter can enhance its profitability by generating additional revenue through the resale of sulfuric acid. The difficulty relies on the fact that this could be market-dependent. Still, another solution is to co-locate an industry with sulfuric acid needs nearby, such as chemical facilities or a hydrometallurgical plant. As mentioned above, the acid byproduct can be utilized in a hydrometallurgical facility, including processing and refining other metals or further copper operations.
- **Processing Pyrites:** Copper mines have the potential to capitalize on pyrites contained in the same deposit as copper-bearing ores by converting them into sulfuric acid. This process not only adds value to what might otherwise be a waste product but also contributes to the performance of the mining operation.

Exploiting Canadian Opportunities:

- **Canada's High Sustainability Standards:** Leveraging the higher sustainability standards prevalent in Canada, such as those outlined in the Towards Sustainable Mining (TSM) initiative by the Mining Association of Canada (MAC), can provide a significant competitive advantage. These standards ensure environmentally responsible practices, enhancing the reputation and marketability of Canadian copper products.
- **Refining Where It Makes Sense:** As mentioned above, establishing electrolytic refineries in regions where the electric grid is both clean and affordable can significantly enhance operational efficiency. These refineries can take advantage of renewable energy sources, reducing their carbon footprint and operational costs.

- **Regional Market:** Taking advantage of the extensive North American market and the availability of scrap feedstock can facilitate a steady supply of raw materials, ensuring continuous production.
- **Infrastructure & Logistics:** Access to well-developed sea and railway networks can optimize logistics for export activities. Efficient transportation options enable timely and cost-effective delivery of copper products to global markets.

Research and Development:

- **Involving Academia:** Increasing funding at the university level to support graduate research is essential for driving innovation within the sector. Fostering robust academic-industry collaboration will enhance overall efficiency and sustainability and build capacity to refine and implement new process technologies.
- **Incentives for Innovation:** Setting up incentives for research and development can encourage private and public sector investment in innovative technologies and processes. These incentives can take the form of grants, tax breaks, or subsidies to reduce the financial burden on companies investing in R&D.
- **Copper Sulfide Hydrometallurgy:** While at present all copper sulfide ore are subjected to a mineral flotation step to produce a copper concentrate for smelting, researching copper sulfide ore leaching could lead to the development of a new economically viable hydrometallurgical route at site. This research can lead to breakthroughs in processing low-grade ores, making previously uneconomical deposits feasible for mining. Optimizing recovery of other metals or leach residue management could be a competitive advantage.
- **Process Tailings:** Developing advanced technology for reprocessing tailings where economically feasible can help recover additional value from mining operations. This approach maximizes resource utilization and mitigates the environmental impact of tailings storage.

Strengthen Competitivity:

- **Bolstering Competitiveness:** Ensuring competitiveness in energy, equipment, and labour is crucial for maintaining an edge in the global market. This involves investing in efficient technologies, securing affordable energy sources, and maintaining a skilled and productive workforce.
- **New Technologies:** Investigating the potential of artificial intelligence (AI) and robotic equipment to reduce operational costs can lead to significant efficiency gains. Automation and AI can optimize mining and processing operations, reducing labour costs and increasing precision and safety.
- **Energy Access**: Securing access to low-cost energy sources is essential for maintaining cost-effective operations. Companies can reduce operational expenses and environmental impact by exploring renewable energy options or negotiating favourable energy contracts.

Circularity:

- **Circular Copper Economy:** Designing an integrated circular value chain for copper is essential to enhance recycling and resource efficiency. Current systems in Canada face challenges related to logistics and supply chain coordination, which need to be addressed to facilitate easier recycling. Given that the market may or may not provide Canada with a technical advantage in recycling, Canada should establish policies and regulatory conditions that best support recycling.

- **EPR:** Enforcing Extended Producer Responsibility could significantly enhance copper recycling rates. This approach requires producers to take responsibility for the end-of-life disposal of their products, similar to the highly integrated and recycled lead batteries used in internal combustion engine (ICE) vehicles.
- **Analysis:** Developing a comprehensive strategy based on existing circularity analyses, such as those conducted by the International Council on Mining and Metals, can provide a robust framework for improving recycling practices and resource efficiency.
- **Scaling Up Recycling:** Considering end-of-life and scrap copper at regional and North American scales can optimize recycling efforts. This approach ensures that recycling systems are efficient and effective at multiple local and continental levels.
- **Tax Credits:** Taking advantage of tax credits and grants from provincial and federal governments based on local job creation for secondary smelter projects can provide significant financial benefits. Programs similar to the support given to Indiana's Exurban Secondary Copper Smelter project by the Indiana Economic Development Corporation in the United States can serve as models.

Coordination with the Government:

- **Coordination Between Industry and Different Levels of Government:** Strengthening coordination between industry and government is vital for refining and implementing an effective strategy. Regular consultations and collaborative efforts can help align industry needs with government policies and support mechanisms. Coordination between the different levels of government (federal and provincial) is necessary.
- **Closer Ties with the Federal Government:** Fostering closer ties with the federal government is essential to effectively communicating the needs and priorities of the mining and metallurgy sector. Coordination across federal government departments is also necessary. This can facilitate the development of supportive regulations and incentives that drive industry growth.
- **Supporting Policies:** Government policy should include tax incentives and assistance providing land to support industry growth. These measures can lower operational costs and encourage investment in new mining and processing projects

Regulatory Framework:

- **Balanced Regulations:** The regulatory framework should be competitive with similar Western countries and not overly restrictive. A balanced approach to regulation can ensure environmental protection while fostering innovation and growth within the mining and metallurgy industry.
- **Indigenous Rights and Adding Certainty:** Pursue regulatory frameworks that appropriately reflect Indigenous rights while increasing certainty for communities and companies involved.

2.2 The Role of Copper: A Conductive Metal Driving Electrification

2.2.1 General Properties

Copper, a reddish metal, stands out for its remarkable electrical and thermal conductivity, which is second only to silver. Its relative resistance to corrosion and outstanding ductility makes it highly workable. A desirable property of copper is that it retains its chemical properties even after use, making it easily recyclable. Copper's properties are significantly influenced by its purity and source, with variations arising from factors such as oxygen content, impurities like arsenic and bismuth, and the thermal and mechanical treatment of the metal.[16,17]

It was the earliest metal found and used in its native form by humans, dating from 8700 BCE in Iraq. The development of early metallurgical processing, specifically the smelting of copper ores, marked the end of the Neolithic age and the beginning of the Chalcolithic age. Although copper is easy to work with, its softness made it less ideal for tools and weapons, leading to the use of significantly tougher bronze, a copper alloy containing around 12% tin. The high malleability and workability of brass, another copper alloy comprising 5–40% zinc, was also uncovered around the bronze age and later widely spread throughout the Roman world for coinage and military purposes. As iron metallurgy developed and supplanted the use of bronze, pure copper became less popular for millennia. It was only with the advent of electricity by the mid-19th century that the outstanding electrical conductivity of copper made it the metal of choice for wires and conductors.

Copper is essential for various biological functions, including enzyme activity and the development of red blood cells, collagen, and the central nervous system.[18] Copper deficiency can lead to serious health issues, while acute copper toxicity is rare.[19] Chronic exposure is typically non-problematic, except in specific conditions like Wilson's disease or vineyard sprayer's disease, an occupational exposure affliction caused by workers applying copper sulfate and lime as a fungicide to grape vines. Copper and copper alloy surfaces have shown effective antimicrobial properties, controlling various moulds, algae, bacteria, and harmful microbes, thus reducing hospital infection rates.[20–22]

2.2.2 Role in Clean Technologies and Energy Storage

With the need to transition to a low-carbon economy, a scaled-up and more widespread electrification based on cleaner energy sources appears as a solution. This is why copper, a crucial element for electricity production (copper coils in generators), conversion from electrical to mechanical energy (copper windings in motors) or conduction (copper wirings), is considered an element of significant priority. Indeed, copper, along with steel, is the most widely used metal in different clean energy technologies.[23–26] The consensus is that copper is critical for the electricity grid and networks, as well as for solar photovoltaic, wind power, electric vehicles, and bioenergy. In contrast, copper's more moderate but significant role is recognized for hydroelectric, geothermal, nuclear, concentrated solar, and components in hydrogen electrolyzers.

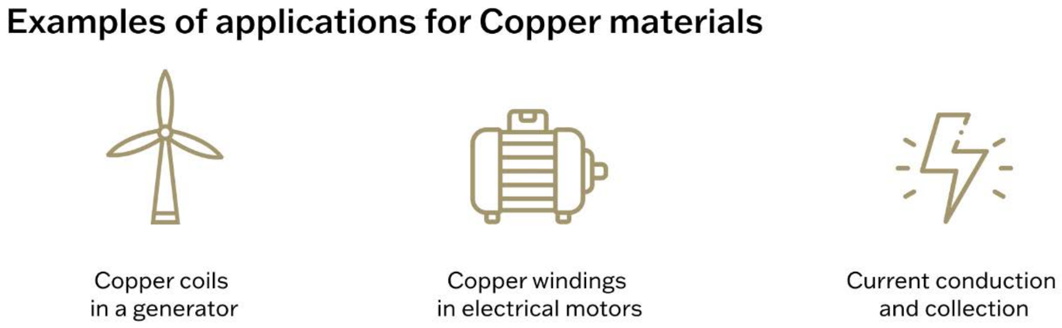


Figure 2.2.1 Examples of applications for copper materials

In general, low-carbon electricity production and clean technologies are also more copper-intensive than fossil fuel-generated electricity: producing 1 TWh of energy from solar and wind could consume 300% and 200% more equivalents of copper than 1 TWh from a gas power plant,[26] or even more.[27] In those cases, copper is needed for the wiring, cables, turbine, and transformer of a wind turbine and the heat exchanger, as well as for the wiring and cabling of a solar panel. The widespread use of copper throughout diverse clean energy techniques and the material intensity of those technologies highlight the crucial importance of the copper supply chain for the energy transition.

Similarly, producing battery or fuel-cell electric vehicles is more copper-intensive than building an internal combustion engine (ICE). A 2022 S&P Global analysis estimated that light-duty battery-electric vehicles contain 60 kg of copper per vehicle, compared to 24 kg for an ICE vehicle.[14] Other studies confirm the higher copper intensity of both hybrid and battery-electric vehicles.[28,29]

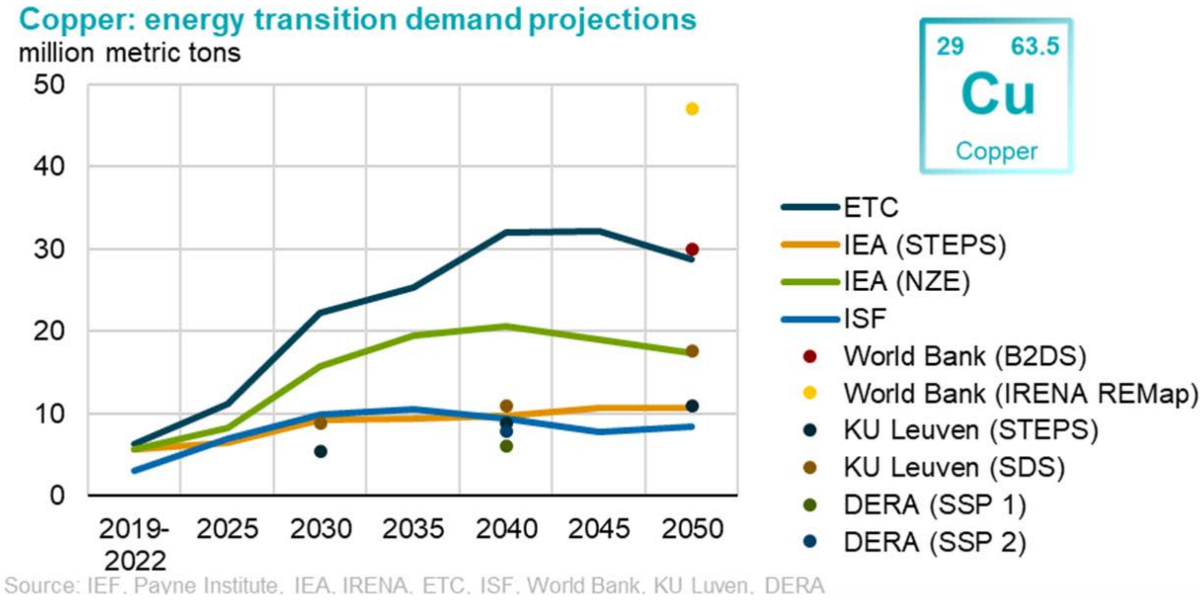
Copper is generally found in three parts of EVs: the motor, the wiring connections of electronics and battery packs, and inside the battery.[30] EV motors contain more than a mile of copper wiring in the stator windings (the static part of the motor). This is where the electrical current is converted to a rotating magnetic field that can drive the movement of the rotor.[30] For Li-ion batteries, copper foil is used as a current conductor for the graphite anode, while aluminum foil is used for the cathode for better stability. The copper current collector makes up around 8% of the weight of the total battery and has a thickness of 6–20 μm. This foil can reach 35 kg of copper for mid/large-sized EV batteries.[31] Thinner foils improve efficiency but are more challenging to obtain.[32] Future opportunities include replacing a flat sheet structure with either meshes or foam.[33] Surrounding the actual battery, busbars, cables and wiring made of copper are also required for the overall battery pack.

Autonomous electric vehicles will require various sensors, such as radar, lidar, or cameras. Each sensor requires printed boards using 50–100g of copper and additional wiring.[34] Furthermore, the multiplication of charging stations for EVs will also increase copper cabling demand.[27]

2.2.3 Substitutes

The properties of copper make it difficult to substitute. Still, aluminum is generally considered in some cases as an adequate candidate for replacing copper wirings, as it is cheaper, more abundant and lighter (30.5% the density of copper). It is the most common conductor used for transmission lines.[35–37] Aluminum wiring was also popular in North America during the 1960s—1970s but was phased out due to fire hazards and faulty installations.[38] The main drawbacks include a lower conductivity (only 60% as conductive) and more brittleness, pressing for ongoing research to create more conductive aluminum materials.[39] Aluminum production processes are also more GHG-emitting than copper processing, and aluminum cannot replace copper for anode current collectors or subsea and underground cables. Plastics and aluminum are also used as replacements for copper pipes and plumbing, as well as titanium and stainless steel for heat exchanger applications.

2.2.4 Supply and Demand



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Figure 2.2.2 Copper demand projections to 2050 according to various energy transition scenarios[40]

The difference between the increased demand for copper and the projected production will lead to a problematic gap, also called the *copper crunch*. In a 2023 analysis, McKinsey projected 36.6 million tonnes of global copper demand by 2031, while current supply projections forecast 30.1 million tonnes the same year.[41] In their critical minerals report and mineral outlook, the IEA also estimated a comparable gap,[23] reaching a 4.5 Mt shortfall by 2030 in their NZE scenario. In all scenarios, this gap would only worsen in the future decade.[42] S&P Global Market Intelligence forecasted that the demand might rise to 50 million tonnes by 2050, and the potential supply gap could be as large as 9.9 million tonnes by then.[14] In general, more copper production than the projected one by accounting for current projects will be required. Some aggravating factors for this issue are that most mines' copper content grade is declining over time and that the development time necessary for opening new projects can take around 17–20 years on average from discovery to production.[23,43,44] Supply risks are also increasing, notably for copper from Latin America, due to social and environmental issues and water stress challenges.

2.3 The Copper Flowsheet: From Sulfide and Oxide Ores to Wires

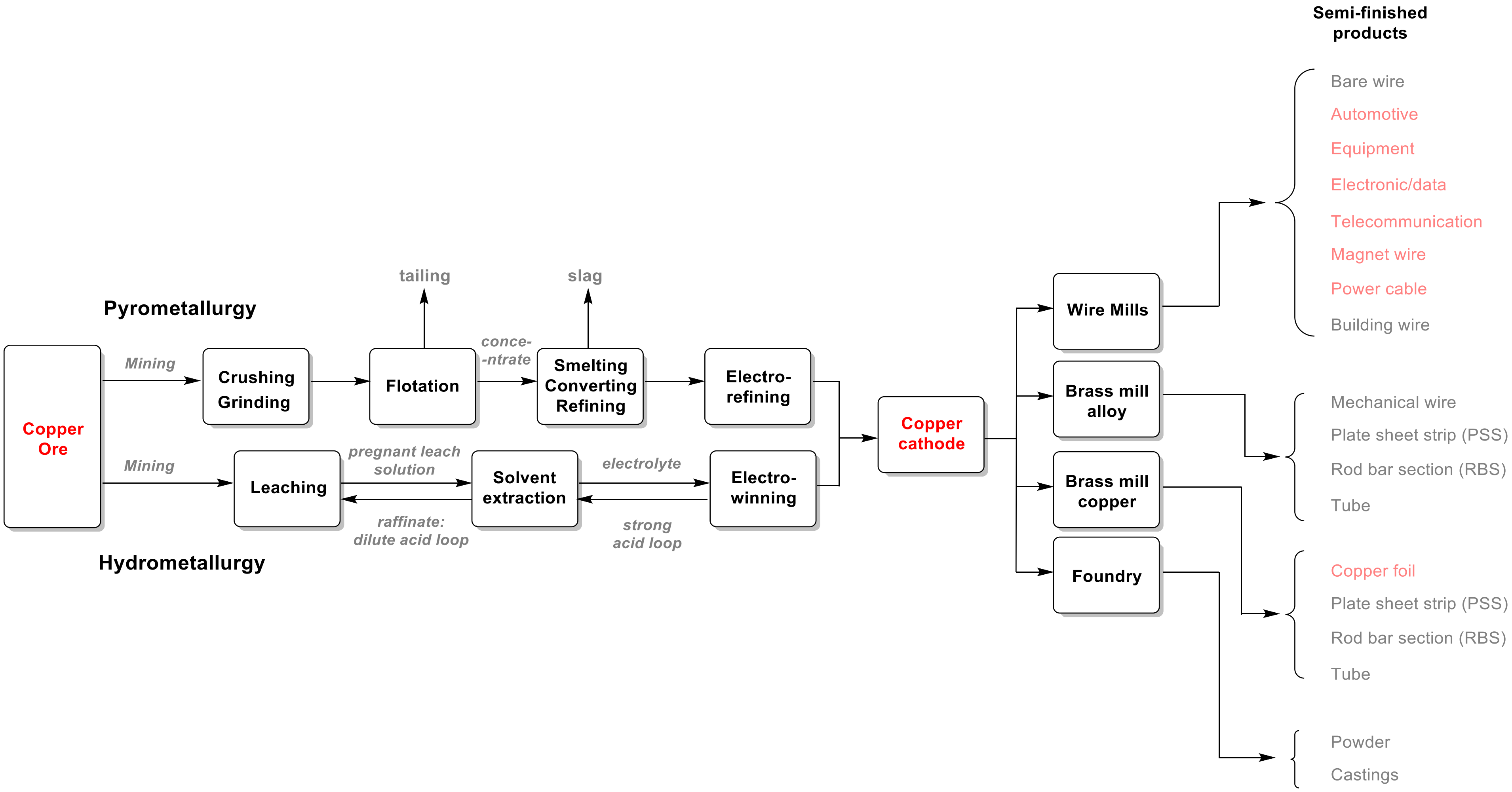


Figure 2.3.1 Simplified flowsheet of copper

2.3.1 Ores, Reserves and Mining

Copper is the 26th most abundant element in Earth's crust, twice as abundant as cobalt. It is moderately accessible, and given the known resources, it is highly improbable that we will run out of copper.[45]

Copper deposits can be classified according to their geological formation: ores are either of magmatic or sedimentary origin. Magmatic formations include liquid magmatic ores (such as the Ni-Cu ores in Sudbury, ON), pegmatitic ores, deposits from submarine volcanic exhalations, and hydrothermal ores (Chile, Peru, Mexico, Utah, Arizona, British Columbia). The latter, also called porphyry ores, are disseminated in igneous intrusions, forming small particles, fractures, and veins. Those deposits generally contain less than 1% copper, representing around two-thirds of global copper resources and 50–60% of production.[16,46] Sedimentary deposits comprise sandstones, partly metamorphized sedimentary ores (African copper belt), marine precipitates and deep-sea concretion nodules.

In terms of mineral formation, copper has a strong affinity for sulfur and often forms sulfide compounds, such as chalcopyrite $\mathbf{CuFeS_2}$, chalcocite $\mathbf{Cu_2S}$, bornite $\mathbf{Cu_5FeS_4}$, covellite $\mathbf{CuS}$. About half of the global copper output is from chalcopyrite.[46] Copper oxides include azurite $\mathbf{Cu_3(CO_3)_2(OH)_2}$, chrysocolla $\mathbf{(Cu,Al)_2H_2Si_2O_5(OH)_4 \cdot \mathit{n}H_2O}$, malachite $\mathbf{Cu_2CO_3(OH)_2}$, cuprite $\mathbf{Cu_2O}$ and tenorite $\mathbf{CuO}$. Oxides were formed near the surface when copper minerals came into contact with water. Sulfides, particularly chalcopyrite, are difficult to process through hydrometallurgical methods, so most copper production was generated through smelting. While oxides ores can be technically treated by smelting, as was carried out in the not-so-distant past, the preferred economic method today is by leaching.

Table 2.3.1 Reserves, production, and refining of copper by country in thousands of tonnes[11]

Country	**Mining Production in 2022**[a] (tonnes x 10^3)	**Country**	**Refinery in 2022**[a] (tonnes x 10^3)	**Country**	**Identified Reserves in 2024**[a] (tonnes x 10^3)
Germany	/	**Canada**	**278**	Germany	/
Japan	/	Indonesia	310	Japan	/
Korea	/	Zambia	349	Korea	/
Poland	393	Peru	391	**Canada**	**7,600**
Canada	**520**	Australia	401	Kazakhstan	20,000
Kazakhstan	593	Mexico	486	Zambia	21,000
Mexico	754	Kazakhstan	494	Indonesia	24,000
Zambia	797	Poland	586	Poland	34,000
Australia	819	Germany	609	China	41,000
Russia	936	Korea	638	United States	50,000
Indonesia	941	United States	952	Mexico	53,000
United States	1,230	Russia	1,010	Congo (Kinshasa)	80,000
China	1,940	Japan	1,550	Russia	80,000
Congo (Kinshasa)	2,350	Congo (Kinshasa)	1,770	Peru	120,000
Peru	2,450	Chile	2,150	Australia	100,000
Other countries	2,850	Other countries	2,830	Other countries	180,000
Chile	5,330	China	11,100	Chile	190,000
World total (rounded)	**21,900**	**World total (rounded)**	**25,900**	**World total (rounded)**	**1,000,000**

[a]Data from the 2024 U.S. Geological Survey.[11]

In terms of production companies, the copper sector is not as concentrated as that of other critical minerals. According to the latest data from the United States Geological Survey, Chile continues to lead in copper ore mining, accounting for 24% of global output in 2022.[11] Peru (11%), DRC (11%), China (9%), and the U.S. (6%) are the key actors in copper mining. Moreover, the top four copper mining companies, Freeport-McRoran, BHP, Codelco, and Anglo American, represent less than 30% of global output, showing a relatively diversified sector.[47] However, copper smelting and refining are primarily dominated by the Chinese industry, which accounts for 43% of refined copper produced in 2022. Other leading refining countries do not compare in scale. In addition to being a leading miner and refiner, China accounts for approximately 54% of the global refined copper consumption.[48] Worldwide copper reserves are primarily localized in South America, with Chile and Peru making up 31% of global reserves, while Australia, Russia and the DRC hold significant accessible reserves. Canadian reserves are quite small, about 1% of total world reserves.

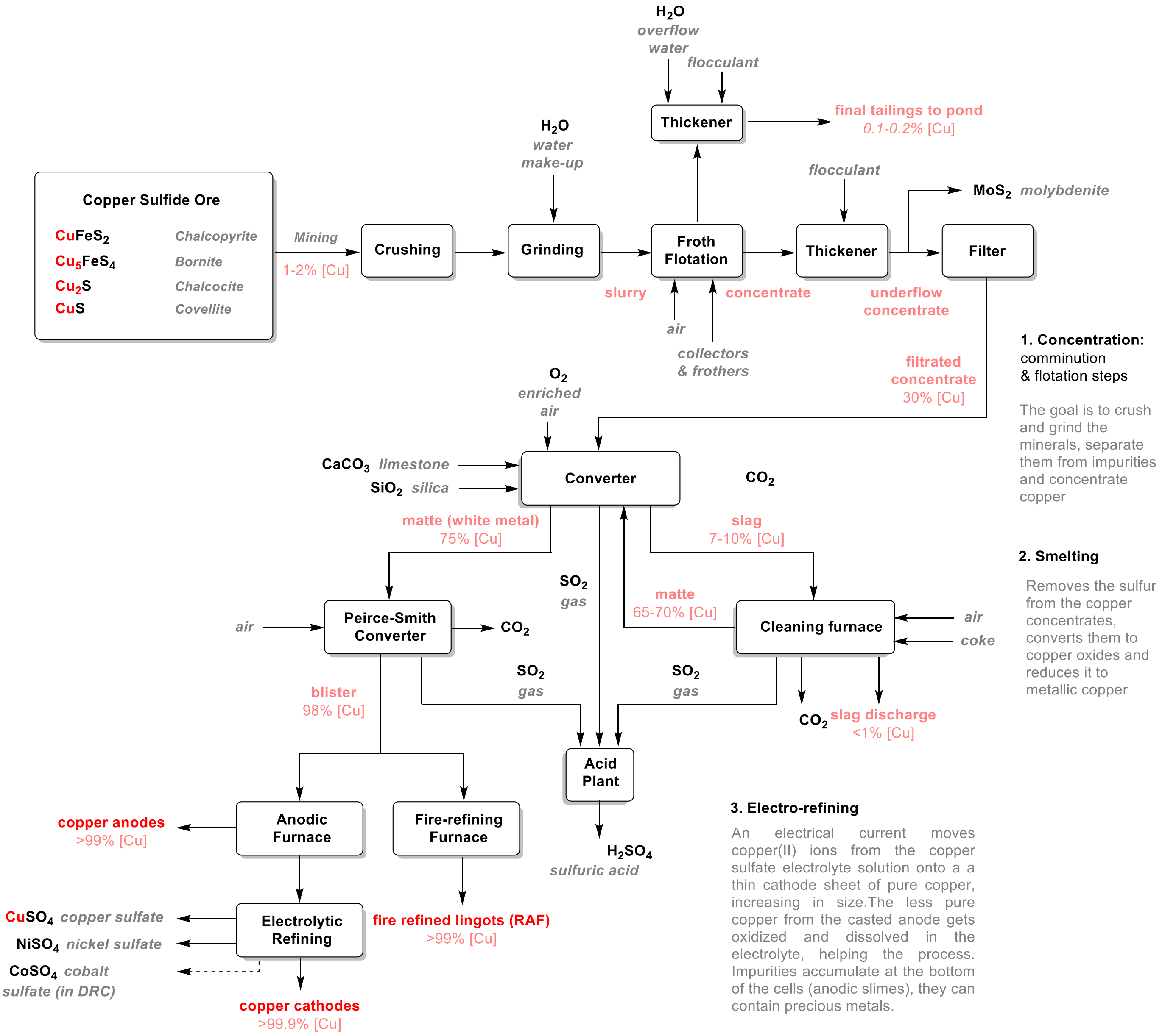
The majority of global copper output comes from mega-mines that can reduce costs with large-scale capacity and economies. This is the case for Chile, home to two of the largest three copper mines in the world. For instance, the open-pit Escondida mine, owned by BHP, Rio Tinto, and JECO, contributed 7% of global copper production in 2020.[49]

Several factors affecting the copper extraction segment can threaten global value chains. First, a global decrease in ore quality and copper concentration pushes production costs upwards, increasing the quantity of tailings and the cost of emission controls.[50] Secondly, as over one-third of copper supply originates from South America, interruptions in operations there can have global repercussions. Social and labour unrest in Chile over the past 5 years have impacted copper supply and prices.[51,52] Public dissatisfaction with the royalty arrangements as well as local disagreements related to environmental performance led to the shutdown of the Cobre Panama mine, the 16th largest copper mine in 2020.[53] Thirdly, copper, like lithium, is particularly exposed to climate risks and water stress: mines in South America, Zambia and Australia overlap regions recognized by the IEA as having high to extremely high water stress levels, and 80% of copper output in Chile is concerned by this issue.[54] Fourthly, copper supply can be locally intimately tied to the supply of other critical minerals: this is the case for cobalt and copper in DRC, where around 70% of cobalt is extracted as a by-product of copper mines.[50] Molybdenum is also an important by-product of copper mining.

2.3.2 Processing

Two main metallurgical routes are presently in use. The **pyrometallurgy** of copper sulfides requires concentration of the mineral before smelting and conversion, which results in **copper matte and blister**. The following **electro-refining** step will produce purified copper anode products necessary for wire or foil manufacturing. **Hydrometallurgical routes**, traditionally used for copper oxide ores, follow an acid-leaching and solvent extraction process to obtain and concentrate **copper sulfate**, resulting in a pure copper cathode after **electrowinning**. Commercial processes can be either heap leaching or dump leaching, leaching methods based on sulfide ores are under development.

2.3.2.1 Pyrometallurgy



1. Concentration:
comminution
& flotation steps

The goal is to crush and grind the minerals, separate them from impurities and concentrate copper

2. Smelting

Removes the sulfur from the copper concentrates, converts them to copper oxides and reduces it to metallic copper

3. Electro-refining

An electrical current moves copper(II) ions from the copper sulfate electrolyte solution onto a a thin cathode sheet of pure copper, increasing in size.The less pure copper from the casted anode gets oxidized and dissolved in the electrolyte, helping the process. Impurities accumulate at the bottom of the cells (anodic slimes), they can contain precious metals.

Figure 2.3.2 Flowsheet of the pyrometallurgy of copper

Copper sulfide concentrates are typically treated through pyrometallurgical steps, *i.e.* smelting. This is the traditional way of obtaining copper and is still the mainstream category of technology used today. The main copper sulfide minerals present in sulfide ore is predominantly chalcopyrite. However, bornite, chalcocite, and covellite can also be present.

The concentration of copper ores comprises comminution and flotation steps. The goal is to crush and grind the minerals, and concentrate by flotation the copper content from 0.5–2% to around 20–40%. Water, flocculants, air, frothers, lime and collectors are necessary for those processes, while dried and filtered copper concentrate is produced, and tailings are stored near the mine. Molybdenum can be separated at this stage for further processing. While most concentrators are also co-located with the mine, in former times, the smelter was typically located at the mine site. An example being the Gaspé smelter in Canada (now closed, which commenced operation in the 1950s. With the rise of custom smelter plants, in particular after WW2, the smelter is now typically distant from the mining site. This is the situation in British Columbia.

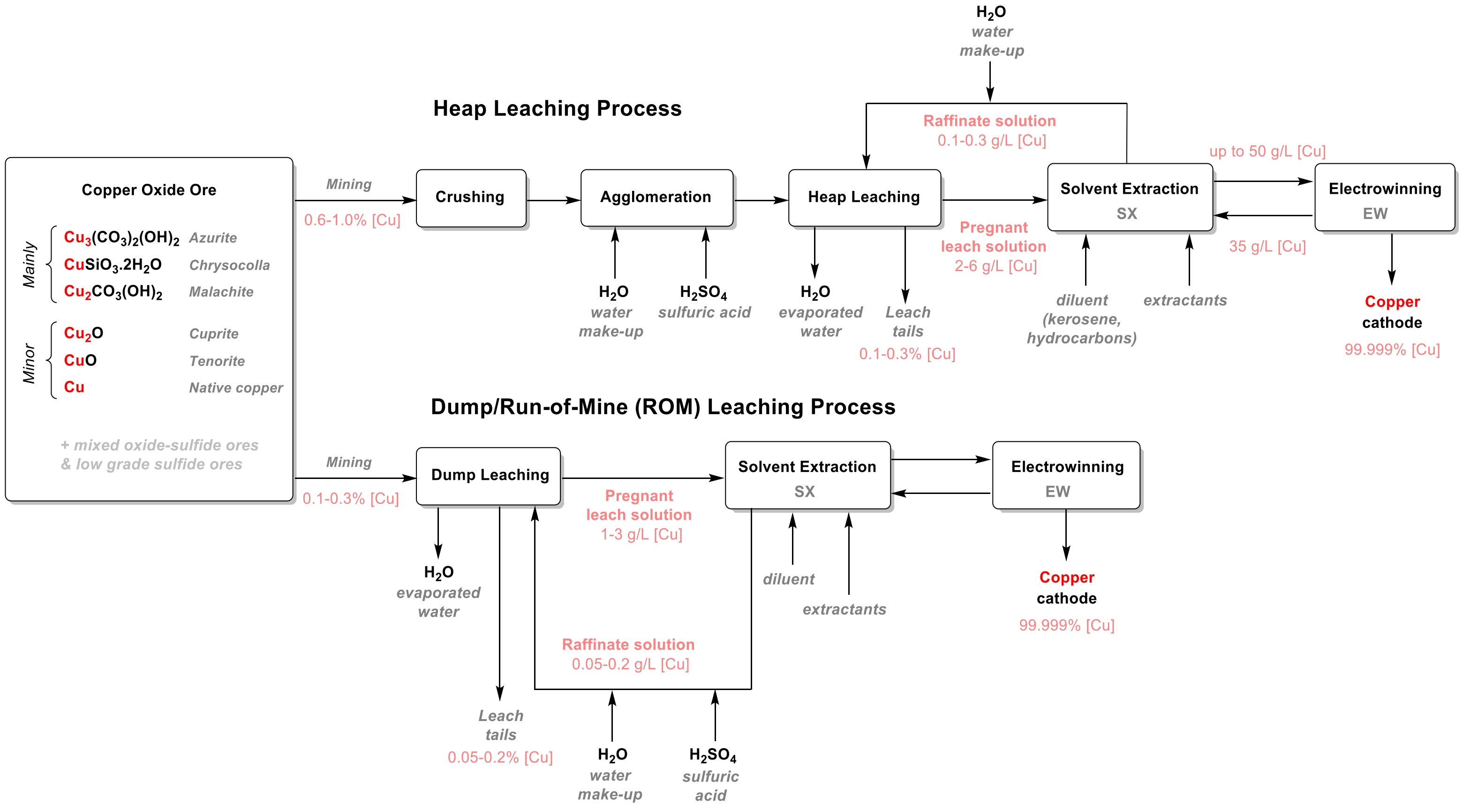
After concentration, copper is then smelted and converted. The chemical reactions occurring during the smelting processes aim to remove sulfur, iron, and silicates from the copper concentrate, and reduce it to metallic copper, either as a matte product (75% Cu) after smelting or blister product (98% Cu) after subsequent converting. Iron and silicate are separated in the slag, which is discarded, while sulfur is oxidized to sulfur dioxide gas $\mathbf{SO_2}$, which can be captured to produce sulfuric acid. If not recycled, sulfur dioxide gas can be toxic and responsible for acid rain. Arsenic emission can also be a concern, depending on the ore mineralogy. Fossil fuels such as coal, fuel oil, or natural gas are necessary for heating and as a reducing agent; thus, most processes emit GHG. Fluxes such as limestone, silica, or dolomites are also essential inputs, as they help to form more liquid slag.

Smelting operations are evolving, with various advanced technologies in use. Traditional reverberatory smelting, such as employed at the above-noted former Gaspé smelter, is no longer in use. Flash and bath smelters are among the main technologies. In 2022, flash technologies accounted for 66% of smelting operations. Notably, newly developd bath smelting Chinese technologies, are projected to contribute about 23% of smelting capacity by 2027. China, a significant player in the industry, produced nearly 50% of the world's smelted copper in 2022 and is home to 9 of the largest 20 copper smelters globally.[45]

After smelting and conversion, blister copper can be either fire-refined and melted as lingots for sale or cast in the shape of copper anodes in furnaces. Copper anodes are then electro-refined to cathode copper at the copper refinery. This plant consists of a series of electrolytic tanks, each containing anodes and cathodes. In electrorefining, the supplied electricity electrochemically dissolves copper from the anodes held in an acidified copper sulfate solution, and this causes selective plating of dissolved copper in the very pure form on the copper cathodes. The electricity requirement at a copper refinery is moderate, at approximately 350 kWh per tonne of cathode copper. This last electrochemical step is why electricity is crucial in copper refining: it requires large amounts of inexpensive and clean electricity, although less so for electrorefining than for electrowinning. Therefore, jurisdictions where electric power is cheap and plentiful are often attractive, but not necessarily in the exact location where ore is extracted or processed.

The obtained copper cathode is over 99.99% pure and is ideally suited for use in rod or wire mills, other electrical uses as well as at brass mills, or foundries to manufacture semi-finished products such as copper foil, wires, powders, castings, *etc*. Nearly 75% of copper is used in electrical wires or for wiring in industrial machinery.[43] As for copper foil used for current conductors in batteries, they are either rolled or electrodeposited.[32,33,55,56]

2.3.2.2 Hydrometallurgy



1. **Leaching** allows the obtention of copper sulfate solutions by using acid and water onto copper oxide ores. Copper sulfides are less susceptible to leaching but new technologies can process them (bioleaching, O_2 pressure, chloride, etc.)

2. **Solvent extraction (SX)** removes the copper(II) ions from the copper sulfate solution by mixing it with diluents (hydrocarbon, paraffin, kerosene, etc.) and extractants (specialty chemicals).This is a closed loop and increase the concentration of copper.

3. **Electrowinning (EW)** uses electricity and an inert lead anode to deposit pure copper on the cathode, while the concentrated copper solution from SX acts as an electrolyte.

Figure 2.3.3 Flowsheet of the hydrometallurgy of copper

Hydrometallurgy, or the processing of copper ores through in-solution chemical processes, typically using acid, has been used in the U.S. since at least the 1920s. Until 1968, copper was typically recovered as cement copper by deposition on iron. In 1968, the first copper ion exchange plant with copper electrowinning was operated in Arizona. This new technology was far superior, and the development accelerated the application of the leaching of copper oxide ores. Thus, leaching, solvent extraction and electrowinning processes, or SX-EW, represented 19.6% of global copper production in 2022, a trend steadily increasing since the 1960s.[45] Copper oxide ores are more fitting toward SX-EW techniques, as copper sulfide minerals cannot be leached directly without being oxidized first. Under the right conditions, bacteria can oxidize copper sulfides through specific bioleaching processes. Alternative technologies, such as O_2 pressure or chloride treatment technologies, were also developed for copper concentrates. Efforts are currently underway to enable low-grade sulfide ores to be heap leached at the mine sites. Copper sulfide leaching technologies can be expensive to develop, slow and usually focused on one deposit mineralogy rather than smelters, which are more universal in feedstock.

Leaching, the first step of the hydrometallurgical route allows the obtention of copper(II) ions by using acid and water on copper oxide ores. The primary acid is usually sulfuric acid, thus obtaining copper (II) sulfate **$CuSO_4$** in the solution. Alternative techniques using hydrochloric acid or ammonia are more marginal. Heap leaching is the primary process, and it is suitable for large-capacity operations with a higher grade of oxidic copper ores. Ores undergo crushing before being deposited on a pile for acid treatment, while the pregnant liquor is collected at the bottom. The treated copper oxide minerals are typically azurite, chrysocolla, or malachite, but sometimes cuprite, tenorite, or native copper are present.

Dump leaching, a more marginal process, typically has a lower production rate than heap leaching. It is relegated to lower-grade ores and depending, can bypass the need for crushing. Bacteria are required for the oxidation of sulfidic ores, and the entire process necessitates longer timelines of 1–2 years.

After acid treatment, the pregnant leach solution undergoes solvent extraction prior to electrowinning. The solvent-extraction (SX) process removes the copper ions from the pregnant leach solutions by mixing them with different solvents (hydrocarbons, paraffin, kerosene, *etc.*) and extractants (specialty chemicals selective for sequestrating copper ions). By working in a closed loop and Includeing mixing, gravity separation and stripping steps, the copper concentration is increased to 40–50 g/L. Iron is removed, nickel, cobalt, zinc, antimony, and various precious metals can also be recovered. The barren sulfuric acid can also be recycled for leaching.

The final step, electrowinning (EW), uses electricity and an inert lead anode to deposit a layer of pure copper on a stainless-steel sheet cathode. The higher concentration copper sulfate electrolyte solution produced from the solvent extraction step is used as the electrolyte, allowing copper ions to migrate and deposit onto the cathode. The main difference between electrowinning and electrorefining, as used on copper anodes at the end of the pyrometallurgical route, is that electrowinning needs a higher voltage potential, which makes this step more energy-intensive. Typical power usage averages about 2,000 kWh/tonne of cathode copper. The copper cathodes can then be sold and transported to rod and wire mills, brass mills and semifinished manufacturers.

Alternatively, copper precipitation and cementation is another process that allows the conversion of copper(II) ions in solution to metallic copper, without the use of electrical current. However, the purity of copper cement can typically be lower than that of copper cathodes obtained by electrolytic reduction (EW). Canadian start-up company Destiny Copper is developing a process to optimize copper precipitation at high purity, which could replace energy-intensive electrowinning and also be used for scrap leaching and recycling.

2.3.2.3 Scrap Recycling

Copper can be readily recycled and the metal can be reused without losing quality. It is estimated that around two-thirds or more of all the copper ever extracted throughout history is still in use.[57] Depending on how recycled copper is counted, the reported average percent of recycled copper varies somewhat. Thus, the IEA estimates that the copper recycling rate is around 45.5%, while the ETC calculates a 60% rate.[25,50] According to the International Copper Study Group, in 2022, 32% of global copper use could be traced back to recycled copper. This represented around 8.7 million tonnes of copper per annum from end-of-life products (old scrap) or discarded copper products during manufacturing processes (new scrap). Another category of secondary copper source is direct scrap, obtained from melting and refining processes in copper manufacturing. At the refinery level, secondary refined copper production reached 16.2% of total refined copper production in 2022.[45]

Copper scrap is inspected, graded, and analyzed chemically if necessary. Depending on the purity of the collected scrap purchased, it can be either directly melted for relatively high-purity batches or fire-refined before casting into ingots, billets, or other shapes for further processing. Alternatively, it can be electrolytically refined if the purity is lower. Copper alloys can also be recycled after identification and melting.[58] Although secondary copper supply could meet 45% of the demand necessary for the energy transition, more primary output will be needed in the future.[25]

3 Graphite

3.1 The Canadian Strategy for Graphite

3.1.1 Graphite in Canada

Table 3.1.1 Non-exhaustive selection of former and future graphite extraction and processing projects in Canada

Selection of Operational and Future Natural Graphite Extraction Projects

Project Name	Company	Province	Type	Status
Lac Knife	Focus Graphite	QC	Flake Graphite	Updated FS 2023
Lac Carheil	Metals Australia	QC	Flake Graphite	PFS underway
Lac Tetepisca	Focus Graphite	QC	Flake Graphite	Exploration
Lac des Iles	Northern Graphite	QC	Flake Graphite	Operational
La Loutre	Lomiko	QC	Flake Graphite	PEA 2021
Matawinie	Nouveau Monde Graphite	QC	Flake Graphite	Updated FS 2025
Miller & Asbury	Canada Carbon	QC	Vein (Lump) Graphite	Exploration
Uatnan	Nouveau Monde Graphite + Mason	QC	Flake Graphite	PEA 2023
Albany	Zentek	ON	Hydrothermal Graphite	PEA 2015
Bissett Creek	Northern Graphite	ON	Flake Graphite	FS 2012, Updated EA 2018
Graphite West	Empire Metals Corp	ON	Hydrothermal Graphite	Exploration
Kearney	G6 Energy Corp	ON	Flake Graphite	DFS 2018
Manitouwadge	Volt Carbon Technologies	ON	Flake Graphite	Exploration
Black Crystal Mine	Eagle Graphite	BC	Flake Graphite	Unknown

Selection of Operational & Future Graphite Processing Facilities

Project Name	Company	Province	Product Type	Status/Commercial Start
Regen Resources Recovery	Regen Resources Recovery	ON	Synthetic Graphite Recovery	Unknown
Graphite & Carbon Terrebonne Facility	Imerys	QC	Exfoliation & Processing	Operational
Bécancour Anode Material Plant	Nouveau Monde Graphite	QC	Anode Material	2027 or before
Baie-Comeau Anode Material Plant	Northern Graphite	QC	Anode Material	2027
Innova Cleantech	Innova Cleantech	AB	Methane to Graphite + Hydrogen	Pilot
Graphene & Anode Material Plant	NanoXplore	QC	Anode Material*	2026
GraphPure & GraphRenew Facility	Green Graphite Technologies	QC & ON	Purification & Recovery	Pilot
Air Classifier Facility	Volt Carbon Technologies	ON	Dry Beneficiation Equipment	2025

*NanoXplore's Future Products: Silicon/Graphene; Coated Spherical Purified Graphite; Conductive Graphene

Canada is a notable player in the graphite industry. According to the U.S. Geological Survey, Canada ranked 7th for world natural graphite extraction in 2022, with 13,000 tonnes of graphite produced, and 9th for global reserves, representing 5,700,000 tonnes. More optimistic reporting by Natural Resources Canada indicates that Canada ranked 6th in 2022, not considering South Korean production but with similar figures as the USGS. NRCan also discloses a higher graphite reserve, amounting to 5,900,000 tonnes.[59,60]

All Canadian production comes from a single site: the Northern Graphite-operated Lac-des-îles mine in Québec.[61] The company recently acquired Mousseau West, an area close to the first production site, to prolong its activities.[62] No milling, shaping, purification or coating facilities operate in Canada.

Northern Graphite started to develop a mining project in Bissett Creek, Ontario,[63] and has collaborated to open a graphite anode refinery in Baie-Comeau, Québec.[64–66] The company Nouveau Monde Graphite is opening up a graphite mine in Matawinie, Québec,[67] while they started the construction of a battery anode material plant in Bécancour, Québec, in 2025 to better integrate the graphite supply chain vertically. Mitsui and Panasonic participated.[67,68] Finally, they are collaborating with Mason Graphite on a joint mine/concentrator in Lac Guéret, Québec, for the Uatnan mining project, which is thought to have one of the richest graphite deposits in the world.[69–71] Meanwhile, Canada Carbon Inc. plans to re-use former lump/vein mines in Québec (Miller and Asbury) to produce high-quality graphite products for nuclear application.[72] Volt Carbon Technologies, a company developing lithium solid-state batteries and an innovative graphite flake particle separator called Air Classifier, also holds properties in the Manitouwadge flake graphite project in Ontario and in Lochabar, Québec.[73,74] Their process could replace graphite flotation steps, thus avoiding water usage, chemical use and decreasing energy consumption. The company is building a demonstration plant in Scarborough, Ontario.

Lomiko recently received funding from the Natural Resources Canada (NRCan) and the U.S. Department of Defense for its La Loutre exploration project in southern Quebec.[75]

Lithion Technologies, a Quebec-based company specializing in black-mass processing to extract lithium, cobalt, and nickel from recycled batteries, is also interested in developing solutions for graphite circularity in partnership with Nouveau Monde. Similarly, Green Graphite Technologies, a company based in Montreal and Kingston, is developing modular purification solutions for natural graphite. Those include novel processing steps from natural graphite feeds or graphite recovery methods from recycled sources to produce battery-grade graphite. Green Graphite Technologies has secured collaborations with Nouveau Monde and Eagle Graphite, and has recently received $3.5 million from NRCan.[76] Finally, NanoXplore, a Montreal-based company and the world's largest producer of graphene, is treating natural graphite to convert it into graphene products. They plan to produce anode materials for batteries, such as silicon/graphene; coated spherical purified graphite and conductive graphene. Their parent company, VoltaXplore, is developing silicon-graphene-based li-ion batteries.

Canadian startups focusing on biographite R&D, which processes biowaste into graphite, are represented by CarbonIP Technologies and previously by NanoTerraTech.

3.1.2 Target

Our 2022 report, 'Roadmap for Canada's Battery Value Chain,' established the following objectives for graphite. As it should be needed in anodes for the next two decades and due to the solid Canadian reserves, Canada should seek to capture far more than 10% of the North American EV market by 2030. A leader scenario to reach 35% of the North American market can be considered.

Graphite Mandated Benchmark (10% of 2030 North American Market)		
	2030	**2040**
Graphite (ktpa CSPG)	111	223
Anode active material plants needed	3	5
New refining facilities	1	2
Graphite Leader scenario (35% of 2030 North American Market)		
Graphite (ktpa elemental)	350	750
Anode active material plants needed	3	5

3.1.3 Scenario Outline

Canada should maximize natural graphite extraction and processing by following an ambitious, multifaceted strategy to become the primary North American supplier of coated spherical purified graphite for electric vehicle (EV) battery anodes. This comprehensive approach involves several key initiatives that leverage Canada's geographical and industrial strengths.

- The development and expansion of graphite mines and milling/shaping facilities should be prioritized, focusing on British Columbia (BC) and Québec. In BC, the current projects should be accelerated, while in Québec, existing facilities should be reinforced and upgraded to increase their production capacity and efficiency. These regions are rich in natural graphite deposits, making them ideal for large-scale mining and processing projects.
- Canada should establish two regional coating hubs, one in BC and one in Québec. These hubs would specialize in the crucial process of coating spherical purified graphite, which is essential for battery anodes. By having dedicated facilities in both regions, Canada can ensure a steady and reliable supply of

high-quality coated graphite to meet the needs of the rapidly expanding EV market. Collaboration and technology transfer with Japanese, Korean and American companies will be necessary for processing. These hubs would also create job opportunities and stimulate economic growth in their respective regions.

- In addition to natural graphite, a synthetic graphite hub development should be pursued, perhaps in Alberta's industrial heartland or the western provinces. Alberta's and Saskatchewan's existing petrochemical infrastructure and expertise make them ideal locations for this initiative. Pet coke, currently discarded as waste, can be a potential venue. By leveraging the established industrial bases of the two provinces, Canada can aim to produce synthetic graphite, offering a reliable alternative to natural graphite. Biosourced graphite processing technologies and methane pyrolysis coupled with hydrogen production could also be advanced locally. Diversifying graphite sources would enhance the country's resilience and flexibility in the global market.

3.1.4 Signature Projects

- Advance and strengthen mining and shaping/milling projects in QC and BC
- Strengthen a QC anode and coating hub with initiatives like the Bécancour Nouveau Monde facility and the VoltaXplore one.
- Develop a coating and anode hub in BC.
- Build a synthetic graphite processing facility and pursue R&D in Edmonton.

3.1.5 Strategic Priorities

- **An Ambitious Production Goal & Aggressive Piloting and Scaling for Processing:**
    - **Ambitious Targets:** Canada should aim for an accelerated production rate, targeting 2-3 million tonnes per annum of raw graphite. This approach is intended to deplete existing graphite reserves within 10 to 15 years rather than 20. This accelerated depletion strategy ensures that Canada rapidly meets growing market demand and maximizes the utilization of its graphite resources while they are most needed.
    - **Immediate Initiatives:** Launch aggressive piloting and scaling efforts without delay. This includes initiating pilot programs that test and refine graphite processing methods to ensure they are scalable and economically viable. Immediate action will also involve setting up facilities and infrastructure to support the rapid expansion of graphite production and processing.
    - **Direct Support for Pilot:** Implement direct financial incentives specifically for processing pilot programs. These incentives should address the current lack of funding in graphite processing and aim to unlock financial bottlenecks in the midstream part of the supply chain. By providing targeted financial support, the government can stimulate

    the development of necessary processing technologies and infrastructure.
  - **Unlocking Projects:** Introduce government incentives similar to the U.S. Inflation Reduction Act (IRA) to unlock critical graphite projects. Such incentives could include tax breaks, grants, and low-interest loans to promote investment in graphite extraction and processing. These measures would provide the financial stability and encouragement companies need to invest in and expand their operations. Bipartisan initiatives could futureproof this method and ensure regulatory stability.
- **Coating Processes in Central Hubs:**
  - **Centralized Processing:** Consider establishing a central node within a hub-and-spoke system, where smaller milling and shaping facilities are closer to graphite mine sites. These smaller facilities would feed semi-processed graphite into more extensive central coating facilities. This system optimizes logistics and ensures efficient processing by reducing transportation distances and costs.
  - **Strategic Locations:** Develop large regional coating hubs in British Columbia (BC) and Québec. These hubs would serve as major centres for coating spherical purified graphite. Existing projects, such as Northern Graphite's Baie-Comeau project, Nouveau Monde Graphite's Bécancour project and VoltaXplore, should be reinforced and expanded to serve as the foundation for these hubs.
  - **Specific Plans for British Columbia:**
    - **Two-Year Pilot Program:** Propose a two-year pilot program to establish a coating facility in BC. This pilot facility will test processes and provide valuable data, paving the way for constructing a larger plant targeted to start as soon as possible.
    - **Integration with Trail Smelter Area:** Explore the possibility of integrating the BC coating processing hub with the existing Trail Smelter. The smelter's established industrial infrastructure, transportation networks, and access to clean power sources make it an ideal location for a coating facility.
  - **Operational Models:**
    - **Vertical Integration:** Coating facilities could be vertically integrated within existing mining firms, ensuring streamlined supply chain management and enhanced control over production.
    - **Or Independent Operation:** Alternatively, these facilities could operate independently, fostering competition and innovation within the graphite processing industry.
  - **Financial Support:** Unlocking government funding is crucial for developing these coating hubs. Government grants, subsidies, and incentives can provide financial support for initial setup, research and development, and ongoing operations.
- **Research & Development:**
  - **Investigate and Support Alternative Graphite Sources:** Several technologies have shown promising results, such as the pyrolysis of wood waste to graphite, as demonstrated by the New Zealand company

    CarbonScape's process. Domestic companies, such as CarbonIP Technologies, or NanoTerraTech, which previously aimed to produce biographite as an anode material, should be supported and scaled. The pre-combustion carbon capture technology proposed by Innova Cleantech or Aurora Hydrogen in Alberta has shown promising results, converting methane and natural gas into hydrogen and graphite. Such technologies should be supported and tested at the demonstration level.
    - **Reducing & Optimizing Waste:** Focus on optimizing and limiting waste produced during natural graphite processing. Implement advanced techniques to minimize environmental impact and enhance resource efficiency.
    - **Sulfur Management:** Investigate and address sulfur-related issues in graphite processing. Develop strategies to effectively manage and utilize sulfur waste, turning potential environmental liabilities into value-added products.
    - **Cleaner Hydrometallurgical Processes:** Optimize clean hydrometallurgy purification methods for graphite. Emphasize developing processes that are less harmful to the environment and more energy-efficient. Avoid hydrofluoric acid steps.
    - **Energy Efficiency for Synthetic Graphite Processes:** Advance synthetic graphite production methods that demand less energy and produce fewer carbon emissions. Focus on innovative technologies that reduce the overall environmental footprint of synthetic graphite manufacturing.
    - **Recycling:** Enhance graphite circularity by developing robust recycling processes. Promote the reuse of graphite materials to create a more sustainable and resilient supply chain.
    - **Pilot Support:** Provide piloting support across all Technology Readiness Levels (TRLs). Current support often starts at TRL 6 and above, so expanding support to earlier stages can foster innovation and accelerate the development of new technologies.
- **A Potential Synthetic Graphite Hub in the West:**
    - **Leverage Petrochemical Infrastructure:** Establish a synthetic graphite hub in the Edmonton region to capitalize on the existing petrochemical infrastructure and expertise. This hub would leverage Alberta's industrial strengths to produce synthetic graphite efficiently. Saskatchewan could also be a viable alternative. Consider using pet coke that is currently wasted and buried. It is obtained as a by-product of refineries and can be valued and converted into anode-grade synthetic graphite, along with pitch imported from the U.S.
    - **Alternative Locations:** Consider processing synthetic graphite in BC using hydroelectric power to reduce carbon emissions and exploit the province's clean energy resources.
    - **Utilizing Existing IP:** Benefit from U.S. and Canadian intellectual property in cleaner synthetic graphite processes, similar to those of

    Novonix. Implement these technologies to create a more sustainable synthetic graphite production chain.
  - **Carbon Management:** Develop a clear strategy for carbon capture, utilization, and storage (CCUS) to mitigate synthetic graphite production's high energy and carbon intensity. Integrate clean energy solutions to reduce the environmental impact further.
- **Engagement, Education and Workforce:**
  - **Building Expertise:** Create a comprehensive knowledge base and training programs to educate stakeholders on the importance of anode production. Building expertise from the ground up is crucial with no existing North American anode plant.
  - **National Commitment:** Foster a national commitment to reducing greenhouse gas emissions and establishing a robust domestic battery supply chain. Engage with communities to ensure widespread support and understanding of the benefits.
  - **Stakeholder Relationships:** Develop strong relationships with First Nations communities to ensure successful mining operations. Respectful and meaningful engagement with these stakeholders is essential for project certainty and community support.
  - **Future Leader Narrative:** Position Canada as a potential future leader in graphite production, especially in light of China banning graphite exports from December 1st, 2023. Control the narrative to highlight Canada's strategic importance in the global graphite market.
  - **Education and Public Engagement:**
    - **Critical Minerals Awareness:** Educate the public on the importance of critical minerals, emphasizing their role in sustainable energy and technological advancements. Increased public knowledge and pressure can encourage the government to focus on critical mineral spending and support.
    - **Technoeconomic Analyses:** Provide techno-economic analyses and job creation estimates to convince stakeholders and the general public of the economic benefits of investing in graphite production and processing.
  - **Skill Retooling:** Address the limited workforce by retooling general skills and developing specialized training programs. Ensure that the workforce is equipped to meet the demands of the growing graphite industry.
- **Protection from Price Volatility and Secure Off-takers:**
  - **Strategic Partnerships:** Secure long-term partnerships with Korean and Japanese anode companies to establish a stable market for Canadian graphite. These partnerships will ensure a consistent demand and provide financial stability.
  - **Technology Transfer Agreements:** Negotiate fair technology transfer agreements to facilitate the adoption of advanced processing technologies. Ensure that these agreements benefit both Canadian companies and their international partners
  - **Price Stability Mechanisms :**

        - **Government Procurement:** Implement government procurement policies, contracts for differences, and government-guaranteed future purchases of locally sourced critical minerals to enforce price stability.
        - **Buffer Stock Mechanisms:** Establish buffer stock mechanisms similar to those used in the potash industry to de-risk the market. A Canadian buffer stock would provide a stable source of graphite during geopolitical disruptions and stabilize prices for suppliers.
    - **Recycling Incentives:** Provide incentives for recycling graphite and building up the back end of the supply chain. This will enhance the resilience and sustainability of the graphite supply chain.
    - **Direct Intervention:** Recognize that other governments actively intervene in the graphite supply chain. Canada must also take proactive measures to ensure its market remains competitive and secure.
- **Regulatory Tools:**
    - **Investor Confidence:** Ensure transparent pricing to alleviate uncertainty for investors. Clear and consistent pricing information will attract investment and support the growth of the graphite industry.
    - **Streamlined Approvals:** Expedite the permitting process for critical minerals, including graphite. Government support for Preliminary Economic Assessments (PEA), Pre-Feasibility Studies (PFS), and Feasibility Studies (FS) will accelerate project development.
    - **Carbon Credits:** Implement carbon credits for critical minerals projects to encourage environmentally sustainable practices. These credits will incentivize companies to reduce their carbon footprint and adopt cleaner technologies.

3.2 Graphite: The Dominant Material for Lithium-Ion Battery Anodes

3.2.1 General Properties

Graphite, diamond, and ‘amorphous’ microcrystalline structures are naturally occurring forms of elemental carbon. Graphite deposits are thus labelled natural graphite, while synthetic graphite is manufactured from petroleum by-products. Graphite can also be sourced from biomass after pyrolysis and processing of lignocellulose, or obtained from methane/natural gas pyrolysis.[77–79]

In all cases, graphite is composed of stacked layers of carbon atoms arranged in honeycomb-like hexagonal rings. Within each layer, the intra-planar bonding is quite strong, but the forces holding the different sheets together are relatively weak, allowing them to slide over each other easily. Due to the molecular and electronic structure across layers, graphite has good electrical conductivity. All those structural features give this grey-black mineral the properties of both a metal and a non-metal.[80] The metallic properties include thermal and electrical conductivity; the non-metallic ones include high thermal resistance and lubricity. Additionally, graphite is stable over various temperatures, resistant to corrosion and most acids, and chemically inert. These properties make it suitable for many industrial applications. Some primary end uses of graphite are in refractories, lubricants, brushes for electrical motors, friction materials, electrodes for furnaces, steelmaking, pencil leads, headphones, neutron moderator for nuclear reactors, batteries, and fuel cells.[80–82] It is important to note that the graphite electrodes used in electric arc furnaces make graphite an important element for electrifying metallurgical processes for several key metals and critical minerals. The U.S., the E.U., and Canada currently list graphite as a critical mineral or raw material.[1,83,84]

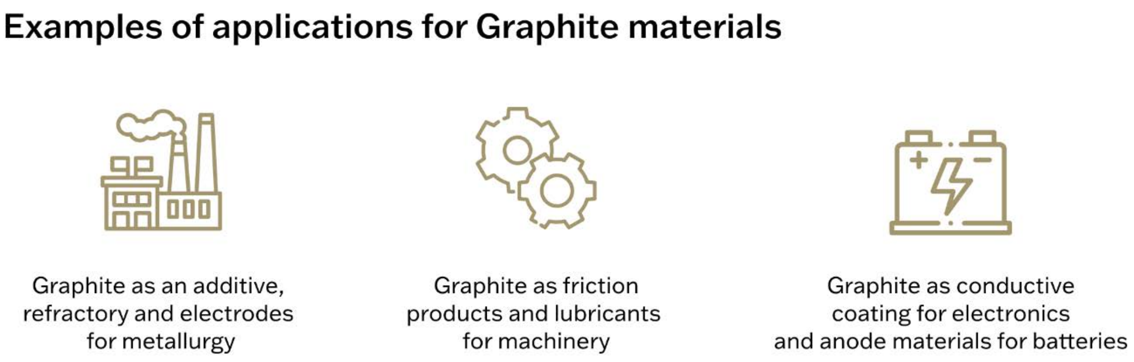


Figure 3.2.1 Examples of applications for graphite materials

3.2.2 Role in Energy Storage

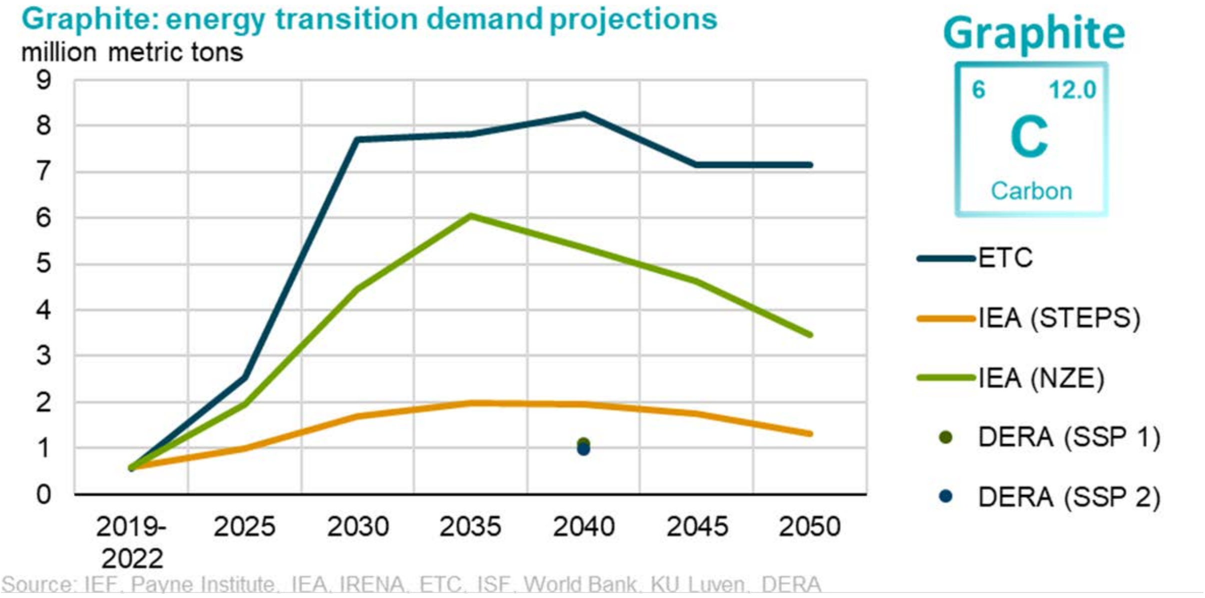
Graphite anodes are a primordial element of Li-ion batteries. They are the single-largest component used and represent 28% of the total weight of EV batteries, up to 70 kg of graphite in an EV *vs.* 10 kilograms in a hybrid vehicle.[85,86] Each battery can also contain 10 to 20 times more graphite than lithium by weight.[87] Their use is also widespread: graphite anodes are fundamental to every Li-ion battery type, while the cathode materials may vary: from lithium iron phosphate (LFP) to nickel cobalt manganese (NMC), lithium cobalt oxide (LCO), lithium manganese oxide (LMO), or lithium nickel cobalt aluminum oxides (NCA), all types contain graphite anodes.

Two main reasons can explain the superior properties of graphite for battery anode usage: firstly, its capacity to reversibly accumulate and release lithium ions from/to the electrolyte, thus supporting the storage of electricity and creation of an electrical current; secondly, the relative stability against degradation at the electrode/electrolyte interface occurring by the creation of solid electrolyte interphase. This area acts as a protective layer, which prevents further electrolyte decomposition while maintaining the required cycling ability of the battery.[88]Additionally, graphite is relatively low-cost, abundant, and has a long cycle life. For fuel cells, graphite is the leading material for constructing bipolar plates, which distribute the fuel and oxidant evenly to the cells.

3.2.3 Substitutes

in the short to medium-term future, graphite anodes are still expected to dominate the battery market. However, newer technologies for anodes might replace graphite in the longer term. Those alternative anode materials include silicon (higher energy density, but a higher volume expansion/contraction leading to degradation), lithium titanate anodes (long life cycle, lower energy density, faster charging/discharging), lithium metal anodes (only in the case of solid-state batteries, would potentially boost energy density, but dendrite formation could lead to safety problems, and even more lithium resources would be required), tin oxides, titanium oxide, niobium and molybdenum sulfide. Projections, however, place those anode technologies 5 to 10 years away from market deployment, but with large uncertainty.[89] Worley Consulting Insights estimates a market share of 8% in 2030 and further 16% in 2016 for silicon-based anodes, 7% for lithium titanate in 2040%, and 7% for lithium metal anodes the same year.[90]

3.2.4 Supply and Demand



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Figure 3.2.2 Graphite demand projections to 2050 according to various energy transition scenarios[40]

The World Bank Group estimates a 494% growth in graphite demand by 2050 compared to 2018 production levels, representing a demand of 4.5 million tonnes of graphite in 2050.[89] Benchmark Mineral Intelligence evaluated the demand for natural graphite for anodes at 2.8 million tonnes in 2030 *vs.* 0.18 million tonnes allocated for this purpose in 2020.[91] That's why a predicted supply shortfall of 30% for graphite is forecasted by 2040.[92] Those constraints are further exacerbated by a lower battery anode material fabrication yield: making a single tonne of anode material can take 3 tonnes of natural flake graphite, which is higher than for other minerals.[91]

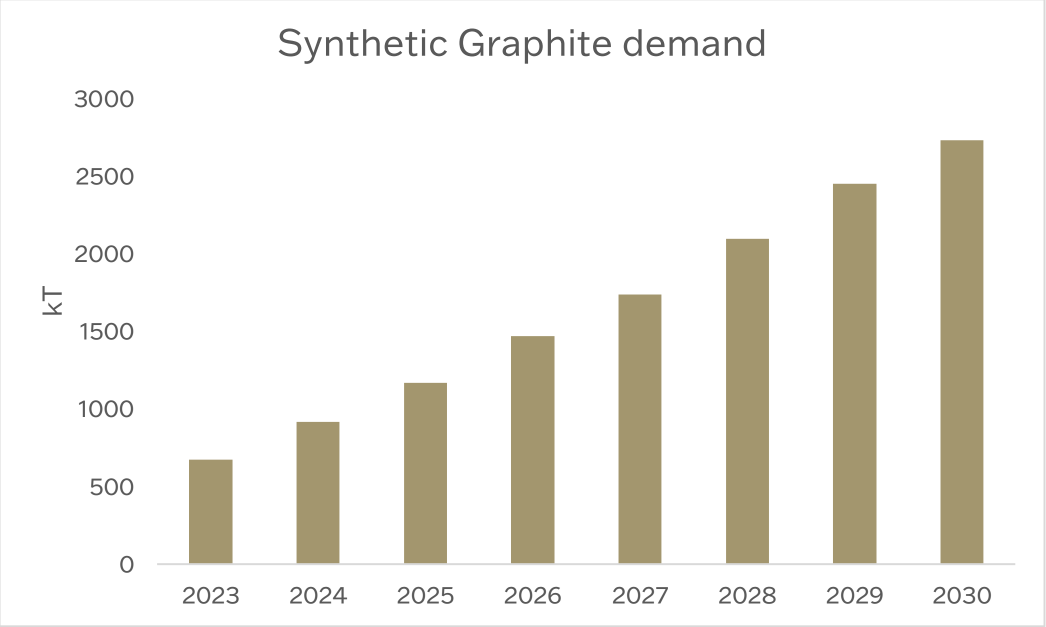


Figure 3.2.3 Global Synthetic Graphite Demand Projection to 2030[90]

The global demand for synthetic graphite was around 674 kT in 2023 and is expected to grow to 2,734 kT by 2030.[90] As for feed materials, Needle Coke demand by the battery market is expected to grow more than 13% CAGR between 2024 and 2030. Calcine Pet Coke demand by the battery market is anticipated to grow more than 36% CAGR from 2024 to 2030. China will lead the pet coke market followed by North America, Europe, and rest of the countries.[90]

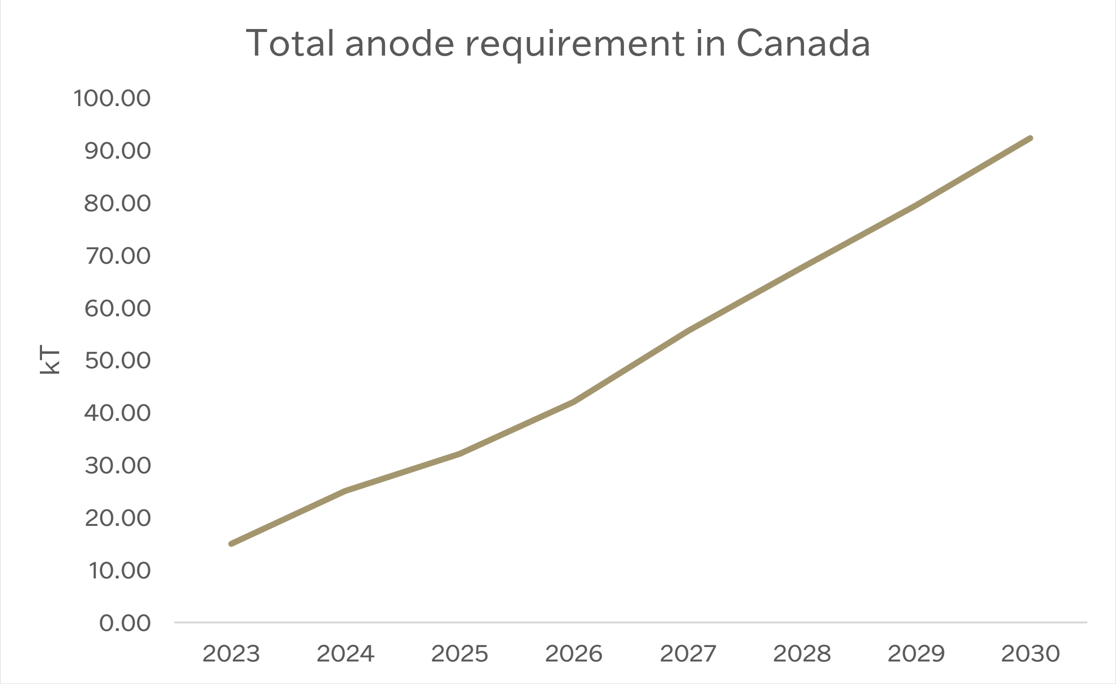


Figure 3.2.4 Anode material demand projection in Canada[90]

Worley Consulting Insights estimates demand for battery anode material to reach around 93 kT by 2030.[90]

3.3 The Two Graphite Flowsheets: Natural or Synthetic

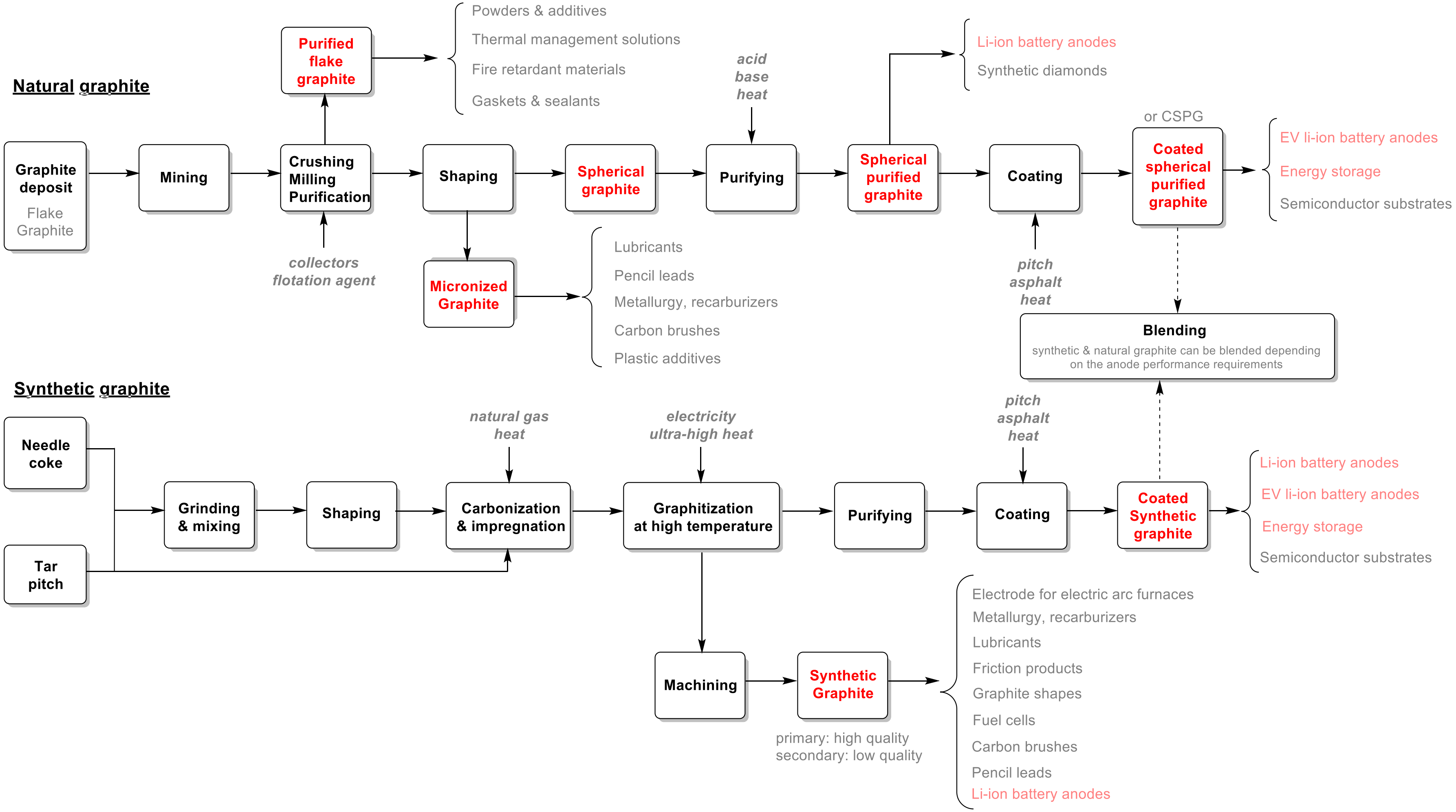


Figure 3.3.1 Simplified flowsheet of natural and synthetic graphite

3.3.1 Natural Graphite Ores & Reserves

Carbon is between the 12th and 17th most abundant element in Earth's crust, and its estimated concentration ranges from 180 to 270 parts per million.[93] Carbon's behaviour in its geochemical cycle is influenced by its different forms. Most carbon in the crust (80–90%) is found in carbonate rocks, and the remaining exists in living and fossil organic matter, as well as in the form of CO_2 in the atmosphere or dissolved in the ocean. These forms of carbon dominate the carbon cycle. Graphite, which accounts for less than 0.5% of carbon in the Earth's crust, is primarily formed through high-temperature thermal alteration of organic matter from biogenic sources deposited in sedimentary rocks and subsurface reservoirs. It is stable and unreactive in the crust and remains mostly unchanged under surface weathering conditions. It tends to recrystallize only through burial and thermal metamorphism. As a result, graphite remains largely isolated from the previously described overall carbon cycle.

Graphite ore is classified into three types: **lump** or **vein graphite**, known for its high quality; **flake graphite**, used in electric vehicles and fuel cells; and **amorphous graphite**, the most abundant and lowest grade, used in lubricants, crucibles, and steel production. Flake size also affects battery performance, with larger flakes being more effective but costly. Jumbo flakes can expand when heated, making them suitable for gaskets, seals, and flame retardants, while smaller flakes are used in lower-value industries and small electronic devices.[94]

China, Brazil, Madagascar, Mozambique, Tanzania and Russia are the most important graphite reserves. According to the data provided by the U.S. Department of Geological Survey, those 6 countries make up over 83% of the world's estimated reserves.[59] The reserves from Sri Lanka are unique as they represent the only large deposit of vein/lump graphite, which is of the highest quality grade.

Table 3.3.1 Estimated reserves & mining production of natural graphite by country in tonnes[59]

Country	**Mining Production in 2022**[a] (tonnes)	**Country**	**Reserves in 2024**[a] (tonnes)
United States	/	United States	/[b]
Germany	170	Austria	/[b]
Austria	500	Germany	/[b]
Vietnam	500	Ukraine	/[b]
Ukraine	1,000	Vietnam	/[b]
Mexico	2,000	Norway	600,000
Sri Lanka	2,600	Sri Lanka	1,500,000
Turkey	2,800	South Korea	1,800,000
Tanzania	6,120	North Korea	2,000,000
North Korea	8,100	Mexico	3,100,000
Norway	10,380	**Canada**	**5,700,000**
India	11,000	Turkey	6,900,000
Canada	**13,000**	India	8,600,000
Russia	16,000	Russia	14,000,000
South Korea	23,800	Tanzania	18,000,000
Brazil	72,000	Madagascar	24,000,000
Madagascar	130,000	Mozambique	25,000,000
Mozambique	166,000	Brazil	74,000,000
China	1,210,000	China	78,000,000
World total (rounded)	**1,680,000**	**World total (rounded)**	**280,000,000**

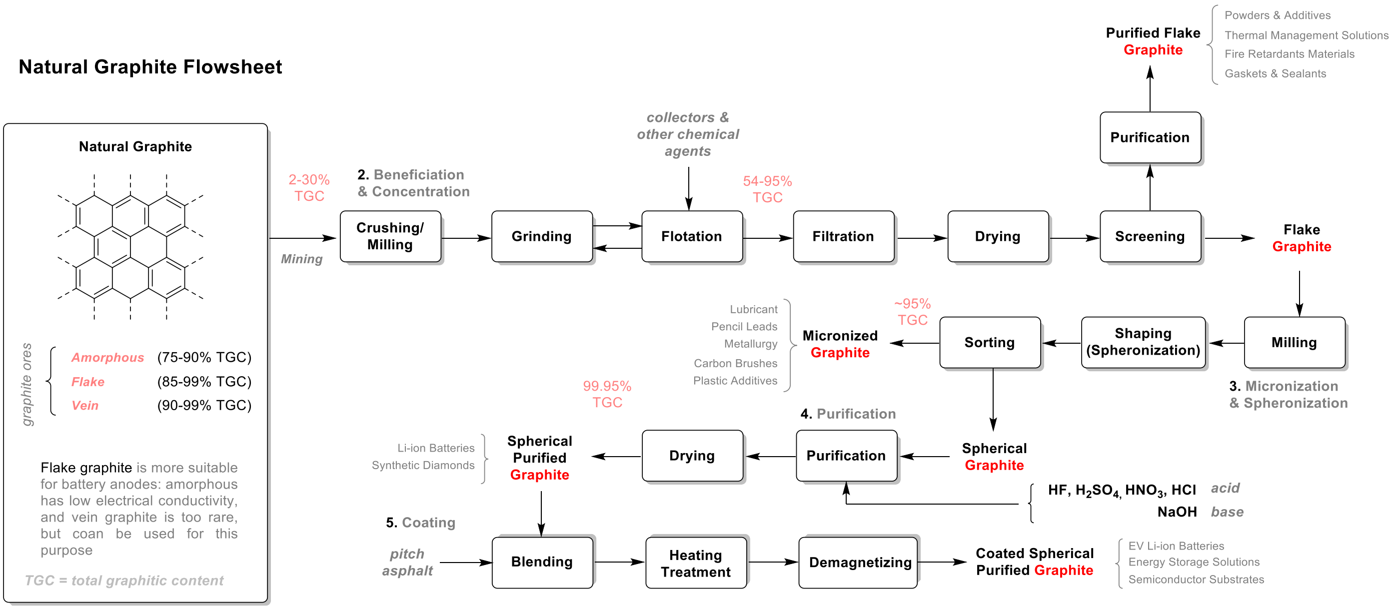
[a]Data from the 2024 U.S. Geological Survey, NRCan's dataset differs slightly.[59,60]
[b]Reserves included in 'World Total'.

China is undeniably the key graphite player, making up 72% of natural graphite production in 2022. Chinese flake graphite production has shifted from older Shandong mines to newer ones in the Heilongjiang province; the recent decline in larger flake sizes is due to aging mines, rising costs, resource depletion, and stricter environmental regulations, while the main Heilongjiang mines focus on smaller flake graphite production to meet the demand for lithium-ion batteries.[15,16] However, the worldwide ratio of the Chinese output is expected to drop from 72% last year to 48% in 2030, while the ones from Madagascar should rise to 8% and up to 22% in Mozambique.[95] Other African countries such as Tanzania and Namibia are forecasted to host large-scale graphite mining projects, while additional projects are being developed in Australia and Sweden. A graphite anode plant is particularly commissioned to be opened there.[59]

In 2021, 66% of the global use of graphite was from synthetic sources and only 34% from natural ones.[60] In the same year, 52% of synthetic graphite was used for industrial electrodes (electric arc furnaces, refining furnaces, industrial silicon, *etc.*), 14% for recarburizing, and 14% for battery anodes.[96] China also dominates the synthetic graphite industry, representing 58% of the total synthetic graphite production in 2021, Japan 15% and the U.S. 8%.[97]

3.3.2 Processing

3.3.2.1 Natural Graphite Processing



1. Mining of graphite ores, mostly flake graphite in the case of battery anode purposes, can be performed in open air or underground. Ammonium Nitrated Fuel Oil (ANFO) is commonly used as an explosive.

2. Beneficiation & Concentration is a series of multiplealternating stages of crushing, attrition milling and flotation milling to separate graphite from other rocks. Additives such as pine oil, kerosene, diesel, methyl isobutyl carbinol and sodium silicate are used in small quantities as foaming agents, collectors, flocculant and depressant. Concentrated flake graphite is obtained after drying and screening.

3. Micronization & Spheronization: the graphite concentrate is pulverized and spheronized to produce spherical graphite, with particle size ranging from 10 to 25 microns. Lower-value micronized graphite is collected as a by-product.Spherical shape improves packing & density for battery uses, while allowing a uniformly thin spread on the anode.

4. Purification steps can include several chemical or thermal processes, sometimes in combination. **Acid-washing** removes organic & mineral impurities by using corrosive acids (HF, H_2SO_4, HNO_3, HCl). **Acid-base method** removes metal, sulfides and silicon oxides impurities by using acid such as sulfuric acid H_2SO_4 and base such as sodium hydroxide (soda) NaOH and heating (100-550°C). **High temperature method** uses ultra-high heating (2000-3000° C) in inert gas or chlorine to vaporize impurities.

5. Coating: a thin layer of pitch or asphalt is added onto the spherical purified graphite, which are then baked during a carbonizing step at over 1,200°C. The coating prevents degradation during charge cyles and inhibits side-reaction with the electrolyte, thus improving battery capacity and life.

Figure 3.3.2 Flowsheet from natural graphite to coated spherical purified graphite

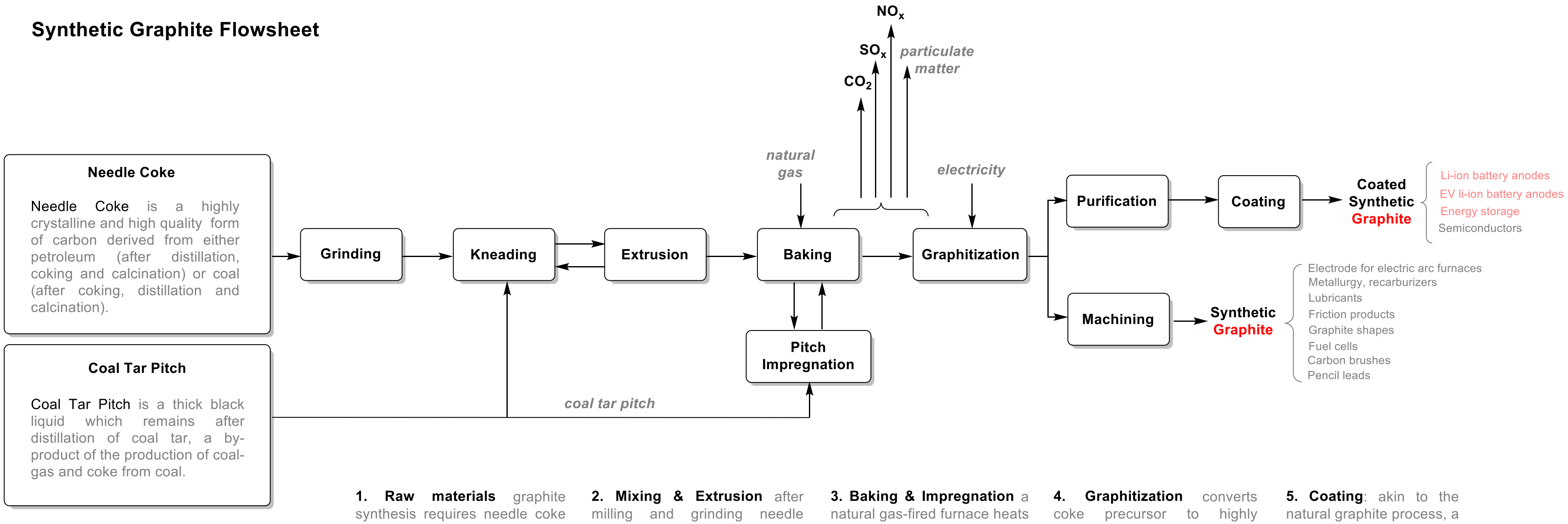
Graphite ores, mainly flake graphite, are more available and suitable for battery anode applications and can be extracted through open-pit or underground mining. Once the graphite ore is mined, the next crucial step is beneficiation and concentration. This involves multiple alternating stages, including crushing, attrition, milling, and flotation milling. These stages are designed to separate the valuable graphite from other rock materials. Various additives are used in small quantities during this process to enhance the separation efficiency. These additives include pine oil, kerosene, diesel, methyl isobutyl carbinol, and sodium silicate, and they are used as foaming agents, collectors, flocculants, and depressants. Through these processes, a concentrated form of graphite is obtained after the drying and screening stages, which removes excess moisture and refines the material. Those concentrated flake graphite products are suitable for thermally resistant materials and carbon additives.

Concentrated graphite is then subjected to further processing, where it is pulverized and spheronized to produce spherical graphite. After this spheronization process, sometimes called spheroidization, the particle sizes of this spherical graphite typically range from 10 to 25 microns. The spherical shape of the graphite particles is essential for improving the packing density and uniformity when the end-product graphite is applied to battery anodes, enhancing the batteries' performance. During this process, lower-value micronized graphite is also collected as a byproduct; those micronized graphite products are suitable for lubricant, electric furnace electrodes, carbon brushes, *etc.*

Following spheronization, graphite undergoes purification, which can involve several chemical or thermal processes, sometimes combined. One standard method is acid washing, where corrosive acids such as hydrofluoric acid HF, sulfuric acid H_2SO_4, nitric acid HNO_3, and hydrochloric acid HCl remove organic and mineral impurities. Another method involves acid-base treatments that remove metal, sulfides, and silicon oxide impurities using acids like sulfuric acid and bases such as sodium hydroxide NaOH at elevated temperatures ranging from 100 to 550°C. Alternatively, the high-temperature method involves ultra-high heating between 2,000 and 3,000°C in an inert gas or chlorine atmosphere to vaporize any remaining impurities. This high-quality graphite product for high-performance electronic applications is called Spherical Purified Graphite (SPG). Purification steps, whether chemical or thermal treatments, are the most environmentally impactful processes of the natural graphite value chain: Toxic and hard-to-handle acids are used, and the thermal purification process is energy-intensive.

The final step in the process is the coating technique for producing Coated Spherical Purified Graphite (CSPG). This involves applying a thin layer of pitch or asphalt to the spherical purified graphite. The coated graphite is then baked during a carbonizing step at temperatures exceeding 1,200°C. The coating is not just an additional step but a crucial one, as it prevents degradation of the graphite material during battery charge cycles and inhibits side reactions with the electrolyte. This step significantly improves the overall battery capacity and longevity, making the graphite more suitable for anode applications.

3.3.2.2 Synthetic Graphite Processing



Needle Coke

Needle Coke is a highly crystalline and high quality form of carbon derived from either petroleum (after distillation, coking and calcination) or coal (after coking, distillation and calcination).

Coal Tar Pitch

Coal Tar Pitch is a thick black liquid which remains after distillation of coal tar, a by-product of the production of coal-gas and coke from coal.

1. Raw materials graphite synthesis requires needle coke from pet coke as the main raw material while coal tar pitch (15-30% content of the mixture) serves as the binder. Both materials come from the petroleum/coal industry, and most processes used to obtain them (distillation, coking, calcination) are energy-intensive and emit significant GHGs over their lfe-cycle.

2. Mixing & Extrusion after milling and grinding needle coke, the grains are screened to obtain appropriate size requirement. Coal tar pitch is added as a binder in a mixer to blend raw materials into a paste. The mixers are heated to allow the pitch to penetrate the pores of the coke. An extruder or press shapes the hot mixture into the suitable form.

3. Baking & Impregnation a natural gas-fired furnace heats the mixture at 800-1200°C in a step also called carbonization. The pitch is carbonized into coke, and the mixture is now tightly combined. Organic matter and impurities are volatilized, resulting in toxic gas emission on top of GHG ones. Baking lasts 18-24 h. Subsequent addition of pitch during impregnation and re-baking helps to reduce porosity. Several cycles are sometimes necessary.

4. Graphitization converts coke precursor to highly crystalline graphite. Ultra-high temperature (2800-3200°C) is required in the absence of oxygen in an Acheson electric furnace. Remaining organic impurities are volatilized. The process takes 3-5 days, and cooling can take up to 3 weeks.

5. Coating: akin to the natural graphite process, a thin layer of pitch or asphalt is added onto synthetic graphite. A 1,200 °C carbonizing step is also necessary. The coating prevents degradation during charge cyles and inhibits side-reaction with the electrolyte, thus improving battery capacity and life.

Figure 3.3.3 Flowsheet of synthetic graphite

Primary synthetic graphite is expensive to produce but has a high purity and significant electrical and thermal conductivity due to a process that creates almost perfectly shaped graphite crystals. Secondary synthetic graphite is a by-product of the production of primary synthetic graphite; it is considered a lower-cost material, typically used in powder.

Despite its better purity and predictability, synthetic graphite requires calcined petroleum needle coke and tar pitch as feedstock. Calcined petroleum needle coke is an environmentally harmful residual product from petroleum refining. It must be heated at high temperatures to pre-process it and make it eligible for graphite production.[98] Coal tar pitch is the remaining liquid obtained after the distillation of coal tar. It is a by-product of coal gas and coke production. Both materials necessitate energy-intensive steps and emit a significant amount of GHGs.[99] Needle coke is the primary raw material for graphite, while coal tar pitch is used as the binder and accounts for only 15–30% of the mixture's content. It should be noted that pet coke can also be eligible for synthetic graphite without upgrading to petroleum needle coke. A significant quantity of pet coke is produced as a by-product of refineries/upgraders. It is often buried as it does not meet the requirements for mainstream off-takers, but it is potentially usable for battery-grade synthetic graphite. Valuing this 'waste' for energy storage could be a potential pathway.

Needle coke first undergoes grinding and milling steps before a screening process to obtain grains of the required size. Coal tar pitch is then added as a binder in a mixer to blend raw materials into a paste. Additionally, the mixers are heated to allow the coal tar pitch to penetrate pores at the surface of the needle coke particles. An extruder or press shapes the hot mixture obtained into suitable forms. A natural gas-fired furnace will heat the mixture at 850–1,200 C in a baking step. This high temperature will allow the carbonization of the coal tar pitch onto the surface of the coke particles, thus tightly combining the mixture. Impurities and organic compounds are volatilized, which results in toxic gas emissions such as NOx, SOx and particulate matter on top of GHG emissions. This baking process can last 18-24 hours. Pitch is then re-added to the mixture during impregnation steps before re-baking to reduce the product's porosity. Several impregnation/baking steps are sometimes necessary.

During graphitization, the intermediate product is converted to highly crystalline graphite. An Acheson electric furnace heats the precursor at very high temperatures (2,800–3,200 C) without oxygen, allowing the remaining organic impurities to be volatilized. The process takes 3-5 days, and the necessary cooling takes up to 3 weeks. The obtained graphite can then be machined and sold for various uses, such as lubricant recarburizers, electrodes for electric furnaces, *etc.*

Several post-processing steps, such as milling, shaping (such as spheronization), or classification and coating, are also possible for synthetic graphite. However, the variety of industrial processes and the general lack of information concerning the necessity of these steps compared to the natural graphite route do not paint a uniform picture of the synthetic graphite pathway to anodes. It would seem that synthetic graphite has been used directly as an active anode material in some processes, while other routes included post-processing before the fabrication of anodes. The U.S. Argonne National Laboratory did not include these steps in their GREET model.[100]

A broader consensus indicates that the coating step, similar to the natural graphite processing route, is necessary to produce lithium-ion battery anodes. It starts with adding a thin layer of pitch or asphalt to synthetic graphite and requires a subsequent 1,200 C carbonizing step.

3.3.2.3 Alternative Graphite Sources: The Pyrolysis of Wood Waste or Methane

Biographite, a sustainable alternative to traditional graphite, is emerging as a key material, and can be suitable for battery anode purposes. Derived from bio-based sources such as agricultural and forestry waste, biographite offers significant environmental benefits, including reduced carbon emissions, valuing biowaste and resource conservation.[90]

Several companies are pioneering biographite production. Graphjet Technology has launched the world's first commercial biographite facility in Malaysia, using palm kernel shells to produce 3,000 tonnes annually, enough to support 40,000 EV batteries per year. This process emits significantly less CO_2—2.95 kg per kg of graphite and creates 200 local jobs. CarbonScape, operating in New Zealand, produces carbon-negative biographite from wood for lithium-ion batteries in partnership with Northvolt. Meanwhile, Birla is advancing Biocrude Derived Anode Material (BDAM) for lithium-ion batteries, focusing on renewable feedstocks to improve sustainability and efficiency in graphite production. In Canada, CarbonIP Technologies is an Alberta-based company focusing on biographite research and production.

Methane pyrolysis offers a novel approach to hydrogen production by converting natural gas into hydrogen and valuable solid carbon byproducts like carbon black, graphite, and carbon nanotubes.[90] Unlike traditional steam methane reforming (SMR), which emits significant CO_2, methane pyrolysis operates without direct CO_2 emissions and requires lower energy inputs than electrolysis. This method integrates seamlessly with current systems by utilizing existing natural gas infrastructure, minimizing the need for new investments. However, challenges remain in achieving widespread commercial adoption due to higher natural gas requirements and the relative immaturity of the technology, rated between three and eight on the International Energy Agency's readiness scale. Scaling production and reducing energy inputs remain critical research areas.

Innovative companies like Hazer Group. Innova Cleantech and Aurora Hydrogen are leading advancements in methane pyrolysis. Hazer's Commercial Demonstration Plant (CDP) in Perth, Australia, marks the world's first commercial-scale facility to produce clean hydrogen and high-purity graphitic carbon using methane pyrolysis with an iron ore catalyst. This dual benefit of hydrogen and valuable carbon products enhances its commercial appeal, with applications in batteries, aerospace, and manufacturing. Meanwhile, Aurora Hydrogen, based in Edmonton, employs a patented microwave-based method producing sand-sized carbon particles. These versatile byproducts support diverse industries, from steelmaking and construction to advanced materials like synthetic graphite and graphene.

3.3.2.4 Comparison of the Natural and Synthetic Graphite Production Processes

An estimation evaluated that the carbon footprint of natural graphite is 1–2.15 kg of CO_2 emitted per kg of graphite produced, while producing 1 kg of synthetic graphite would emit an equivalent of 4.86 kilograms of CO_2, 79.8 g of nefarious sulfur oxide gas (SO_x), 13.5 g of toxic nitrogen oxides (NO_x) and 5.5 g of particulate matter.[101–103] Accurate figures and life cycle assessments of this sector are still debated. It is accepted that synthesizing graphite from the conventional pathway is more energy-intensive and far from being environmentally friendly, making this route poorly adapted for a decarbonized industrial pathway. The highly GHG-emitting nature of the Chinese energy mix, where most synthetic and natural graphite is processed, is at fault. A more recent analysis by Worley Consulting Insights estimates that manufacturing 1 kg of natural graphite anode material produces approximately 9.6 kg CO_2, while on the other hand, 1 kg of Battery-grade synthetic graphite made from oil feedstock produces about 17 kilograms of CO_2, considering this time new processes that are or will be implemented in the Western world.[90]

Additionally, anode materials per kg are more expensive for synthetic graphite (USD $12–$13) than natural graphite (USD $4–$8).[91] Resource security concerns and high-purity products can still attract industrials to opt for the synthetic route.

In 2021, 40% of battery anodes were fabricated from natural graphite, while 57% came from the synthetic route. Benchmark Mineral forecasted a rise in natural graphite usage in Li-ion batteries, making a 49% share for 2030. Synthetic graphite will decrease to a 41% share, and newer non-graphite-based anode technologies might slowly appear commercially.[104] Currently, many anode manufacturers use a blend of natural and synthetic graphite depending on the performance required by the off-takers, with a higher ratio of synthetic for long-range and high-performance usage such as EV, while lowering this ratio for shorter-range applications such as electric scooters.

3.3.2.5 Graphite Life Cycle

Most graphite products have a relatively short life span, being worn or dissipated.[105] 71% of wasted graphite ends up in landfills, and most recycled graphite is from broken electrodes and used in recarburizing steps (raising the carbon content of a metal alloy, such as steel). Anode materials account for 5 to 15% of a lithium-ion battery's total cost but 20% by weight.[90] The lack of established graphite recovery technologies has resulted in the disposal of spent graphite as waste, leading to resource loss and environmental contamination. Despite current recycling rates estimated at <1%,[25] graphite recycling, particularly from batteries, has the potential to be environmentally responsible and profitable.

Recycled graphite, which is typically heavily contaminated and historically been unsuitable for reuse in batteries, is now being made feasible by companies like Altilium, and X-Batt. A 2021 review explored nine different pathways, including pyrometallurgical and hydrometallurgical methods, to recycle graphite anodes from used Li-ion batteries.[102]In Canada, Battery X, Graphite One, Lab4 Inc., Nouveau Monde Graphite and Lithion are all advancing solutions to recycle graphite for battery purposes. Altilium has also recently proven that over 99% of graphite can be recovered from old EV batteries.[90]

4 Iron

4.1 The Canadian Strategy for Iron

4.1.1 Targets

Iron Mandated Benchmark (10% of 2030 North American Market)		
	2030	**2040**
Iron (ktpa elemental)	38	75

4.1.2 Scenario Outline

Canada already has significant operations in high-purity iron ore mining and steelmaking, and the mandated benchmark quantity of supplementary iron necessary for LFP cathode manufacturing is unlikely to be a bottleneck. However, iron sulfate is traditionally the chemical intermediate necessary to produce precursors to LFP cathodes. Canada can encourage iron sulfate production from steel mills, it should also support the commercial viability and scaling of new pCAM and CAM processes using iron powder or iron oxide to bypass iron sulfate and avoid controversial sodium sulfate waste issues.

- **Produce Iron Sulfate from Existing Steel Mills:** The pickling step in steel mills necessitates the treatment of steel with sulfuric acid; this is an opportunity to produce iron sulfate as a byproduct to sell for pCAM/CAM LFP cathode makers.
- **Leverage Canada's Iron Products and Support Clean Cathode Manufacturing Processes:** NanoOne has developed cleaner processes to use iron powder or iron oxide with other precursors to produce CAM in one pot and avoid sulfate salt issues. These initiatives should be supported to ensure commercial viability and scaling, as they can boost competitiveness and increase social mandate against Chinese CAM processes. Rio Tinto's RTIT plant in Quebec already produces pure iron powder as a by-product of its titanium operation.

4.2 Iron: An Abundant Material Needed Mostly for Steel but also LFP Cathodes

Iron, a silvery grey and soft metal in its pure form, is the 4th most abundant element in the Earth's crust. On top of being indispensable for life processes, as iron-bearing proteins are required for oxygen transportation in blood, iron has also become the most used metal through nearly 5,000 years of metallurgical innovations. Iron is a cost-effective and versatile material thanks to its wide availability and various physical properties (high strength, malleability, ductility, magnetic properties, *etc.*). Mainly combined with carbon in **steel** (< 2% C) and **cast iron** (2–4% C), iron's properties can be finely tuned with different metal alloys: for instance, the addition of chromium and nickel increases corrosion resistance in **stainless steels**, while tungsten, molybdenum and vanadium can enhance hardness and wear resistance in **tool steels**. Consequently, iron and steel are found everywhere in modern society: in consumer goods, mechanical & electrical equipment, vehicles (cars, trucks, ships and rail), infrastructure, and buildings.

Figure 4.2.1 Examples of applications for steel and iron materials

The popularity of iron also results in its high energy requirement and large carbon footprint: the manufacturing of iron and steel accounts for almost **7% of global GHG emissions** and **8% of global energy demand**. Additionally, a boost in steel demand from emerging countries will most likely drive a global increase in steel production: the IEA's Stated Policies Scenario forecasted a global steel production growth from around 1.9 Gt in 2019 to over 2.5 Gt in 2050.[106]

In parallel with the steelmaking processes, commercially available iron compounds, such as **iron(II) sulfate heptahydrate** $FeSO_4.7H_2O$ or **iron(III) chloride** $FeCl_3$**, are primarily obtained from the treatment of steel scrap with acids** or the leaching of iron sulphides or ilmenite.[107,108] Iron sulfate is the traditional reagent used as a precursor to cathode material for lithium-iron-phosphate (LFP) batteries. For more details of this process, please refer to the phosphate section of this report.

4.3 The Iron Flowsheet: An Ironmaking and Steelmaking Industry Looking to Decarbonize

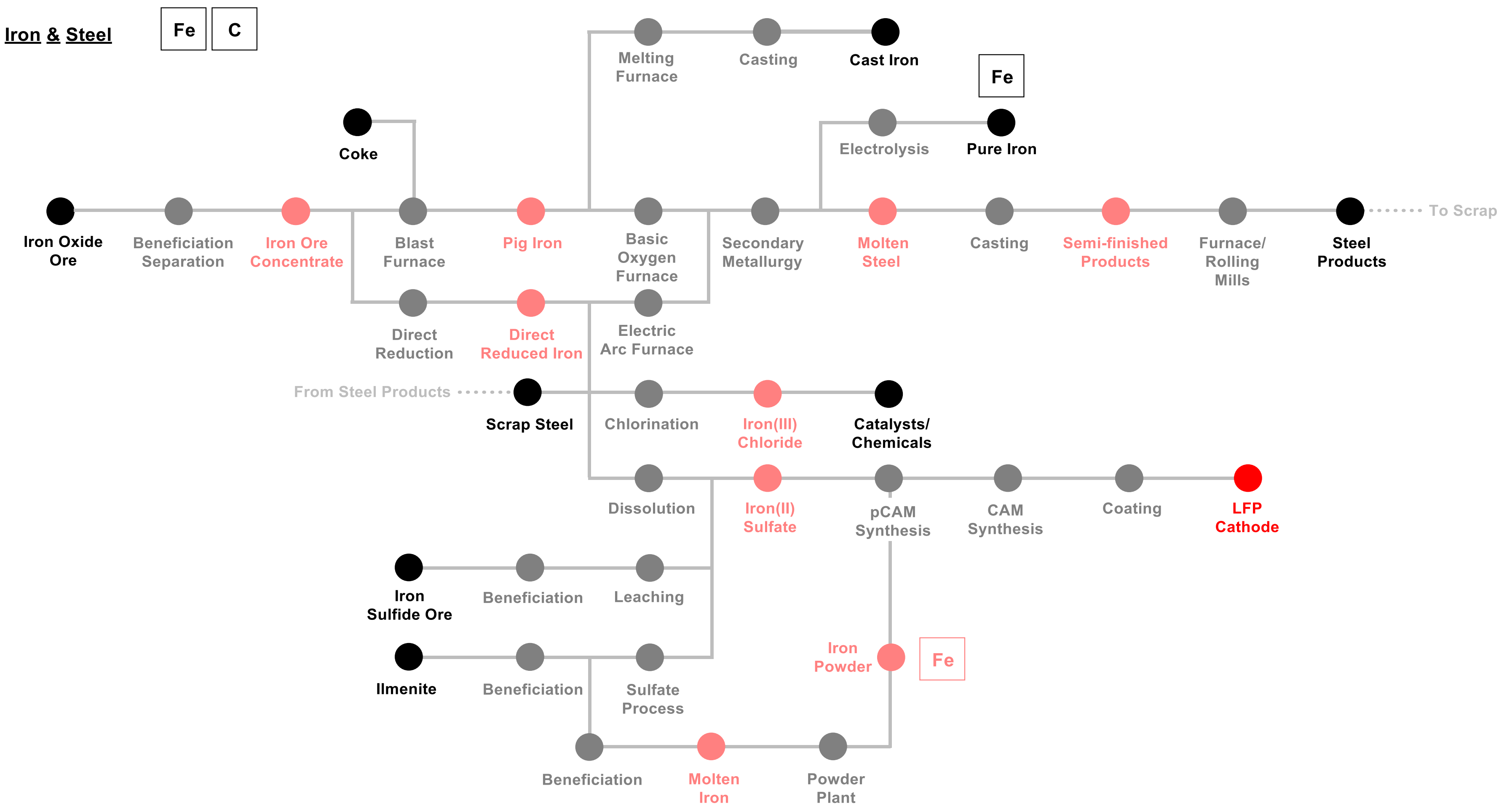


Figure 4.3.1 Simplified flowsheet of iron/steel to LFP cathodes

Compared with other elements, iron is undeniably the primary metal extracted: 2.6 billion tonnes of iron were mined globally in 2022, representing **93% of the total mined metals**. 98% of this iron is purposed solely for steelmaking. Despite its availability, iron mainly occurs in silicate minerals, which are not economically viable to process. The mining industry thus focuses primarily on extracting oxides such as **hematite** Fe_2O_3 and **magnetite** Fe_3O_4. Two main metallurgical routes currently dominate the steelmaking industry: the integrated and mini-mill routes. However, both processes aim to separate iron from oxygen first and then control the carbon content of the steel.

The integrated, or **blast furnace–basic: oxygen furnace** route (BF-BOF) starts by smelting the iron feed with limestone using coke as a reductant. It produces **pig iron**, a high-carbon crude intermediate, refined by adding oxygen at high temperatures. Secondary metallurgy and forming steps will generate semi-finished and finished steel products. This process, closely tied to coal and fossil fuels, represents the leading route, accounting for **92% of iron and steel global production in 2022**.

The mini mill route alternative, or **direct reduced iron–electric arc furnace route** (DRI-EAF), first uses a reducing gas to produce iron from the feed. Impurities are separated while the carbon content is adjusted inside an electric arc furnace to make steel. This process has recently gained more attention as it relies mainly on electrical energy, and the reducing gas (traditionally issued by natural gas, coal or syngas) could be replaced by decarbonized hydrogen. DRI processes only represented 8% of **iron and steel global production in 2022.**

It is worth noting that while iron is virtually entirely recyclable, only **32% of the global metallic input for steel production comes from scrap**, mainly during the EAF process. Alternative steelmaking routes include smelting reduction processes, which avoid the carbon-intensive coke-making step, or novel electrometallurgical processes such as molten oxide electrolysis (MOE) or low-temperature **electrolysis** (LTE), where a strong electrical current directly reduces the iron oxide feed.

Table 4.3.1 Estimated reserves & mined production of iron content by country in thousands and millions of tonnes

Country	**Iron content mined in 2022** (in tonnes x 10^{3})[a]	**Country**	**Iron content reserve in 2024** (in tonnes x 10^{6})[b]
Mexico	6,800	Chile	NA
Mauritania	7,950	Mauritania	NA
Kazakhstan	8,890	Mexico	NA
Turkey	10,700	Turkey	99
Chile	11,100	Sweden	600
Peru	12,900	South Africa	620
Ukraine	21,300	Kazakhstan	900
US	24,700	Peru	1,200
Sweden	27,700	US	1,300
Other Countries	32,200	Iran	1,500
South Africa	40,500	**Canada**	**2,300**
Canada	**41,400**	Ukraine	2,300
Iran	51,300	India	3,400
Russia	55,800	China	6,900
India	156,000	Other Countries	9,500
China	170,000	Russia	14,000
Brazil	276,000	Brazil	15,000
Australia	584,000	Australia	27,000
World Total Rounded	**1,540,000**	**World Total Rounded**	**87,000**

[a] Data from the 2024 U.S. Geological Survey in thousands of tonnes of iron content mined.
[b] Data from the 2024 U.S. Geological Survey in millions of tonnes of iron content mined.

Table 4.3.2 Estimated production of pig iron and raw steel by country in millions of tonnes

Country	**Pig Iron production in 2022** (in tonnes x 10^{6})[a]	**Country**	**Raw Steel production in 2022** (in tonnes x 10^{6})[a]
Mexico	2	Ukraine	6
Iran	3	**Canada**	**12**
Italy	3	Mexico	18
Canada	**6**	Vietnam	20
Ukraine	6	Taiwan	21
Turkey	9	Italy	22
Vietnam	12	Iran	30
Taiwan	13	Brazil	34
U.S.	19.8	Turkey	35
Germany	24	Germany	37
Brazil	27	South Korea	66
South Korea	42	Russia	72
Russia	52	U.S.	80.5
Japan	64	Japan	89
Other countries	67	India	125
India	80	Other countries	195
China	866	China	1,020

World Total Rounded	**1,300**	**World Total Rounded**	**1,880**

[a]Data from the 2024 U.S. Geological Survey in millions of tonnes of iron content mined.

Australia, Brazil, China, and India are responsible for 67% of iron ore production in iron content. China's steelmaking capacity is heavily concentrated, representing 54% of global crude steel production.[109,110] Canada is historically a significant iron and steel producer: The U.S. Geological Survey estimated that Canada ranked 7th on global iron extraction in iron content in 2022, 7th on international iron reserves and that Canada was the 15th raw steel producer the same year, with almost 12 million tonnes of crude steel produced. NRCan reports eight iron ore extraction sites: 3 in Labrador, 4 in Northern Quebec and one in Nunavut.[111] Canada's mining operations concentrate mainly on the Labrador Through, a geological iron belt formation between Labrador and Quebec. As for steel production, Ontario holds most of the BF-BOF steelmaking plants. Electric Arc Furnace/mini-mills operations are more spread out: they can be found in Alberta, Saskatchewan, Manitoba, and Ontario. Almost 46% of Canadian-made steel originates from the EAF route.[112] Finally, it is worth noting that the only DRI-EAF plant is the ArcelorMittal operation in Contrecœur, QC.

To bypass the use of iron sulfate and avoid the sodium sulfate/sulfate salts waste issues linked to pCAM and CAM manufacturing, the Canadian company NanoOne developed a one-pot process using pure iron powder or iron oxide as an iron source. They have partnered with Rio Tinto to use their high-purity iron powder produced in Sorel-Tracy, Quebec as a by-product of their RTIT titanium smelter. First Phosphate, a Quebec-based company seeking to develop phosphate deposits, a phosphoric acid plant, and a cathode active material plant for LFP batteries, has recently been collaborating with GKN Powder Metallurgy to lease their metal-powder-making technology for producing iron powder.[113,114]

5 Lithium

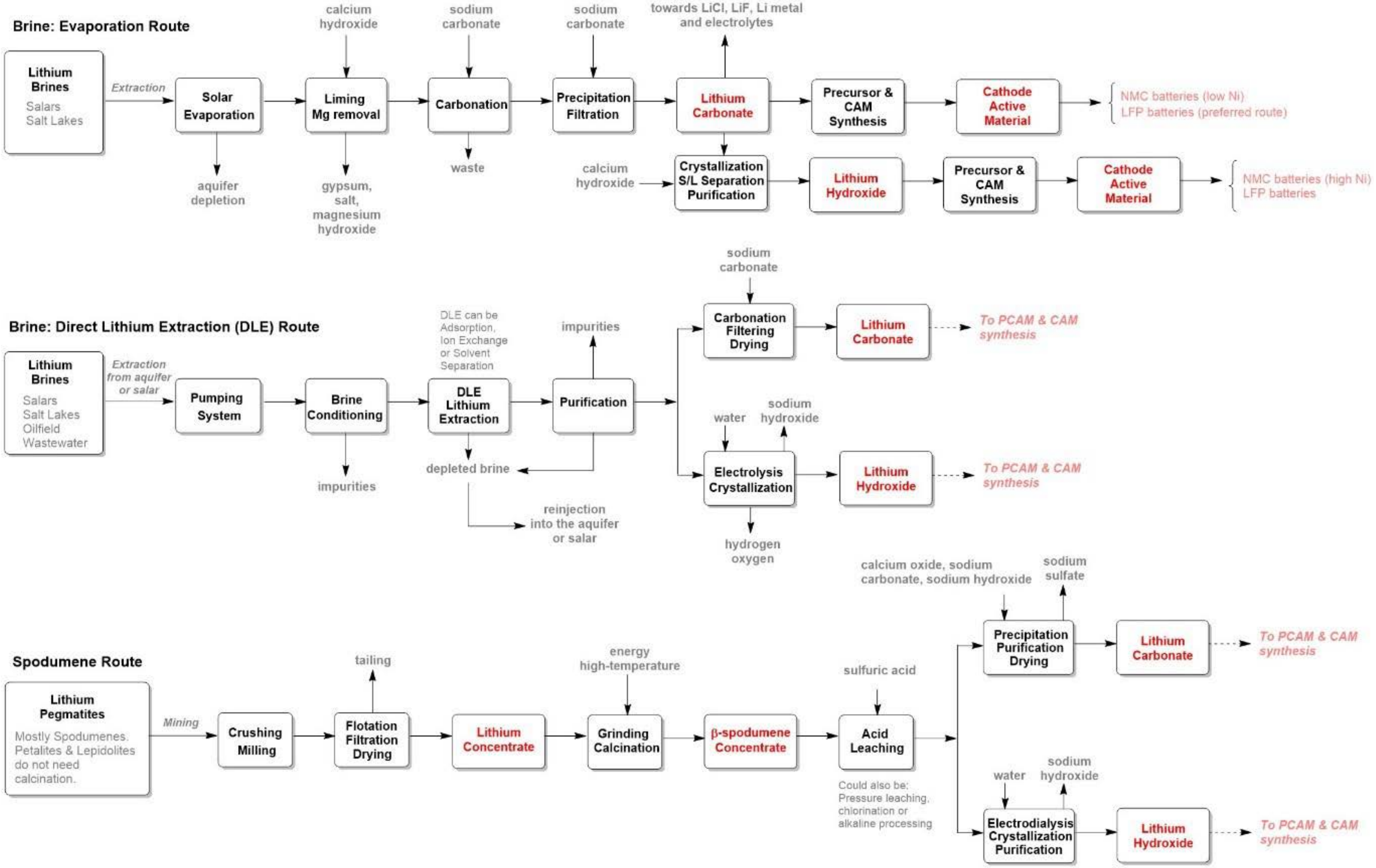


Figure 4.3.2 Simplified Lithium Flowsheet: Brine evaporation, DLE and spodumene routes

5.1 The Canadian Strategy for Lithium

5.1.1 Lithium in Canada

Table 5.1.1 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 LithiumTantalum 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.[115,116] 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.[117,118] Additionally, several early-stage pegmatite mining projects are being developed in Manitoba, notably by Grid Metals Corp. for Donner Lake and Falcon West,[119] and around Snow Lake by Snow Lake Lithium and Foremost Lithium.[120,121]

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.[122] 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.[123] Neighbouring spodumene projects in Northern Quebec, such as **James Bay Lithium**, owned by Allkem (AU),[124,125] or the **Rose lithium-tantalum** project, owned by Critical Elements (CA), are also in motion.[126,127]

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.[128,129] Nemaska Lithium and Livent have agreed to supply Ford with LiOH for its EV batteries for 11 years.[130]

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.[131] 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.[132,133]

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.[134] 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,[135] while the latter specializes in developing electrochemical processes and electrolyzers for refining LiCl to LiOH.[136]

Northwestern Ontario has attracted several hard-rock lithium mining projects,[137] and a LiOH processing plant in Thunder Bay, ON, is planned by Avalon Advanced Materials.[138] 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.[139]

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.

5.1.2 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 significantly higher capacity.

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

5.1.3 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.

5.1.4 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.

5.1.5 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.

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

5.2.1 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.[140] Lithium doesn't exist in elemental form; it is primarily sourced from pegmatite rocks with lithium silicates or brines containing lithium chloride.[46] 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 ($E^\circ = -3.040$ V), meaning that elemental lithium has a strong tendency to lose one electron to become a positive ion Li^+.[141] 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.[142,143] 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,[1,83,144–150] and the U.S. Department of Energy anticipates its status to remain critical from 2025 to 2035.[151]

Figure 5.2.1 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.[152] 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.[152–154] 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.[153] 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.[152] Lithium oxides, hydroxide and carbonate are harmful caustic bases, and lithium hydroxide can cause caustic burns.[154] 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.[155,156] 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.

5.2.2 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.[157]

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.[158] 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.[50]

5.2.3 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.[159]

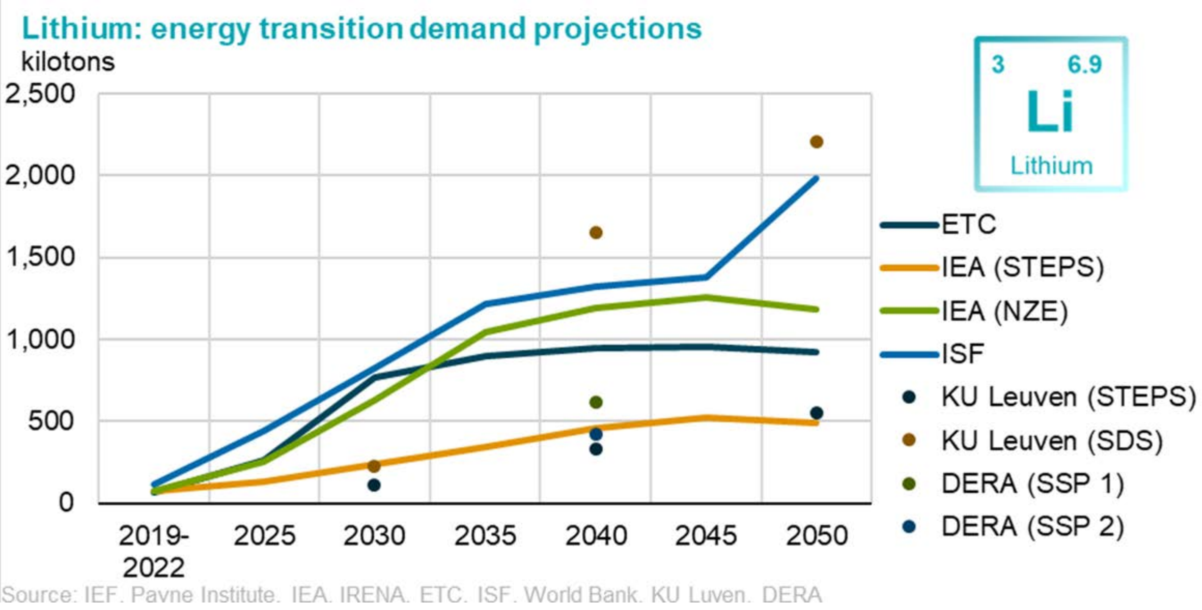
Several improvements, such as John Goodenough's replacement of TiS_2 by cobalt dioxide CoO_2 for the cathode in 1979 and the use of carbon (petroleum coke) as an anode, as Akira Yoshino found in 1985, gave rise to the safer lithium-ion technology. Commercialized by Sony in 1991, the first li-ion rechargeable 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.

5.2.4 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.[160] While some promising advancements in the battery field, such as solid-state batteries, still rely on lithium,[161] 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.[25,151]

5.2.5 Supply and Demand



Source: IEF. Payne Institute. IEA. IRENA. ETC. ISF. World Bank. KU Luven. DERA

Figure 5.2.2 Lithium demand projections to 2050 according to various energy transition scenarios[40]

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.[162,163] 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.[25,163–165]

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.[115,140] 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.[166] 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.[166] Lithium exploration also saw a 90% spending increase in 2022, strongly driven by Canada and Australia.[166] 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.

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

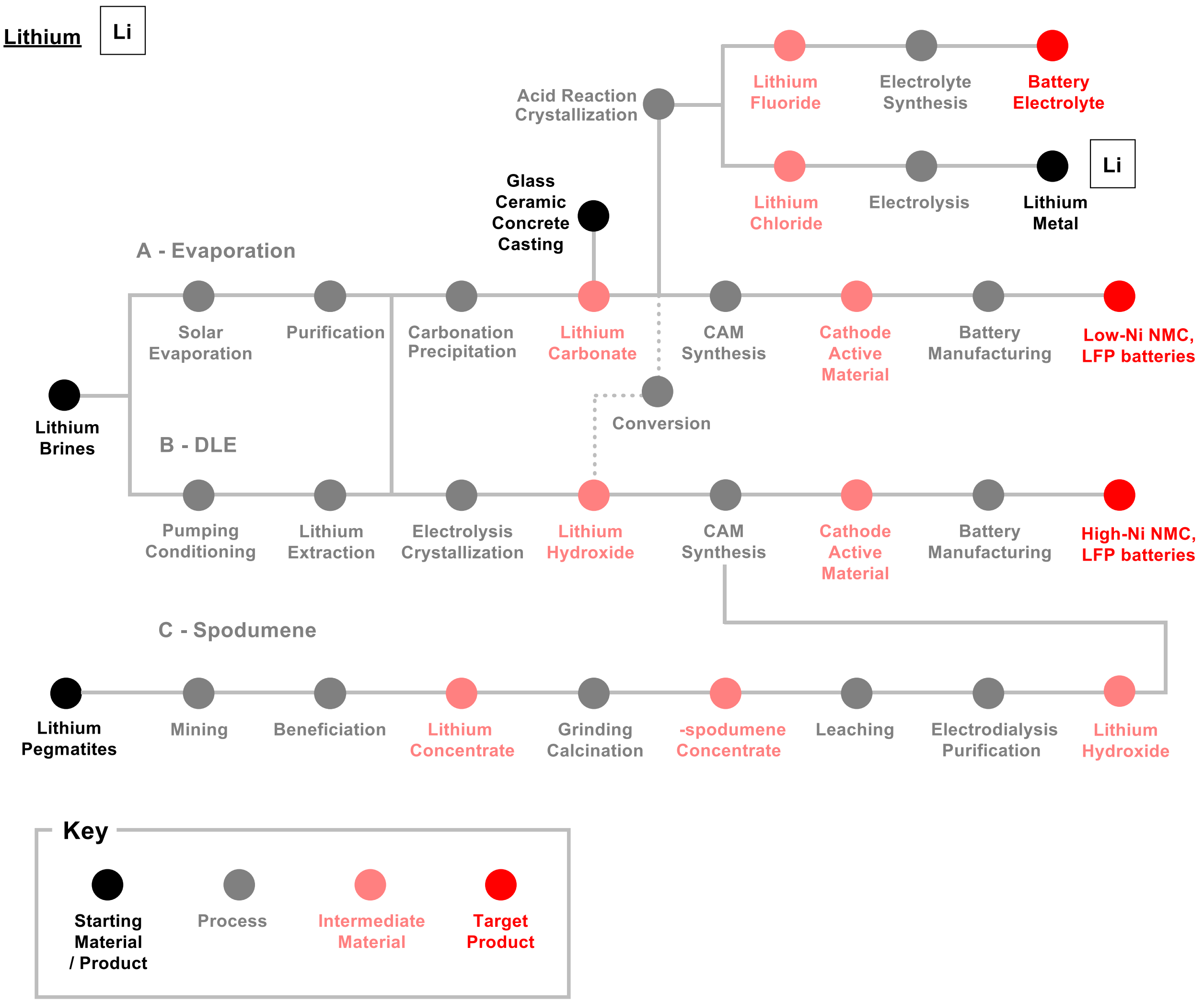


Figure 5.3.1 Simplified flowsheet of the lithium value chain

5.3.1 Lithium Ores, Production and Reserves

5.3.1.1 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).[153] This makes lithium a relatively widely distributed resource compared with lead (16 ppm in Earth's crust) or zinc (1 ppm).[154] Seawater also contains lithium, with an average concentration of 0.18 ppm,[160] 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.[167–170]

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.[171–175] It is estimated that lithium brine deposits make up around 66% of resources, while pegmatites represent 26% and clay only 8%.[176]

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.[152,154]

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.[152] 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.[177] This represents a significant opportunity for territories where the oil gas industry is already implanted, such as Texas, Arkansas, Alberta and Saskatchewan.[132,133,178,179] Finally, geothermal brine exploitation is planned at the Salton Sea in California.[180,181] Those projects could rely on low-carbon geothermal energy to extract lithium, thus potentially leading to negative CO_2 intensities.

5.3.1.2 International Lithium Production, Reserves and Resources

Table 5.3.1 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**

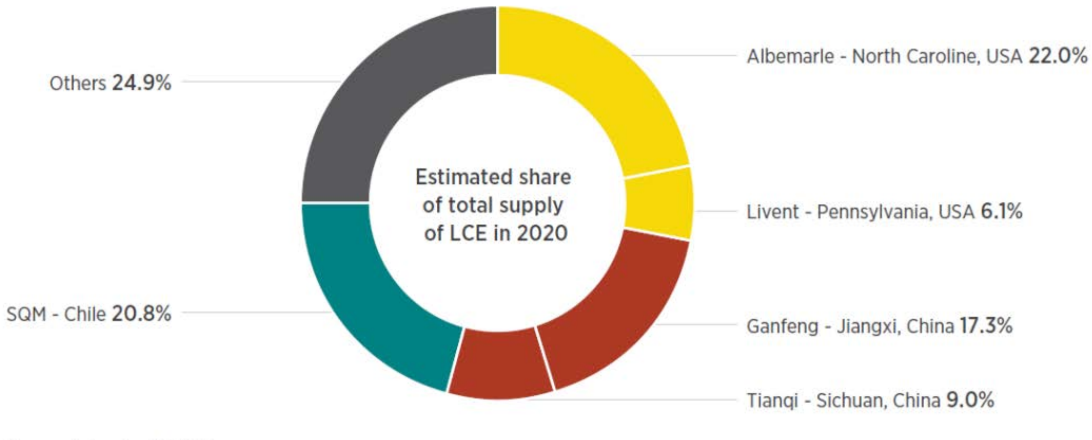
[a] Data from the 2024 U.S. Geological Survey,[116] NRCan's dataset differs slightly.[115]
[b] U.S. Production numbers are withheld from world total to avoid disclosing proprietary data.

Table 5.3.2 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.[116]
[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.[116] 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.[165] 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 5.3.2 Lithium supply by company in 2020[165]

5.3.1.2.1 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.[182] 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.[183,184] 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.[185,186] 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.[163,187–189]

5.3.1.2.2 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.[190] 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.[160] SQM has been particularly under scrutiny recently.[160,191] Chile's lithium remains the least carbon-emitting on the planet thanks to the solar evaporation process.[188,192–194]

5.3.1.2.3 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.[195] 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,[196] while the latter uses DLE with a selective adsorption plant to produce Li_2CO_3 and LiCl.[197,198] 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.[199,200] 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.[201–203] 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.[204]

5.3.2 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.[50] 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.[166] Projections for 2030 by the IEA indicate that the geographic concentration of refining facilities will slowly diversify.[205]

5.3.2.1 Evaporation: The Traditional Brine Processing Technology

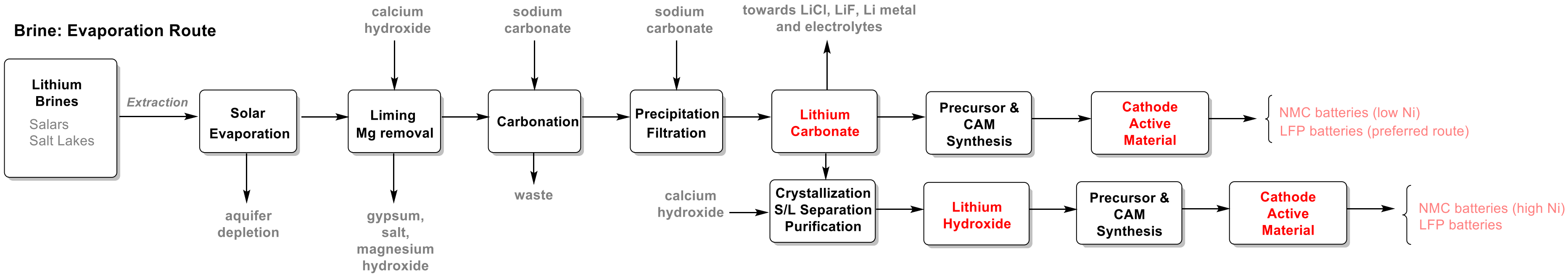


Figure 5.3.3 Brine evaporation flowsheet

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.[140,152,154] 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.[165,206] Nevertheless, Li_2CO_3 can be converted into $LiOH \cdot H_2O$ through an energy-demanding causticization/crystallization extra step.[207]

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.

5.3.2.2 Direct Lithium Extraction: The Novel Brine Process

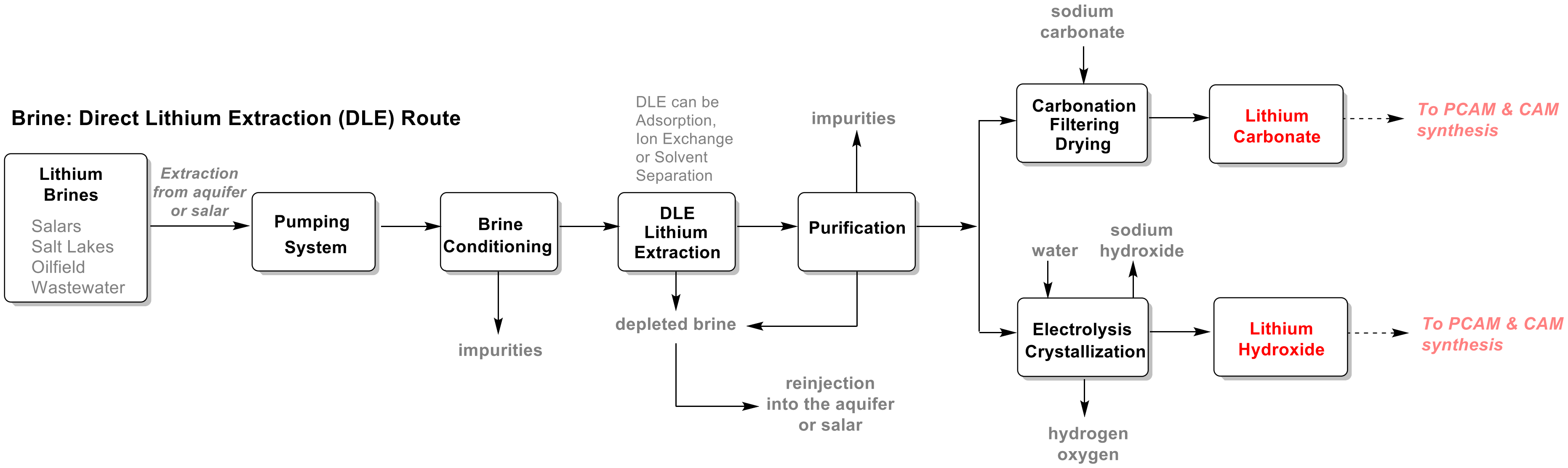


Figure 5.3.4 Direct Lithium Extraction flowsheet

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.[198]

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 $\gamma\text{-Al(OH)}_3 \cdot n\text{H}_2\text{O} \cdot \text{LiCl}$. 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.[152] 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.

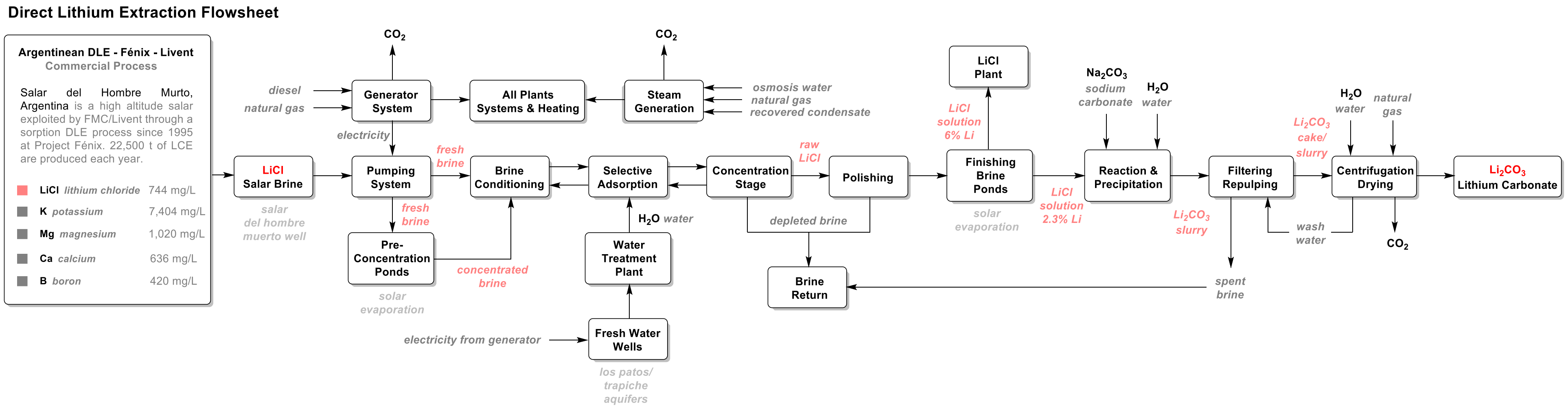


Figure 5.3.5 The DLE/Evaporation flowsheet of Project Fénix in Argentina

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.

5.3.2.3 Spodumene Processing

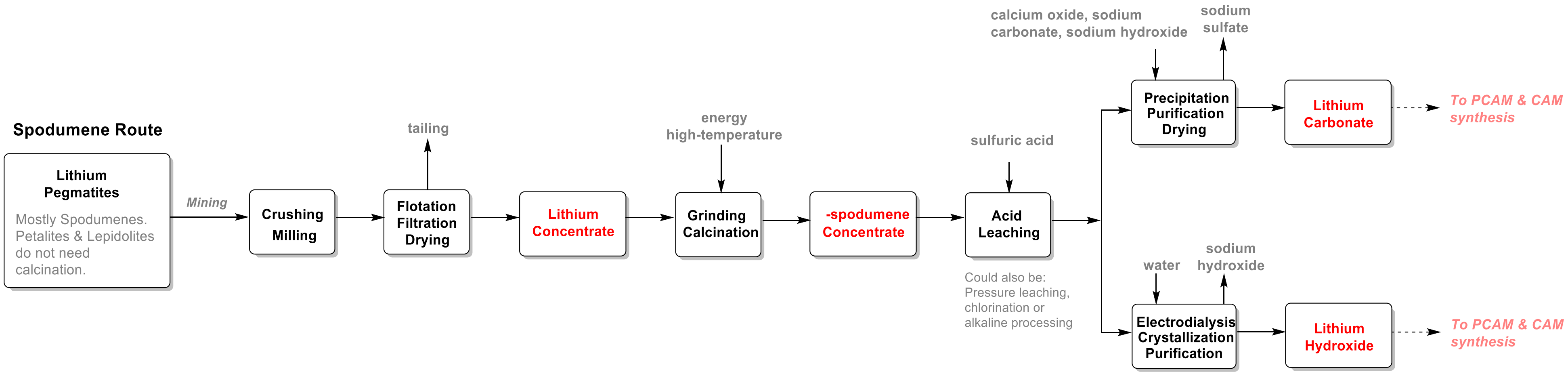


Figure 5.3.6 Flowsheet of spodumene processing

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.[140,152,154] 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.

5.3.2.4 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.[208]

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.[192]

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.[187]

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.[188] 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.[50,193] However, the brine route would still require less freshwater.[194]

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%),[89] 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).[162]

6 Nickel

6.1 The Canadian Nickel Strategy

6.1.1 Nickel in Canada

Table 6.1.1 Non-exhaustive selection of former and future nickel extraction and processing projects in Canada

Selection of Operational Nickel Extraction Sites				
Project Name	**Company**	**Province**	**Type**	**Status**
Voisey's Bay	Vale	NL	Nickel Sulfide	Operational
Raglan	Glencore	QC	Nickel Sulfide	Operational
Nunavik Nickel	Canadian Royalties	QC	Nickel Sulfide	Operational
Sudbury Intergrated Nickel Operations	Glencore	ON	Nickel Sulfide	Operational
Strathcona	Glencore	ON	Nickel Sulfide	Operational
Nickel Rim South	Glencore	ON	Nickel Sulfide	Operational
Coleman Mine	Vale	ON	Nickel Sulfide	Operational
Garson	Vale	ON	Nickel Sulfide	Operational
Clarabelle	Vale	ON	Nickel Sulfide	Operational
Copper Cliff Complex	Vale	ON	Nickel Sulfide	Operational
Creighton	Vale	ON	Nickel Sulfide	Operational
Fraser	Vale	ON	Nickel Sulfide	Operational
Totten	Vale	ON	Nickel Sulfide	Operational
Thompson Mine	Vale	MB	Nickel Sulfide	Operational
Selection of Future Nickel Extraction Projects				
Project Name	**Company**	**Province**	**Type**	**Status**
Dumont	Dumont Nickel	QC	Nickel Sulfide	FS 2019
Crawford Project	Canada Nickel	ON	Nickel Sulfide	FS 2023
Eagle's Nest	Wyloo	ON	Nickel Sulfide	FS 2025
Makwa-Mayville	GridMetals Corp	MB	Nickel Sulfide	PEA 2014
Minago	Norway House Cree Nation	MB	Nickel Sulfide	FS 2011
Baptiste Nickel Project	FPX Nickel	BC	Awaruite	PFS 2023
Turnagain Project	GigaMetals	BC	Nickel Sulfide	PFS 2023
Selection of Former, Operational and Future Nickel Metallurgical Plants				
Project Name	**Company**	**Province**	**Type**	**Status**
Long Harbour Nickel Processing Plant	Vale	NL	Hydrometallurgy	Operational
Sudbury Smelter	Glencore	ON	Pyrometallurgy	Operational

Copper Cliff Smelter & Refinery	Vale	ON	Pyrometallurgy	Operational
Thompson Smelter	Vale	MB	Pyrometallurgy	Closed in 2018
Fort Saskatchewan Refinery	Sherritt	AB	Hydrometallurgy	Operational
NetZero Nickel	Canada Nickel Company	ON	Pyrometallurgy	2027

Selection of Future Nickel Sulfate Plants

Project Name	**Company**	**Province**	**Type**	**Status**
Bécancour Nickel Sulfate Plant	Vale	QC	Nickel Sulfate Plant from Vale's products	2026
North American Nickel	Electra Battery Materials	ON	Nickel Sulfate Plant + pCAM	Unknown

The U.S. Geological Survey ranks Canada as the 6th largest nickel producer in the world for extraction in both 2021 accounts and 2022 estimates, which agrees with data from Natural Resources Canada.[209–211] Historically, Canada was much more prominent in the nickel sector during the most part of the 20th century,[212] and was especially leading the way for both extraction & refining in the Sudbury area. Canada now only accounts for 4–5% of the world's nickel production. Production decreased in 2021 due to a 70-day strike at Vale's Sudbury mine over bargaining for a better collective worker agreement with United Steelworkers.[213–215] Domestic production is located in four provinces: Quebec with the Raglan mine in Nunavik (Glencore), the Sudbury region in Ontario (Glencore, Vale), Labrador at the Voisey Bay mining site (Vale), and Thompson, Manitoba (Vale). All operated deposits are sulfide ores.

The main nickel processing plants and refineries in Canada: There are currently several operational nickel refineries in Canada: one in Fort Saskatchewan, AB, operated by Sherritt, converts mixed sulfide precipitates (MSP) from its operations in Moa Bay, Cuba, to nickel powder according to an ammonia pressure hydrometallurgical process.[216,217] Glencore (previously Falconbridge) owns an electric furnace smelter in Sudbury, ON to refine its sulfide concentrates from the Raglan mine and its neighbouring Sudbury INO mine.[218–221] The obtained nickel matte is shipped to Nikkelverk, Norway, for leaching and subsequent nickel cathode production by electrolytic refining.[222] Within the Sudbury Basin, Vale (previously Inco) also owns a nickel smelter and refinery in Copper Cliff. The same company previously owned a refinery in Thompson, Manitoba, which was shut down in 2018.[223] Vale has also opened a hydrometallurgical plant in 2009 in Long Harbour, Newfoundland, to process concentrates from its Voisey Bay site to pure nickel cathode.

Three sizeable Canadian projects concerning low-grade ultramafic nickel sulphide mining are currently at an advanced stage. One is in the Golden Triangle/Copper Corridor of North British Columbia; GigaMetals operate the Turnagain deposit; the Crawford project is operated by Canada Nickel near Timmins, Ontario; and the Dumont project is managed by Dumont Nickel and is located in Abitibi in

Northwestern Quebec. All three projects can be upgraded into good concentrates, which can be treated through various processes such as hydrometallurgical pressure oxidation, pyrometallurgical flash smelting or roast-EF smelting. All three projects also plan to sequester carbon in the tailings by mineralizing CO_2 into magnesium carbonate, starting from serpentinite or brucite. Several smaller nickel sulfide projects also exist in Ontario and Manitoba, such as Wyloo's Eagle's Nest project, an underground mine project with nickel, copper and PGEs in the Ring of Fire, the Makwa-Mayville projects in the Bird River Greenstone Belt in Manitoba, and the Minago project by the Norway House Cree Nation in Manitoba's Thompson Nickel Belt.

Additionally, FPX is looking to open an awaruite mine in Baptiste, BC. Awaruite is not a sulfide nor an oxide nickel ore but a high-content native nickel–iron ore. Simple beneficiation processes after mining could provide 60% Ni concentrate, ready for leaching for battery cathode purposes and would yield MHP as a by-product. This process would bypass pyrometallurgy or early hydrometallurgy stages and be among the lowest carbon-intensive nickel production sites in the global nickel market.[224–227] A scoping report for such a leaching facility was published in early 2025.[228]

Bécancour, QC– A new hub for nickel-rich battery material production: With its proximity to major highways, railways and deep-water port, important government incentives and inexpensive access to green hydropower, Bécancour, Quebec, has attracted many midstream actors of the EV value chain.[229,230] Vale, General Motors, and South Korean company Posco Chemicals will build a refinery and cathode active material plant capable of producing 25,000 tonnes of nickel sulfate per year starting in 2026 that General Motors will use for its Ultium batteries. The quantity of nickel is sufficient to supply batteries for 350,000 electric vehicles a year.[231–233] Concurrently, Ford, SK On and EcoPro BM formed a joint venture and secured federal and provincial government funding to open their own cathode active material plant in Bécancour in 2026.[234–237] Currently, SK On is known for supplying Ford with NMC9 batteries to Ford for its EV truck F-150 Lightning using cathode materials from EcoPro BM. The new site was announced as capable of manufacturing up to 45,000 tonnes of cathode active materials per year, sufficient to support the fabrication of 225,000 electric vehicles annually. However, Ford recently announced that it is backing off from this project, leaving EcoPro BM and SK On to find another off-taker. Additionally, BASF was previously clearing land for a future cathode active material and recycling site, with the ambition to expand up to a production of up to 100,000 tonnes of cathode active material a year.[238,239] However, this project seems to have been cancelled as well. Finally, Northvolt, a Swedish battery cell manufacturer, has begun construction of its new plant on the southern shore of Montréal, despite overall financial challenges and the filing for bankruptcy protection in the U.S. and Sweden.[240,241]

In Ontario, Electra Battery Materials is building a cobalt sulfate refinery in Temiskaming Shores and plans to explore the feasibility of a battery nickel sulfate refinery as well. Additionally, Electra plans to operate battery recycling operations, from black mass to recover materials such as MHP and lithium carbonate. Several other Canadian players, such as Li-cycle, Lithion, Battery X and Recyclico, are interested in producing nickel sulfate from black mass.

Volkswagen is currently building its first North American EV battery cell gigafactory in St. Thomas, Ontario, planned to open in 2027.[256,257] Volkswagen currently relies on nickel-rich batteries such as NCM 712 for its EVs. Stellantis and Energy Solution Battery have opened a battery cell factory in Windsor, Ontario, to manufacture NMC units. The production of modules is operational while cell manufacturing is planned for later in 2025.[257–259] Umicore had announced interest in opening a CAM plant in Loyalist, Ontario, but the project was paused in 2024. The same year, Honda announced a major project to manufacture both electric vehicles and batteries in Alliston, Ontario. Finally, General Motors previously planned the manufacture of battery modules and packs at its Ingersoll site in Ontario, but the current status of the project is unknown [261]

6.1.2 Target

Our previous report, 'Roadmap for Canada's Battery Value Chain,' established nickel objectives: Canada can reach 10% of the 2030 North American EV market as a baseline, but a leader scenario aiming at 35% should be implemented. Canada hosts much larger nickel resources than the USA, making a target much higher than the 10% share of the vehicle market relevant and necessary for re-shoring supply chains.

Nickel Mandated Benchmark (10% of 2030 North American Market)		
	2030	**2040**
Nickel (ktpa elemental)	37	74
New mines	1	2
New refining facilities	1	2
Nickel Leader scenario (35% of 2030 North American Market)		
Nickel (ktpa elemental)	130	175
New mines	3–4	4–5
New refining facilities	2	3

6.1.3 Scenario Outline

Canada should maximize nickel production to capture a significant share of the North American market and aim to bring 130,000 tpa online by 2030 through ongoing project, new ones and operating assets.

- Ramp up the current mining and processing nickel sulfide chain (NL, QC, ON) and imported laterite processing (AB).
- In the short term, the import and processing of international supplies in Canada (MHP, MSP or Matte).

    - In the long term, mining operations in BC and a large processing centre should be developed to produce $NiSO_4$, nickel metal, or pCAM with black-mass integration for future battery circularity.

6.1.4 Signature Projects

- Strengthen brownfield expansion of existing nickel mining and processing structures (NL, QC, ON, AB)
- Develop 3–4 large new mining operations (35–40 ktpa of elemental nickel).
- Build a large metallurgical facility in BC using either hydrometallurgy alone or a mix of hydro-and pyrometallurgy and integrating black mass on top of nickel ores as a feedstock. It should first use imported laterite precipitates as feedstock while supporting domestic sulfide concentrates when it comes online later through pressure oxidation.

6.1.5 Strategic Priorities

- **Build a Large Nickel Processing Complex in BC for Emerging Supply based on Synergies:**
    - **Smelt Turnagain sulfide concentrates to matte:** The planned complex will specialize in smelting Turnagain sulfide concentrates to produce matte, a semi-refined form of nickel. This involves the pyrometallurgical treatment of concentrates at extremely high temperatures to separate nickel from other elements. The resulting matte will serve as an intermediate product and will be further refined.
    - **Sulfur Capture and Synthesis of Sulfuric Acid:** In the smelting process of sulfide concentrates, sulfur dioxide (SO_2) is a common byproduct, which will be captured and processed into sulfuric acid. This conversion mitigates harmful emissions and generates a valuable chemical used extensively in mining and chemical industries. The sulfuric acid can be utilized on-site for leaching processes or sold to other industrial users, creating a beneficial byproduct stream that enhances the economic viability of the complex.
    - **Additional Sulfuric Acid from Zinc Smelting Operations at Trail:** The zinc smelting operations at Trail could serve as a supplementary source of sulfuric acid. This integration allows the nickel complex to leverage existing infrastructure and resources, ensuring a consistent supply of sulfuric acid for leaching operations. This collaboration also exemplifies efficient resource use, promoting sustainability by reducing the need for new acid production facilities.
    - **Leaching Decar Awaruite Ores with Sulfuric Acid:** The Decar Awaruite ores differ from the traditional nickel sulphide ores in that it does not contain sulphur and it is strongly magnetic. The sulfuric acid produced by the Turnagain ore smelting and/or originating from the Trail smelter could potentially be used to perform hydrometallurgical processing of awaruite. The legacy infrastructure from the pulp and paper industry,

such as the sulfuric plant in Prince George, is another alternative. Indeed, the treatment of awaruite concentrates by pressure leaching with sulfuric acid leads to the production of nickel sulfate. Alternatively, another innovative approach would be to involve the pressure oxidation of sulfide concentrate, using a small quantity of awaruite as a neutralizing agent. This method not only breaks down sulfide minerals more effectively but also manages the acidity levels in the process, reducing the need for additional neutralizing chemicals. This alternative route offers flexibility in processing different types of ore, enhancing the adaptability of the complex to various feedstocks.

- **Utilization of Kitimat Port for Importing Reagents:** Kitimat port's strategic location will be crucial for importing necessary reagents and raw materials, such as acids, bases, and other chemicals essential for ore processing. The port's infrastructure supports efficient logistics, ensuring timely delivery and reducing potential bottlenecks in the supply chain. This accessibility is vital for maintaining continuous operations and optimizing production schedules.
- **Securing Sodium Hydroxide Supply:** Sodium hydroxide ($NaOH$) is an essential reagent in various hydrometallurgical processes, including concentrate leaching and neutralizing acidic waste streams. Ensuring a steady supply of $NaOH$ will be critical for the complex's operations. This involves determining the optimal location for $NaOH$ production and addressing the management of chlorine byproducts, a common issue in $NaOH$ production. Another option for treating low-magnesium materials would be to use ammonia as a base to make ammonium sulfate by-products.
- **Access to Affordable and Green Power:** The complex's energy requirements will most likely be substantial, necessitating access to affordable and green power. British Columbia's rich hydroelectric resources offer a sustainable and cost-effective energy source, aligning with global sustainability goals. This access will not only lower operational costs but also reduce the carbon footprint of the nickel production process, enhancing the complex's appeal to environmentally conscious markets and investors.
- **Production of $NiSO_4$ for pCAM or Direct pCAM Production:** The facility will focus on producing nickel sulfate ($NiSO_4$), a key precursor for precursor cathode active material (pCAM), used in the manufacturing of lithium-ion batteries. The $NiSO_4$ can be obtained through the leaching of nickel matte from the nickel sulfide smelter or from the leaching of awaruite concentrates or nickel sulfide concentrates. Producing pCAM directly from the nickel sulfate solution may be possible without the solid nickel sulfate hexahydrate intermediate. The choice between producing $NiSO_4$ or directly producing pCAM will depend on several factors, including the stability of pCAM and the proximity to battery manufacturing facilities. If pCAM is stable only for a few days or weeks, the production facility must be located near battery manufacturers to prevent degradation. However, if pCAM can be stored for months, the

    complex can operate with greater flexibility regarding location and logistics.
  - **Production of Nickel Metal for Export and Market Hedging:** Alternatively, or in addition to producing battery materials such as $NiSO_4$ or pCAM, the complex could produce refined nickel metal in the form of nickel cathodes. This output will cater to various industries, including stainless steel manufacturing, which is a significant consumer of nickel. Producing nickel metal provides a hedge against market fluctuations and uncertainties in battery technology by allowing transactions with the LME as a market of last resort, ensuring the complex remains economically viable even if demand for battery-grade materials fluctuates.
  - **Integration of Black Mass Leaching and Recycling:** The facility should incorporate processes for leaching and recycling black mass, the mixture of materials recovered from end-of-life batteries. This initiative is critical for establishing a sustainable and circular supply chain for nickel and other valuable elements, such as lithium and cobalt. While economically and technically challenging, starting these processes now will position the complex as a leader in sustainable resource management.
  - **Connection to U.S. Markets and Western U.S. Battery Manufacturing:** Providing that tariff tensions are eased and geopolitical circumstances allow it, establishing robust connections with U.S. markets and Western U.S. battery manufacturing facilities can be a strategic priority. This connection will facilitate the export of nickel products and support the development of an integrated North American market for nickel-based products. It will also help the complex tap into the growing demand for electric vehicles and renewable energy storage solutions in the region. Diversifying by tapping into different markets from friendly nations will be necessary if the tariff war lags on.
  - **Collaboration with Downstream Industries:** The complex should actively collaborate with downstream industries to define export destinations for its products, focusing on major markets such as Japan, Korea, and the U.S., if the situation allows. This collaboration will ensure that the complex produces materials that meet the specifications and quality standards required by these markets, enhancing the competitiveness and marketability of its products.
  - **Clear Definition and Coordination of the Processing Facility:** The successful operation of the processing facility requires clear definition and coordination across different industries involved in the supply chain. This includes aligning production schedules, ensuring consistent quality control, and facilitating effective communication between all stakeholders. A coordinated approach will optimize the facility's output, reduce inefficiencies, and maximize economic returns.
- **Research & Development:**
  - **Prioritizing Proven Technology:** While innovation is essential, the immediate focus should be on implementing proven technologies that

can be quickly and reliably deployed. This approach minimizes risks and ensures that the nickel projects proceed without unnecessary delays. By leveraging existing technologies, the complex can achieve rapid development and start generating revenue sooner.

- **Preparing for Battery Circularity and Black Mass Recycling:** As mentioned for the planned metallurgical complex, developing industrial processes for recycling black mass is crucial for achieving a circular economy in the battery industry. This involves recovering valuable metals such as nickel, cobalt, and lithium from spent batteries, which can then be reused in new battery production. Establishing efficient recycling processes will reduce the demand for virgin materials and lower the environmental impact of battery production and disposal.
- **Developing Economically Viable Salt-Splitting Methods:** Developing economically viable salt-splitting methods is essential for addressing the challenges associated with sodium sulfate (Na_2SO_4) disposal. Sodium sulfate is a byproduct produced when sodium hydroxide neutralizes sulfuric acid in leaching or purification processes, for example, when MHP or awaruite is refined, or when pCAM is produced. It is often a voluminous waste, especially for mines and battery material plants outside of China. Disposal of sodium sulfate-containing effluents to ocean waters is a viable approach for coastal locations but may be more difficult to permit. Disposal of effluents *via* deep wells —similar to what is done widely in the oil industry— may be feasible in some locations (such as Alberta and Saskatchewan) but may also introduce permitting challenges. Salt-splitting would involve separating sodium and sulfate ions into valuable sodium hydroxide and sulfuric acid products, reducing waste and potential environmental impacts. Long-term demonstrations and validation of these methods are crucial to ensure they are both technically feasible and economically viable for large-scale implementation. It is worth mentioning that if magnesia or ammonia is used as a neutralization agent, sodium sulfate is not the issue.
- **Optimizing Hydrometallurgical Methods:** Smelters are more universal than hydrometallurgical processes to treat nickel concentrates, but they emit GHGs, and other air contaminants including SO_2 and metals-bearing dusts. Research efforts should focus on optimizing hydrometallurgical methods to process a broader range of nickel feeds. Typically, other transition metals such as copper, cobalt, zinc and iron, and alkali/alkali-earth elements like sodium, magnesium, potassium and calcium can be contaminants of concern for hydrometallurgical processes. Arsenic, selenium and antimony are usually easily addressed.
- **Developing Robust Processes for Dealing with Impurities:** Managing impurities becomes a critical aspect of maintaining product quality. Research will focus on developing robust processes for removing impurities such as arsenic, lead, and other undesirable elements. These processes will ensure that the final products meet the stringent purity standards required for high-value applications, including battery manufacturing.

    - **Re-Processing of Value Tails and Slags:** Reprocessing value tails and slags offers an opportunity to recover additional valuable elements, including platinum group elements (PGE) and other byproducts. This initiative not only maximizes resource utilization but also reduces the environmental impact of waste disposal. By extracting these elements, the complex can generate additional revenue and enhance its overall economic viability.
        - **Optimization of PGE Recovery and Other Value-Added Elements:** In particular, optimizing the recovery of Platinum Group Elements (PGEs) and other value-added elements is essential for maximizing the economic returns from the complex. These elements include ruthenium, rhodium, palladium, osmium, iridium and platinum. Those elements would be absent from any imported MHP/MSP, but could be present in economic quantities from imported matte.
    - **Public-Private Partnerships for Applied R&D:** Engaging in public-private partnerships will facilitate applied research and development, leveraging the expertise and resources of both sectors. These partnerships will accelerate the development of new technologies and processes, ensuring that innovations are quickly brought to market.
- **Build a Net-Zero and Competitive Nickel Supply Chain:**
    - **Access to Clean and Affordable Electricity or Alternative Sources with Offsets:** As mentioned earlier in the specific requirements for a large nickel processing complex, ensuring access to clean and affordable electricity is fundamental to the successful operation of a nickel supply chain that aims to be both competitive and environmentally sustainable. The integration of this requirement into a national clean energy strategy for critical minerals is required. Additionally, exploring options for carbon offsets to compensate for any non-renewable energy used will further align the supply chain with global carbon reduction goals.
    - **Implementation of CO_2 Sequestration at the Mine Site:** To minimize the carbon footprint of nickel mining operations, CO_2 sequestration techniques can be implemented at the mine site for some deposit types. This involves capturing carbon dioxide emissions from the air directly or from emissions produced during mining and processing and storing them underground or using them in industrial applications. Notably, natural deposits of brucite or serpentine can be used to mineralize carbon dioxide by forming new, stable and storable rocks. These strategies are envisioned for large nickel projects such as Turnagain or Crawford, and they could potentially achieve net zero at the mine level. This potential for net zero has still to be nuanced by the fact that there is currently no viable technology option today for capturing CO_2 for heavy equipment, the most likely source at mine sites. CCS could be viable in the case of a large stationary emitter, such as a fossil-fuel plant or in-site refinery. Capturing CO_2 at a centralized smelter or refinery and

transporting it to the mine site would not be successful unless the CO_2 price reaches >$200/t.

- **Design of Efficient Waste Disposal Systems for Slag, Leach Residues, and Other Solid Residues:** The design and implementation of efficient waste disposal systems for slag, effluents from leaching facilities, and solid residues are critical to maintaining environmental sustainability. This involves developing processes to treat and manage waste materials generated during nickel extraction and processing. Techniques such as solidification, stabilization, and recycling of waste products will be explored to minimize environmental impact.
  - **The Different Environmental Issues Between Smelters and Hydrometallurgical Facilities:** Smelters have SO_2 and metal-bearing dust, which can cause widespread pollution issues. Slag as a solid residue is more benign and can sometimes be used as a construction material, mainly as an aggregate replacement. Hydrometallurgical plants have fewer air pollution issues but can have challenging effluent and leach residues. The effluents are often managed by ocean disposal (e.g. sulfate-chlorides effluents from the Long Harbour plant). Leach residues are more voluminous than slag and are generally less chemically stable.
- **Implementation of a Hub and Spoke Model for Concentrate Production and Refining:** A hub and spoke model will be adopted, wherein nickel concentrate is produced at the mine sites and then transported to central hubs for further refining. This model optimizes logistics and processing efficiency by centralizing complex refining operations while keeping initial processing close to the ore source. The refined products, such as mixed sulfide precipitate (MSP) and mixed hydroxide precipitate (MHP) or high-purity end products, can then be distributed to various markets. This approach reduces transportation costs and environmental impact while ensuring consistent product quality.
- **Development of Transportation Infrastructure for Concentrates and Intermediates:** Developing robust infrastructure and leveraging the existing one for transportation is essential for efficiently moving nickel concentrates and intermediates from mine sites to refining hubs and final markets. This includes constructing and maintaining roads, railways, ports and dry ports, as well as establishing efficient logistics networks. A nominal 35 ktpa nickel mine will produce 150–350 ktpa of nickel concentrates to be transported to central processing facilities.
- **Securing a Stable Supply of Sodium Hydroxide, Ammonia or Magnesia:** As previously noted, sodium hydroxide (NaOH) is a critical reagent in the hydrometallurgical processing of nickel. Securing a stable and reliable supply of NaOH is essential for continuous operations that utilize this reagent. This involves negotiating long-term contracts with suppliers, exploring options for local production, and ensuring efficient storage and handling facilities. Addressing potential supply chain disruptions and managing the environmental impact of NaOH

    production and use will be key considerations. Alternatively, ammonia or magnesia are also viable reagents for different parts of the processes with different supply chain complexities. Ammonia reduces waste management issues but introduces byproduct management issues: the ammonium sulfate produced can be sold as fertilizer.

- **Collaboration with the Government**
    - **Coordinated Efforts Between Government and Industry for the Midstream segment:** A coordinated effort between government and industry is crucial to investing in refining and processing capacity for nickel. This involves establishing policies and incentives that encourage private investment and facilitate public-private partnerships. A significant issue that appears to hang over the nickel supply chain is the lack of interest in substantial expansion and cooperation by the dominant companies in Canada. By working together, stakeholders can build a robust and integrated battery nickel supply chain, leveraging each other's strengths and resources.
    - **Facilitation of Government-Level Coordination and Interprovincial Collaboration:** Effective coordination between different levels of government and interprovincial collaboration will be necessary to develop a seamless supply chain. This includes aligning regulatory frameworks, sharing resources, and fostering communication between provinces. Such collaboration will streamline operations, reduce bureaucratic hurdles, and ensure that all regions benefit from the development of the nickel supply chain.
    - **Development of an Integrated Supply Chain for New Mines Starting Production:** Ensuring that the supply chain is ready for new mines expected to start production before 2030 involves forward planning and investment in infrastructure, technology, and human resources. This preparation will enable a smooth transition from mining to processing and distribution, ensuring that new operations are integrated into the supply chain without delays.
    - **Funding to Support Mine Production:** Funding programs, such as those from the Canada Infrastructure Bank (CIB) or the Critical Mineral Infrastructure Fund (CMIF), will play a crucial role in bringing new mines into production. These funds can be used to develop necessary infrastructure, support technological innovation, and enhance operational efficiency. Depending on geopolitical imperatives, the U.S. Department of Energy (DOE) and the Department of Defense (DoD), as well as Japan, Korea, the European Union and its member countries, can also be potential funding sources.
    - **Creation of Incentives for Businesses in the Critical Minerals Space:** Creating incentives for businesses operating in the critical minerals sector will attract investment and innovation. These incentives can include tax breaks, grants, and subsidies for research and development, as well as streamlined regulatory processes. Encouraging businesses to invest in nickel processing and refining will enhance the supply chain's capacity and competitiveness.

- **Protection from Price Volatility and Secure Off Taker:**
    - **Facilitation of Stability and Certainty through Government Procurement:** Government procurement policies can provide stability and certainty for the nickel supply chain by ensuring a consistent demand for locally sourced critical minerals. This can be achieved through contracts for differences, government-guaranteed future purchases, or buffer stock mechanisms. Contracts for differences have been successfully applied in Alberta for the development of renewable energy.[248] Such measures will protect the supply chain from market fluctuations and ensure a steady revenue stream for producers. Several mechanisms are explored in a recent report published by the Centre for Net-Zero Industrial Policy.[249]
    - **Securing Korean and Japanese Cathode and Battery Manufacturing Companies:** Attracting Korean and Japanese cathode and battery manufacturing companies to Canada as off-takers will create a reliable demand for nickel products. These companies are key players in the global battery market and securing their business will strengthen the supply chain's market position. Negotiating fair technology transfer agreements will also ensure that Canadian companies benefit from the expertise and innovation of these international partners. Canadian firms also hold intellectual property of value, especially in the metal processing space.

6.2 Nickel: The Most Wanted Metal for High-Performance NMC Battery Cathodes

6.2.1 General Properties

Nickel is a silver-white metal with a brilliant polish aspect, ductile and malleable properties and a hardness superior to iron. Along with iron, cobalt, and gadolinium, nickel is one of only ferromagnetic elements around room temperature, *i.e.*, it exhibits a strong attraction to magnetic fields and the possibility of becoming a permanent magnet. On the other hand, its electrical conductivity is more moderate, only slightly surpassing iron. Nickel also bears a relatively high melting point (1,455ºC), and along with its alloys, it maintains its strength and integrity at elevated temperatures, making it suitable for high-temperature uses. One significant chemical property of nickel is its good corrosion resistance, especially in alkaline environments (with a basic/high pH) marine or industrial atmospheres, where a protective oxide layer formed primarily of nickel oxide NiO readily forms. However, an acidic or highly oxidizing environment can significantly weaken this protective layer and jeopardize the metal's integrity. Because of those versatile characteristics, nickel forms numerous alloys, improving strength, toughness, corrosion resistance, and high-temperature properties. Almost 60% of nickel production is used for stainless steel, but other alloys have found significance in aerospace, chemical processing, the oil and gas industry, shipbuilding, or naval armour. Nickel plating on base metals commonly strengthens used items (keys, pins, scissors, paper clips, *etc.*). Finally, nickel and its compounds play an essential role as a catalyst, as it can absorb 17 times its volume of hydrogen. Nickel catalysts are used for several important reactions within the chemical industry, such as hydrogenation (fats and oil for the food industry), reforming of hydrocarbon (production of gas and fuels), methanation (production of synthetic natural gas), ammonia synthesis (critical for fertilizer industry) or steam reforming (H_2 production from hydrocarbons), thus highlighting the crucial role of this metal for several strategic sectors.

Figure 6.2.1 Examples of applications for nickel materials

The unintentional use of nickel in alloys such as bronze dates back to 3500 BC.[250] An alloy of 60% copper, 20% nickel and 20% zinc, known as Baitong/Paktong, sometimes translated as "white copper", was produced in China as early as 1700–1400 BC. It was exported to Europe around the 17th century and was used for knives, forks and spoons as an inexpensive alternative to silver.[153,212] The element was first isolated and analyzed by Swedish mineralogist Axel Fredrik Cronstedt in 1751 from a sample of what is now thought to be a nickel arsenide ore from a cobalt mine in Los, Sweden. He coined it nickel, which comes from "Kupfernickel" or "false copper," the nickname given by Saxon miners who initially thought it was a copper ore from which they could not extract the red metal properly.[153,212,251] Refined metallic nickel was first produced in Germany in 1838, and small quantities of sulfide ores were mined in Norway, Sweden, Germany and Russia. The earlier uses of nickel remained copper-nickel-zinc alloys such as German Silver or nickel-silver, for those alloys were easy to cast, cheap to fabricate and resistant to tarnishing. By 1857, the United States Mint was the first to issue a coin containing 12% nickel, and by the 1870–1880s, the first alloy steel incorporating nickel was used, thus increasing the demand. Nickel-steel armour plates such as the Harvey or the Krupp armour became crucial for steel naval amor in the 1890s, accelerating nickel production because of the significant military applications. France dominated nickel production from 1875–1905, thanks to Garnier's discovery of laterite ores in Kanaky-New Caledonia in 1863. Canada later took the lead throughout the 20th century after discovering a large sulfide deposit in the Sudbury Basin and its exploitation in 1886. By 1950, the Sudbury area supplied 95% of nickel to Western countries.[212] Canada's position in the nickel sector has been displaced since the 1980s, mainly due to a decrease in deposit grade and the recent exploitation of laterites in Indonesia, Australia, and the Philippines.

Nickel is an essential nutrient for some plants and anaerobic bacteria but can be toxic to others.[252] In nickel-rich soils, "hyper-accumulator": plants can accumulate up to 1% nickel by dry weight.[153] While nickel levels in food and water are usually low, and its absorption by humans is usually minimal,[253] it poses a risk of chronic dermatitis from skin contact and cancer from inhalation of nickel fumes or soluble compounds, which are known human carcinogens linked to lung, nasal, and paranasal cancers.[252] Metallic nickel is also anticipated to be a human carcinogen, having caused local sarcomas in animal studies.[254] About 100,000 Canadians, primarily in industrial machinery repair, welding, and metal manufacturing, are estimated to be exposed to nickel at work.[255] High lung cancer risks have been observed among calcining workers in Canadian nickel smelters and hydrometallurgy workers in Norway due to exposure to water-soluble nickel compounds like nickel sulfate and nickel chloride.[256] Significant work has been done to understand this issue, making current workplace health impacts well-managed through appropriate engineering control and PPE. Québec City has been noted to have nickel contamination issues due to historic shipping of fine nickel concentrate.[257–261] Hypersensitivity by contact with nickel can cause allergic reactions such as dermatitis, asthma or conjunctivitis, a well-documented phenomenon due to the abundance of nickel-plated jewelry items— it is estimated that 10–20% of the population reports a reaction to nickel.[153,254,262]

6.2.2 Role in Energy Storage

The IEA identifies nickel as highly critical for EVs, battery storage, geothermal and hydrogen, and moderately critical for wind, concentrating solar power and nuclear.[50] While the major use of nickel for clean technologies remains as cathodes for Li-ion batteries, additional strong demand growth is expected from alkaline hydrogen electrolyzers and stainless steel in wind turbines.[25]

Nickel is critical as it is used in the most energy-dense of currently available battery technologies and nickel-based batteries are expected to remain a substantial part of the battery transition over the coming decades. Indeed, nickel shows excellent performance as a rapid and reversible redox centre necessary for repeated charge-discharge cycles. This is likely due to nickel's particular electronic configuration, geometry, and crystal structure when associated with oxygen.[263,264]

Historically, most applications were first found by the nickel-iron batteries patented at the end of the 19th century by Edison and Jungner. They even powered EVs as early as 1910, but as nickel-iron stopped being a material of choice, the rugged nickel–cadmium cathodes gradually came to dominate the broader rechargeable batteries market. Due to the toxicity of cadmium, they were succeeded first by nickel metal hydride batteries (NiMH), featuring nickel hydroxide $Ni(OH)_2$ as a cathode, and then the much more energy-dense lithium-ion batteries (Li-ion).

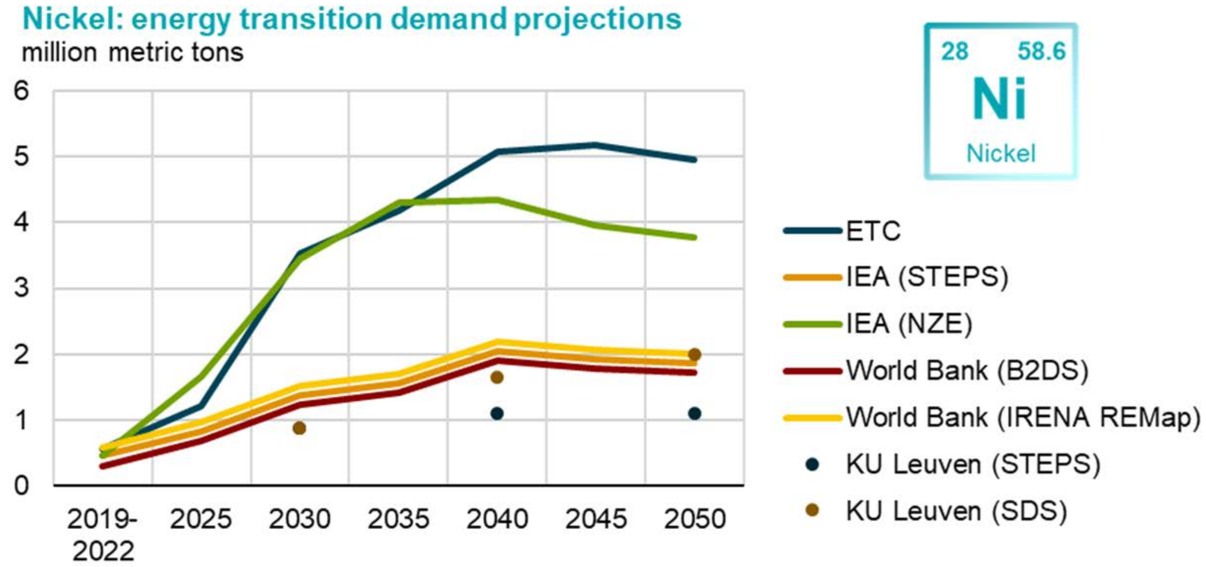
The latter used mixtures of lithium nickel oxide $LiNiO_2$ with other lithium metal oxides for improved stability, such as $LiCoO_2$, $LiMnO_2$ and $LiAlO_2$. Those cathode technologies include lithium nickel manganese cobalt oxides (NMC) batteries, representing 60% of the battery market share in 2022, lithium nickel cobalt aluminum oxide (NCA), representing a share of about 8%, and lithium nickel cobalt manganese aluminum oxide (NCMA) batteries.[265] All those chemistries hold the advantage of yielding good specific energy, making them particularly suitable for long-range electric vehicles, especially when compared to LFPs. Nickel-based cathodes powered 80% of the battery capacity in new plug-in electric vehicles in 2021.[266] Although LFP has been rising to about 50% of global market share, and have especially dominated the Chinese market, nickel-based batteries are expected to remain a significant part of the battery mix for decades to come. Nickel-based batteries are expected to remain the dominant battery chemistry ex-China.

In addition to their widespread use, the nickel content ratio has significantly increased over the years. In the case of NMCs, it has evolved from NMC 333 (one part nickel, one part manganese, one part cobalt) to NMC 622 to the current NMC 811 (eight parts nickel, one part manganese, and one part cobalt).[267,268] A Korean manufacturer has recently revealed plans to produce NMC with 95% nickel content.[269] Higher nickel content leads to increased energy density, better storage capacity, lower costs, and stepping away from cobalt's human rights and geopolitical challenges. This trend toward nickel-rich batteries will likely continue, but specific optimization and stability challenges must be overcome first.[270] In 2020, the average battery contained 29 kg of nickel, which could go up to 80 kg for some models.[271,272]

6.2.3 Substitutes

The substitution of nickel is highly dependent on battery technology and cathode markets. High nickel chemistry cathodes can be replaced by more cobalt, but the political and social implications of using more cobalt could be harmful. Cobalt can also be cost-prohibitive as it is also more expensive than nickel. Replacing NMC and NCA batteries with lithium iron phosphate batteries (LFP), an already mature technology that circumvents nickel for cathodes, is growing in popularity and would be more likely. However, this would be a trade-off in reduced energy density and poor performance in cold weather.[25,151] Stainless steel applications can reduce their nickel content by using ultrahigh-chromium alloys, or by moving to a lower quality 200 series stainless steel, with the additional drawback of having a sub-par performance products. Titanium alloys can also substitute regular stainless steel in corrosive environments but are generally much more expensive.[209]

6.2.4 Supply and Demand



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Figure 6.2.2 Nickel demand projections to 2050 according to various energy transition scenarios[40]

The overall nickel market is thought to be well-supplied, but the increasing demand for batteries will put pressure on higher purity nickel (class 1) production; as such, this metal is identified as a critical material for the medium-term 2025–2035 by the U.S.[151] The IEA accounted for a 40% rise in demand for nickel from 2017 to 2022, strongly driven by the energy sector.[273] According to Benchmark Mineral Intelligence, the 2021 global nickel market demand only accounted for 12% for battery purposes, while 69% was still reserved for stainless steel. However, this demand would evolve to 43% for batteries and 45% for stainless steel in 2035.[164] Last year, the U.S. Department of Energy estimated in its highest demand scenario that about 43% of the nickel demand is expected to be from electric vehicles batteries, stationary storage batteries and solid oxide electrolyzers in 2025 while this demand could jump to 78% in 2035.[151] Initially, most nickel sulfate, the chemical intermediate necessary for cathode batteries, came from class 1 nickel, a higher purity grade of metal obtained from sulfide ores. However, nickel sulfate production has increasingly relied on laterite sources, as the sulfide ore production was insufficient. Diverse and more impure nickel intermediates obtained from laterite ores, such as mixed hydroxide precipitates (MHP) or nickel matte obtained from nickel pig iron, have already increased in popularity as alternative supply chain routes had to diversify. Today, class 1 nickel is obtained from sulfide and laterite ores, with MSP and MHP being the primary source of nickel sulfate now.

6.3 The Nickel Flowsheet: A Complex Journey from Sulfide and Laterite Ores to Stainless Steel and Nickel Sulfate

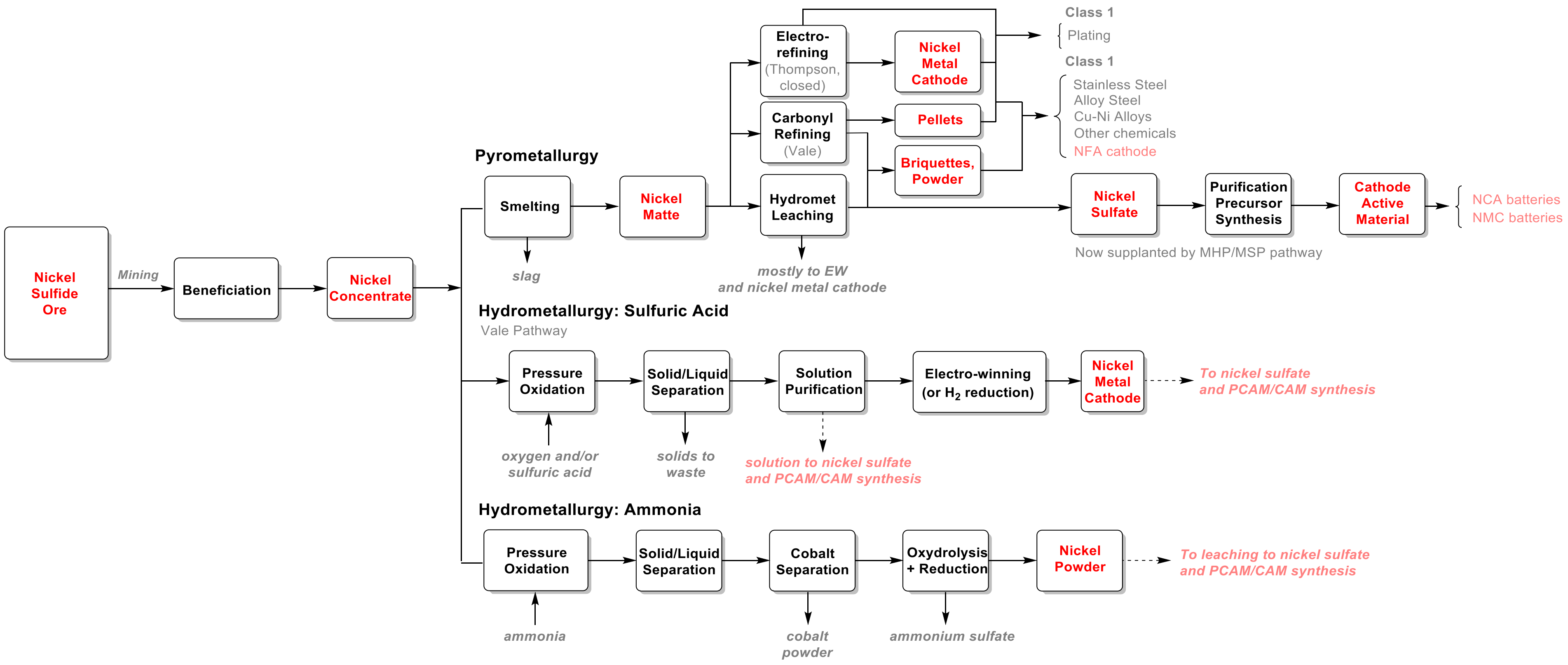


Figure 6.3.1 Simplified nickel sulfide flowsheet

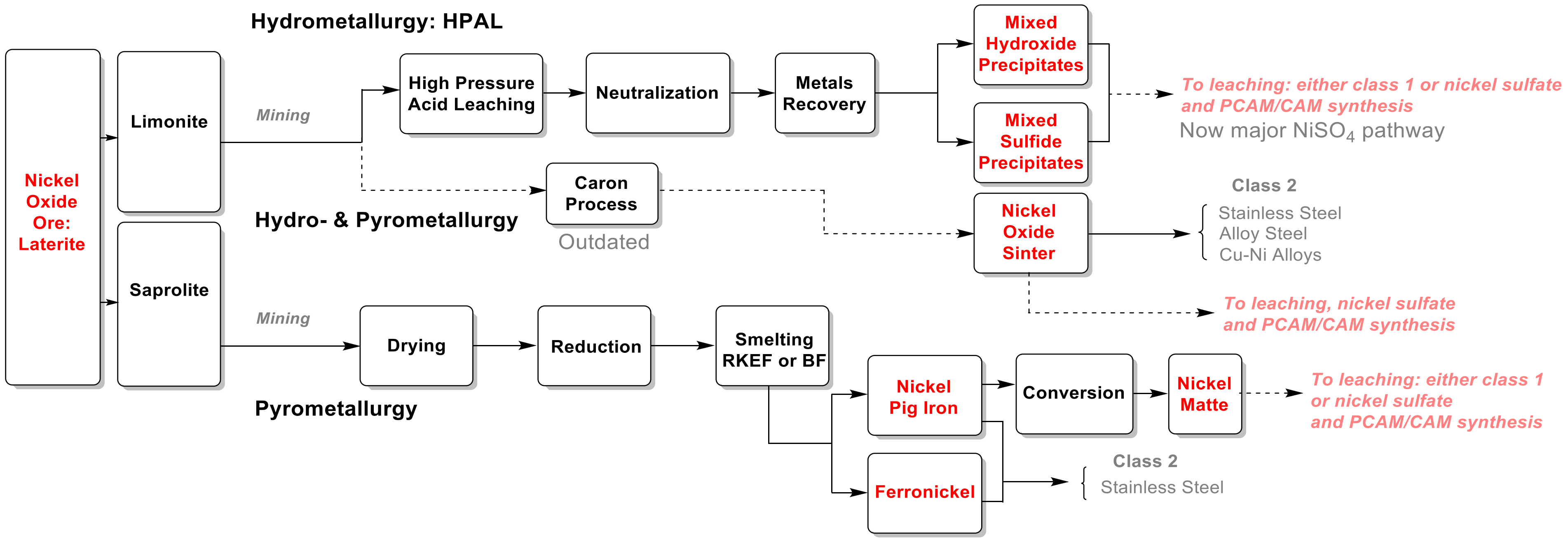


Figure 6.3.2 Simplified nickel oxide flowsheet

6.3.1 The Types of Nickel Ores, Mining and Reserves

Although nickel makes up for around 3% of the Earth's composition, it only comprises about 0.009% of Earth's crust, most nickel being buried in deeper layers such as Earth's core. As such, it is ranked 23rd or 24th most abundant element in the crust,[153,212,251] which is comparatively more common than copper, zinc or lead.

Sulfide ores are massive deposits formed thousands of meters deep by either magmatic activity or hydrothermal alterations after a reaction between nickel-bearing rocks with sulfur. The main mineral of interest in **pentlandite** $(Ni,Fe)_9S_8$, and nickel sulfide ores are commonly associated with copper and cobalt metal, most often with **chalcopyrite** $CuFeS_2$ and **pyrrhotite** Fe_7S_8 minerals.[212,251] Historically, significant reserves were mostly found in northern regions: Russia, Canada, Finland, and also Australia and South Africa (associated with high platinum values). Those types of ores are the main sources of **class 1 nickel products**.

In contrast, the main source for **class 2 products** comes from **nickel oxide ores**, also called **laterites**. They are formed by infiltration of water and weathering of peridotite rocks over a long period. The laterite weathering process requires a tropical or subtropical humid environment, thus explaining why the majority of nickel oxide deposits are confined around the equatorial belt, such as Indonesia, the Philippines, the Caribbean and New Caledonia.[274] Other resources from Australia, Brazil, or Madagascar are much older. Similar host rocks exist in northern regions but have not seen similar weathering.

Two types of laterites can be found: **limonite** in the most superficial layers and **saprolite** (nickel silicate or garnierite) in deeper layers. Saprolites are higher in nickel content and magnesium, while iron is lower than limonites. In 2019, 70% of worldwide nickel production came from laterite ores, while 30% came from sulfide resources. The share of laterite ores production has been rapidly increasing for several years and the laterite dominance is expected to increase in the future decade.[275]

Awaruite Ni_3Fe is another type of nickel ore which is not a sulfide nor laterite but rather a native nickel-iron alloy that can be found in potentially economic level in British Columbia.[224,225,227] Finally, in addition to land deposits, extensive nickel resources could also be found among **manganese nodules** on the ocean floor.[276]

6.3.2 International Nickel Production and Reserves

Table 6.3.1 Estimated reserves & mining production of nickel by country in tonnes

Country	2022 Ni mining production[a] (in tonnes)	Country	Ni Reserves in 2024[a] (in tonnes)
United States	17,500	United States	340,000
Brazil	88,500	China	2,100,000
China	114,000	**Canada**	**4,200,000**
Canada	**143,000**	Philippines	4,800,000
Australia	155,000	New Caledonia	7,100,000
New Caledonia	200,000	Russia	8,300,000
Russia	222,000	Other countries	>9,100,000
Philippines	345,000	Brazil	16,000,000
Other countries	404,000	Australia	24,000,000
Indonesia	1,580,000	Indonesia	55,000,000
World total (rounded)	**3,270,000**	**World total (rounded)**	**>130,000,000**

[a] Data from the 2024 U.S. Geological Survey, NRCan's dataset differs slightly.[209,211]

Global nickel production has grown and increased by around 1.5 times from 2015 to 2023, with Indonesia and the Philippines contributing significantly to this expansion, representing 59% of global output in 2022 estimations,[209,276] Indonesia alone accounts for an impressive 48% of global production. Both countries rely on laterite ores and are expected to drive around 70% of global production by 2025.[277] This nickel boom in Southeast Asia also shifted the principal extracted ores globally from sulfides to laterites. Other significant mining players are Russia, New Caledonia, Australia, Canada and China.

Indonesia also dominates nickel reserves, accounting for 42% of the world's available global reserves. Both Australia and Brazil hold significant reserves compared to their nominal production.

6.3.3 Processing

6.3.3.1 Overview of the Processing Supply Chain

The overall value chain of nickel is quite complex and although the industrial processing routes are interwoven, the principal differences and key steps rely on the type of nickel source (nickel sulfide or laterite), the different intermediates (concentrate, matte, mixed precipitates, nickel pig iron, *etc.*), and the different purity of end-products (Class 1 vs. Class 2). Both hydro- and pyrometallurgy technologies are available for the different sources of nickel ores, except for saprolite/garnierite which specifically require smelting. The most crucial chemical product for cathode active material manufacturing is nickel sulfate, which is why securing routes for its production is considered strategic.

6.3.3.2 Class 1 & 2 Nickel Products

Nickel market products are commonly divided into two different classes according to their nickel content, with Class 1 being of higher purity (> 99.7% nickel content) than Class 2 (< 99.7%). Contrarily to other metals such as copper, which usually requires a high purity because of its electrical and thermal applications, nickel's use as an alloy metal does not require the same imperatives: Class 2 products such as nickel oxide, metallized nickel oxide, ferronickel or nickel pig iron have a sufficient purity for applications such as stainless steel, despite significant levels of cobalt, copper, and other traces of impurities. That is why they are usually thought of as "charge nickel", meaning they are nickel forms that can be thrown into a stainless-steel furnace charge. Class 2 products originate solely from the processing of laterite nickel oxides. Nickel metals such as briquettes, powders, pellets, or cathodes are categorized as Class 1 products and can be leached with sulfuric acid to produce the nickel sulfate destined for EV batteries. This was formerly the route of choice for nickel sulfate production. Class 1 products were usually obtained by processing sulfide ores through hydrogen reduction, electrolytic methods, or carbonyl refining. Impurities of most metals are mostly removed, while trace cobalt levels can remain high in some produce forms.[212] Most projections predict an incoming shortage of Class 1 nickel products. However recent developments of Class 1 nickel refining capacity in China and Indonesia will mitigate this. Indeed, both the IEA and Benchmark Mineral estimate that the development of different processing routes connecting laterite ores to nickel sulfate (either through high-pressure acid leaching HPAL of laterites,[274] or nickel matte obtained from nickel pig iron) will be both necessary and desirable to fulfill the increasing demand for electric vehicles, as sulfide ore processing will not be enough to sustain this market transition to electric batteries.[50,164] Additionally, the processing of MHP to nickel sulfate has proven more affordable and faster than production *via* Class 1 nickel, thus favouring the industry to choose this direction. Those recent developments have shown the critical growth of nickel sulfate production without going through the traditional Class 1 or Class 2 nickel products.

6.3.3.3 The Importance of Nickel Sulfate as a Platform Chemical

Leaching Process:
to nickel sulfate

Using sulfuric acid to dissolve nickel from various sources (Nickel matte, pure nickel metal, mixed hydroxide precipitates, mixed sulfide precipitates, nickel oxide sinter,...), a useful nickel sulfate hexahydrate powder $NiSO_4(H_2O)_6$ intermediate can be obtained after crystallization. Nickel refineries can also produce nickel sulfate solution, although the main product is usually nickel metal obtained through electrowinning. Copper electrolytic refining can also produce nickel sulfate as a byproduct. Nickel sulfate is an important intermediate for the synthesis of precursor for cathode active materials.

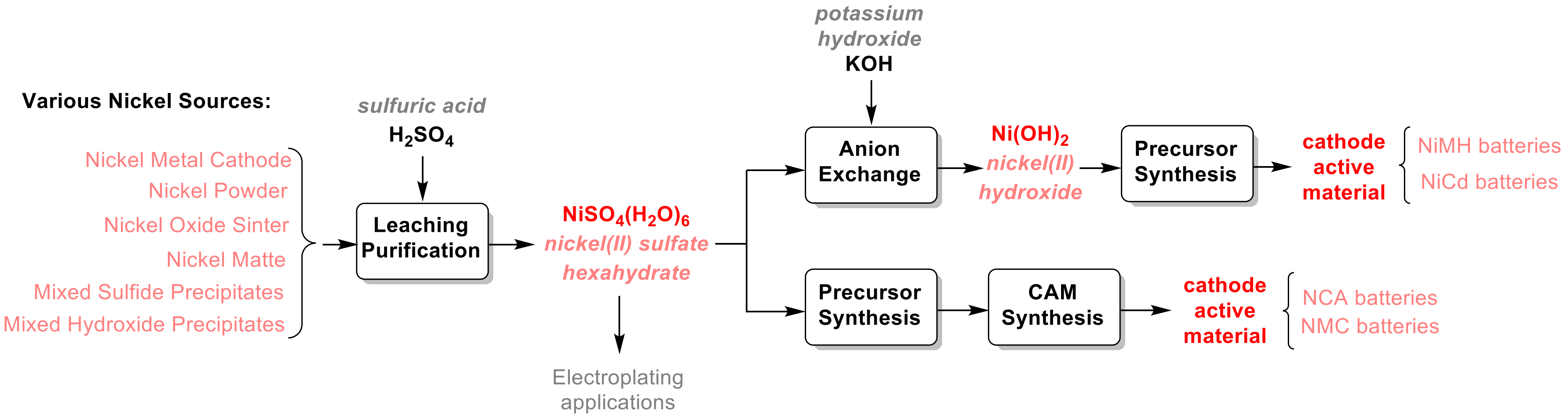


Figure 6.3.3 Nickel sulfate flowsheet

The ubiquitous chemical used to synthesize nickel-based cathode active materials for Li-ion batteries is nickel sulfate hexahydrate $NiSO_4 \cdot 6\ H_2O$, a blue-green crystal readily soluble in water. This compound can be obtained through various nickel sources, either from pure nickel powder, MHP, nickel oxide NiO, nickel carbonate $NiCO_3$, or even from impure nickel matte originating from sulfidic ores or lateritic nickel pig iron. Nickel sources are typically dissolved by sulfuric acid and crystallized to yield nickel sulfate, generating either more sulfate as a byproduct while leaching sulfide sources (matte or concentrate) or hydrogen gas when leaching nickel powder.[262] Some impure nickel sulfate is also obtained as a by-product of electrolytic copper refining.[252] This specific low-purity grade of nickel sulfate, although marginal, would be considered as Class 2, while most pure nickel sulfate would be Class 1. On top of being used as a precursor chemical for cathode materials, nickel sulfate is used as an electrolyte in nickel electrolytic refining and plating. Nickel hydroxide $Ni(OH)_2$ is another related platform compound that was previously important, as it was the precursor for cathode material in slowly phasing out nickel-cadmium NiCd batteries and for anode material in nickel metal hydride NiMH batteries.

6.3.3.4 Mixed precipitates: MHP& MSP

While nickel concentrate and nickel matte are the traditionally obtained intermediates along the nickel sulfide ore processing chain, mixed hydroxide precipitates (MHP), as well as mixed sulfide precipitates (MSP), are the primary intermediates produced when processing laterite ores through the high-pressure acid leaching route. They present an exciting way to convert abundant laterite resources into the pure Class 1 nickel products or nickel sulfate necessary for batteries. Those intermediates bear the advantages of being readily available from the numerous refining projects existing in Indonesia; they can be easily converted to nickel sulfate while providing interesting volumes of cobalt as a by-product. Converting MHP or MSP to nickel sulfate could also be significantly cheaper than leaching nickel metal.[278,279] However, potentially higher carbon emissions linked to some specific laterite processing route projects and problematic tailings management in Indonesia are usually described as their drawbacks.[50,164,280] The increased moisture content of MHP is another significant concern, as it would increase the need for water management and transportation quantities are higher than for MSP or nickel matte.[279]

6.3.3.5 Indonesia: The New Global Nickel Giant

In addition to dominating the upstream nickel extraction process, Indonesia's ban on nickel ore exports in 2019–20 and its push for domestic processing have further solidified its role in the global nickel supply chain. This resulted in 2020 Indonesian nickel ore exports to China dropping by nearly 90%, while nickel pig iron exports doubled compared to 2019. In response, Chinese companies have invested heavily over USD 30 billion in Indonesia's nickel supply chain to secure resources.[50] Consequently, Indonesia now has the upper hand in planned nickel refineries, representing 88% of future refining facilities for 2023–2030 while overtaking China as the largest nickel refiner (Indonesia refined 43% of nickel in 2022 *vs.* 17% in China).[166]

As Chinese companies have high stakes in Indonesian metallurgy plants, this can hinder their eligibility for specific policies such as the U.S. Inflation Reduction Act.[281]

Indonesia currently relies on the pyrometallurgy of saprolites to produce nickel pig iron, and ferronickel through smelting for class 2 products and on the hydrometallurgy (High-Pressure Acid Leach, HPAL) refining of limonites for MHP intermediates, nickel sulfate and class 1 products. Recently, a technique previously used for copper smelting, the oxygen-enriched side blow furnace (OSBF), has been adapted to the smelting of limonites to matte and Class 1 products. The nickel pig iron to nickel matte route, pushed forward by Tsingshan, is a way to crossover the different routes and value saprolite feedstock for class 1 and EV purposes, but at a higher energy cost and environmental cost.[50,282] In 2023, the primary nickel production route in Indonesia was the smelting of saprolite through rotary kiln electric furnaces (RKEF), representing around 90% of the production *vs.* lower than 10% for the leaching of limonite through HPAL.[42] The Philippines is the second largest nickel mining country, but only two HPAL refining plants are operating, and a few more are being considered.[166,283]

6.3.3.6 From Sulfide Ores: A Cleaner Process for Higher Purity Nickel

6.3.3.6.1 Nickel Sulfide Ore Beneficiation

Concentration

comminution & flotation steps

The goal is to crush and grind the minerals, separate them from impurities, other metals (like copper) and concentrate nickel for further refining, either through pyrometallurgy or hydrometallurgy.

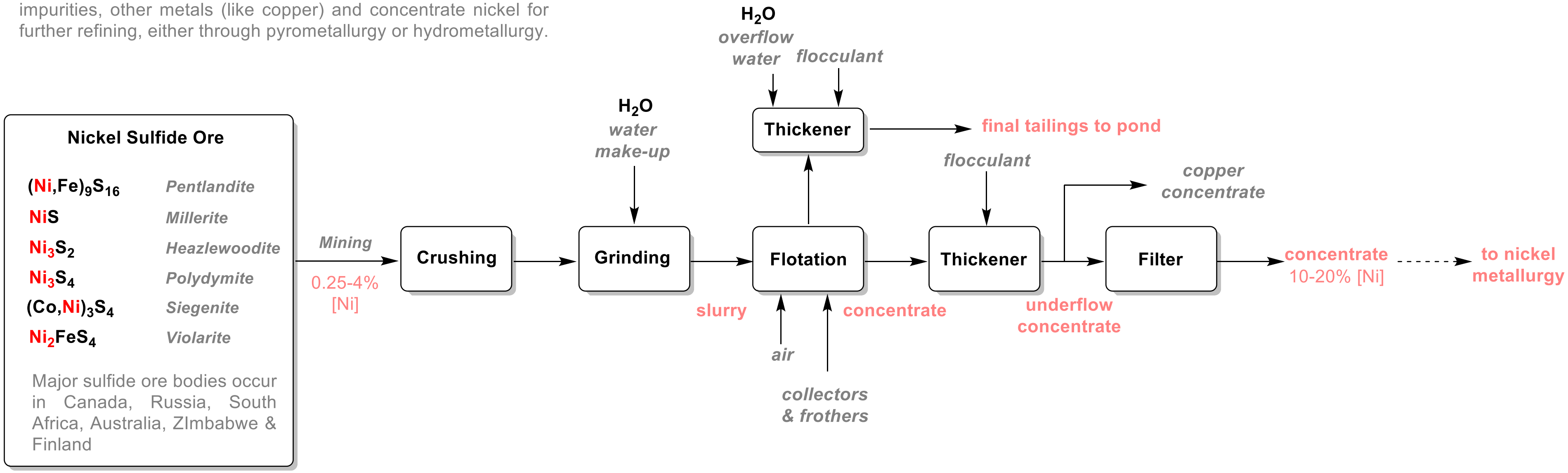
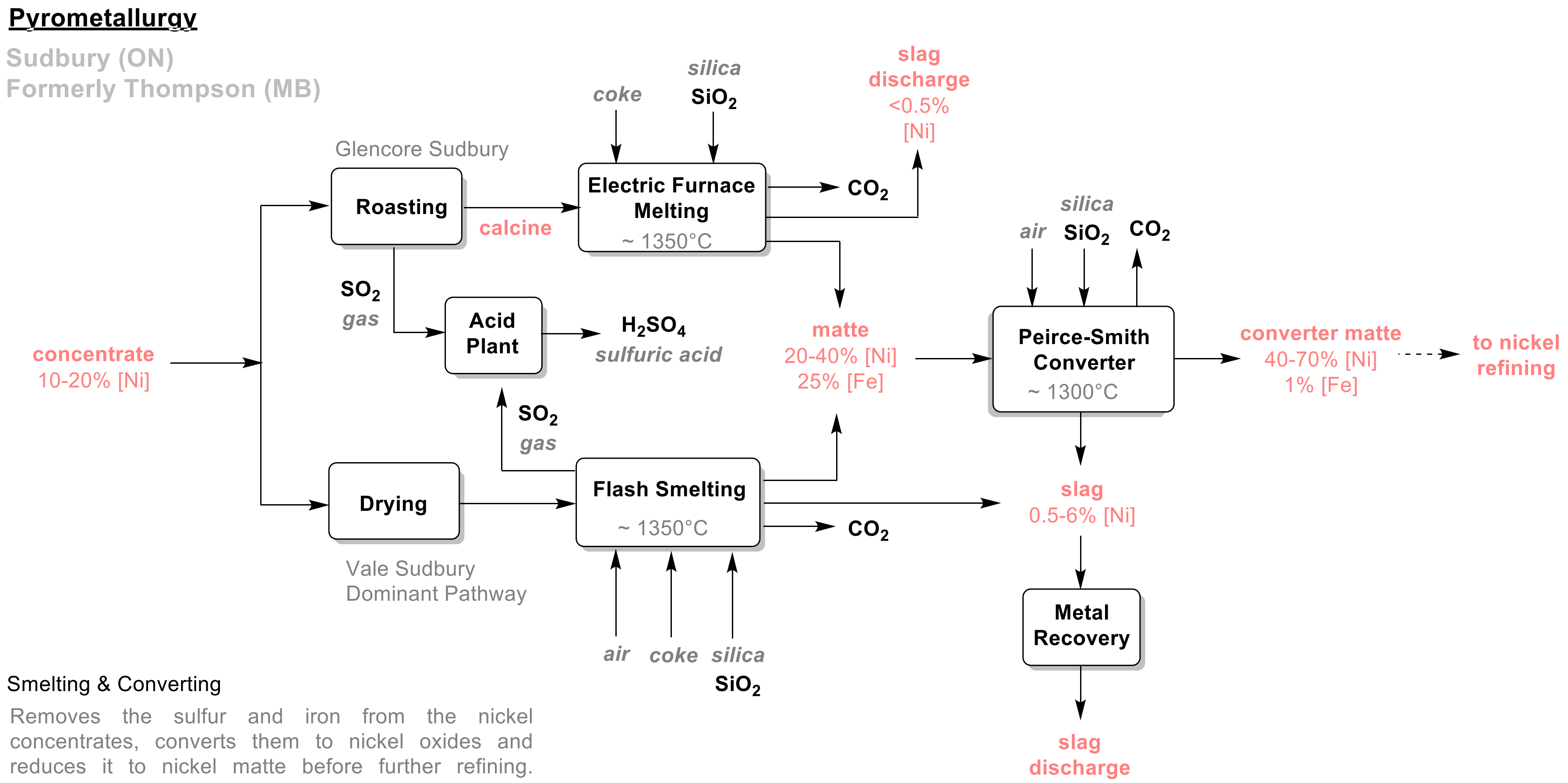


Figure 6.3.4 Nickel sulfide concentration flowsheet

When nickel sulfide ores are treated, pentlandite $(Ni,Fe)_9S_8$ makes the majority of the mineral of interest, but heazlewoodite Ni_3S_2 and millerite NiS can be present, and more marginal minerals like polydymite Ni_3S_4, $(Co,Ni)_3S_4$ or violarite Ni_2FeS_4 can also appear. Arsenide and sulfarsenide nickel compounds can also be present. Nickel deposits often occur with copper, cobalt and platinum group elements (PGE), and they can be classified between high-grade, making most of the traditional nickel mines, and low- to mid-grade. Akin to the copper industry, a global decrease in ore grade for nickel deposits in the past decades has led the industry to start looking more closely at lower-grade deposits.

After mining, nickel sulfide ores undergo a beneficiation process. The goal is to crush and grind the minerals, separate them from other metals (such as copper), and transform the mined ores (0.25–4% Ni) into concentrates (10–20% Ni). Every deposit has a specific beneficiation process tailored to optimize this step, depending on the mineralogy of the site. Froth flotation is the primary method used in the nickel sulfide industry for beneficiation, where air and chemical additives are introduced into a slurry containing ground ore.[284] This process causes sulfide minerals to adhere to air bubbles and float to the surface, allowing them to be collected, while gangue minerals settle as tailings. While simpler ores may undergo straightforward processing, complex ores containing problematic minerals like talc or nickeliferous pyrrhotite present significant challenges, requiring more intricate flowsheets and larger equipment. Differential flotation is also used to separate nickel and copper, with the resulting concentrates often requiring additional processing to meet market and environmental standards.

6.3.3.6.2 Nickel Sulfide Pyrometallurgy: From Concentrates to Matte



Smelting & Converting

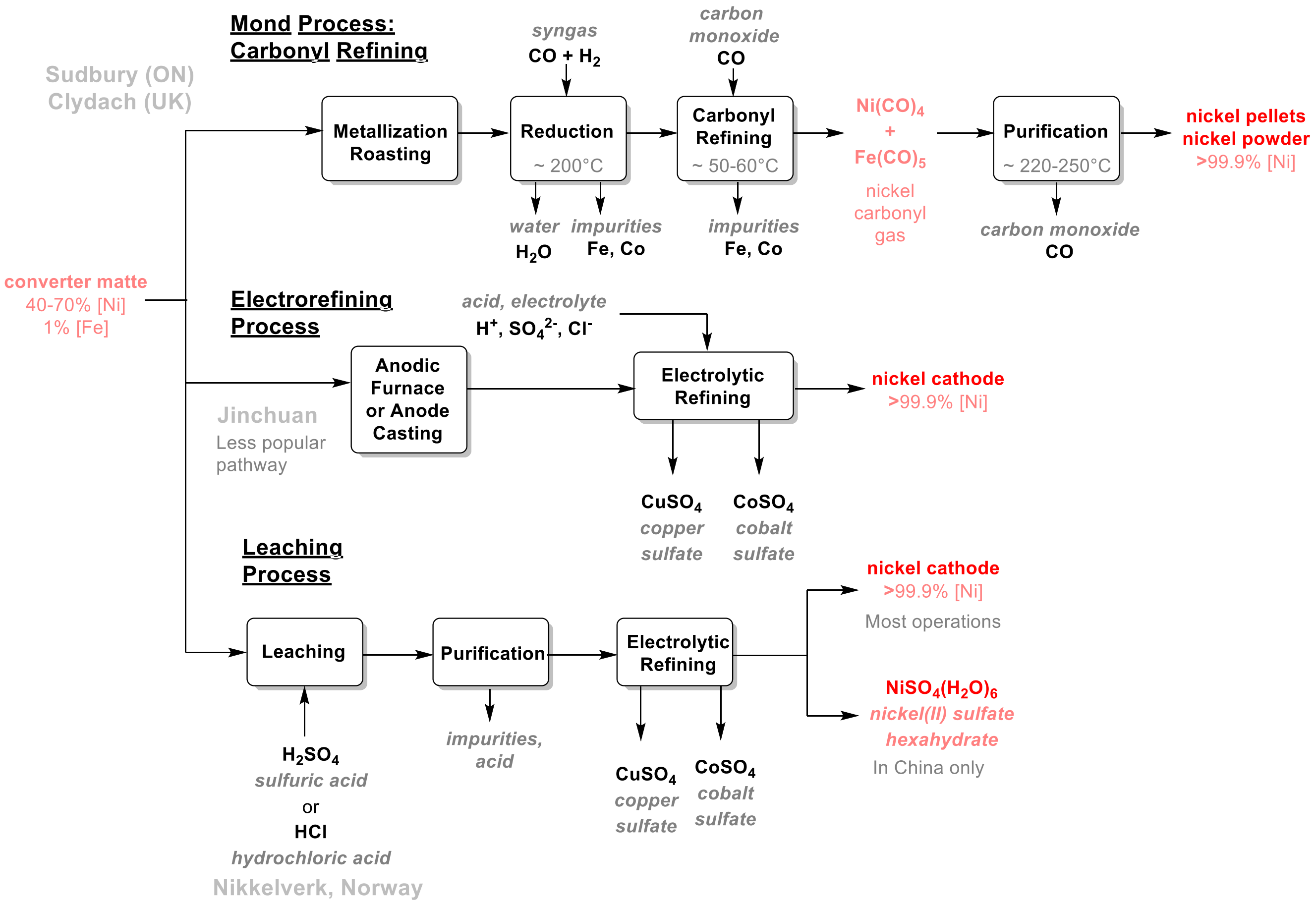
Removes the sulfur and iron from the nickel concentrates, converts them to nickel oxides and reduces it to nickel matte before further refining. Glencore owns an active smelter in Sudbury (ON), and Vale previously operated a smelter in Thompson (MB), which shut down in 2018.

Figure 6.3.5 Nickel sulfide pyrometallurgy: From concentrates to matte

Most sulfide ore concentrates undergo a series of pyrometallurgical processes, including roasting, smelting, and converting. Roasting removes much of the sulfur, while smelting further reduces sulfur content, producing an impure copper-nickel-iron-sulfur matte. It uses the energy released from sulfur oxidation and added energy, primarily electricity. The goal is controlled oxidation to convert much of the nickel to metal form, while most sulfur is converted to SO_2 gas for capture, and iron and other minerals like silicates are rejected as slag.[285] Smelting can be carried out in different types of furnaces, such as reverberatory furnaces, which use fossil fuel; electric furnaces or flash furnaces, which use a bit of fossil fuel and the exothermic heat from sulfide reacting with high-purity oxygen as energy. Electric furnaces typically have concentrate roasting ahead of the furnace, while flash furnaces typically oxidize all the desired sulfur in the furnace. Although the processes vary, coke is generally used as the reductant, and silica or lime as flux. Smelters are efficient at handling impurities like sulfur and iron and are excellent at recovering copper and platinum group elements (PGEs), but they struggle with cobalt and volatile impurities like arsenic. Typically, volatile mercury and arsenic dust can pose environmental issues. Smelter temperatures depend on the slag composition and, ultimately, the magnesium content, but they can vary between 1200–1400°C.[212] The process requires significant electricity, particularly in electric furnace smelting, and the viability of sulfuric acid byproducts is crucial for the economic operation of some smelters. Smelters in locations without viable sulfuric acid markets may emit very substantial amounts of sulfur dioxide to atmosphere rather than making a non-marketable byproduct.

During converting, a portion of the remaining iron and sulfur are removed from the impure matte produced during smelting, resulting in a sulfur-deficient copper-nickel matte with a higher grade. Converting is usually a batch operation, often in a Peirce-Smith converter, and the obtained slag can be recycled back to the smelting furnace. Silica flux addition is also necessary. A final nickel matte product is obtained, with a nickel content of 40–70%, remaining copper, iron (0.5–5%) and varying levels of PGEs. Typically the sum of nickel, copper and cobalt content is in the range of 70–75%.

6.3.3.6.3 Nickel Refining: From Matte to Pure Nickel or Nickel Sulfate



Mond Process:
Carbonyl refining

Nickel oxide NiO impurities are reduced to metallic nickel by reacting with hydrogen H_2 present in syngas at 200°C. This impure nickel further reacts with carbon monoxide at 50-60°C to form nickel carbonyl gas $Ni(CO)_4$, leaving solid impurities behind. Heating nickel carbonyl at 200-250°C will decompose it back to solid metallic nickel, this time in a very pure form. The Mond process can produce nickel powder or pellets.

Electro-refining:

An electrical current moves nickel(II) ions from the nickel sulfate and nickel chloride electrolyte solution onto a a thin cathode sheet of pure nickel, increasing in size.The less pure nickel from the casted anode gets oxidized and dissolved in the electrolyte, helping the process. Impurities accumulate at the bottom of the cells (anodic slimes), they can contain precious metals. Some concentrate from Glencore is sent to Nikkelverk in Norway for electro-refining.

Leaching Process:
to nickel cathode

There are two different leaching processes used, sulfuric and chloride (i.e. Nikkelverk). Generally speaking they both use purification methods to make Cu, Co, and Ni cathodes although there is one that uses ammonia leaching on matte (Kwinana) and some that use sulfuric acid leaching followed by hydrogen reduction to make Ni powder (i.e Implats which is only a minor nickel producer). Only Chinese operations can go from sulfide matte to $NiSO_4$ directly.

Figure 6.3.6 Nickel Refining Flowsheet

For Class I products, nickel refining is indispensable. Depending on the copper content and desired product, the converter matte obtained is either cast into anodes for electrolytic refining or separated into nickel and copper sulfides, with nickel further refined through leaching and electrolysis or the carbonyl method.[251]

In the electrorefining process, an electrical current moves nickel(II) ions from the cast nickel anode into a nickel sulfate or nickel chloride electrolyte solution and then onto a thin layer of pure nickel bonded on a cathode sheet, increasing in size along the process. The cathode sheets are made of stainless steel or titanium, and the pure nickel layer is stripped after 1 or 2 days of deposition. The less pure nickel from the casted anode, originating from the converter matte, gets slowly oxidized and dissolved in the electrolyte, thus helping the process. Impurities accumulate at the bottom of the electrolytic cell in the form of anodic slimes, from which precious metals can be extracted and precipitated. Copper, arsenic, iron and cobalt can be isolated this way. Gold and PGE necessitate more complex processes. The nickel produced through electrorefining has a high purity of higher than 99.9%. Electrorefining matte anodes was the primary process used by the now inactive Thompson, Manitoba smelter and refinery.

The leaching of nickel matte materials through hydrochloric acid and sulfuric acid is another major pathway to nickel refining. The various leaching and purification processes are complex and vary greatly. Still, the matte is generally leached by a strong acid, and the resulting nickel-bearing leach liquor can be refined to a nickel cathode through electrowinning. Here, contrary to electrorefining, the nickel ions from the leach solution are directly deposited onto cathodes by applying an electrical current, and the ions do not originate from an impure nickel anode. Lead is used as the anode for the sulfate process, while titanium coated with a platinum group metal oxide is used in the chloride process.[212] Electrowinning is very electricity-intensive but also produces ultra-pure nickel. Some leaching processes do not go through electrowinning but rather through nickel reduction and precipitation *via* hydrogen, usually using an ammoniacal nickel sulfate solution.

It is worth noting that the leaching of nickel matte with sulfuric acid could directly produce the desired nickel sulfate $NiSO_4$ required to produce precursors to cathode active material (pCAM) for NMC batteries. This could bypass the various extra steps currently used for its current production, where nickel is first refined and purified from matte to pure nickel before being leached in sulfuric acid for nickel sulfate crystallization.

Finally, nickel oxide powder, obtained from the roasting and grinding of nickel matte, can be reduced to metallic nickel following the carbonyl refining process. By reacting with hydrogen H_2 present in syngas and at 200°C, an impure metallic nickel powder will form a complex with carbon monoxide at 50–60°C to form a nickel carbonyl gas, leaving solid impurities behind. After heating at 200–250°C, the nickel carbonyl will decompose back to a solid metallic form, but this time with a higher purity. This process, known as the Mond Process, can produce pure nickel powders or pellets.

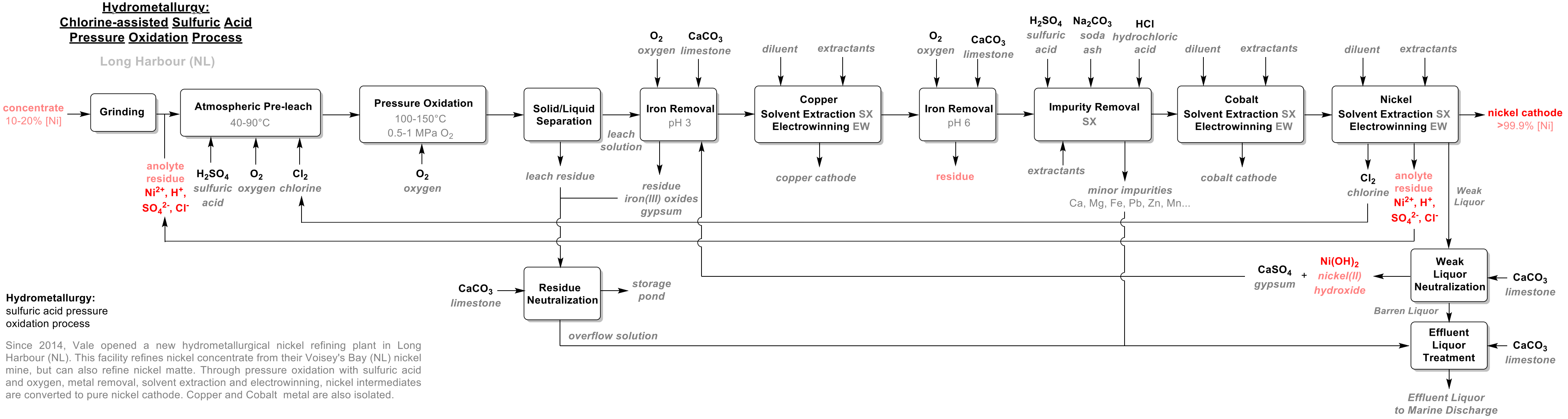
Contrary to other refining processes, the carbonyl refining pathway relies on particularly hard-to-handle toxic gas but produces extremely high purity nickel particles.

6.3.3.6.4 Nickel Sulfide Hydrometallurgy: From Concentrates to Nickel Products

Hydrometallurgical operations are more specific to the ore deposits than smelting and require a more complex flow and a steady supply of chemicals. They are also less susceptible to isolating precious byproducts such as PGEs, but they can be more efficient at cobalt recovery. However, hydrometallurgical facilities are more flexible to some impurities than smelters; they can operate economically on a smaller scale and provide versatility for the products they synthesize. Indeed, hydrometallurgical plants can produce pure class I metallic nickel after electrowinning or hydrogen reduction or intermediates such as MHP or MSP, which could be refined elsewhere, and they are also amenable to direct nickel sulfate production for pCAM.[286]

In Canada, one Vale facility is currently processing nickel sulfide concentrate through a chloride-assisted sulfuric acid pressure oxidation method, while Sherritt previously processed nickel sulfide concentrates following an ammonia-leaching hydrogen reduction method. These facilities are described further below. Internationally, the USA used to run sulfuric acid operations in the 1960s, while BHP's Kwinana plant in Australia currently refines nickel matte from its Australian smelter using the Sherritt ammonia leach-hydrogen reduction process and also produces nickel sulfate since 2021 by dissolving Class 1 nickel in sulfuric acid.

In 2014, Vale opened a new hydrometallurgical nickel refining plant in Long Harbour, NL. This facility refines nickel concentrates from the Vale-owned mine at Voisey's Bay, NL, but it can also refine nickel matte (**Figure 6.3.7**). Through pressure oxidation with sulfuric acid and oxygen metal removal, solvent extraction and electrowinning, nickel intermediates are converted to pure nickel cathode, while copper and cobalt metal are also isolated. This facility could potentially be suitable for directly producing nickel sulfate or pCAM from sulfide concentrates following solvent extraction of the nickel.

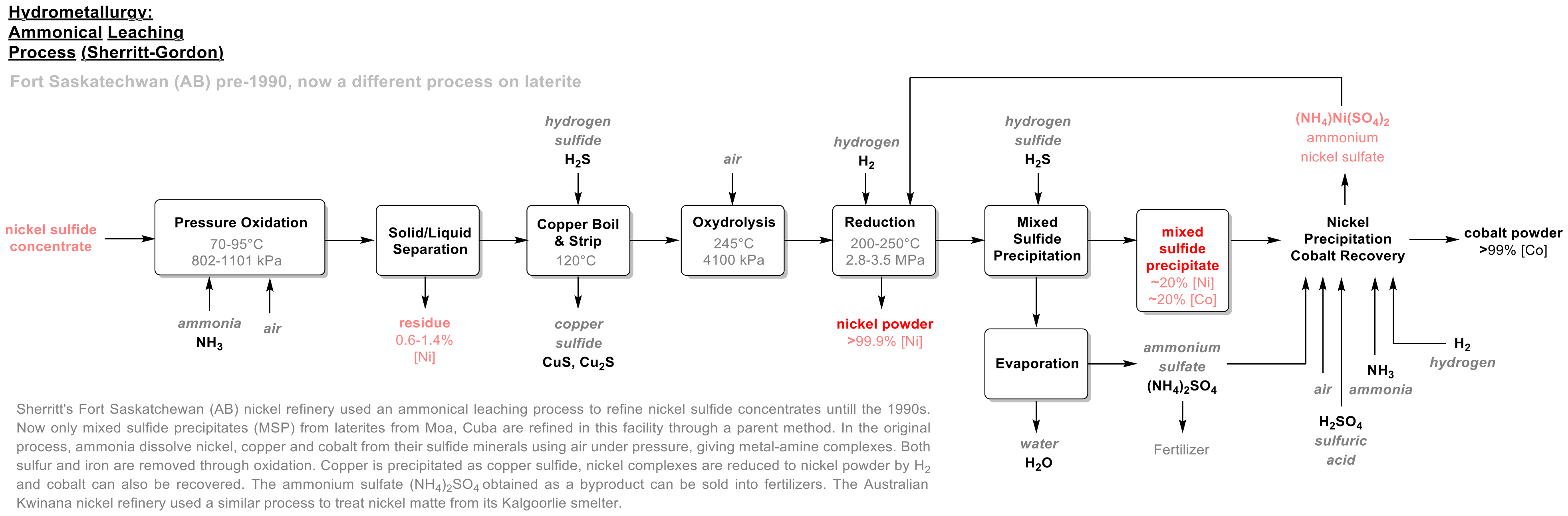


Hydrometallurgy:
sulfuric acid pressure
oxidation process

Since 2014, Vale opened a new hydrometallurgical nickel refining plant in Long Harbour (NL). This facility refines nickel concentrate from their Voisey's Bay (NL) nickel mine, but can also refine nickel matte. Through pressure oxidation with sulfuric acid and oxygen, metal removal, solvent extraction and electrowinning, nickel intermediates are converted to pure nickel cathode. Copper and Cobalt metal are also isolated.

Figure 6.3.7 Vale Long Harbour's hydrometallurgical facility flowsheet

Sherritt's nickel refinery in Fort Saskatchewan, AB, previously used an ammoniacal leaching process to refine nickel sulfide concentrates until the 1990s (**Figure 6.3.8**). Currently, only mixed sulfide precipitates (MSP) obtained from Cuban laterites are refined in this plant. In the process, ammonia would dissolve nickel, copper and cobalt from their sulfide form using pressurized air, thus yielding metal-amine complexes. Ammonia levels and temperatures are adjusted to precipitate a cobalt-nickel intermediate which is refined to cobalt metal. A further solution treatment step uses sulfur and SO_2 to precipitate copper as copper sulfide. The nickel complexes are then reduced to a metallic nickel powder using H_2, and the ammonium sulfate byproduct obtained would be sold to the fertilizer industry. The process is complex, requires significant amounts of thermal energy, and depends on a cheap ammonia supply. The ammonia leach residues can also pose environmental issues.



Hydrometallurgy: Ammonical Leaching Process (Sherritt-Gordon)

Fort Saskatchewan (AB) pre-1990, now a different process on laterite

Sherritt's Fort Saskatchewan (AB) nickel refinery used an ammonical leaching process to refine nickel sulfide concentrates untill the 1990s. Now only mixed sulfide precipitates (MSP) from laterites from Moa, Cuba are refined in this facility through a parent method. In the original process, ammonia dissolve nickel, copper and cobalt from their sulfide minerals using air under pressure, giving metal-amine complexes. Both sulfur and iron are removed through oxidation. Copper is precipitated as copper sulfide, nickel complexes are reduced to nickel powder by H_2 and cobalt can also be recovered. The ammonium sulfate $(NH_4)_2SO_4$ obtained as a byproduct can be sold into fertilizers. The Australian Kwinana nickel refinery used a similar process to treat nickel matte from its Kalgoorlie smelter.

Figure 6.3.8 Former Sherritt ammonia process flowsheet

Alternatively, many processes exist for the hydrometallurgy of nickel sulfide concentrates and matte as a refining step after smelting. Amongst those other technologies, we can find chloride-based pressure leaching, nitric acid-based pressure leaching, atmospheric-pressure sulfuric leaching, nitric-acid leaching, bioleaching, *etc.* Although less widespread than their high-pressure sulfuric acid and ammonia counterparts, these methods have specific advantages and drawbacks. Chloride-based processes, for instance, allow for high recovery of metals but can be very corrosive to the plant's equipment and construction materials. Bioleaching uses microorganisms to produce MHP or MSP from sulfide ores or can also be used as an alternative concentrator, it can be a simple and flexible process, potentially helpful in recovering nickel from tailings and stabilizing arsenic waste, but the processing speed is slow and temperature sensitive. More details on these methods can be found in the literature.[216,287]

6.3.3.7 From Laterite Ores: An Abundant Source with Carbon-Intensive Steps

As laterite deposits are not present in Canada, this section will focus on giving a non-exhaustive brief overview of the techniques used to exploit, process and refine limonite and saprolite deposits, typically the mineralogy of ores found in Indonesia, Cuba, New Caledonia or the Philippines.

Laterites were traditionally refined to Class 2 stainless steel and industrial alloy products. Saprolites are mainly processed through smelting in blast furnaces or rotary kiln and electric furnaces (RKEF), yielding either ferronickel or nickel pig iron (NPI). On the other hand, limonites are processed either through a mixed hydro-pyrometallurgical method called the Caron process, producing nickel oxides, or through hydrometallurgy *via* a high-pressure acid leaching method (HPAL), yielding mixed precipitates such as MHP and MSP. The underlying advantage of the HPAL route is that the precipitate products can be transported and leached at different refineries to produce nickel sulfate for pCAM or other class 1 products. HPAL also allows cobalt recovery and is less energy-intensive than the Caron process. Facilities using the Caron process in Brazil, Australia and the Philippines have also gradually shut down, leaving only one operating plant in Cuba. Another available pathway is the Tsingshan/Eramet approach to convert a class 2 product, namely nickel pig iron (NPI) originating from saprolite smelting, into nickel matte, a potential class 1 intermediate. $NiSO_4$ could then be produced after matte leaching. One facility in Indonesia also uses a novel pyrometallurgical process with sulfur addition to making nickel matte.

Nickel Pig Iron (NPI), an 8–15% nickel intermediate product, was commercially produced at scale in China in the 2000s. The smelting of low-grade saprolite ores from Indonesia, the Philippines and New Caledonia to nickel pig iron (NPI) has been done in blast furnaces in China since 2006 and in Rotary Kiln – Electric Furnaces (RKEF) in Indonesia since 2015. NPI produced by the RKEF route has a higher grade than the one made by blast furnaces. The process, similar to pig iron production for the steel industry, requires coke as a reductant, lime and laterite, rejecting slags, pollutants and

GHGs.[288] This route appeared as an inexpensive, although carbon-intensive, way to produce class 2 nickel products that can be directly added to alloying and stainless steel mills.

High-grade saprolite ores are converted to ferronickel product for alloying applications through the Rotary Kiln- Electric Furnace (RKEF) pathway, but limonites can also be smelted this way (**Figure 6.3.9**). This represents most nickel processing operations in Indonesia, supplanting the blast furnace method. After preparing, drying, screening and crushing the saprolite ores, the mineral is calcined and pre-reduced inside a rotary kiln, using coal as a reductant and oil or natural gas as a fuel inside a rotary kiln. Temperatures can rise to 900–1000°C. The resulting calcine is then smelted at 1400–1650°C in an electric furnace, thus separating impurities in a dumped slag and producing crude ferronickel.[212] This crude ferronickel still contains a range of minor impurities and needs to be refined before being sold for alloying purposes. Both the calcination/pre-reduction step and the smelting are GHG-emitting processes, releasing air pollution in a similar way to coal power plants. The RKEF pathway is energy-intensive, both in terms of fossil fuel feed as well as electricity.[289] When electricity is supplied by coal-fired power plants, RKEF processing to lower grade (NPI) or higher grade (FeNi) iron alloy products is the most carbon-intensive method in widespread use for nickel production.

Pyrometallurgy
Rotary Kiln - Electric Furnace:

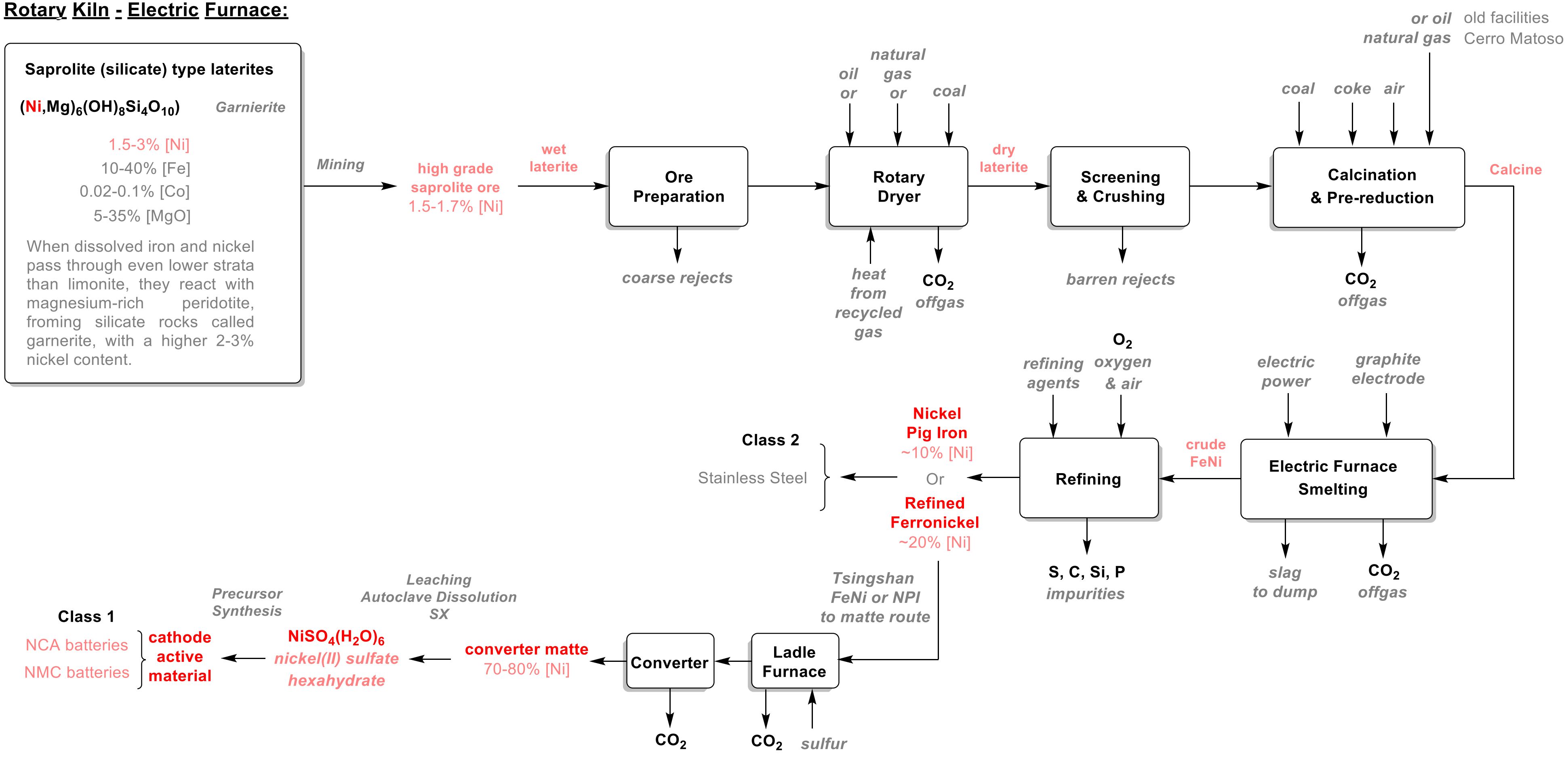
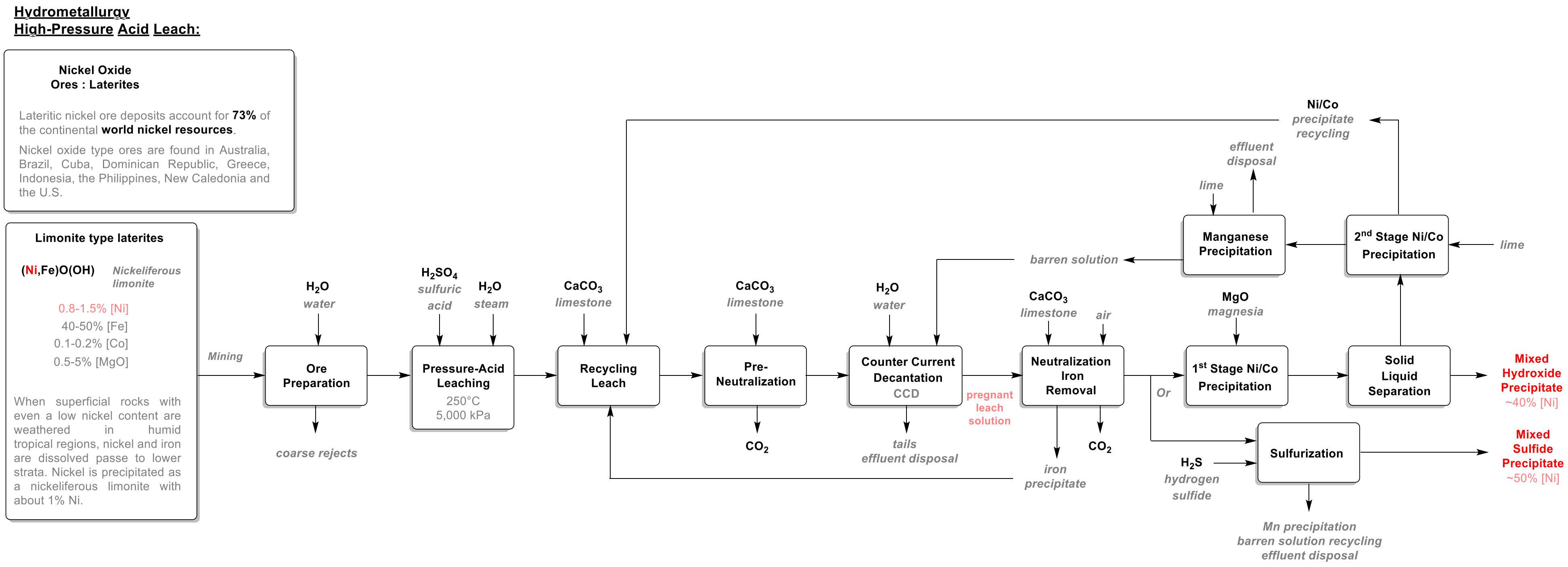


Figure 6.3.9 RKEF flowsheet from saprolite to NPI/FeNi

High-pressure acid Leaching (HPAL) is the most common technology for processing lower grades of limonite ores (**Figure 6.3.10**).[274] The ores are first delumped and slurried with water before being fed into an autoclave. Sulfuric acid at 250°C will leach the prepared materials under a pressure of up to 5,000 kPa. The subsequent pre-neutralization step requires limestone $CaCO_3$ to quench the acid, directly releasing CO_2. A multi-stage counter-current decantation step will then wash and separate the liquor into a pregnant solution containing nickel salts while rejecting tailings. After an additional neutralization step using limestone and emitting CO_2, iron and aluminum oxide are precipitated, and a residue can be recycled back to the decantation step. Nickel and cobalt are then precipitated using MgO or NaOH and undergo a solid-liquid separation, and a mixed hydroxide precipitate or MHP, containing 40% of nickel (dry), is produced. Alternatively, mixed sulfide precipitates MSP, containing >50% of nickel (dry), can be obtained after sulfurization with hydrogen sulfide H_2S. The HPAL method was pioneered in Cuba and has since been adopted in Australia, the Philippines, Papua New Guinea, Madagascar and New Caledonia, and is now becoming widespread in Indonesia. This approach has required a very high capital intensity, although that is being reduced through implementation in Indonesian industrial parks which provide significant infrastructure benefits. Acid supply is the biggest component of the opex, and high magnesium or aluminum content can increase the cost. This is why HPAL is sometimes not suitable for ores with a high MgO content. Most operational HPAL facilities failed to ramp up to design capacity.[284] However, HPAL recovers cobalt more efficiently than smelting, which can result in lowering the opex. Cuba's Moa Bay HPAL plant, operating since 1959, now supplies Sherritt's Fort Saskatchewan with MSP for its ammonia-based hydrometallurgical plant.



Lateritic nickel ore deposits account for **73%** of the continental **world nickel resources**.

Nickel oxide type ores are found in Australia, Brazil, Cuba, Dominican Republic, Greece, Indonesia, the Philippines, New Caledonia and the U.S.

When superficial rocks with even a low nickel content are weathered in humid tropical regions, nickel and iron are dissolved passe to lower strata. Nickel is precipitated as a nickeliferous limonite with about 1% Ni.

Effluent waste is almost always disposed to the ocean, although some may use evaporation (Australia), while others may have less solution treatment prior to disposal

Figure 6.3.10 HPAL process flowsheet from nickel oxide to mixed precipitates

The Caron process converts limonite ores into nickel oxide, and it heavily relies on fossil fuels and syngas for energy and reduction, as well as on ammonia for leaching. On top of emitting GHGs, this process also rejects solid waste residues like all metallurgical processes. In this case, they are called tailings (or leach residues), like all metallurgical processes. Nickel oxide sinter is produced after calcination, a product suitable for industrial alloys and stainless steel. It is usually accepted that the Caron process is no longer seen as economic, as 50% of the energy requirement comes from the ore drying and reduction steps, which come from the high moisture content of limonite minerals.[212] This is now supplanted by HPAL.

Finally, the Tsingshan approach to the projected supply gap for $NiSO_4$ production is to convert NPI to matte. It is based on a mature technology previously used by Eramet in New Caledonia but shut down due to economic reasons. The process would add elemental sulfur to NPI inside a converter, while blown air would oxidize iron, which could be separated from a higher-grade nickel matte. However, this class 2 to class 1 reallocation solution could lead to several issues: an extra processing step adds up to higher production costs and could increase environmental problems as it is energy-demanding in carbon-intensive grids.[282] This approach is anticipated to be a swing producer, allowing NPI producers to make a value-added product when the price differential is high, and produce only NPI if price differential is low.

6.3.3.8 A Comparison of the Carbon Intensity of the Different Processing Routes to Nickel Sulfate Hexahydrate

It is generally accepted that the Indonesian's laterite processing to refined nickel products is more carbon intensive than the Canadian nickel sulfide pyrometallurgical route. In a recent LCA analysis performed by Minviro for the German Association of the Automotive Industry (VDA), the pyrometallurgical route (RKEF) in Indonesia is estimated to have the highest GHG impact at 97.9 kg CO_2 eq. per kg of nickel in $NiSO_4 \cdot 6H_2O$, compared to 33.3 kg CO_2 eq. for the Indonesian HPAL route and 7.1 kg CO_2 eq. for Canadian smelters. A previous analysis by the same authors had similar findings; they concluded that both the worst and best South East Asia RKEF case scenarios have significantly more CO_2 intensity than any case of nickel sulfide pyrometallurgy in Canada.[280]

7 Phosphate

7.1 The Canadian Phosphate Strategy

7.1.1 Phosphate in Canada

Table 7.1.1 Non-exhaustive selection of former and future phosphate extraction and processing projects in Canada

Former Phosphate Extraction Site				
Site Name	**Company**	**Province**	**Type**	**Status**
Kapuskasing	Agrium (Now Nutrien)	ON	Igneous	Closed since 2013
Selection of Future Phosphate Extraction Projects				
Project Name	**Company**	**Province**	**Type**	**Status**
Lac à Paul	Arianne Phosphate	QC	Igneous	FS 2013
Lac à l'Orignal	First Phosphate	QC	Igneous	PEA 2023
Bégin-Lamarche	First Phosphate	QC	Igneous	PEA 2024
Mine Arnaud	Investissement Québec	QC	Igneous	Paused 2017
Martison	Fox River Resources	ON	Igneous	PEA 2022
Wapiti & Fernie	Canadian Phosphate (Fertoz)	BC	Sedimentary	Exploration
*Note: most DLE brine projects are coupled with refining plants				
Selection of Future Phosphoric Acid Plants				
Project Name	**Company**	**Province**	**Product Type**	**Status**
Saguenay Plant	Arianne Phosphate	QC	MGA, PPA	PFS 2024
First Saguenay Plant	First Phosphate + Prayon Technologies	QC	MGA, PPA + LFP CAM (nearby site)	N.A.
Hearst Plant	Fox River Resources + JESA Technologies	ON	SPA/MGA	Start in 2027-2029
PPA: Purified Phosphoric Acid (battery-grade, Food, Electronics); SPA: Super Phosphoric Acid (Specialty Fertilizers); MGA: Merchant Grade Acid (Fertilizer, Animal feed, Industrial Acid)				

The only phosphate ore mine in Canada, which was previously operated by Agrium (now Nutrien), in Kapuskasing, Ontario, closed in 2013.[290–292] No phosphate rock has been produced in Canada ever since. Canada has around 0.1% of the world's phosphorus reserves,[293] so the output of prospective mines might be negligible globally. However, five extraction projects are being developed: Lac à Paul (Arianne Phosphate) and Lac à l'Orignal (First Phosphate) in Quebec, Wapiti and Fernie in British Columbia (Canadian Phosphate/Fertoz), and Martison in Ontario (Fox River Resources). Unfortunately, the federal government did not recognize the exploration priority as the Natural Resources Canada *2022 Map of Top 100 exploration projects* did not include phosphate ore deposits at the time.[294]

One phosphoric acid plant commissioned by Arianne Phosphate was previously projected in Belledune, New Brunswick,[295,296] but the project might be relocated to the Saguenay region instead. The port of Saguenay is also where First Phosphate anticipates developing a phosphoric acid plant in partnership with Prayon Technologies. The projected plan would go through a hemi-dihydrate process for MGA production and *via* a membrane filtration purification for PPA.[297] First Phosphate has found agreements with NorFalco (Glencore) for sulfuric acid supply for its PPA plant, and has moved for a vertical integration down to iron phosphate production (LFP pCAM) and even LFP CAM, projected in Saguenay-Lac-St-Jean. Collaboration with GKN Hoeganaes has been announced to license iron powder-making technology to process First Phosphate's magnetite deposits. First Phosphate also signed an MoU with U.S.-based Ultion to purchase an LFP and LFMP CAM production technology license. Fox River Resources partnered with American company JESA Technologies to achieve pilot plant production of MGA using a hemi dihydrate process earlier this year.[298] Phostech Lithium, one of the first companies to commercialize LFP since 2003, owns a cathode factory in Candiac, Quebec. Now acquired by Nano One Materials, the plant focuses on a new one-pot process for LFP cathode synthesis.

7.1.2 Target

Our previous report, 'Roadmap for Canada's Battery Value Chain,' established the following objectives for lithium iron phosphate battery production: reach 50 GWh per annum of LFP battery production in 2030 and 100 GWh in 2040. Aiming this target and using purified phosphoric acid (PPA, H_3PO_4 at 85 wt.%) as the required precursor for synthesizing LFP cathode active materials, the amount of PPA needed can be calculated.

Phosphoric Acid Mandated Benchmark (10% of 2030 North American Market)		
	2030	**2040**
Phosphoric Acid (in kt of battery-grade PPA 85 wt.%)	80	160

7.1.3 Scenario Outline

As the new demand for phosphoric acid purposed for LFP batteries can only be met by bringing new phosphate projects online, Canada should focus on 3–4 phosphate extraction projects. Start by exploiting igneous deposits for cathodic material before sedimentary ones. Two processing hubs capable of producing Merchant Grade Phosphoric Acid (MGA) and Purified Phosphoric Acid (PPA) should be developed, one in Quebec and one in BC.

7.1.4 Signature Projects

- Develop 3–4 major phosphate mining projects (QC, BC, ON)

- Build phosphoric acid processing hubs, one in the western provinces (BC) and one in Quebec. The igneous feeds from Quebec can be converted to PPA as a priority for pCAM and CAM projects, while sedimentary feeds can be used first in fertilizer.

7.1.5 Strategic Priorities

- **Major Mining Projects and Chemical Processing Hubs:**
  - **Focus on Key Mining Projects:** Prioritize developing 3–4 major phosphate mining projects, mainly focusing on projects in Quebec, such as Arianne Phosphate and First Phosphate. These projects are well-positioned to become leading producers in the region. Additionally, focus on the Canadian Phosphate project in British Columbia and consider the potential for the Fox River project in Ontario. These projects are strategically located to meet growing demand in North America and beyond.
  - **Establish Processing Hubs:** Construct two strategically located processing hubs—one in Quebec and another in British Columbia—designed to convert phosphate ores into phosphoric acid using the wet process. These hubs will play a crucial role in the value chain, ensuring that phosphate ore is efficiently converted into phosphoric acid for various downstream applications.
  - **Phosphoric Acid Production:** Ensure that these phosphoric acid plants have the flexibility to produce both Merchant Grade Acid (MGA) and Purified Phosphoric Acid (PPA) based on market demand and industry needs. This adaptability will allow the hubs to cater to various industries, including fertilizers, animal feed, and battery manufacturing.
  - **Collaborate with Industry Leaders:** Partner with leading companies specializing in PPA production technology, such as Nutrien, Innophos, Prayon, JESA and ICL. These collaborations will leverage existing expertise and technology, ensuring the efficient and high-quality production of phosphoric acid at the hubs.
  - **Optimize Locations:** Carefully select the locations of these hubs to optimize geographic efficiency, potentially co-locating them with significant mining sites. This will reduce transportation costs, minimize environmental impact, and enhance the overall efficiency of the operation.
  - **Integrate Gypsum Management:** Fully integrate the management of gypsum impurities generated during the wet process. This involves finding sustainable uses for gypsum byproducts, such as in construction materials, to reduce waste and create additional revenue streams.
- **Use a Mineralogy-driven Approach:**
  - **Target Battery Applications First for Batteries:** Focus on converting higher-grade igneous phosphate deposits primarily into Purified Phosphoric Acid (PPA), which is crucial for battery applications. Only produce Merchant Grade Acid (MGA) from these deposits, if necessary, to maximize the value of the resource.

    - **Utilize Sedimentary Deposits for Fertilizers:** Direct sedimentary phosphate deposits towards the fertilizer and animal feedstock industries by focusing on their conversion into MGA. These deposits can later supplement PPA production as demand for battery-grade materials increases.
    - **Blend Feedstock:** If necessary, consider blending sedimentary and igneous phosphate feedstocks to achieve the desired grades of MGA or PPA. This flexibility will allow for more efficient use of available resources while meeting the specific requirements of different industries.
- **Access to Energy, Chemicals, Infrastructure, and Talent:**
    - **Secure Clean Energy:** Ensure access to clean, reliable, and affordable energy sources to power the processing hubs. This is crucial for maintaining competitive production costs and minimizing the environmental footprint of operations.
    - **Obtain Essential Chemicals:** Secure a stable supply of necessary chemicals and reagents, particularly sulfuric acid, essential for the wet process used in phosphoric acid production. There is also the possibility of collocating or obtaining sulfuric acid from the metallurgy of sulfide ores such as copper, nickel, or iron. Establishing strong supply chains for these inputs will be critical to the success of the processing hubs.
    - **Develop Infrastructure:** Build the midstream hubs around existing infrastructure and transport networks, including road and rail systems. This will facilitate the efficient movement of raw materials and finished products, reducing costs and improving logistics.
    - **Attract Global Talent:** Encourage the recruitment of global talent with expertise in phosphate processing, chemical engineering, and related fields. This will ensure that the hubs are staffed with highly skilled professionals capable of driving innovation and maintaining high standards of operation.
- **Find Synergies Between Industries:**
    - **Utilize Gypsum Byproduct:** Repurpose gypsum byproducts from the wet process as building materials, particularly when processing igneous deposits or when it has low impurities. This reduces waste and creates a valuable secondary product that can be marketed to the construction industry.
    - **Repurpose Hydrofluoric Acid:** Identify uses for hydrofluoric acid byproducts, such as selling them to the graphite processing industry or hydrometallurgical plants. This approach turns a potential waste product into a valuable resource for other industries.
    - **Sell Value-added Byproducts:** Capitalize on the potential for some sedimentary deposits to contain rare earth elements (REE), niobium and vanadium, which can be recovered and sold to their respective industries. The South African company Rainbow Rare Earth has developed a process to recover rare earth from phosphogypsum stacks from phosphoric acid plant operations. This adds another layer of value

to the phosphate mining and processing operations and could synergize and connect several critical mineral flowsheets.

  - **Secure Sulfuric Acid Supply:** Collaborate with other mining industries, such as nickel sulfide, copper sulfide, or pyrite processing plants, to secure a reliable supply of sulfuric acid. In the East, sulfuric acid could be sourced from these industries, while in the West, it could be obtained as a byproduct from the oil and gas industry.
    - **Generate Power from Sulfuric Acid Production:** The conversion of sulfur to sulfuric acid releases energy, which could generate electricity through turbines for a neighbouring phosphoric acid plant if the sulfuric acid plant and phosphoric acid facilities are collocated. Excess electricity can also be sold to the local grid.
- **Pursue the Recognition of the Importance of Phosphate**
  - **Federal Recognition:** In June 2024, the federal government of Canada recognized phosphorus as a critical mineral. This new status is welcome, as it would make phosphate projects eligible for government incentives and allow them to compete for funding on an equal footing with other critical mineral projects. Pursuing this recognition to add phosphorus to provincial critical minerals lists in British Columbia and other provinces beyond Ontario and Quebec could be the next step.
    - **This Makes Phosphate Projects Eligible for Support From:**
      - The Canada Growth Fund
      - The Business Development Bank of Canada
      - Export Development Canada
      - The Canada Infrastructure Bank
      - Sustainable Development Technology Canada
      - Scientific Research and Experimental Development tax incentives
  - **Unlock Government Support:** The recent federal recognition should also help secure government support for transportation infrastructure and access to mining and processing sites, thereby lowering the capital expenditure (CAPEX) required for these projects.
  - **Raise Awareness:** Advocate for the importance of phosphate, not just for fertilizers but also for its role in the battery industry. This should involve public awareness campaigns and targeted engagement with government and industry decision-makers.
- **Regulatory Framework**
  - **Clarify Mineral Permits**: Work with provincial authorities to clarify mineral permit requirements, particularly in British Columbia, where sedimentary deposits may fall under quarrying or mining regulations. Clear guidelines will help streamline the permitting process.
  - **Streamline Mining Permits:** Push for streamlined mining permit processes, allowing timely approvals and adherence to adequate timelines. This will enable projects to move forward without unnecessary delays, ensuring that operations can commence as planned.

7.2 Phosphate: An Essential Compound for Life, Fertilizers but also LFP Cathodes

7.2.1 General Properties

Phosphate PO_4^{3-} is a commonly found ion composed of one central atom of phosphorus and four atoms of oxygen. Combined with its derivatives and conjugate acids, such as **phosphoric acid H_3PO_4**, it is Earth's most abundant form of phosphorus. Being an integral part of DNA and bone structures and responsible for biological energy storage, phosphorus is essential to all life forms, and its intake is crucial to the development of most organisms. Phosphate ions are part of a naturally occurring yet slow phosphorus cycle, migrating from plants, animals, and microscopic organisms to soil and water bodies before gradually depositing as sediments at the bottom of the ocean, giving birth to phosphate rocks after millions of years. Phosphorus is crucial for plant growth and is mainly used for **fertilizer**. However, the overuse and uncontrolled leaching of phosphates into the environment can lead to threatening toxic algae bloom, a concerning phenomenon known as eutrophication. In addition to its end application as a fertilizer, phosphate can be processed into various valuable phosphorus chemicals, such as detergents, flame retardants, pesticides, therapeutics, and ligands.[299]

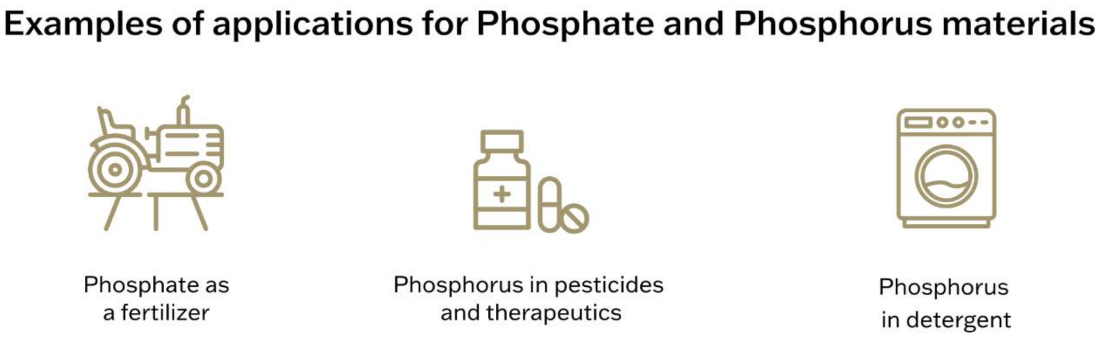


Figure 7.2.1 Examples of applications for phosphate and phosphorus materials

7.2.2 Role in Energy Storage

In general, using polyanionic compounds such as phosphates instead of oxides in the cathode material can reinforce the ionic bonding and, thus, increase the electrochemical potential. **Lithium iron phosphate $LiFePO_4$**, or LFP batteries, has become an attractive cathode chemistry option for lithium-ion batteries compared to other technologies like nickel-cobalt-manganese (NMC) and nickel-cobalt-aluminum (NCA). This olivine structure was discovered by Goodenough and commercialized as early as 2007.[300]

LFP has thus gained increasing appeal due to the high cost of battery metals because it uses inexpensive and abundant iron and phosphorus (90% of mineral cathode content) instead of cobalt and nickel. However, LFP remains exposed to lithium prices. Instead of using lithium hydroxide, the primary lithium intermediate in nickel-rich chemistries, LFP relies mainly on lithium carbonate, although lithium hydroxide can also be used.[301] Additionally to lithium, LFP is also made from iron phosphate, a common food additive.

LFP battery cells were on average 32% cheaper than lithium nickel manganese cobalt oxide (NMC) cells in 2022.[302] Other than the cost of production, LFP has various advantages over other Li-ions technologies: higher safety for battery fire, good stability, a longer and more sustainable life-cycle and the advantage of not depending on socially and environmentally challenging cobalt supplies. Additionally, LFP does not require the same humidity control level during manufacturing processes as other cathode materials do.[303]

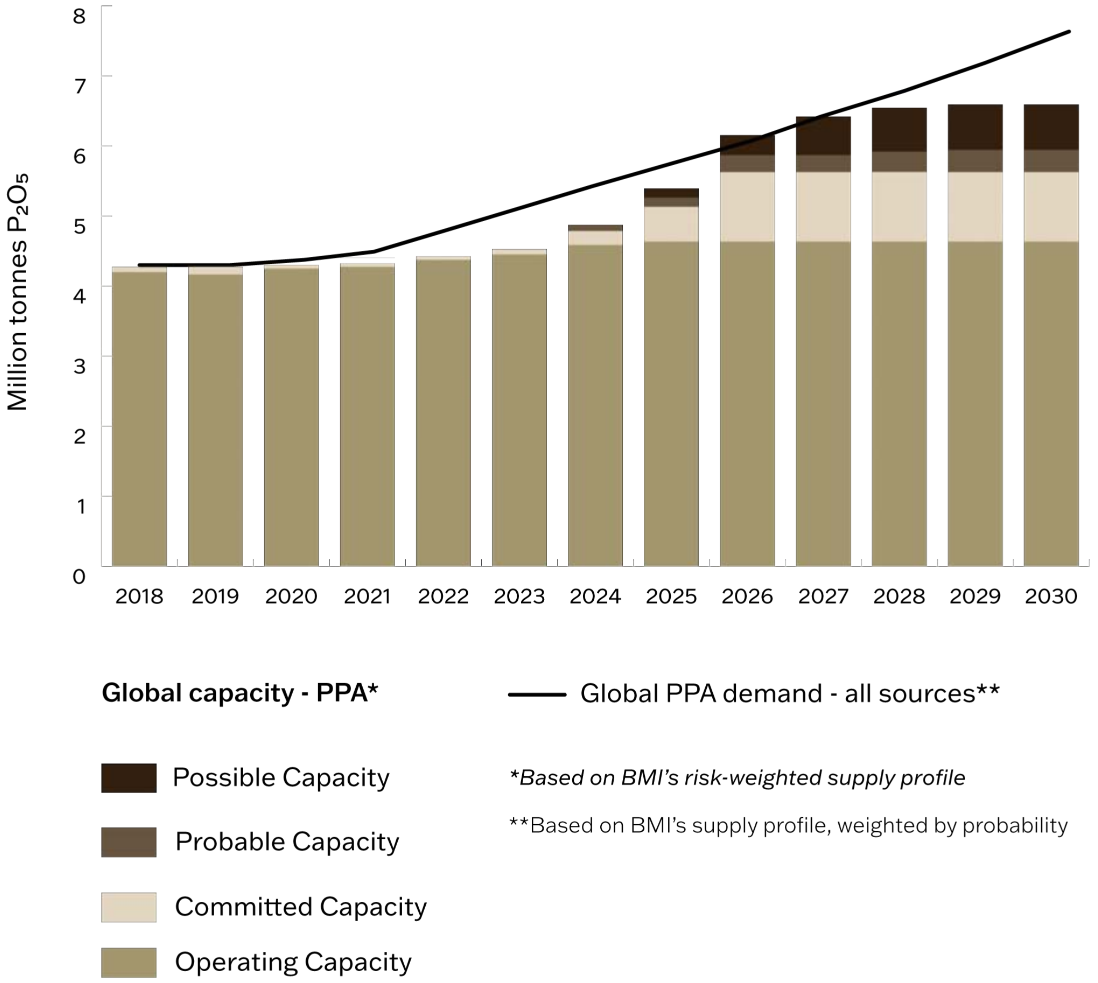
However, the LFP technology also presents important drawbacks, such as lower conductivity, energy density, and decreased efficiency at lower temperatures. However, most of those issues have been overcome due to increased research and engineering optimization (such as in coating, doping or particle size). LFP recycling is also less economically attractive than NMC recycling as only lithium recovery would be viable, unlike NMC which would have nickel, cobalt and lithium. Lithium manganese iron phosphate cathodes, or LMFP, is a next-generation iteration improvement of LFP technologies using additional manganese and could increase battery energy density while keeping a lower cost compared to high-nickel chemistries. Combined with the patent expiry in 2022, LFPs are now an attractive alternative to other Li-ion batteries. On top of usage for EV batteries and mobility, the excellent cycling capabilities of LFP make this technology particularly attractive for energy storage systems. Finally, unlike NMC cells which can follow several designs, LFP cells are usually prismatic.

Another common use for phosphorus in energy storage is in electrolytes for lithium-ion batteries. **Lithium hexafluorophosphate $LiPF_6$** is thus a common electrolyte salt, with the cation Li+ used as the charge carrier and PF_6- as a bulky counter anion. Although ubiquitous in li-ion systems, $LiPF_6$ can degrade at high temperatures and release toxic HF acid in the presence of water.[304]

7.2.3 Substitutes

With potassium and nitrogen, phosphorus is a limiting factor for plant development, so there is no substitute for its use as a fertilizer. For battery chemistry purposes, phosphate can be bypassed by selecting cathodes different from LFP or LMFP. NMC, NCA or newer generation batteries such as lithium-sulfur or sodium-ion technologies do not use phosphorus.

7.2.4 Supply and Demand



**Based on BMI's risk-weighted supply profile*

**Based on BMI's supply profile, weighted by probability

Figure 7.2.2 Purified phosphoric acid production and demand projection from Benchmark Minerals' 2023 Market Outlook[305,306]

Before the rise of LFP, the global demand for phosphate grew at a 2% yearly rate, but the Li-ion boom is drastically increasing the demand for purified phosphoric acid. Indeed, the EV sector only represented 5% of the purified phosphoric acid demand last year, but this share is likely to increase to 24% by 2030.[307] In 2023, LFP accounted for 66% of battery output in China.[308] In 2024, the American battery industry market share in GWh for LFP is still lower than 8%.[309] Although no U.S. cars were powered by LFP in 2020, BloombergNEF projected last year that the demand for LFP-powered vehicles is expected to exceed 160 GWh by the end of the decade, representing 40% of the total demand for electric vehicles in the U.S.[310] Key players in the electric vehicle industries, such as Ford, Rivian, Mercedes-Benz, and Volkswagen, have unveiled plans to use LFP in North America, and General Motors is also interested. Additionally, Tesla released its plan in October 2021 to switch to LFP batteries for all its standard-range cars.[311,312] Tesla has since confirmed that half of its vehicles produced in Q1 2022 were using LFP.[313] As such, the global LFP market is expected to grow from $10B USD in 2021 to $50B by 2028.[314]

Benchmark Minerals Intelligence reported earlier this year that a global supply gap of 0.8 Mt of purified phosphoric acid (PPA) is expected by 2030 due to growing demand and underinvestment in this value chain.[315,316]

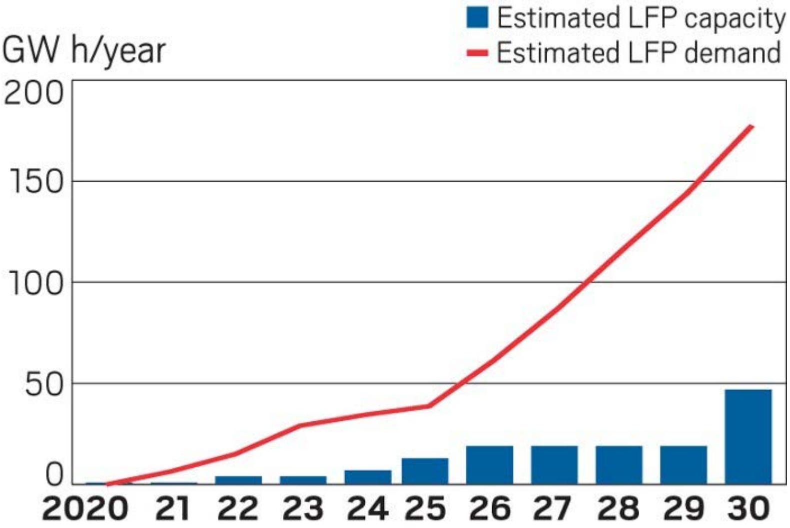


Figure 7.2.3 U.S. demand for lithium iron phosphate (LFP) batteries in passenger electric vehicles is expected to continue outstripping local production capacity. (Source: BloombergNEF)[317]

7.3 The Phosphate Flowsheet: From Rocks to Phosphoric Acid

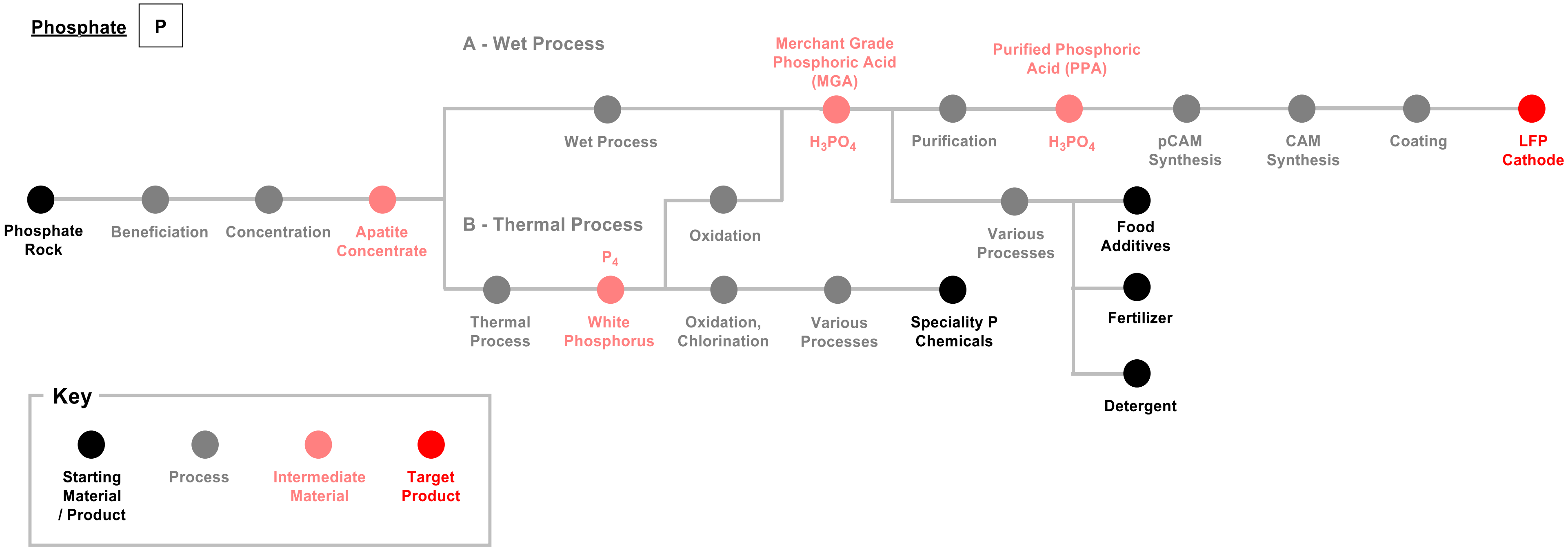


Figure 7.3.1 Simplified flowsheet of phosphate and phosphorus products

7.3.1 Ores & Reserves

Phosphorus is not a rare element on the surface of the Earth. It is thought to make up between 1,000 to 1,300 ppm by mass of the Earth's continental crust, and as such, it is more abundant than chlorine, sulfur, or even carbon.[318–321] It is Earth's crust's 11th most abundant element. However, most exploitable phosphorus sources reside in sedimentary phosphate rocks, typically **fluorapatite $Ca_5(PO_4)_3F$** or **hydroxyapatite $Ca_5(PO_4)_3OH$**. The availability of those phosphate rocks is finite, and various estimates of the longevity of the world's reserve vary between complete depletion within the next 70 to 400 years.[322] The continuously changing assessment of this controversial issue can be explained by relying on limited but ever-changing new information and considering the future economic and technological dynamics of exploitation and evaluation.[323] The exact magnitude of the scarcity of phosphorus is still far from settled. However, a concept known as peak phosphorus, the point in time when the maximum production rate of phosphorus will be reached, has emerged as an analogy to the concept of peak oil.[324] However, It is reasonably accepted that there is no imminent shortage of phosphate resources.[325]

86% of the commercial reserves of phosphate rocks are split between only six countries, and 67% of the reserves lie solely within Morocco/Western Sahara. At the same time, China, Egypt, Tunisia, Russia and Algeria hold smaller but relevant deposits. Russia is also the only supplier of high-purity phosphate rocks. An extensive deposit in Norway made the news in the summer of 2023 as it could potentially store as much phosphate as the currently proven global reserves.[326] Canada held an estimated **76×10^6 tonnes of phosphate rock in 2016**,[293] approximately 0.1% of the global phosphate reserves at the time; the U.S. Geological Survey did not update this data since no ore was mined. Providing that this number did not change drastically, and compared to the current reserve estimates, this would rank **Canada as the 18th country with the largest phosphate rock reserves**.

Table 7.3.1 Estimated mining production of marketable phosphate rocks in 2022 by country in thousands of tonnes

Country	**Production of P-rocks in 2022**[a] (tonnes x 10^3)	**Country**	**Production of P-rocks in 2022**[a] (tonnes x 10^3)
Mexico	442	Australia	2,500
Other Countries	750	Senegal	2,600
Turkey	900	Tunisia	3,560
Uzbekistan	900	Peru	4,200
Finland	923	Egypt	5,000
Syria	1,100	Brazil	6,200
Kazakhstan	1,500	Saudi Arabia	9,000
Togo	1,500	Jordan	11,300
India	1,740	Russia	14,000
Algeria	1,800	United States	19,800
South Africa	1,990	Morroco	39,000
Vietnam	2,000	China	93,000
Israel	2,170	**World Total (rounded)**	**228,000**

[a] Data in thousands of tonnes of marketable phosphate rock, from the 2024 U.S. Geological Survey.[325]

Table 7.3.2 Estimated reserves of marketable phosphate rocks in 2024 by country in thousands of tonnes

Country	**Reserves of P-rocks in 2024**[a] (tonnes x 10^3)	**Country**	**Reserves of P-rocks in 2024**[a] (tonnes x 10^3)
Mexico	30,000	Finland	1,000,000
Togo	30,000	Jordan	1,000,000
Vietnam	30,000	Australia	1,100,000
India	31,000	Saudi Arabia	1,400,000
Senegal	50,000	South Africa	1,500,000
Israel	60,000	Brazil	1,600,000
Turkey	71,000	Algeria	2,200,000
Canada[b]	**76,000**[b]	Russia	2,400,000
Uzbekistan	100,000	Tunisia	2,500,000
Peru	210,000	Egypt	2,800,000
Syria	250,000	China	3,800,000
Kazakhstan	260,000	Morroco	50,000,000
Other Countries	800,000	**World Total (rounded)**	**74,000,000**
United States	1,000,000		

[a] Data in thousands of tonnes of marketable phosphate rock, from the 2024 U.S. Geological Survey.[325]
[b] Data from the 2016 U.S. Geological Survey.

In 2022, the global extraction capacity of phosphate rocks reached 228 x 10^6 tons, with significant players in phosphate mining such as China (41% of 2022 global production), Morocco (17%), the U.S. (9%), Russia (6%) and Jordan (5%).[325]

Even though most global phosphorus resources are sedimentary ores, under 10% of global phosphate is **igneous,** meaning it originates from phosphate dissolved in magmatic rocks and not directly from sedimentary ores. Significant igneous occurrences are found in Brazil, Canada, Finland, Russia, and South Africa. Although igneous phosphate rocks have a lower P_2O_5 content than sedimentary ones on average (8.1 wt.% *vs.* 21.3 wt.%), the concentrated ores obtained after beneficiation, also called **marketable phosphate** concentrates, are of higher grades for igneous rock sources (36.9% wt. % *vs.* 29.6 wt.% for sedimentary).[327] igneous phosphate also bears the advantage of less potential contamination of radioactive heavy metals (cadmium, thorium, uranium, *etc.*), more efficient processing, and a higher phosphorus content after concentration.[296] This is why igneous phosphate ores could be prioritized as feedstock for cathode production.

7.3.2 Processing

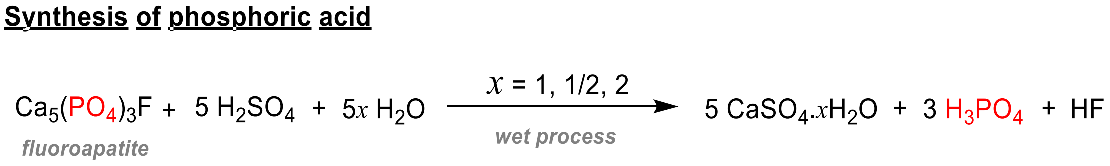
The effect of such concentrate grades means that, contrarily to other minerals and metals, it is not very economically viable to transport marketable phosphate concentrates to process them elsewhere; this is why most conversion from concentrates to phosphoric acid is conducted domestically.[307] In 2022, almost two-thirds of the global capacity for phosphate rock refining into purified phosphoric acid (PPA) was in China, representing a market share of 42%. Moreover, the Chinese share of PPA supply is expected to increase to 73% of the total capacity by 2030.[316] In 2023, only 3% of the global supply of phosphate products with the proper grade was actually usable for cathode active materials.

7.3.2.1 Beneficiation

The typical process of phosphate mining involves extracting a mixture of phosphate rock, clay, and sand matrix from the ground by a dragline. The phosphate is separated from the sand and clay through beneficiation to obtain the concentrated phosphate product. The beneficiation steps require screening, washing, and flotation: the phosphate rock ores are first crushed before having high-pressure water guns create a slurry. Calcium phosphate compounds are easily separated from the sand impurities through froth flotation and using fatty acids.[328,329] The obtained concentrates, or marketable phosphate rocks, can be sent to produce **wet-process phosphoric acid** (WPA) or smelted through the thermal process to obtain **elemental white phosphorus** P_4. Those phosphate concentrates have P_2O_5 contents of at least 28%, but most marketable rocks have content above 30%.

7.3.2.2 The Wet process: Direct to Phosphoric Acid

It has been estimated that over 90% of the phosphate rock exploited is converted to phosphoric acid according to the 'wet process' (**Figure 7.3.2**). The method consists of the digestion of fluorapatite minerals by concentrated sulfuric acid. **Calcium sulfate,** also called **gypsum** or **phosphogypsum,** which is yielded as a by-product (about 4–6 tonnes produced per tonne of phosphoric acid), is later precipitated and filtered out, and the wet phosphoric acid obtained is purified and concentrated.[330] The process usually starts with the milling and sizing of phosphate concentrate feed before adding sulfuric acid to the processed concentrate inside a reactor at atmospheric pressure at 70–80°C.[331]



Synthesis of phosphoric acid

$$\underset{\text{fluoroapatite}}{Ca_5(PO_4)_3F} + 5\,H_2SO_4 + 5x\,H_2O \xrightarrow[\text{wet process}]{x = 1,\ 1/2,\ 2} 5\,CaSO_4.xH_2O + 3\,H_3PO_4 + HF$$

Figure 7.3.2 Conversion of phosphate rock to orthophosphoric acid through the wet process

The gypsum formed during the reaction is consistently separated through a filter from the phosphoric acid produced. This calcium sulfate filter cake is then washed several times to optimize phosphoric acid recovery. The filtered weak acid usually has a 42–54% P_2O_5 content, which is still too low for specific applications such as battery cathode. Still, after concentration reaches around 54% P_2O_5 content, the acid can be commercialized as **merchant grade acid** (MGA), which is eligible for fertilizers and animal feed products.

Both the temperature of the wet process and the P_2O_5 concentration in the reactor affect the type of gypsum hydrate produced: dihydrate $CaSO_4{\cdot}2H_2O$ is formed at lower temperatures, while hemihydrate $CaSO_4{\cdot}½H_2O$ is made at 80–90°C. Depending on the hydrate byproduct obtained, the corrosion, precipitation, filtration, and, ultimately, the purity of the phosphoric acid can differ. That's why wet-process plant designs vary according to the hydrate byproduct, either going through dihydrate, hemihydrate, or both.[331]

Depending on the plant location, byproduct content and regulations, the gypsum produced is either pumped to the sea or local river, stockpiled, or used in the gypsum industry. Phosphogypsum can notably be used as an additive to Portland cement, road pavements, soil conditioners, or artificial reefs. However, depending on the phosphate rock source, the gypsum produced can be slightly radioactive due to the presence of uranium, thorium, radium, radon and polonium. As such, discarding or stockpiling those dangerous phosphogypsum slags can pose a double environmental threat, with weak radioactivity from the toxic heavy metal contaminants and a high potential for toxic algae bloom eutrophication due to remaining phosphate. Igneous phosphate sources have the advantage of producing gypsum with fewer contaminants and are suitable for their sales and use in the construction, cement and agriculture industries.[332,333]

The fluorine-containing byproducts, labelled HF or **hydrogen fluoride** gas in the reaction scheme above, can be recovered by passing the gas through a water scrubber to produce **hydrofluoric acid**. Fluorine can also be retrieved as silica tetrafluoride SiF_4 using clay or activated silica. After conversion, **fluorosilicic acid**

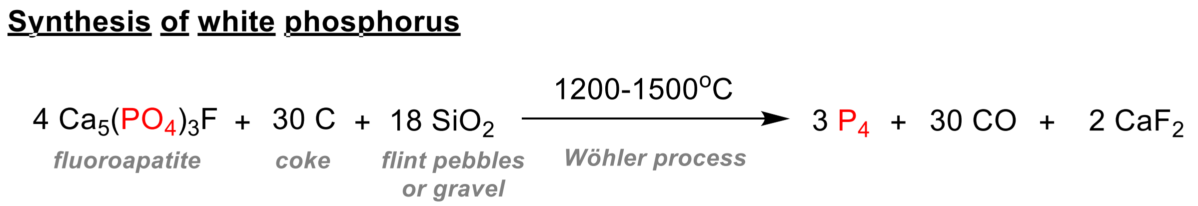
H_2SiF_6 or sodium fluorosilicate can be sold as a byproduct. Fluorosilicic acid has numerous applications, such as wood preservatives, rust removers, and concrete additives. However, it is mainly used to produce AlF_3 or cryolite, necessary additives for aluminum production.

As MGA grade is unsuitable for many applications, further phosphoric purification is necessary to obtain **purified phosphoric acid,** or PPA (62% P_2O_5 content and above), and even more for battery-grade PPA. Several technologies can be used for purification, such as solvent extraction, neutralization and precipitation, or crystallization. Precipitation was previously widespread for synthesizing sodium triphosphate, a standard detergent, but it has mostly been supplanted by solvent extraction, which is more flexible and efficient. This method preferentially extracts phosphoric acid *via* a mixture of organic solvents while cationic impurities are separated. Anionic impurities are separated through precipitation and evaporation to remove sulfate, fluoride and heavy metals. After extraction, the purified acid is recovered from the organic phase using countercurrent water or aqueous alkali stream. The depleted phosphoric acid solution, or raffinate, is obtained as a byproduct and can be sold to manufacture triple superphosphate fertilizer. Using additional sulfuric acid during extraction or to treat the raffinate can improve recovery effectiveness. Alternatively, or on top of the solvent extraction method, the crystallization purification process yields very high-purity phosphoric acid, suitable for battery and electronic markets. It uses PPA as a feedstock, which is cooled down to 8–12°C to slowly crystallize as hemihydrate compounds before being filtered, washed and melted.[331] Finally, novel methods such as nanofiltration using specialty membranes are emerging.

It is estimated that the wet process accounts for more than half of the global sulfur supply, taking the form of sulfuric acid, thus showing how tightly the phosphorus and sulfur industries are interdependent.[334] The quantity of sulfuric acid used during the wet process can vary according to the content of the phosphate rock concentrates: a concentrate containing more alkaline rocks, such as calcium oxide CaO, will need more acid to be treated.[297] The colocation of a sulfuric acid production plant near a phosphoric acid processing facility can also be beneficial: the exothermic conversion of sulfur to sulfuric acid could generate energy for both sites.[333] Generally, most phosphoric acid produced is used for the fertilizer industry. The remaining part of phosphate rocks can be converted to molecular phosphorus P_4 through the thermal process for subsequent reactions.

7.3.2.3 The Thermal Process: An Energy-Intensive Route

Historically, phosphoric acid was also synthesized by oxidizing the white phosphorus obtained to afford phosphorus pentoxide, the anhydride version of phosphoric acid. However, because the reaction is strongly endothermic, this thermal process requires electric furnaces, which are highly energy intensive. These issues caused the development of the wet process, which circumvented the need to go through a white phosphorus intermediate to obtain phosphoric acid. Nevertheless, this **thermal process** (the Wöhler process) remains the most efficient pathway to produce pure molecular phosphorus. An electric furnace heating around 1450°C is fed the three raw materials: Phosphate rocks that are either sintered or pelletized, dried metallurgical coke for the carbon source, and silica deposits such as pebbles, gravel, or coarse sand (**Figure 7.3.3**).[335]



$$4\ Ca_5(PO_4)_3F + 30\ C + 18\ SiO_2 \xrightarrow[\text{Wöhler process}]{1200\text{-}1500^{\circ}C} 3\ P_4 + 30\ CO + 2\ CaF_2$$

Figure 7.3.3 Conversion of phosphate rocks to white phosphorus through the Wöhler process

**

The P-gas produced are then condensed and washed with water. The white phosphorus afforded is then stored underwater to prevent it from self-ignition. Even though the wet process mostly supplanted the thermal pathway, around 83% of the P_4 obtained is still converted to phosphoric acid through combustion.[335] This phosphoric acid is purer than obtained through the wet process and can be used accordingly for more sensitive applications. Only about 12% of the white P_4 produced is converted into fine chemicals and heavy phosphorus compounds, including PCl_3, PCl_5, and P_4S_{10}, with the remaining being used for all other industrial phosphorus species.[336] Most P_4 produced in the U.S. in 2022 was primarily used to synthesize glyphosate herbicide.[325,337] PCl_5 is notably used for producing $LiPF_6$ **electrolyte salt**, and the Canadian company Targray is a world leader in its synthesis.

7.3.2.4 Synthesis of LFP Cathode

Several methods for producing LFP,[338] include freeze-drying, hydrothermal, microwave heating, polyol process, supercritical water, co-precipitation, solid-state reaction, calcination, solvothermal, sol-gel, rheological, and combustion. The most used methods remain the hydrothermal process (**Figure 7.3.4**),[339,340] and the solid-state (**Figure 7.3.5**). The majority of LFP factories in China use the latter. This process starts with the reaction of iron sulfate $FeSO_4$ and phosphoric acid to produce iron(III) phosphate $FePO_4$. The iron phosphate powder is mixed with lithium carbonate and a carbon source to form the conductive coating. The mixture is then heated to temperatures of 700-800 °C to form the olivine structure that allows it to function as a cathode.[310] One-pot processes, such as the method used by Nano One, are also emerging. More details on the different processes can be found in reviews from the literature.[339,341]

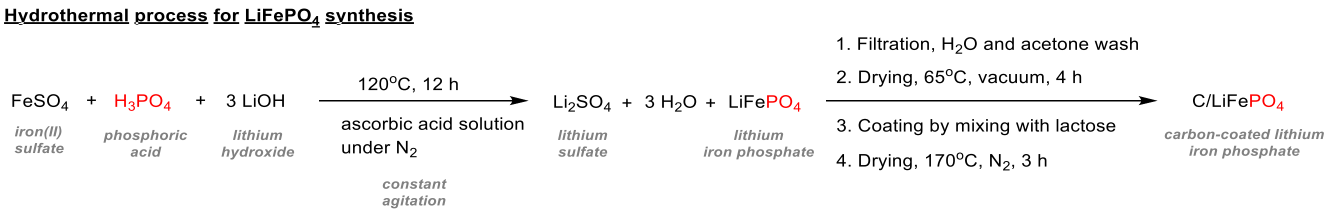


Figure 7.3.4 Example of LiFePO₄ synthesis through a hydrothermal process

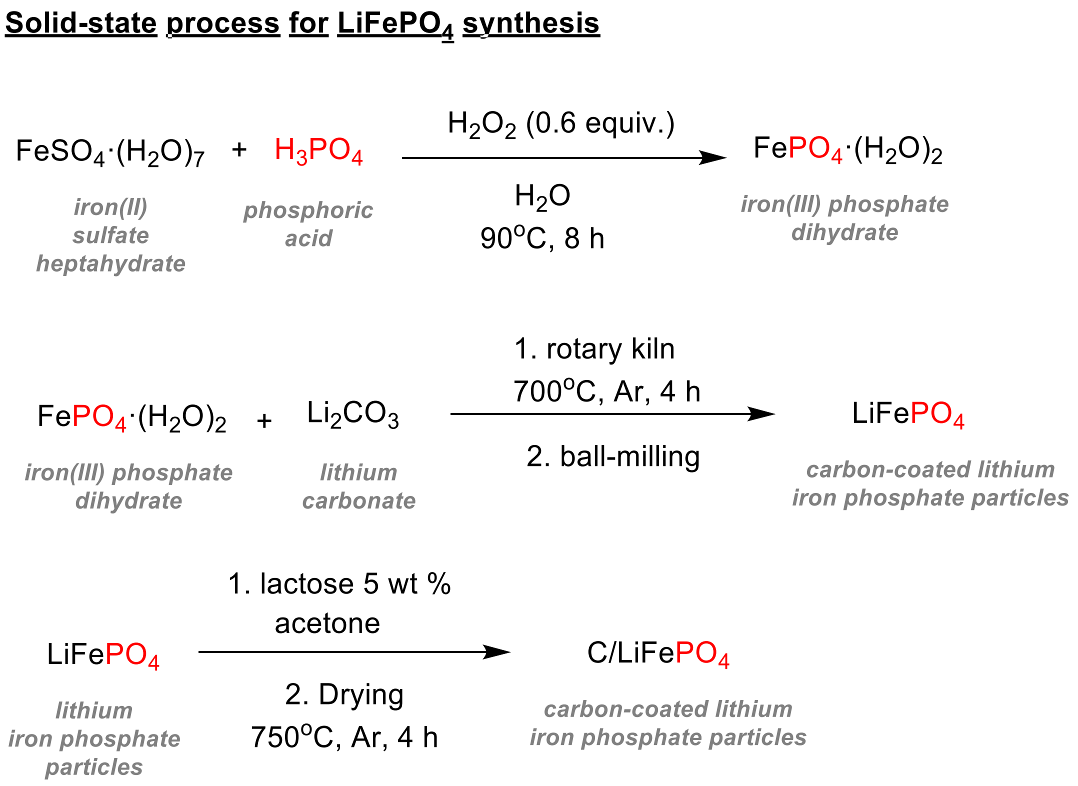


Figure 7.3.5 Example of LiFePO₄ synthesis through a solid-state methodology

The solid-state reaction is most adapted for manufacturing as it is inexpensive and creates an ordered crystal structure. However, it requires high temperatures and long sintering times and does not necessarily yield the best results. In comparison, the hydrothermal process creates a more complex and ideal carbon coating, allowing for better conductivity and performance. The main drawback of this solution-based methodology is its difficulty scaling on a production site.

Phostech Lithium was one of the first companies to commercialize LFP, receiving the first license to manufacture LFP commercially in 2003. After that, the company graduated to more massive LFP factories, culminating in a 2,400 t per year plant near Montreal in 2012. However, progress was slow due to cautious investors, and the company struggled financially until the German chemical company Süd-Chemie bought a majority stake in 2005. Süd-Chemie financed pilot facilities and the Montréal plant, but the company's hydrothermal process was more expensive than Phostech's solid-state method. Clariant acquired Süd-Chemie in 2012 and promptly sold the LFP business to Johnson Matthey. Now acquired by Nano One Materials, the Montreal factory is the only facility in North America that can produce meaningful quantities of LFP.

Today, there is growing interest in producing LFP cathode materials outside China. In October 2022, the Israeli chemical maker ICL Group announced plans to build a 30,000 t per year LFP cathode powder factory in Missouri with a $200 million US Department of Energy grant. The Norwegian start-up Freyr Battery and Utah-based American Battery Factory also plan to make LFP cathode material in the US for their battery factories in Georgia and Arizona, respectively. In addition, China's Gotion High-Tech hopes to establish LFP cathode material production in Michigan.

One potential difference between ICL's Missouri plant and Chinese factories is the starting materials. ICL is evaluating using iron oxide rather than iron sulfate, which can be difficult to procure outside China. Iron oxide is more expensive, but the process produces higher-quality LFP. ICL plans to use technology from Aleees, a Taiwanese LFP maker with nearly two decades of experience, to produce high-quality LFP.

8 The Rare Earths

8.1 The Canadian Rare Earth Strategy

8.1.1 Rare Earths in Canada

Table 8.1.1 Non-exhaustive selection of current and future REE extraction, processing and recycling projects in Canada

Selection of Future REE Extraction Projects				
Site Name	**Company**	**Province**	**Type**	**Status**
Nechalacho/Tardiff	Vital Metals	NT	bastnäsite	Scoping study
Wicheeda Rare Earth	Defense Metals	BC	bastnäsite	PFS 2025
Bear Lake Project	Searchlight Resources	SK	possibly monazite	Exploration
Alces Lake	Appia Rare Earths & Uranium Corp.	SK	monazite	Exploration
Elliot Lake	Appia Rare Earths & Uranium Corp.	ON	uranium, monazite	Exploration
Eco Ridge Mine	Radio Fuels Corp.	ON	uranium, monazite	Exploration
Strange Lake	Torngat Metals	QC	gerenite, gagarinite, kainosite, other	PFS projected in 2025
Ashram	Commerce Resources	QC	monazite, bastnäsite, xenotime	Advancing Updated PEA
Kwyjibo	SOQUEM	QC	apatite, britholite, allanite, kainosite	PEA 2018
Kipawa- Zeus	Québec Precious Metals, Investissement Québec	QC	eudialyte, mosandrite, britholite	FS 2013
Foxtrot	Search Minerals	NL	HREE	PEA 2022
Selection of Operational & Future REE Processing Facilities				
Project Name	**Company**	**Province**	**Product Type**	**Status**
Saskatoon Processing Facility	Vital Metals	SK	Mixed Rare Earth Carbonate	Cancelled
SRC Rare Earth Processing Facility	SRC	SK	Mixed Rare Earth Carbonate, Separated REO, separated metals and alloy	Operational
Sept-Iles Separation Facility	Torngat Metals	QC	Separated REO	2028+

Hub100 Demonstration Plant	Cyclic Materials	ON	recycled mixed REO	Operational
Commercialization & Demonstration Facility	Ucore	ON	Separated REO	Operational
Saint-Hubert Demonstration Plant	Geomega	QC	Separated REO	Construction

8.1.1.1 Summary

Despite ranking 10th in REE reserves globally in 2024, Canada did not mine or process REEs at scale in 2023. Active mining projects can be found in the Northwest Territories, BC, Saskatchewan, Quebec, Ontario, and Labrador. In contrast, a processing plant, going from digestion to separation and metallization, is projected in Saskatchewan, and Geomega plans to build a magnet recycling demonstration plant in Quebec.

8.1.1.2 Upstream

Torngat Metals is a Quebec-based company focused on developing the Strange Lake Project, located in Nunavik at the Labrador-Quebec border. This deposit has a high proportion of HREEs. A PFS is expected to be completed by 2025, and production is targeted to begin in 2028. A separation facility is also projected in the Sept-Îles Industrial Park.

Vital Metals, an Australian rare earth company, was the first to initiate rare earth mining in Canada through its Nechalacho project in the Northwest Territories, a bastnäsite-rich deposit. The extracted ore was to be processed into a concentrate and further refined at Vital's rare earth processing facility in Saskatoon, Saskatchewan. Due to financial difficulties, the project was paused or scaled down, and the processing facility project has been cancelled. The financial situation preceded a 9.9% stake in Chinese purchase by Shenghe Resources in 2023. Vital Metals had planned to sell Shenghe its bastnäsite stockpile but finally sold it to the SRC for $3.3 million after the federal government's involvement.[342]

A longer list of REE mining projects is available in Table 8.1.

8.1.1.3 Midstream & Downstream

Additionally, two Canadian-based companies hold expertise along the midstream and downstream of the REE magnet value chain: Ucore Rare Metals and Neo Performance Materials. The Saskatchewan Research Council has launched a midstream facility in Saskatoon, and Cyclic Materials is a new company in Ontario focusing on REE recycling.

Ucore, a Nova Scotia-based mineral processing company, is proprietary of a novel solvent extraction method for REE separation enhanced by computerized column technology, able to separate LREE & HREE with the same equipment. An 80 tpa commercial and demonstration plant operates in Kingston, Ontario, while the Strategic Metal Complex production plant is commissioned in Alexandria, Louisiana, for 2025. It is projected to reach a capacity of 7,500 tpa in 2026. Ucore has received support from a $5M incentive from the state of Louisiana, a $360,000 grant from the Greater Alexandria Economic Development Authority, and a $4M OTA from the U.S. DoD. Additionally, Ucore received $4.3 M from the government of Canada to produce NdPr, Pr and Nd over 6 months from 13–15 tonnes of Canadian and US feedstock sources in Canada.

Neo Performance Materials, a Toronto-based firm, has numerous activities in mainland China but also operates LREE separation in Narva, Estonia, while projecting to manufacture sintered NdFeB magnets there, in addition to already active operations in Thailand and the U.K. The company owns three business units: Neo Magnequench, focusing on downstream REE magnetic powders and bonded/sintered magnets; Neo Chemicals & Oxides, which deals with midstream REE separation, mixed oxides and catalysts; and Neo Rare Metals, which targets hafnium and gallium recycling as well as tantalum metal. The company is uniquely positioned to be fully integrated from REE separation to metals & alloys to magnet making and recycling. The Narva sintered magnet plant is forecasted to produce 2,000 tpa of magnets, reaching 5,000 tpa in the second phase.

The SRC Rare Earth Processing Facility is unique in Canada because it is a publicly funded company operating in the REE midstream segment on Canadian territory. With this venture, the Saskatchewan Research Council has shown a strong will to develop and derisk the REE industry in Canada. The Saskatoon facility focuses on monazite as a feedstock and its hydrometallurgical processing, separation, and metallization. The SRC also has proprietary technology for automated solvent extraction cells and metal smelting. The facility can produce medium/heavy mixed REE carbonate, La/Ce mixed REE Carbonate, NdPr metal alloy, and HREEs in the form of dysprosium oxide and terbium oxide. The smelting unit will be capable of producing neodymium, praseodymium and didymium mix as ingots. The SRC recently announced that the facility had produced REE metals commercially in the summer of 2024 and will be fully operational by 2025 to produce 400 tpa of NdPr metals.[343] Prairies Canada announced in August 2024 a $16 million support for the SRC Rare Earth Processing Facility to develop processing capacity for the bastnäsite ore acquired from Vital Metals. This funding comes after an earlier support of $13.5 million from NRCan and Prairies Canada to establish the SRC processing centre.[344]

Cyclic Materials, founded in 2021 and based in Kingston, Ontario, specializes in recycling REEs from end-of-life products such as electric vehicle motors, wind turbines, MRI machines, and data centre electronic waste. Copper scrap will also be recycled and sent to the Horne smelter. Their proprietary technology enables the process of waste through a hydrometallurgical process to recover recycled mixed rare earth oxide (rMREO). They opened their Hub100 commercial demonstration plant in 2024,[345] and have secured collaborations with Glencore, Vacuumschmelze, Solvay, Ucore, SYNETIQ, Polestar, *etc.*

8.1.2 Scenario Outline

Canada should strengthen a domestic REE processing and magnet manufacturing hub in Saskatchewan, anchored in the already operational SRC REE Processing facility, before opening several rare earth mines in western provinces and territories. Collaborating with off-takers such as material manufacturers and EV motor producers is crucial to meet their requirements.

- **In the Short Term, Secure a Strong Midstream REE Processing:**
    - **Establish a Strong Centralized REE Processing Hub:** Bolster the Canadian monazite processing capacity by importing monazite concentrates first and waste materials as feedstock to maximize the production of individual Rare Earth oxides and metals. Ensure an optimal production of heavy rare earth products when possible. Leverage the already existing Canadian refining facilities and IPs, such as the Saskatchewan Research Council processing plant, Ucore, and Cyclic Materials. In parallel, a bastnäsite processing pathway and importing concentrates should be developed as a later priority.
    - **Manufacture Magnets:** Use the processed REOs, metals and alloys from the to processing hub to make sintered permanent magnets in magnet or magnetic powder plants. Secure partnerships with major material companies, EV motor producers, and OEMs to build a customer-driven, reliable chain.
    - **Foster REE Process Optimization:** Develop ‘test kitchen’ pre-production hubs, gathering talents and resources to optimize a Canadian REE value chain and improve processes.
- **In the Medium Term:**
    - **Develop Mining Capacity:** Ramp up mining capacities in the Northwest Territories, Quebec, Saskatchewan and British Columbia to feed the processing hub with high-grade concentrates of monazite and bastnäsite.

8.1.3 Signature Projects

- 3–4 REE mines (Such as Nechalacho, Wicheeda, Alces Lake, Strange Lake, *etc.*)
- One centralized processing hub, anchored in the SRC plant in Saskatoon
- One permanent magnet plant

8.1.4 Strategic Priorities

- **Establishing Midstream REE Processing Hub:**
  - **Support a Centralized Hub:** Develop a hub-and-spoke model to streamline the REE supply chain's chemical processing, separation, and refining stages. This hub will produce individual rare earth oxides or metals critical for downstream applications.
  - **Anchor the Hub in Existing Facilities**, such as the Saskatchewan Research Council (SRC) in Saskatoon, which already produces REE metals from monazite concentrate. Supporting the viability, development and expansion of this facility should be pursued.
  - **Leverage existing Canadian intellectual property:** Such as Ucore for REE separation or Cyclic Materials for REE recycling from old magnets and waste. Both companies have a footprint in Kingston, Ontario, and have attracted funding and partnerships.
  - **Feedstock Diversification:** Start with reliable monazite feeds, which is the first feedstock used by the SRC, then expand capabilities for bastnäsite and ionic clays as processes mature. Recycled mixed rare earth oxide should also be considered as an alternative feedstock that advances circularity. Start processing with the import of foreign concentrates, then use domestic ones when the mine come online.
  - **Magnet Manufacturing Integration:** Co-locate a permanent magnet manufacturing facility with the processing hub to develop the downstream segment of the supply chain. Secure partnership with Original Equipment Manufacturers (OEMs) and EV motor producers to ensure demand and reliability. Encourage e-waste recycling as a supplemental material source for magnet manufacturing
    - A magnet production hub will benefit from being located near clients (OEMs, Tier 1 suppliers, EV motor manufacturers, *etc.*). However, this could prove difficult for the colocation of a magnet plant in Saskatchewan. In this case, locating the plant in Ontario and/or securing strong partnerships with domestic or international off-takers is necessary.
  - **Pre-Commercial Test Hub:** Create a 'test kitchen' pre-production hub to optimize processes, explore commercialization strategies.
  - **Develop Processing Expertise Abroad and Export IP and Engineering Services:** A secondary strategy for the midstream is to gain experience in optimizing processes abroad and establish credibility internationally. An example of this would be the partnership between the SRC, Hatch and Aclara, a South American junior miner projecting to develop a heavy rare earth separating facility in the U.S.
- **Ramp Up Domestic Mining Capacities:**
  - In the medium term, and parallel to the development of the processing hub, mining operations in the Northwest Territories, Quebec, Saskatchewan, and British Columbia should be advanced to

    feed the processing hub with high-grade concentrates. Lessons should be learned from the recent Vital Metals situation to increase viability and investor confidence.

- **Access to Energy, Chemicals, Infrastructure and Talent:**
    - **Energy Access:** Ensure clean, affordable energy to support energy-intensive refining processes.
    - **Chemical Supply:** Guarantee reliable access to essential reagents such as acids and sodium hydroxide.
    - **Infrastructure Integration**: Build the supply chain around robust transport networks, including road and rail. Access to REE deposits in the northern territories or northern Quebec necessitates infrastructure investment.
    - **Talent Development:** Facilitate access to global expertise while fostering domestic education and training programs.
- **Develop Synergies:**
    - **Coordination with the Nuclear Industry**: Collaborate with the nuclear industry (*e.g.* AECL, OPG, Cameco, Orano) and standards (CNSC) to manage and monetize uranium and thorium waste from monazite processing. This collaboration could reduce regulatory barriers and unlock REE mining potential.
    - **Phosphate Co-Production:** Leverage opportunities to produce phosphate as a byproduct of monazite processing.
    - **REE Co-production from Sedimentary-Based Phosphogypsum**: Conversely, recovering REEs from sedimentary apatite deposits in Western Canada, or from phosphogypsum made by a future phosphoric acid plant could be an interesting venue to explore. South African company Rainbow Rare Earths is investigating operations in South Africa, Brazil, and Morocco.
- **Research & Development:**
    - **Secure Long-Term Investments** for an R&D strategy based on developing extraction, refining and scaling processes specific to Canadian feeds and off-takers.
    - **Optimize the Process for Different Feedstock:** Address the issue of feedstock and concentrate diversity by building a robust processing method which can be customized for monazite and bastnäsite first, then for recycled mixed rare earth oxide concentrates, and eventually for clays.
    - **Heavy REE Production:** optimize the separation of HREE from standard monazite and bastnäsite feedstock, and later on from clays, as to maximize the output of HREE.
    - **Beneficiation:** optimize the beneficiation processes on mining sites to obtain higher-grade rare-earth oxide concentrates.
    - **A Magnet Production Focused on EVs and High Performance:** For permanent magnet production, focus on optimizing grain boundary diffusion processes to decrease the reliance on HREEs and prioritize the production of sintered magnets over bonded magnets.
- **Material Standards:**

    - **Harmonize the EV Supply Chain** by issuing standards and specifications for REE feedstocks, intermediates, and magnets. Initiatives such as the Product Category Rules (PCR) developed by the Rare Earth Industry Association (REIA) and their collaborators help define common, consistent guidelines to perform LCA on the REE supply chain.[346] Similar international initiatives based on this work should be supported.
- **Protection from Price Volatility:**
    - **Market Stability Mechanisms:** Facilitate stability and certainty through government procurement, contract for differences, government-guaranteed future purchase of locally sourced critical minerals, or buffer stock mechanisms.[249]
    - **Ex-China Economics:** Develop and understand the economics for specific pricing for the ex-China REE industry.
- **Meeting the Off-takers' Requirements**:
    - **Collaborate with Off Takers Down the Supply Chain:** REE miners and processors should collaborate with the off-takers (magnet manufacturers, EV motors manufacturers, OEMs) to understand and identify their material standards requirements and perspectives
    - **Design Flowsheets that Make Sense:** Work backward from those off-takers to design a customer-driven REE flowsheet.
    - **Involve Major Material Producing Companies:** Favour the involvement of major material producers in investing in the REE mining and processing steps to ensure long-term reliability.
- **Encourage Circularity:**
    - **E-Waste Integration:** Encourage rare-earth recycling by processing waste materials (E-waste, old magnets, waste from the REE processing supply chain, *etc.*) on top of primary feedstocks.
    - **Remove Barriers** to the import of electronic waste.
    - **Unified Industry Effort:** Foster collaboration throughout the supply chain to ensure a cohesive REE circularity strategy. Co-locate or integrate rare earth recycling when possible where the REE processing and magnet manufacturing operations are to maximize efficiency and sustainability.

8.2 Rare Earths: An Inseparable Set of Elements Attractive for Magnets

8.2.1 General Properties

Rare Earth Elements (REE) are 17 metallic elements, including the 15 lanthanides associated with scandium and yttrium. Due to physicochemical and commercial properties, they can be split into the more abundant light rare earth elements (LREEs – La to Sm or Eu) and heavy rare earth elements (HREEs – Eu or Gd to Lu, and Y), while scandium is often left out. Didymium is the specific name given to the mixture of neodymium and praseodymium. REEs find applications in high-strength permanent magnets in wind turbines and EV motors. REEs like cerium and lanthanum are used in automotive catalytic converters, industrial fluidized cracking catalysts and polishing powders for glass and ceramics.[347,348] REEs are also critical in optics and display (*e.g.*, phosphors for LEDs or LCD and fluorescent lamps) and medical imaging. Certain REEs are also used in water treatment, as they can selectively bind to phosphate ions in water, making them helpful water treatment additives for preventing algal blooms or phosphate overconcentration.

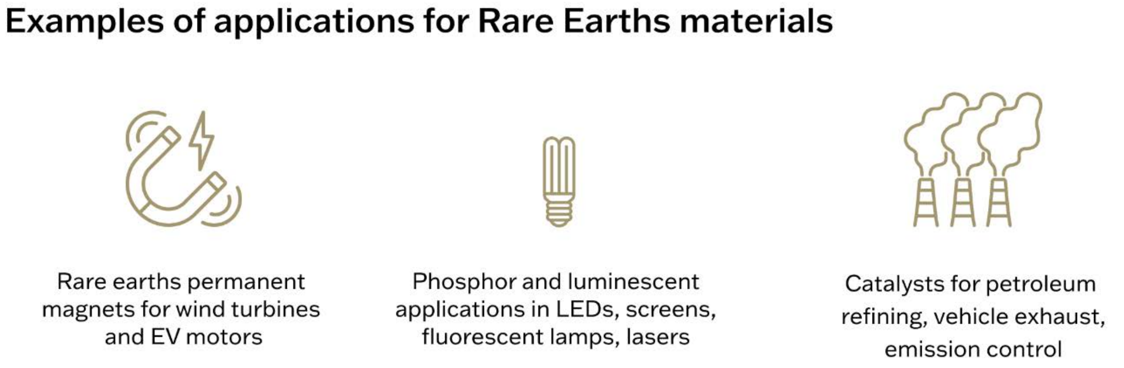


Figure 8.2.1 Examples of applications for rare earths materials

Historically, the early development of the rare earth industry started in the late 19th century and continued until 1930, with the development of incandescent gas mantles using thorium and cerium oxide. *Mischmetal*, a mixture of lanthanides and iron, was also used for flints and metallurgy. This was the initial development of REE alloys together with a specific focus on cerium oxide for lighting purposes. Then, until the 1960s, REEs gained importance in various industries, using cerium oxide in polishing powders, ceramic glazes and as an additive for optical glass. Military research also drove the advancement of REE separation techniques during WWII. Lanthanide luminescence was discovered in 1942, leading to optical applications as phosphors; by 1965, europium-based red phosphors also revolutionized colour television technology. The development of SmCo magnets and later NdFeB magnets in 1983 significantly diversified the applications for REE and allowed vital advancements to our use of permanent magnets. Other applications, such as superconductors or catalytic converters, were also implemented. Lanthanum also became critical for nickel-metal hydride (NiMH) batteries, which were widely used before being gradually supplanted by lithium-ion batteries. Since the 1990s, China has dominated the mining, separation, processing, refining and manufacturing of REE materials. Modern applications have expanded to include advanced magnets for electric vehicles and wind turbines, magnetocaloric materials for refrigeration, energy-efficient lighting (LEDs), and water purification technologies. High-tech innovations now drive the demand for REEs, and their strategic importance arose as their vulnerabilities in global supply chains developed.

Thus, the U.S. Department of Energy considers Neodymium and Dysprosium critical elements in the short term and praseodymium in the medium term.[151] At the same time, NRCan labels all REEs as Critical Minerals.[349]

8.2.2 Role in Clean Technologies

Rare-earth magnets are considered strategic materials because they are difficult to replace without a significant loss of performance. In 2021, they accounted for 43% of the total REE demand. They excel compared to other permanent magnets in applications where weight, size, and efficiency are critical.

In EVs, REE magnets are primarily used in electric motors, specifically **permanent magnet synchronous motors** (PMSMs). These motors rely on the strong magnetic properties of NdFeB magnets to achieve high efficiency, compact size, and superior power density compared to other motor designs. REE magnets can also be found in regenerative braking systems, where kinetic energy can be converted back into electricity, in powertrain components such as cooling fans and electric drive units, and in accessory systems such as sensors and actuators. Aside from EVs, REE permanent magnets can be found in direct-drive wind turbines to convert wind energy into electricity or in consumer electronics such as smartphones, laptops, speakers, microphones and hard disk drives. Precision aerospace, defence, and robotic applications such as guidance systems, precision motors, actuators, and radar also use those types of magnets, and medical devices such as MRI machines need a strong permanent magnet to generate a magnetic field.

The REE-based permanent magnets rely mainly on LREEs such as **neodymium** for $Nd_2Fe_{14}B$ magnets (NdFeB), which are often partially substituted by **praseodymium**, another light element, enhancing cost-efficiency while maintaining performance. Cerium can also substitute neodymium or praseodymium, as it is cheaper and more abundant, but can lead to lower performances. Adding a small amount of HREEs like **dysprosium** or **terbium** is critical for improving the thermal stability of these magnets, especially in high-temperature applications like electric vehicle motors and wind turbines. Indeed, magnets tend to lose magnetic strength at elevated temperatures, and adding HREEs increases the Curie temperature, the temperature above which a material loses its magnetic properties. Coercivity, the measure of a material's resistance to losing its magnetization when exposed to an opposing magnetic field, is also improved by HREE addition. Finally, **Samarium** is used separately for $SmCo_5$ magnets and has found its niche as they are stable under extreme conditions.

The evolution of rare earth magnets reflects technological leaps, starting with samarium-cobalt (SmCo) magnets in the 1970s. These magnets displayed high coercivity but were limited by the scarcity and cost of samarium and cobalt. In 1984, Masato Sagawa at Sumitomo Special Metals and John Croat at General Motors independently discovered neodymium-iron-boron (NdFeB) magnets, revolutionizing the industry by offering magnets 2.5 times stronger than $SmCo_5$ at a lower cost.[350]

As HREEs are rarer, expensive, and extracted almost solely in China and Myanmar, the trend toward minimizing HREEs such as dysprosium and terbium in magnet production has significantly impacted the REE value chain. Techniques like Grain Boundary Diffusion (GDB) have reduced HREE content in magnets without compromising magnetic performances. GDB enhances the coercivity by concentrating HREE at the grain boundaries, and this targeted approach allows for a significant reduction in the overall HREE content, from almost 10% to a couple of percent, lowering costs and increasing sustainability. However, while this trend is expected to continue, there is likely a physical limit to how far HREE reduction can go without compromising magnet performance.

Finally, there are two broad types of NdFeB magnets: bonded and sintered. **Bonded magnets** are created by combining magnetic powders with a binding agent, allowing the production of complex shapes with tight tolerances. They typically exhibit lower magnetic strength than sintered magnets but offer advantages in design flexibility and resistance to cracking. They are used for small electric motors and electronics. On the other hand, **sintered magnets** are formed by compressing and heating magnetic powders without a binder, leading to higher magnetic performance but less flexibility in shaping and a greater susceptibility to brittleness. They can be used in EV motors and wind turbines. Most sintered magnets are also manufactured in China. Outside of China, and before the future advent of the new Neo Performance Materials plant in Estonia, the e-VAC plant in South Carolina or the new plant from South Korean Star Group company, there are only two large sintered magnet plants in Japan, with smaller capacities in other countries.[40]

8.2.3 Substitutes

Other motor designs can be used: Permanent magnets are not necessary for all electric motors, as only **permanent magnet synchronous motors** (PMSM) rely on them. Other designs, such as induction motors, electrically excited synchronous motors (EESM, also known as wound synchronous motors), and synchronous reluctance motors (SynRM), operate without permanent magnets. While PMSMs are highly efficient and boast superior power density compared to these alternatives, they come at a higher cost, largely due to their reliance on REEs.

Induction motors operate using electromagnetic induction and do not require permanent magnets. Tesla initially used induction motors for its EVs before transitioning to PMSMs for better efficiency. They are proven, cost-effective technology, but they are less efficient and bulkier than PMSMs.

Electrically Excited Synchronous Motors (EESMs) use an external electrical current to generate the magnetic field, eliminating the need for permanent magnets. Due to additional components, the trade-off is slightly lower efficiency and a higher fabrication complexity.

Synchronous reluctance motors (SynRM) operate based on the principle of magnetic reluctance, with torque generated as the rotor aligns with the stator's magnetic field. Unlike PMSMs, SynRMs do not require permanent magnets and instead rely on rotor designs with specific air gaps and iron segments. They can have comparable efficiency to PMSMs at higher operating speeds, and their simplified rotor design and absence of expensive magnets reduce manufacturing costs. However, they suffer from a lower torque density than PMSMs, meaning they would require larger motors for a similar performance; they can also suffer from higher losses at lower speeds and thermal challenges, and they are still not widely adopted.

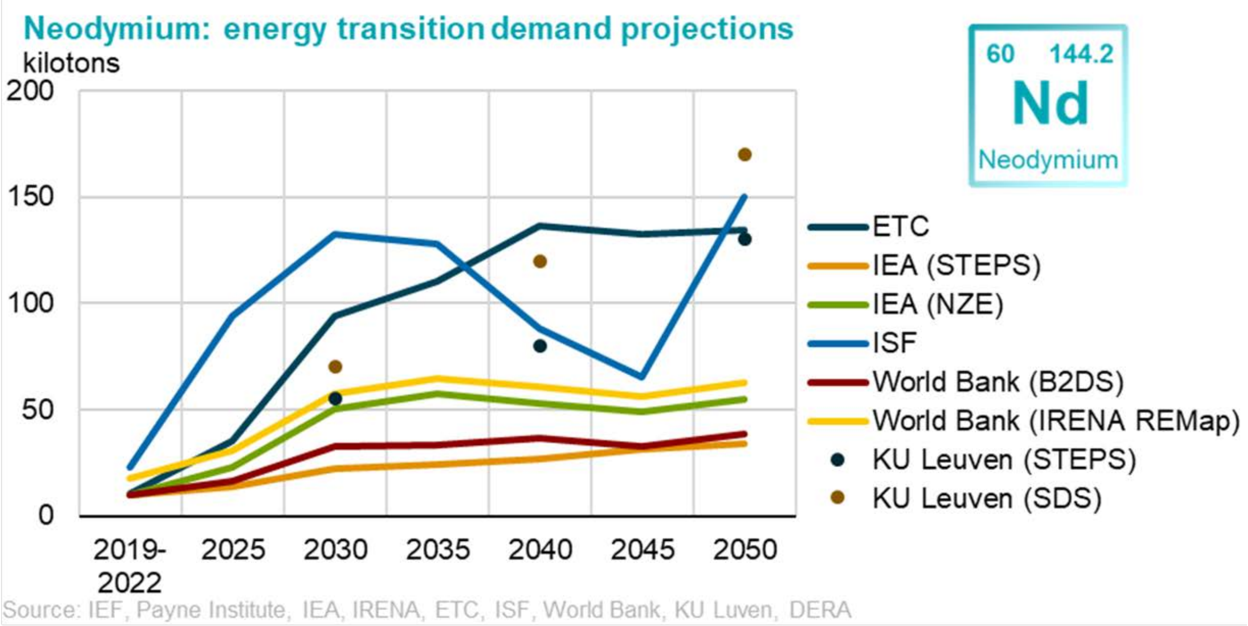
Another viable solution to switching motor design is substituting NdFeB magnets for REE-free permanent magnets. Ferrite magnets are widely available and significantly cheaper than REE-based magnets. They consist of mostly iron oxide and other metal oxides and are typically used in low-cost and low-power applications. However, they exhibit a much weaker magnetic strength compared to NdFeB magnets, thus limiting their use in high-performance applications.

Iron-nitride magnets have shown promise for high-performance applications without the need for REEs. Companies focusing on this solution, such as Niron Magnetics, have received ARPA-E awards and attracted private investments from GM, Stellantis, Samsung Ventures, and Tier 1 automotive suppliers such as Allison Transmission and Magna.[351,352]

AlNiCo (Aluminum-Nickel-Cobalt) is a mature permanent magnet with excellent thermal resistance. However, it has a much lower magnetic strength than NdFeB or SmCo magnets, making it unsuitable for EV applications.

While still an REE-based magnet using samarium, SmCo is highly resistant to demagnetization, has great thermal stability, and has good magnetic strength, although lower than NdFeB. However, being based on samarium, another heavy rare earth, it suffers from the same supply chain vulnerabilities as NdFeB. The cobalt supply chain it relies on is also controversial and highly concentrated in specific countries such as the DRC and China. These factors also explain the high cost of SmCo magnets.

8.2.4 Supply and Demand



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Figure 8.2.2 Neodymium demand projections to 2050 according to various energy transition scenarios[40]

The price of REE has been particularly volatile and is based on non-transparent markets. The rare earth crisis of 2010–2011 highlighted the vulnerabilities of global supply chains dominated by China.[24] By the early 2000s, China controlled approximately 95% of global rare earth production. Concerns over environmental degradation, illegal mining, and resource depletion led China to impose export and production quotas, export taxes, and investment restrictions starting in 2006. In 2010, a 37% reduction in China's export quota caused rare earth oxide prices to surge, exacerbated by reports of interrupted shipments to Japan during a maritime dispute.

This price spike triggered significant shifts in the rare earth market. Recycling, substitution, trade deflection, and opening new mines allowed a relative alleviation of demand and supply constraints, leading to price stabilization by 2012. Subsequently, the World Trade Organization finally ruled against China's export restrictions in 2014. This followed a formal complaint by Japan, the U.S., and the EU, requiring China to lift these restriction measures. This historical crisis highlights the need for more diversified rare earth supply chains and the development of alternative sources.

Between 2017 and 2022, the REE market has multiplied by 2.5, driven mainly by rising clean tech and EV demand. The IEA accounts for a 2023 demand of 93 kt of REE, driven primarily by EV sales and wind turbines, growing the share of clean technologies applications for REE from 8% in 2015 to 18% in 2023. The announced pledge scenario projects a total demand of 131 kt by 2030 and 181 kt in 2050, while the net zero emission by 2050 scenario (NZE) forecasts a demand of 146 kt for 2030 to 200 kt in 2050.[42]

According to Adamas Intelligence, the magnet market is projected to grow by a factor of 4 by 2040. Three main avenues will cause magnet growth: the adoption of EV motors, the potential advent of advanced air mobility such as eVTOL and air taxis, and robotics. An additional production of 400 to 600 ktpa of LREO will be needed by then to meet this demand. According to their analysis, the REE market is projected to be balanced until 2030 but not after, which is why there is a case for an alternative supply chain of rare earth magnets outside of China

8.3 The Rare Earth Flowsheet: From Rocks and Ionic Clays to Permanent Magnets

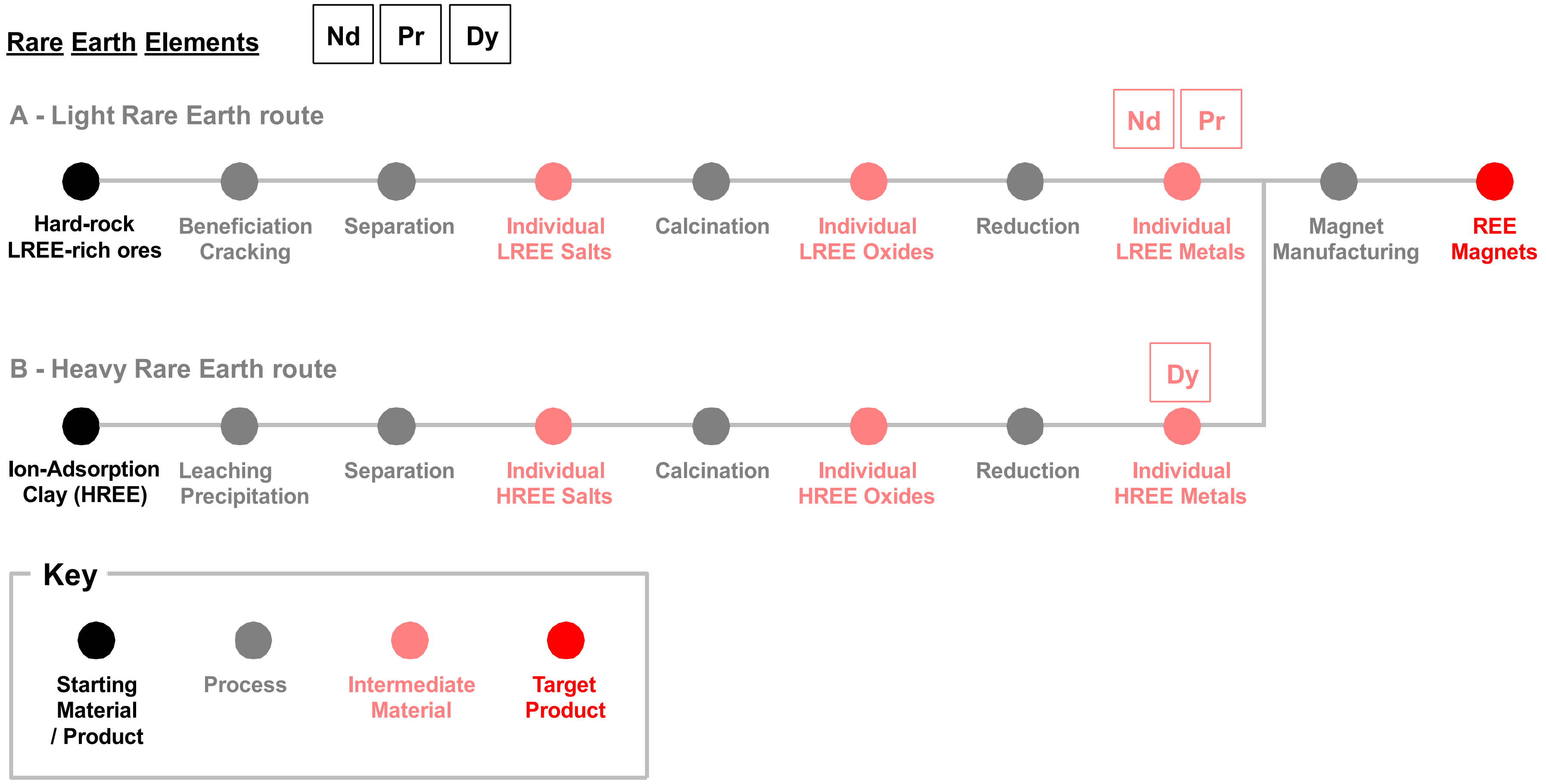


Figure 8.3.1 Simplified flowsheet of rare earth elements

8.3.1 Ores, Reserves & Production

The extraction of REEs originates mainly from hard-rock minerals such as **bastnäsite**, **monazite** and **xenotime**, or soft **ion adsorption clays**, especially in the case of HREE production in Southern China.

Bastnäsite, or bastnaesite, (La,Ce,Y)CO_3F is a rare earth carbonate mineral predominantly enriched with light rare earth elements (LREEs) like cerium, lanthanum, and neodymium. It is often found in carbonatite deposits such as Mountain Pass in the United States and Bayan Obo in China. Bastnäsite typically contains up to 75% REO (rare earth oxide) content, making it a high-grade source. These deposits are often associated with minerals like magnetite, hematite, and fluorite, influencing mining and beneficiation processes. Bastnäsite's high-grade composition and relatively straightforward processing make it a cornerstone of global REE production.

Monazite, (Ce,La,Th)PO4, is a phosphate mineral that contains light and heavy rare earth elements, as well as notable amounts of thorium. It is primarily found in secondary deposits like beach sands in countries such as Australia, Brazil, and India, often as a byproduct of heavy mineral sands mining for rutile, ilmenite, and zircon. Bayan Obo in China also holds a lesser amount of monazite. Monazite's REO content typically ranges between 55% and 70%. While monazite's thorium content can pose challenges due to its inherent radioactivity, many advancements in processing technologies have allowed it to remain one of the primary resources for REEs. However, outside of China, only a few countries possess the infrastructure, social mandate, and commitment to effectively manage and store radioactive by-products.[42]

Ion-adsorption clays (IACs), sometimes called ionic adsorption deposits (IADs), are unique, low-grade rare earth deposits in southern China, Myanmar, and Laos. Unlike other minerals, these clays are enriched in HREEs, which are weakly adsorbed onto the clay particles. This property allows for simple and cost-effective extraction using salt solutions at ambient temperatures, eliminating the need for complex chemical digestion. IAC typically contain less than 0.5% REO. These clays are known for their ease of processing and their cost-efficiency, thus making them critical resources for heavy rare earth production. Additionally, IAC projects show a lower capital intensity, minimal radioactive waste and reduced carbon emissions, which is why those projects are increasingly drawing attention.

The economic viability of IAC projects is increasingly recognized due to their lower capital intensity, ease of processing, reduced carbon emissions, and minimal radioactive waste.

Xenotime YPO_4 is another phosphate mineral predominantly composed of HREEs, including yttrium, dysprosium, and terbium. It is typically found in alluvial and pegmatite deposits and contains up to 62% rare earth oxide (REO). The processing of xenotime is more challenging than monazite due to its resistance to acid digestion.

Despite these technical complexities, xenotime is potentially a highly valuable resource due to its high HREE content.

Table 8.3.1 Estimated reserves & production of rare-earth oxide equivalent by country

Country	**REE Estimated Production in 2023**[a] (in tonnes)	**Country**	**REE Reserves in 2024**[a] (tonnes x 10^3)
Canada	**/**	Burma	NA
Greenland	/	Madagascar	NA
South Africa	/	Malaysia	NA
Tanzania	/	Thailand	4,500
Brazil	80	South Africa	790,000
Malaysia	80	**Canada**	**830,000**
Vietnam	600	Tanzania	890,000
Madagascar	960	Greenland	1,500,000
Russia	2,600	United States	1,800,000
India	2,900	Australia	5,700,000
Thailand	7,100	India	6,900,000
Australia	18,000	Russia	10,000,000
Burma	38,000	Brazil	21,000,000
United States	43,000	Vietnam	22,000,000
China	240,000	China	44,000,000
World Total	350,000	**World Total**	110,000,000

[a]Data from the 2024 U.S. Geological Survey in tonnes of rare-earth-oxide equivalent.[353]

World REE extraction is highly concentrated, with China dominating both mining and processing. In 2023, China accounted for 62% of global REE mining, according to the IEA,[42] and 68% according to the U.S. Geological Survey.[353] Beyond China, other contributors include the United States, Myanmar, and Australia, but their collective output remains relatively small. While most of China's extraction production focuses on light rare earth elements (LREEs), it also produces almost all of the world's heavy rare earth elements (HREEs), sourced from ion-adsorption clays in southern China and Myanmar. By 2030, the dominance of the top three mining countries is projected to decline modestly, with their combined share falling from 85% to around 81%.

Refining operations are even more geographically concentrated than mining. Although small quantities of LREEs are processed in Malaysia and Estonia, China dominates refining capacity for both LREEs and HREEs, with an overwhelming 92% share of global refined output, cementing China's position as the world's largest producer and processor of rare earth elements. Similarly, by 2030, the top three refining nations are expected to maintain a high share of output, though China's share of refined REEs is anticipated to drop to 77%. This concentration level makes REE production one of the least diversified supply chains among key energy transition materials, surpassing even cobalt and natural graphite regarding geographical dependency.

Regarding downstream industries, China also leads in NdFeB magnet production, accounting for approximately 80-90% of global output. Japan represents around 7% of global magnet manufacturing capacity, with smaller contributions from Vietnam and Germany.

8.3.2 Regional Outlook

Myanmar, a fragile global leader in HREEs: Myanmar plays a critical role in the worldwide supply of heavy rare earth elements (HREEs), accounting for 57% of dysprosium and terbium global mined supply in 2023.[354] Most of Myanmar's rare earth extraction occurs in Kachin State, near the Chinese border. This proximity allows for the swift transport of rare earth concentrates across the border for processing. However, tracing these materials can become challenging. Moreover, the region's mining operations are also under significant geopolitical, environmental, and social tensions. This problematic situation introduces uncertainty into an already concentrated global HREE supply chain. The escalating conflict between Myanmar's military junta and rebel groups, including the Kachin Independence Army (KIA), has disrupted rare earth mining and trade routes in Kachin State, particularly in the Panwa region, a key mining hub. The Kachin Independence Organization (KIO) suspended rare earth mining in September 2023 due to environmental damage and protests. This suspension caused a prolonged operational halt and added uncertainty for local workers.[42] These disruptions have threatened China's rare earth supply, which heavily depends on Myanmar's feedstock to meet magnet manufacturing demands. While low prices and rising production have overshadowed important environmental and social issues, the recent events exposed the fragility of this supply chain, thus emphasizing the urgency of diversifying and securing sustainable, ethical alternatives for HREE production.

The U.S. restores its domestic REE supply chain by reopening Mountain Pass: The Mountain Pass Rare Earth Mine, located in California's Mojave Desert, has played a pivotal role in the global REE industry. Discovered in 1949, the site revealed significant bastnäsite ore deposits, leading to the commencement of mining operations in 1952 by the Molybdenum Corporation of America. From the 1960s through the mid-1990s, Mountain Pass was the world's leading supplier of REEs. At the time, it was also essential for various high-tech applications. However, a toxic spill raised environmental concerns, and the increased competition from China led to a decline in production, culminating in a shutdown in 2002. The mine experienced a brief revival between 2007 and 2015 but faced financial challenges, resulting in bankruptcy. In 2017, MP Materials acquired the facility, resuming operations in 2018. The U.S. Department of Defense has actively supported this operation through grants. The IEA estimates that the share of global REE mining output rose from 1% in 2015 to 9% in 2023.[42] Although the concentrates were initially shipped to China for refining, MP Materials started in 2023 the production of separated rare earth products (NdPR oxide, but also Ce chloride, La carbonate and HREE concentrates) on top of the original mixed rare earth concentrate production. So far, the NdPr oxide has been sold to Japanese and Korean magnet manufacturers and automakers. This separation and processing facility in California is completed by the project to open a magnet factory in Fort Worth, Texas, which is planned to produce NdPr metal and NdFeB alloy and magnets. MP Materials has also agreed with GM to provide permanent magnets for their EV engines.

Lynas, mining in Australia, and expanding separation operations in Malaysia and the U.S.: Together with MP Materials, Lynas is a major REE miner outside of China, with an integrated production from mining to separated REE salts. The mining and concentrating occur at Mount Weld in Australia, a large, high-grade deposit of monazite containing both LREE and HREE. The mining operation began in 2007 and has produced mixed REE concentrates since then. The Japanese government notably supported Lynas by providing strategic financing and securing long-term supply agreements with Japanese magnet manufacturers. Lynas opened a processing facility in Kuantan, Malaysia, in 2012 to crack & leach Mount Weld concentrates through an acid, which is then separated through solvent extraction and precipitated to individual REE carbonate or oxalate salts. Calcination to NdPr oxide is also possible, and other products of this facility include HREE SEG oxide (Samarium Europium Gadolinium).[355] The company also projects to separate HREEs such as Dy and Tb in Kuantan in 2025. A new processing facility was opened in Kalgoorlie, Western Australia, to crack and leach mixed REE concentrates to mixed REE carbonate products domestically, thus slowly replacing a step previously undertaken in Malaysia.[356] The mixed carbonate salt can be sold to customers, separated in Kuantan, or, in the future, separated in the U.S. Indeed, the US government granted Lynas $30.4 million USD in 2021 to build an LREE separation plant in Seadrift, Texas, and a further $120 million USD in 2022 to build an HREE facility.[357] More support from the DoD followed, and the Texas separation plant is projected to come online by 2025-2026.

8.3.3 Processing

8.3.3.1 Bastnäsite and Monazite for LREE

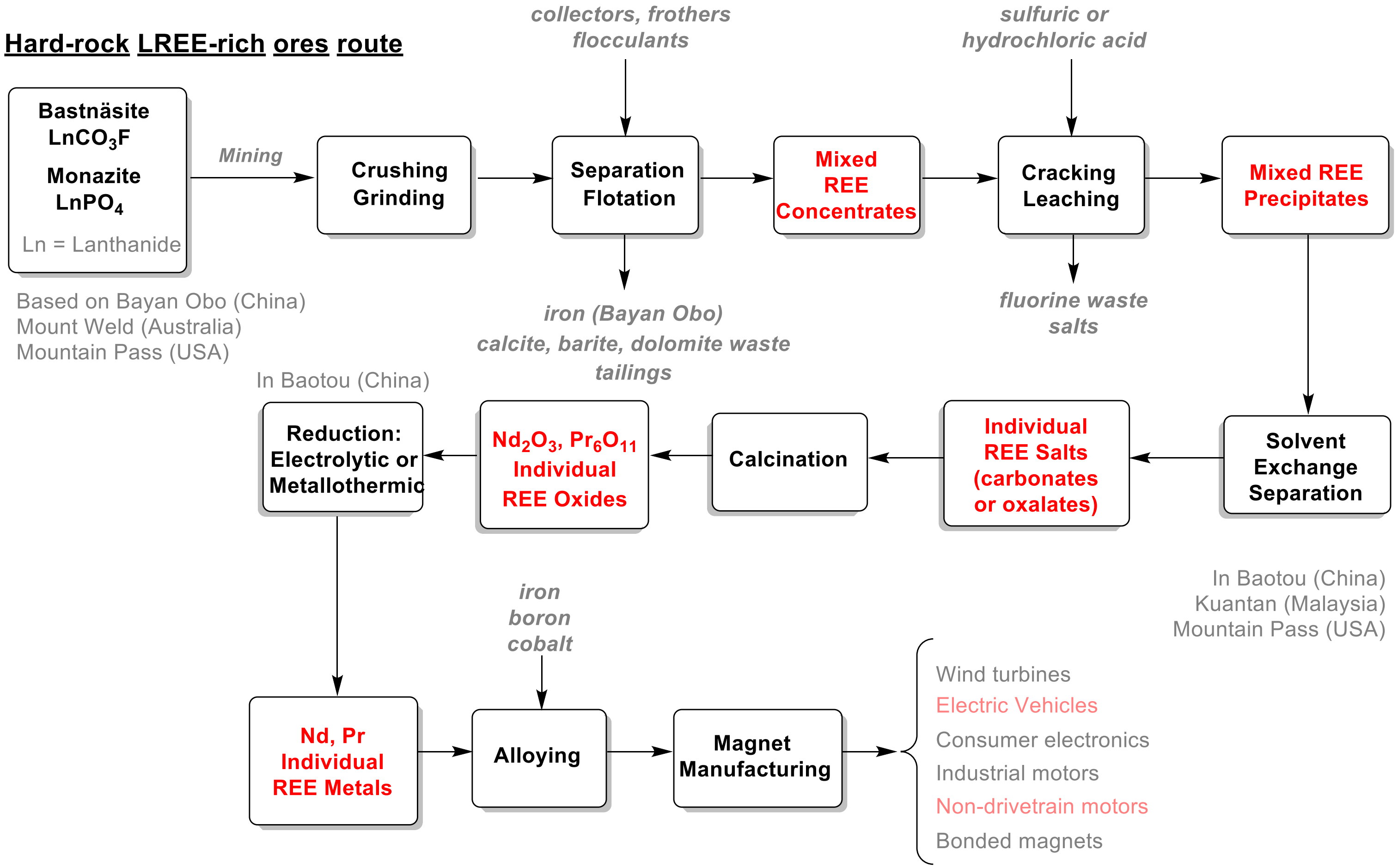


Figure 8.3.2 Flowsheet from hard-rock REE ores to magnets

Bastnäsite ore, mostly from either the Bayan Obo mine in Inner Mongolia, China or the Mountain Pass Mine in California, U.S., is first **beneficiated** through crushing and grinding to fine particles, before undergoing flotation processes. A concentrate is obtained, with 68% REO content at Mountain Pass, or 56% for bastnäsite and 34% for monazite from Chinese operations at Bayan Obo/Baotou. In the Chinese case, an iron concentrate is also produced. In Mount Weld, a 37% REO concentrate is obtained after beneficiation, flotation and filtering.[358]

The following step is the **digestion** of the concentrates to obtain soluble REE ions and precipitate them. It is also called **cracking and leaching**. Bastnäsite concentrate can be leached with acid, followed by calcination. The previous Molycorp process used heating in the presence of air at 620°C, obtaining CeO_2 solid concentrate and dissolved REE chloride salts in the solution.[348] Other processes use calcination to decompose carbonate salts and sulfuric acid to dissolve REE as sulfate ions. The calcination or heated acid-leaching steps then emit CO_2, SO_2, and HF. The use of nitric acid after calcination, or even the alkali digestion at 200°C to form REE hydroxides has been reported.[347] In the case of monazite, its reaction with concentrated sodium hydroxide at high temperatures also yields rare earth hydroxides. They can be separated through treatment with hot water, while the trisodium phosphate byproduct can be sold. The hydroxide salts can be dissolved in hydrochloric or nitric acid. Sulfuric acid digestion of monazite has also been reported and yields rare earth sulfate salts, which can be dissolved in water. Conditions must be controlled adequately to separate thorium selectively. For Bayan Obo and Mount Weld, roasting in a rotary kiln with sulfuric acid seems to be the preferred digestion pathway. Depending on the following treatments, mixed REE chloride or carbonate salts are often the products.

Those mixed REE precipitates must now be individually purified through a **separation** process, often through complex solvent extraction processes. The challenge resides in that REE bears similar chemical properties and has typically low separation factors, making this step difficult. Small differences in acidity, salt solubility, cation hydrolysis, and complexation with other chemicals can be exploited. An initial group separation, such as LREEs from HREEs, is often carried out before refining individual elements. In general, two main methods exist, with solid-liquid systems such as ion exchange or fractional crystallization, which are suitable for high-purity and small quantities; while the main industrial process remains liquid-liquid systems based on solvent extraction principles. The latter category can operate continuously and at high capacity. Depending on the system, several specialty chemicals called extractants might be necessary, such as tri-n-butyl phosphate (TBP), di-(2-ethylhexyl) phosphoric acid DEHPA, carboxylic acids or ammonium salts are used to bind individual rare earths selectively. A detailed description of the separation processes is available in the literature.[347,348] After the process, further treatment of individually separated REE salts with oxalic acid yields individual REE oxalate salts, a marketable product. Carbonate, hydroxide, fluoride or chloride salts are also available. After 900°C calcination of those salts, individual rare earth oxide can be obtained.

8.3.3.2 Ionic Clays for HREE

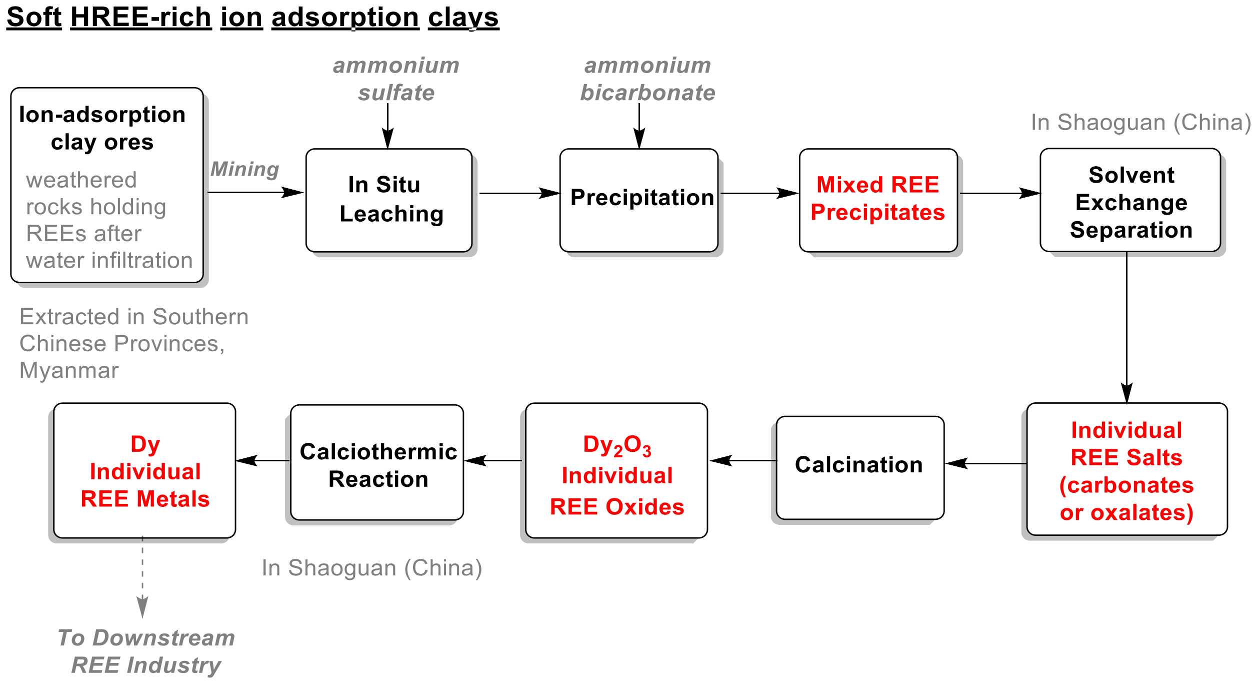


Figure 8.3.3 Flowsheet from Ion Adsorption Clay to HREE metals

Heavy rare earth elements (HREEs) are primarily extracted from ionic adsorption clays (IACs) in China, Myanmar, and Laos.[42] IAC deposits are also common in Brazil, Madagascar and Chile. These deposits involve shallow mining (top 20 meters), minimal crushing, and straightforward leaching processes such as heap or vat leaching under atmospheric conditions. Weakly acidic electrolytes such as ammonium sulfate can readily exchange REE ions in IACs, even in dilute solutions, without beneficiation.[359] Precipitation with ammonium bicarbonate and subsequent solvent extraction will yield salts.

Compared to hard rock mining, which requires deep excavation, intensive crushing, high-temperature roasting, and complex acid leaching, IAC mining is less capital-intensive and has a smaller environmental footprint. Clay waste from IACs can be backfilled, avoiding the need for tailings dams. They also exhibit lower radioactivity than monazite or bastnäsite operations. Most IAC leaching products are separated into individual REE precipitates/salts in China, similar to the monazite or bastnäsite products, with the notable difference in yielding additional HREE salts.

The economic appeal of IAC projects lies in their lower processing costs, reduced carbon emissions, and minimal radioactive waste. However, they face limitations, including low recovery rates (30–40%) and environmental concerns from leaching agents like ammonium sulfate. Indeed, ammonium sulfate remaining in the environment can favour eutrophication and algae bloom. A large number of IACs are also mined illegally.[360] New IAC discoveries in Australia, Brazil, and Uganda offer the potential to diversify supply chains, though scaling these operations remains a challenge.

8.3.3.3 Reduction to Metal, Alloys & Magnet

Two main processes for reducing REE oxides, chlorides, or fluorides to metal exist: fused-oxide or salt electrolysis and the metallothermic method. These processes are sometimes called **metallization**. Metallization is considered an energy-demanding but low-margin step, but future automation might optimize the processes.

The **fused-salt electrolysis** method is suitable for LREEs such as La, Ce, Pr and Nd as the melting point for heavier elements is too high, and this would reach the temperature limit of electrodes and containers. First, adding another salt (mostly alkali metal and alkaline earth salts) to the electrolytic bath mixture is necessary to optimize the conductivity and lower the melting point, then a strong current is passed through electrodes in the bath, reducing the RE oxide or salt to their metallic form at the cathode.[347] Mixtures such as didymium or mischmetal can also be produced. Most electrolysis takes place in China.

The **metallothermic method** necessitates alkali metals, alkaline-earth metals or aluminum as reducing agents. Lithium and calcium are often employed, which is called **calciothermic reduction** in the latter case. It is also suitable for REE oxides, chlorides and fluorides and can produce high-purity metallic HREEs, particularly Gd to Lu and Y. For La, Ce, Pr and Nd, rare earth chloride reagents are preferred, and they are heated at temperatures up to 1,100°C with a reducing agent such as lithium with MgO in crucibles.[347] For HREEs with higher melting points, such as Y, Gd-Er, Lu, and Sc, the RE fluorides, prepared from oxides, are preferred starting materials. They are treated with calcium at 1,500–1,600°C in tantalum crucibles.

After reduction, REE metals can be purified through melting and distillation under an inert atmosphere or vacuum.

REE-based permanent magnets necessitate specific alloys. The calciothermic reduction can also produce alloys directly, a feature that can be used to manufacture $SmCo_5$ magnet alloy. In the case of the NdFeB alloy, the specific quantity of Nd, Fe, and B is added to an induction furnace, thus yielding the 'Neo' alloy.

After strip casting, further hydrogen decrepitation breaks down 'Neo' ingots, and a jet-milled inert atmosphere pulverizes the alloy into fine powders. Magnets can then be manufactured by pressing this powder in a magnetic field.[348] Before final inspection, several steps including sintering, grinding, slicing, electroplating, and magnetization to saturation are performed.[358]

8.3.3.4 Examples of Companies in the Midstream & Downstream Magnet Segments

Most of the steps, from metallization to alloy-making and magnet manufacturing, are mainly occurring in China, except for several players. Shin-Etsu Chemicals and Hitachi perform metal-making in Japan, while Less Common Metals operates in the UK, and Neo Performance Material is active in Estonia. As for magnet manufacturing, TDK, Proterial, and Shin-Etsu Chemicals are active in Japan, Star Group is in South Korea, the Vacuumschmelze group is based in Germany, and Noveon is a U.S.-based company producing sintered magnets from recycled end-of-life products such as electric motors, medical devices and data storage units.[361]

Neo Performance Materials is a company headquartered in Canada that operates inside and outside China. It is currently building a sintered NdFeB magnet plant in Narva, Estonia, specifically for EVs and wind turbine applications. Neo Performance Materials' previous expertise relied on bonded magnets, and this is their first expansion outside of China aimed at more robust and EV-compatible sintered magnets. The company is also unique in being present in any segments of the value chain: REE separation, metallization and alloys, magnet manufacturing and recycling.

Vacuumschmelze is constructing a sintered NdFeB magnet plant in South Carolina to supply GM's EV motors with the support of the U.S. government through tax credits.[362,363] As mentioned above, MP Materials is also constructing a magnet plant in Fort Worth, Texas, with off-take agreements with GM. Commercial production is aimed to start in 2025.[364]

The Australian company Australian Strategic Minerals has also projected to venture into downstream metal reduction in Korea while developing its domestic Dubbo mining in New South Wales.

8.3.3.5 Circularity

The end-of-life recycling rate for REEs is very low and expected to be around 1%[25] However, recycling R&D was accelerated in 2011 within the context of the Rare-Earth crisis and price spikes. So far, the lack of collection systems and high costs have hindered the development of large-scale REE recycling solutions. Solvay previously developed a recycling unit with Umicore in La Rochelle, France, specializing in reprocessing and separating LREEs from fluorescent batteries, but the operations lasted from 2012 to 2016 when REE prices were too low to justify recycling.[357] More recent developments have shown that Solvay is now interested again in expanding its REE separation capacity at La Rochelle.[365] They have also signed an MOU with Cyclic Materials, where Cyclic agrees to supply Solvay with recycled rare earth oxides for further separation.[366] Cyclic Materials itself is an Ontario-based company specializing in recycling REE from end-of-life products such as electronic waste and old motors. Noveon, as mentioned above, also recycles e-waste to produce REE magnets.

8.3.3.6 Comparison of Processing Pathways and Environmental Impacts

The impacts of REE production can pose significant environmental challenges, with implications varying wildly across production pathways and geographical regions.

Life Cycle Assessments (LCAs) highlight that most REE production is concentrated in China, where inefficient processes, high chemical consumption, and coal-heavy energy use exacerbate environmental footprints. A comparative LCA from 2018 indicates that the Bayan Obo mine in China exhibits the highest environmental impacts, driven by poor recovery rates and outdated infrastructure, including a

50-year-old tailing pond, which contributes to higher leakage and ecological damage. In contrast, Mountain Pass benefits from cleaner processes, such as the absence of acid roasting, reliance on natural gas-fired power, and recycling saline wastewater, which collectively reduce its footprint. Mount Weld performs moderately, with impacts partly mitigated by using magnesium oxide instead of ammonium bicarbonate in precipitation, lowering eutrophication. However, its particulate matter emissions remain high due to mining and grinding requirements. It should be noted that this particular LCA analysis did not consider the newly opened separation facility in Mountain Pass or the Kalgoorlie processing plant from Lynas.[358]

Another 2018 LCA analyzed magnet-to-magnet recycling and found that virgin production, which relies heavily on fresh REEs, has a significantly higher environmental impact than magnet-to-magnet recycling.[367] Recycling undoubtedly reduces reliance on mining and decreases fresh REE consumption by approximately 99.9%. It also slashed overall impacts by 64–96%. However, the recycling process heavily relies on electricity and nickel for coating, which accounts for most of its footprint. Transitioning to renewable energy sources, such as wind or hydroelectric power, could reduce recycling impacts by up to 93%, thus highlighting the importance of the electricity grid footprint.

A cradle-to-gate LCA from 2013 analyzed the cradle-to-gate production of the 14 REE metals, choosing Bayan Obo as the processing site with both mass-based and price-based allocation of GHG emissions.[368] The mass-based method allocates emissions proportionally to the abundance of elements, emphasizing energy and material inputs and extractable REE mass. This approach shows that elements like scandium (Sc) and yttrium (Y) have higher impacts due to their lower extractable masses and energy-intensive processing. The price-based method incorporates economic factors, highlighting the high impacts of expensive and less abundant REEs such as scandium, europium, terbium, and dysprosium. Indeed, these elements require more energy and materials for separation as well as reduction, owing to their lower concentrations and extractable masses. Price fluctuations influence this method, amplifying the impact of high-priced REEs. Additionally, the environmental impact of processing waste, especially tailings containing radionuclides from bastnäsite and monazite, poses long-term risks to ecosystems and human health. Addressing waste management and exploring low-impact recycling and production technologies are critical for sustainable REE supply chain development. This point is also supported by another 2022 study, which also emphasized the need for better emission treatment, chemical recycling, closing illegal mines and raising environmental standards.[360]

9 Vanadium

9.1 The Canadian Vanadium Strategy

9.1.1 Vanadium in Canada

Table 9.1.1 Non-exhaustive selection of former and future vanadium extraction and processing projects in Canada

Selection of Former or Future Vanadium Extraction Projects

Site Name	Company	Province	Type	Status
Alberta Vanadium Project	Suncor	AB	Petroleum Fly Ash	Unknown
Athabasca Oil Sand	Shell	AB	Petroleum Fly Ash	Unknown
Huzyk Creek	Vanadian Energy Corp	MB	Vanadadium-graphite	Exploration
Duddridge Lake	Searchlight Resources	SK	Carnotite	Exploration
BlackRock	Strategic Resources	QC	Titanoferous magnetite	FS 2022
Lac Doré	VanadiumCorp	QC	Titanoferous magnetite	PEA 2017, Resource Estimates 2020
Iron-T	VanadiumCorp	QC	Titanoferous magnetite	Exploration

Selection of Operational & Future Vanadium Processing Facilities

Project Name	Company	Province	Product Type	Status
Val-des-Sources (Demonstration)	VanadiumCorp	QC	Electrolyte	Operational since 2024
Sherbrooke (Commercial)	VanadiumCorp	QC	Electrolyte	2026
Saguenay Merchant Pig Iron Plant	Strategic Resources	QC	Ferrovanadium	2028+

Selection of VRFB Manufacturers operating in Canada

Project Name	Company	Province	Product Type	Status
Vancouver VRFB plant	Invinity	BC	VRFB	Operational since 2023
VRB Energy Vancouver	VRB Energy	BC*	VRFB	Founded in 2007

*VRB Energy is a Vancouver-based company with manufacturing and engineering subsidiaries in China

No vanadium is currently produced or separated in Canada, but several opportunities, such as the oil sands in Alberta, uranium ores in Saskatchewan or several titanomagnetite deposits in Quebec, are of interest for primary resources.

A 2005 study already showed that vanadium could be recovered from Suncor's and Syncrude's fly ash samples originating from oil sands operations in Alberta.[369] More recently, vanadium recovery attracted the attention of several oil sand companies from Alberta in the early 2020s, as Shell previously worked on a research project, and Suncor had plans to develop a commercial plant. With funding from Alberta Innovates and the Alberta Government, Shell previously led research in collaboration with the Athabasca Oil Sands Project, the University of Calgary and the University of Alberta to separate vanadium from oil sands-sourced bitumen, projecting to use it for VRFB.[370,371] Suncor previously planned to open a commercial-scale vanadium recovery facility, using by-products from coke-based boilers as a feedstock. The projected operation, dubbed Alberta Vanadium Project (AVP), was reported to require a total investment cost of $36 million, of which Emissions Reduction Alberta would provide $7 million of government funding.[372] It is unclear if those projects are cancelled or paused at the moment.

The Duddridge Lake deposit north of La Ronge, Saskatchewan, has the potential to co-produce vanadium with uranium, cobalt, and copper.[373]

In Quebec, VanadiumCorp is developing two mining projects containing vanadium-bearing titanomagnetite, the Lac Doré and Iron-T properties. The main Lac Doré project has notably 1.49 billion pounds of indicated and measured V_2O_5 concentrate from the mineral resource estimate, and mine development is projected to start in 2029 with a scoped production life of 40 years.[374] This company also plans to venture into the **vanadium electrolyte manufacturing** segment by opening **two plants in Quebec**: one located in Val-des-Sources has been operational since April 2024 and is expected to produce 300,000 litres of electrolytes per year, while a second plant in Sherbrooke is planned to produce 4 millions litres of electrolytes per year in 2026, with goals to produce 26 million litres per year by 2028.[375] The company secured a $500,000 grant for the Val-des-Sources plant from PRIMA Québec.[376]

VRB Energy is a Vancouver-based company founded in 2007 and with manufacturing and engineering subsidiaries in China. It is majority-owned by Ivanhoe Electric, a U.S.-based critical mineral exploration and development company. VRB Energy previously agreed to build in 2021 **100 MW/500 MWh energy storage station** integrated with a solar power station in Hubei, China.[377] As of 2025, it appears that its headquarters have been relocated from Vancouver to Tempe, Arizona. They plan to open two additional factories in China and one in Arizona.

Invinity has built an **8.4 MWh VRFB facility paired with a 21 MWp solar PV plant** deployed by Elemental Energy in Chappice Lake, Alberta in September 2023.[378] This plant was used for solar shifting, which is storing excess energy by solar generation during the daytime and discharging electricity into the evening or when the demand is high. This $45M project was funded by Elemental Energy, the Cold Lake First Nation, the National Bank of Canada with additional support from Emissions Reduction Alberta and Natural Resources Canada.[379]

Moreover, Invinity opened a **manufacturing facility in Vancouver** in June 2023, thus reinforcing its Baojia production plant in Suzhou, China. This plant has the capacity to produce 200 MWh of VRFB per year.[380] The BC Centre for Innovation and Clean Energy (CICE) also announced $0.5 M funding to support Invinity's next-generation

VRFB product, coined Mistral.[381] The company employs over 150 people and is based in the UK and Canada. It has 82 projects across 15 countries.[382]

Vanitec accounts for 33 vanadium projects that are under development or operational in Canada. This includes 24 mining projects, 4 chemical or metallurgical facilities, and 5 energy storage stations.[383]

9.1.2 Scenario Outline

Canada should leverage its assets by prioritizing vanadium recovery, processing and VRFB production in the Alberta Industrial Heartland to take advantage of the proximity to petroleum vanadium sources. Already existing assets, such as Invinity's Vancouver facility or VRB Energy's know-how, should be leveraged and expanded. Primary sources of vanadium can come online in the long term as co-products of mining operations.

- **In the Short Term:**
  - Build a Vanadium processing and recovery plant and VRFB production facility in the Alberta Industrial Heartland or Fort McMurray. Leverage the proximity to the oil sands industry to have steady access to bitumen and petroleum vanadium sources.
  - Encourage sending secondary sources of vanadium to this plant by boosting recovery from fly ashes from coal and oil power plants (AB, SK, Maritimes)
- **In the Long Term:**
  - Develop vanadium co-production by collaborating with iron, uranium, and aluminum mines.

9.1.3 Signature Projects

- Vanadium processing facility and VRFB manufacturing plant in Alberta.
- Uranium, iron, and aluminum mines co-producing vanadium (BC, SK, QC, NL)

9.1.4 Strategic Priorities

- **Build a Vanadium Processing and VRFB Production Hub in Alberta:**
  - **Develop a vanadium recovery and processing facility in the Alberta Industrial Heartland**, integrated with a vanadium redox flow battery (VRFB) production plant.
  - **Leverage the proximity to the oil sands industry:** This location benefits from proximity to the oil sands industry in Edmonton, offering access to petroleum-based vanadium resources, which can streamline extraction and processing. The region's well-established industrial infrastructure makes it an ideal location for such a facility. Fort McMurray's availability of vanadium-bearing petroleum products can also be leveraged.

    - **Secure a consistent supply of key chemicals and reagents**, such as sulfuric acid, limestone, solvents, and alkali, to support efficient vanadium processing and electrolyte and redox flow battery production. The availability of these materials in the region will help reduce costs and operational delays.
    - **Draw inspiration from successful models** like Township in Queensland, Australia, where companies such as Idemitsu, Vecco, and Sumitomo Electric have created a similar vanadium processing and VRFB hub. This collaboration offers valuable insights into how partnerships and location synergies can drive success.
- **Access Primary Vanadium Resources by Developing Synergies with Other Mining Industries:**
    - **Work with iron mining companies in Quebec and Labrador to recover vanadium from titanomagnetite ores,** using the established process of pyrometallurgy, alkali roasting, and leaching. Collaborating with iron mining companies in Quebec and Labrador, such as ArcelorMittal, Rio Tinto, Champion Iron, and Tacora, provides an opportunity to tap into these resources and co-produce vanadium as a byproduct of iron mining operations.
    - **Revisit the historical vanadium production pathway from uranium ores,** previously utilized in Colorado, to establish synergies with uranium miners in Saskatchewan, such as Cameco and Orano. This would allow for the recovery of vanadium from uranium mining activities, providing another primary source of vanadium.
    - **Explore the potential to recover vanadium from byproducts of bauxite processing**, an underutilized resource. Partnering with aluminum mining companies like Rio Tinto in Kitimat could create opportunities to extract vanadium from these byproducts, contributing to the diversification of vanadium supply in Canada.
- **Secure Secondary Vanadium Resources from Waste Generators:**
    - **Focus on identifying secondary waste generators,** including oil and coal-fired power plants in Alberta, Saskatchewan, and the Maritimes, as potential sources for vanadium recovery. These facilities produce fly ash and oil residues, both of which can contain valuable amounts of vanadium.
    - **Collaborate with these power plants** to develop vanadium recovery systems that can be integrated into existing processes, allowing for the efficient extraction of vanadium from waste byproducts. This approach supports sustainability goals and diversifies the sources of vanadium production while reducing waste and promoting a circular economy.
- **Research & Development:**
    - **Invest in research to develop new methods for extracting vanadium from mining tailings,** turning what is often seen as waste into a valuable resource.
    - **Encourage collaboration between academic institutions and industrial partners** to develop more efficient, lower-emission vanadium extraction processes. Special attention should be paid to optimizing

    pyrometallurgical steps to reduce greenhouse gas emissions and coupling them with carbon capture, utilization, and storage (CCUS) technologies to further minimize environmental impacts.
  - **Focus on exploring shorter, more sustainable pathways from vanadium extraction to battery production.** This can include developing innovative techniques that reduce energy consumption and waste, ensuring that Canada's vanadium industry is both competitive and environmentally responsible.
- **Draw Smart Regulations for a Vanadium Industry:**
  - **Advocate for regulatory frameworks encouraging oil and coal plants to facilitate vanadium recovery** from waste byproducts, ensuring these valuable resources are captured and not sent abroad. This will help keep vanadium processing and its economic benefits within Canada.
  - **Support the creation of new mining ventures focused on vanadium co-production**, drawing on successful examples from countries like Australia that have implemented modular mining projects. By streamlining the permitting process and providing regulatory clarity, Canada can accelerate the development of vanadium projects.
  - **Promote collaboration between government, industry, and academia** to create a more efficient vanadium supply chain, ensuring all stakeholders are aligned on the importance of vanadium as a critical mineral. This includes providing funding opportunities for new ventures and supporting the entire value chain from mining to battery production.
- **Government Incentives and Protection from Price Volatility:**
  - **Unlock specific government funding and support mechanisms tailored to vanadium projects**, especially for exploration, discovery, and processing. Countries like the U.S. and China have already implemented similar strategies for critical minerals, and Canada can follow suit by providing financial incentives to develop its vanadium resources.
  - **Implement market-stabilizing measures,** such as government procurement contracts, contracts for differences, and government-guaranteed future purchases of locally sourced vanadium. These mechanisms can protect vanadium producers from price volatility, ensuring stability without significantly increasing the cost of vanadium-based products.

9.2 Vanadium: A Polyvalent Metal for Specialty Alloys, Catalysts, and Flow Batteries

9.2.1 General Properties

9.2.1.1 Physical Properties and Applications

Vanadium is a steel-grey/bluish ductile metal with a very high melting point (1910°C). It is mainly used as an additive in steel and titanium alloys, improving strength and resistance to heat and corrosion. As such, high-strength alloys and special steels have applications in tools, construction, jet engines, motors, axles, crankshafts, and automotive frames. Pure vanadium and vanadium alloys also hold several advantages over stainless steel: a higher thermal conductivity, better strength, and a lower density and thermal expansion, which is why it was considered for fuel cladding in nuclear reactors.[384] Vanadium is also a ceramic additive. Added to glass, it can give the material a blue or green tint, and VO_2-coated glass can block infrared wavelengths.[385] Finally, using vanadium electrolytes in flow batteries for energy storage is considered an essential development of the vanadium industry.

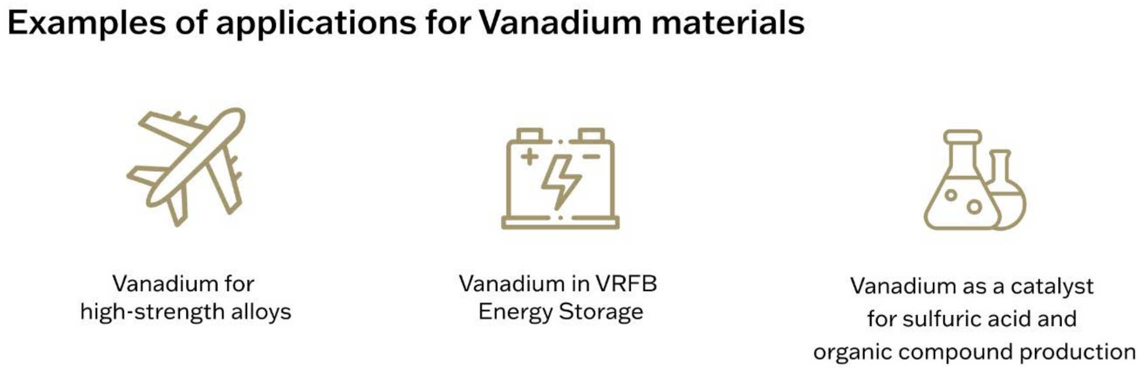


Figure 9.2.1 Examples of applications for vanadium materials

With applications in specialty alloys, catalysis and energy storage, numerous countries and international organizations such as Australia, the U.S., the EU, the IEA, Indonesia, the UK, Brazil, South Africa and Canada consider vanadium a critical material.

9.2.1.2 A Brief History of Vanadium and Its Industry

Andrés Manuel del Rio discovered vanadium in 1801 in the form of vanadinite $Pb_5(VO_4)_3Cl$ from a brown lead sample from central Mexico, coining the new metal erythronium. This newly discovered element had such similarities with chromium that the scientific community confused both materials in the early 1800s, up until Nils Gabriel Sefström rediscovered it in 1830 after treating iron from Sweden with acid. Subsequent investigations and proof by Friedrich Wöhler in 1831 confirmed that it was another metal different from chromium but similar to Del Rio's erythronium.[153] It was Sefström who gave it its accepted name of vanadium, after Vanadís, another name of the Norse goddess of beauty Freyja, because of the beautiful aspect of many vanadium minerals. The isolation of vanadium metal took several decades as using carbon as a reductant from vanadium oxides only yielded vanadium carbide. Sir Henry Enfield Roscoe managed to reduce vanadium chloride VCl_2 with hydrogen in 1867, thus obtaining vanadium metal for the first time.

The production of vanadium-alloyed steel started at scale in England in 1903, and Henry Ford began to support its use for the automotive industry in 1908 when it was incorporated into the Ford Model T car chassis.[384] At the time, vanadium originated from **vanadinite** $Pb_5(VO_4)_3Cl$ deposits in Extremadura in Spain and large deposits of **patrónite** VS_4 from Minas Ragra in Peru. The latter was developed by and fed the Vanadium Corporation of America, a company established by Joseph and James Flannery in Pennsylvania in 1906. This company started to smelt the Peruvian ore. It produced ferrovanadium in Bridgeville by the following year, soon to sell its products to railway companies, to the U.S. government for the construction of the Panama Canal or to armament companies.[386] By 1914, Minas Ragra produced 75% of the global vanadium output.[387]

Due to price collapse and decreases in ore grades through the first half of the 20th century, deposits in southern Africa, Namibia, and Zambia replaced the vanadium produced by Peruvian mines. Then, the co-production of vanadium from uranium ores in Placerville, Colorado, as well as from phosphate deposits in Idaho, became important after World War II.[384] Since the 1950s, vanadium-bearing titanomagnetites, found in Russia, South Africa, Finland, the U.S., and Australia, have become the primary source of producing V-products.

9.2.1.3 The Importance of Vanadium Pentoxide for Alloys and Catalysts

Vanadium pentoxide V_2O_5, also known as vanadium oxide or vanadia, is the most important vanadium compound, as it is both the precursor to vanadium alloys and an essential catalyst. Heating vanadium pentoxide with scrap iron and either ferrosilicon or aluminum (or previously carbon) as a reductant will produce ferrovanadium with a V-content of 35–85 wt.%. Added to steel or other alloys, it produces finer grains and hardens and toughens the material. It is suitable for ferrous alloy pieces needed for high-temperature resistance, wear resistance, weldability, and corrosion resistance to alkaline media or sulfuric and hydrochloric acids.[384,388] After fully reducing V_2O_5 to pure metal form, vanadium can also be used as an alloy for titanium to enhance its strength properties and creep resistance.

Other than alloying, vanadium pentoxide is also a primordial **catalyst** for various essential industrial chemicals. BASF patented the use of V_2O_5 in 1913 to catalyze the conversion of sulfur dioxide SO_2 gas to sulfur trioxide gas SO_3, which then forms sulfuric acid H_2SO_4 in contact with water. Vanadium catalysts were cheaper and more robust in the 1930s, replacing the previously used platinum catalysts.[389] Adopting this inexpensive process led to developing the modern contact process for sulfuric acid production, where vanadium catalysts are now used almost exclusively. This links vanadium to the sulfur recycling processes necessary in many pyrometallurgical processes of other critical minerals such as copper or nickel sulfides. Vanadium pentoxide is also a valuable catalyst to produce maleic anhydride, an essential reagent for polyester resins and curing agent for epoxy resins, and for the synthesis of phthalic anhydride, a precursor to plasticizers. V_2O_5 is also used as a corrosion inhibitor to help capture CO_2 by potassium carbonate K_2CO_3 during the Benfield Process in petroleum refining.

9.2.1.4 The Biological Role of Vanadium and its Toxicity

Vanadium is essential for certain species, and its high concentration in sea life or mushrooms has been reported, but its biological role or benefits are still unknown. However, the structural analogy and similarities between the vanadate and phosphate ions might explain why vanadate sometimes easily substitutes phosphate in certain enzymes.[390] Some bacteria use vanadium for various biological functions, such as respiration, nitrogen fixation and reduction.[391] Certain species of algae, lichens, fungi and bacteria also use vanadium-dependent enzymes to produce halomethanes naturally, a category of gases that deplete the ozone layer.

Despite its role in certain life forms and innocuity in trace amounts, vanadium and its parent compounds (V_2O_5, $NaVO_3$, Na_3VO_4, $VOSO_4$, NH_4VO_3) are toxic in more significant amounts to both humans and animals.[384,385] The International Agency for Research on Cancer (IARC) categorizes vanadium pentoxide as possibly carcinogenic to humans, as it showed cancer-inducing effects in mice by inhalation but lacked sufficient and adequate evidence for humans.[392] However, V_2O_5, in the form of dust, has acute toxicity and can cause respiratory issues such as asthma and bronchitis and lead to eye irritation. CAREX Canada estimated that around 7,600 Canadians are exposed to V_2O_5 at work, especially in the fabricated metal product, boiler, tank and shipping container production industry.[393] Boilermakers, welders, specialized cleaners, processing industry workers, industrial mechanics, petroleum refiners, and ceramicists are among the exposed occupations.

9.2.2 Role in Energy Storage

9.2.2.1 Flow Batteries, an Alternative to Regular Rechargeable Batteries

Vanadium redox flow batteries (VRFB, VRB, or VFB) are a promising technology for safe and long-life span energy storage. Traditional flow batteries are defined as batteries in which two chemicals dissolved in liquid electrolytes are pumped to flow in their respective separated circuits. They undergo a redox reaction where the two circuits meet in two half cells along an ion-transfer membrane, producing an electrical current. Contrary to conventional batteries, the active material and, thus, the chemical energy is not stored in the electrodes but in the liquid electrolytes: in brief, the electrodes do not participate in chemical reactions and are just electron acceptors or donors. Therefore, the actual capacity of flow batteries depends on the amount of electrolyte stored in both tanks.[394] The electrochemical cells can be stacked in parallel or series. Some flow batteries contain solid electroactive components and are thus classified as hybrid flow batteries (HFB). Several flow battery technologies exist, such as chlorine-zinc, bromine-zinc, aqueous or non-aqueous organic electrolyte, *etc.* However, VRFB is the most mature and commercially successful type of flow battery cell.

Bromine-zinc redox flow batteries were the earliest to be discovered and patented by John Doyle in 1879. By the late 19th century, early flow batteries powered airships and cars for demonstration.[395] It was only by the 1970s–80s that flow batteries gained increased interest and that more patents were filed. The Lewis Research Centre in Cleveland, funded by NASA in 1973, notably pursued the advancement of redox flow battery systems using iron and chromium.[396,397]

9.2.2.2 The development of VRFB

Several studies by Oei and Kummer investigated the use of vanadium electrolytes in half-cells in the early 1980s in partnership with the Ford Motor Company,[398] but it was Australian scientist Maria Skyllas-Kazacos, along with Sum and Rychcik who developed and patented the first all-vanadium battery 1986.[399] The Australian Department of Resources and Energy provided the original funding, and the first patents were filed in Australia and the U.S., with the University of New South Wales and Unisearch Limited as applicants. After subsequent research funded by the Australian government and various commercial entities, Unisearch later granted licenses to Thai Gypsum for residential PV applications in Thailand and Mitsubishi and Kashima-Kita for load levelling and PV development in Japan. After acquiring the license from Unisearch in 1998, Pinnacle VRB also granted licenses to Sumitomo Electric Industries in Japan and VRB Power Systems in Canada. The latter was then acquired by a U.S. and China-based company, Prudent Energy, in 2009.[400]

In the U.S., UniEnergy previously held its own VRFB design: In 2012, researchers in Washington began developing a promising vanadium redox flow battery with U.S. Department of Energy (DOE) funding. Despite early success, the company struggled to find U.S. investors, leading to a partnership with a Chinese firm, Dalian Rongke Power. By 2017, manufacturing had shifted to China under a sublicense, which violated DOE rules requiring U.S. production. Since then, Dalian Rongke Power has become a top global manufacturer of VRFB. In 2021, UniEnergy transferred the license to Vanadis Power, a European company planning to manufacture in China and Germany. The DOE approved the transfer without adequate oversight. The situation resulted in the U.S. losing control of taxpayer-funded technology to foreign entities, allowing China to dominate production and deploy large-scale vanadium battery farms.[401]

9.2.2.3 VRFB: Working Principles & Characteristics

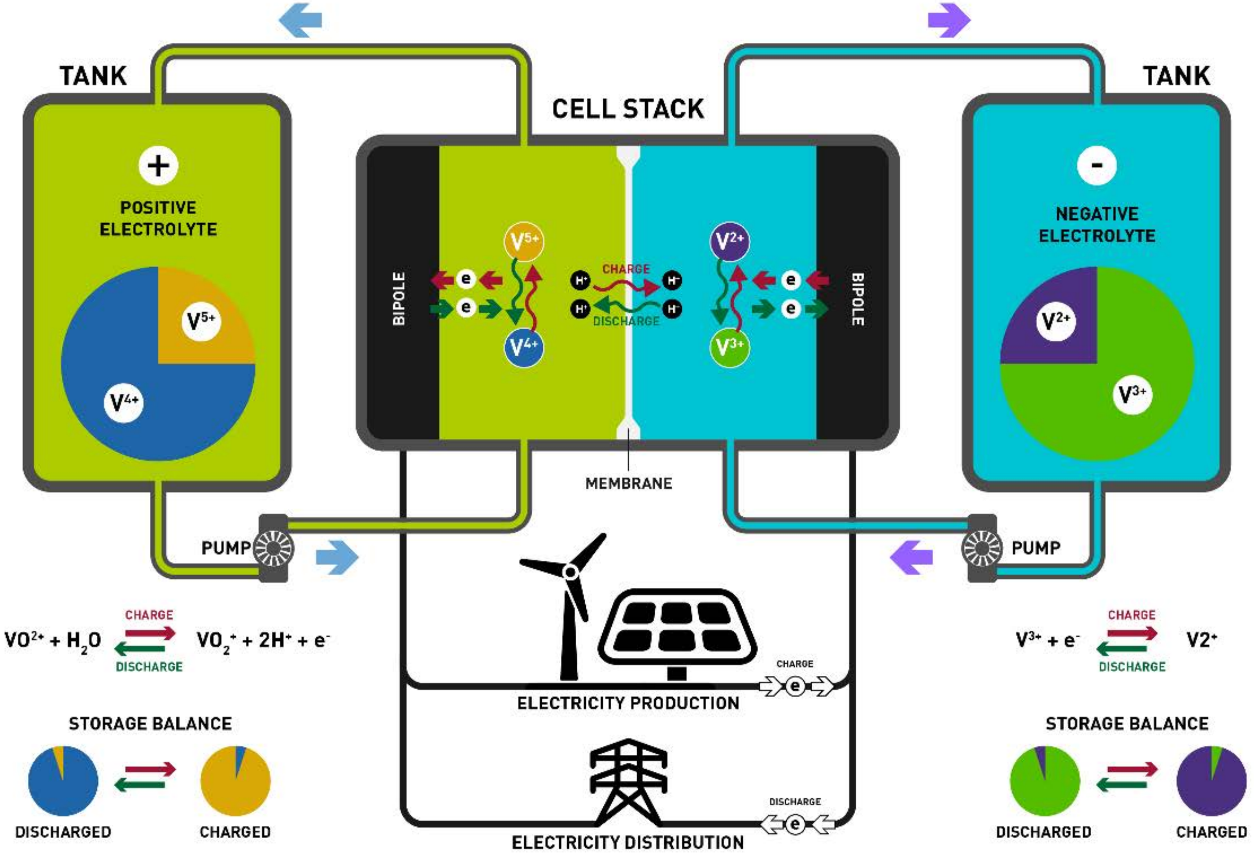


Figure 9.2.2 Description of a VRFB system, source: VRB Energy[402]

As its ions are stable in various oxidation states, vanadium electrolytes can be used in both flow battery half-cells and tanks. Accordingly, the two redox couples used in VRFB are V^{3+}/V^{2+} and VO_2^+/VO^{2+} (pervanadyl and vanadyl ions) for the negative and positive electrode circuits, respectively. During charge, V^{2+} would be oxidized to V^{3+}, and VO_2^+ would get reduced to VO^{2+}, while the opposite reactions would happen during discharge. Pumps help the electrolytes circulate in their half-cell circuits from the tank to the membrane and then back to the tank. In practice, the original VRFB electrolyte solutions were a mixture of vanadium sulfate and sulfuric acid.[394] Chloride or bromide anions have also been proposed, but all electrolytes are mostly aqueous-based, which allows for safety and low cost.[403] The inert electrodes are carbon-based, such as carbon or graphite felt. The ion exchange membrane separator used is often made of Nafion, a fluorinated and sulfonated polymer that can effectively transfer protons H^+ between the two half-cell circuits, thus achieving electrical neutrality. At 25°C, the voltage of a VRFB is 1.4 V per cell.

VRFB are suitable for applications such as electric grid storage or EV charging stations: their performances do not decrease for at least 25 years of operation,[404] and could undergo virtually unlimited charge/discharge cycles (over 10,000 cycles vs. 3,000 on average for Li-ion). Lithium-ion and sodium-ion batteries are only suitable for energy storage durations of 4–8h, thus overlapping with VRFB technology, which has an even longer storage duration, up to 12h.[405] These increased cycling and storage duration performances allow VRFB to be amenable to different types of energy storage beyond the peak replacement use that lithium-ion offers, such as arbitrage, wind smoothing, or overnight availability of renewables. In addition to those characteristics, vanadium is not a conflict mineral, VRFB can operate at 100% depth of discharge without performance loss, and there is a limited fire hazard due to the non-flammability of materials compared to NMC batteries.

As for the drawbacks, VRFB have very low energy densities (25–35 Wh/L)[403] making them too heavy and bulky for electric vehicles and mobility in general. Although fire hazards are limited compared to lithium-ion batteries, due to the use of aqueous electrolytes over flammable organic ones, the toxicity of vanadium compounds can still be relatively problematic. The vanadium electrolytes and VRFB production capacity is still limited, which could be a bottleneck for the supply chain. Another inconvenience is the unwanted migration of vanadium ions from the positive electrode to the negative electrode circuit throughout the membrane, a phenomenon which can lead to a difference in concentration.[394] Finally, VRFB's round-trip efficiency is still lower than that of lithium-ion batteries (75–80% for VRFB compared to 85–95% for LFP and NMC), meaning that VRFB are more prone to energy loss when comparing the charged input and discharged output. [406]

9.2.2.4 The VRFB Industry and Its Deployment Around the World

As indicated, VRFB is a relatively mature technology, but scaling up its rapid adoption could be problematic due to the current low mining level, limited manufacturing production, and high vanadium prices. Despite those issues, a non-exhaustive list of large VRFB deployments is described below.

Mitsubishi Electric Industries and Kashima-Kita Electric Power Corporation installed the first VRFB implementation in Japan for load-levelling usage in 1995.[399] Sumitomo Electric also trailblazed larger-scale VRFB installations by building a 4 MW/6 MWh facility paired with the Tomamae wind farm in Hokkaido, Japan, in 2005.[407] Since then, they opened the massive 15 MW/60 MWh Minami Hayakita Substation VRFB installation in 2015 as a large-scale flow battery demonstration for grid control. This demonstration project was completed by a 17 MW/51 MWh commercial facility coupled with wind turbines in 2022. The Japanese company also has several smaller operations in the U.S., Morroco, Belgium and Taiwan.[408]

In Dalian, China, a vanadium flow battery demonstration plant is operated for energy storage to reduce peak loads and increase the grid stability of the Dalian peninsula. The 100 MW/400 MWh facility was connected to the grid in late 2022 and is projected to be expanded by operator Dalian Rongke Power.[409] Canadian-based company VRB Energy previously signed an agreement in 2021 to build a 100 MW/500 MWh power station in Xiangyang, in the province of Hubei in China.[377] Invinity Systems also built a 2MW/5MWh VRFB plant paired with a lithium-ion storage system in the UK and a 2MW/8 MWh system collocated with a solar PV plant in South Australia.[410] Additionally, Invinity has built several VRFB storage facilities in the U.S., Canada, Europe, South Africa, China, South Korea, Taiwan and Thailand.[411] Other major VRFB manufacturers include Schmid, Delectrik, Cellcube, and UniEnergy Technologies Battery.

It is worth noting that several of these actors are **vertically integrated from mining to electrolyte or battery production**, such as South African mining company Bushveld Minerals buying most shares from Cellcube, Largo Resources venturing into battery making with their subsidiary Largo Clean Resources, Ivanhoe Electric owning the majority of VRB Energy, Australian Vanadium Limited forming VSUN Energy, or VanadiumCorp Resources developing a mine and an electrolyte production plant.[412]

Vanitec, a vanadium-specialized international technical committee and industry association, lists **over 300 VRFB energy storage projects globally** which are either operational, under construction, contracted or announced.[413] Over a third of those projects are located in China.

9.2.2.5 Vanadium as an additive to lithium-ion batteries

Finally, Li-ion batteries, sometimes dubbed lithium vanadium phosphate batteries (LVP), using vanadium as $Li_3V_2(PO_4)_3$ cathode material, or even $LiVPO_4F$, have been proposed.[414–417] Moreover, the addition of vanadium as a doping agent onto regular LFP cathode materials also has performance-enhancing effects.[418]

9.2.3 Substitutes

Vanadium used as an alloy for high-strength low-alloy steels or special steel can be substituted by manganese, molybdenum, titanium, niobium, tungsten, chromium or tantalum. In particular, molybdenum and tungsten alloys can achieve similar performances but at a higher cost.[385] There is no substitute for titanium-vanadium alloys for aerospace.[419]

Regarding energy storage, VRFB can be substituted by LFP or sodium-ion batteries, although those solutions are less suitable for more extended storage durations or as many cycles. Iron-air batteries could also be a substitute for VRFB, but they are more suitable for longer storage durations, up to weeks. Other redox flow batteries based on different electrolytes, such as iron-chromium, halogen, or zinc were developed, but none outperformed vanadium-based redox flow batteries, which also have the advantage of having the most mature value chain.[403]

9.2.4 Supply & Demand

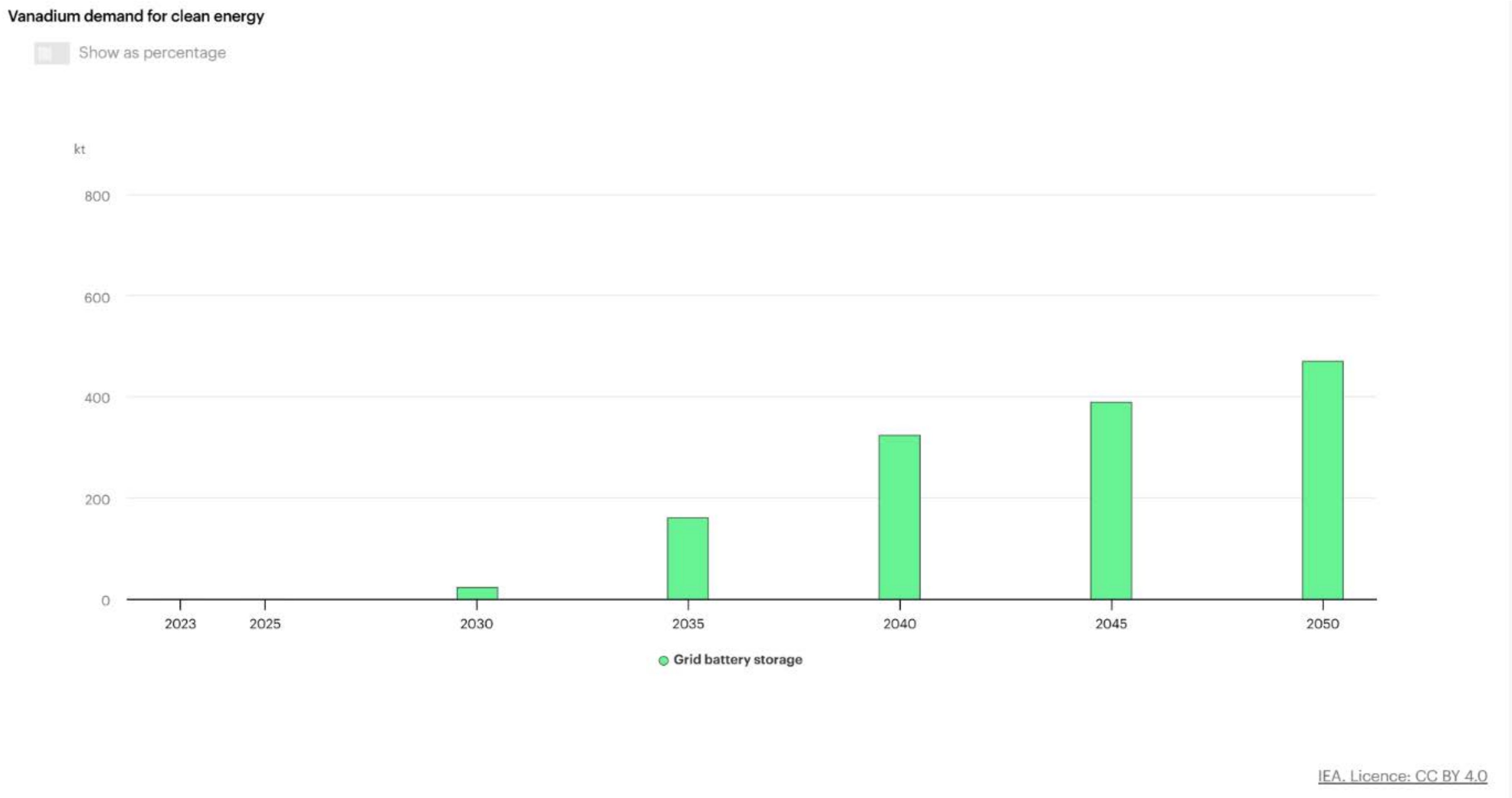


Figure 9.2.3 Vanadium demand for clean energy demand, according to the IEA Stated Policy Scenario. IEA 2024, Critical Minerals Data Explorer, License: CC BY 4.0[420]

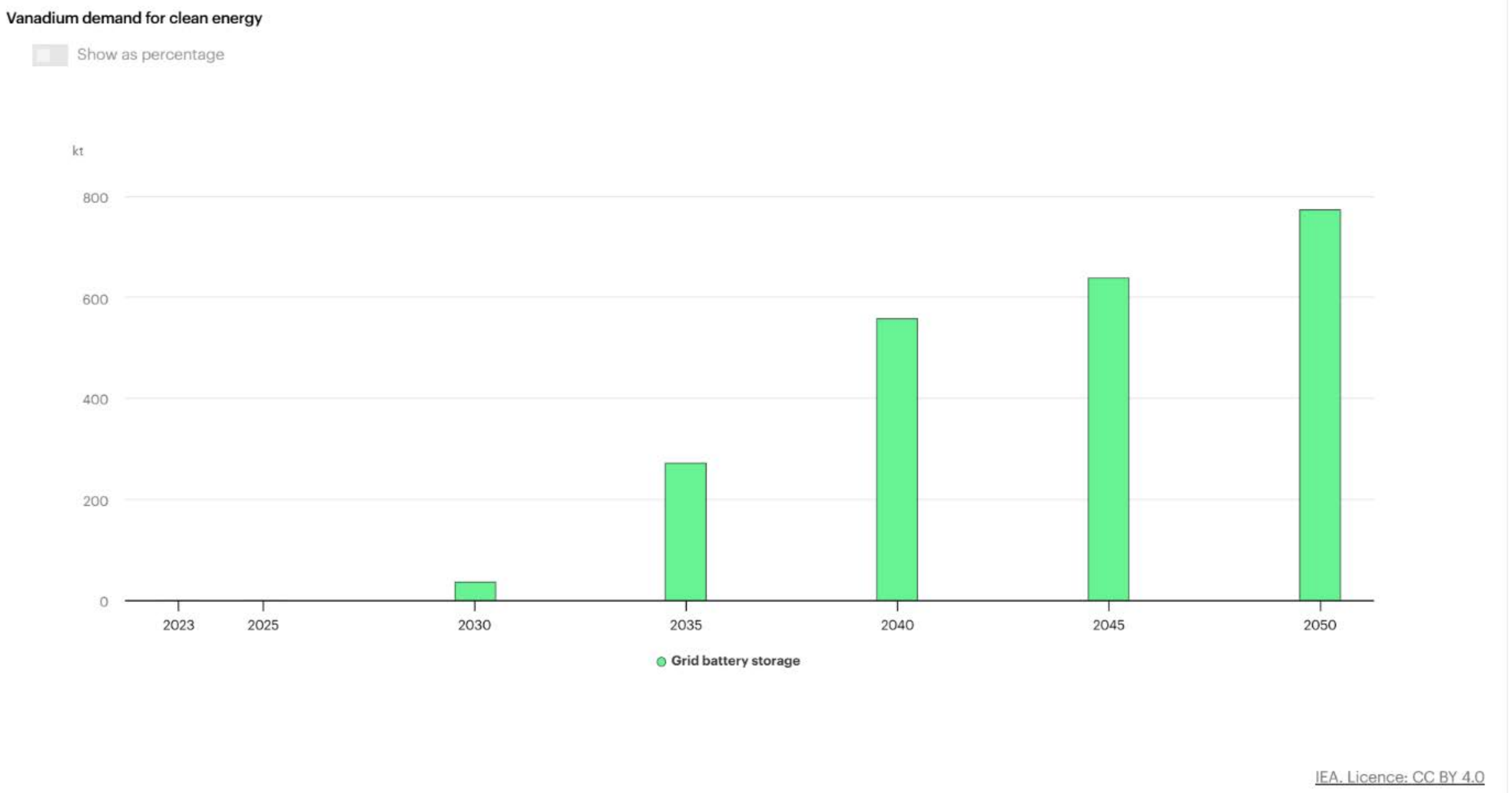


Figure 9.2.4 Vanadium demand for clean energy demand, according to the IEA Net Zero Emissions by 2050 Scenario. IEA 2024, Critical Minerals Data Explorer, License: CC BY 4.0[420]

As vanadium's primary use is as a ferroalloy, its pricing and demand usually depend on the steel industry, particularly the Chinese steel industry.[421,422] The variation of V_2O_5 prices has been volatile due to several events affecting the major producing countries, such as the introduction of vanadium steel standards or the revision of product standards in China and the rationing of electricity in South Africa.[423] The closure of South African and Russian mines seemed to have impacted pricing as well.

According to the different scenarios investigated by the IEA, the projected global demand for vanadium for clean technologies, mainly driven by grid battery storage, would be between 22–35 kt in 2030 and 469–773 kt in 2050.[420] Their boldest NZE scenario estimates an average yearly demand of around 300 kt of vanadium for 2031–2040.[404] Additionally, a variation considering the early adoption of VRFB in the NZE scenario showed that the demand for lithium for energy storage could potentially decrease by 6%.[42]

A more conservative estimation by a work commissioned by the World Bank in 2020 projected that the annual demand for vanadium in 2050 would rise to 138 kt, still representing 189% of the global output in 2018.[89]

Finally, a more recent and bullish forecast by Guidehouse Insights indicated that energy storage alone might consume around 140 kt of vanadium annually by 2031.[413] In their white paper, they estimate that the global annual installed VRFB revenues would grow from under USD $1,000 M in 2022 to almost $ 8,000 M in 2031, following the worldwide VRFB energy capacity increase from around 1,000 MWh in 2022 to almost 34,000 MWh.[424]

All these predictions, with as much variation as they may show, are all based on the fundamental assumption that vanadium flow batteries have a significant potential to capture shares of the energy storage market from Li-ion batteries. The actual extent and timeline of the adoption of this technology and its deployment remain the underlying questions.

9.3 The Vanadium Flowsheet: From Iron Ores, Uranium Ores and Oil Residues to Vanadium Pentoxide and Beyond

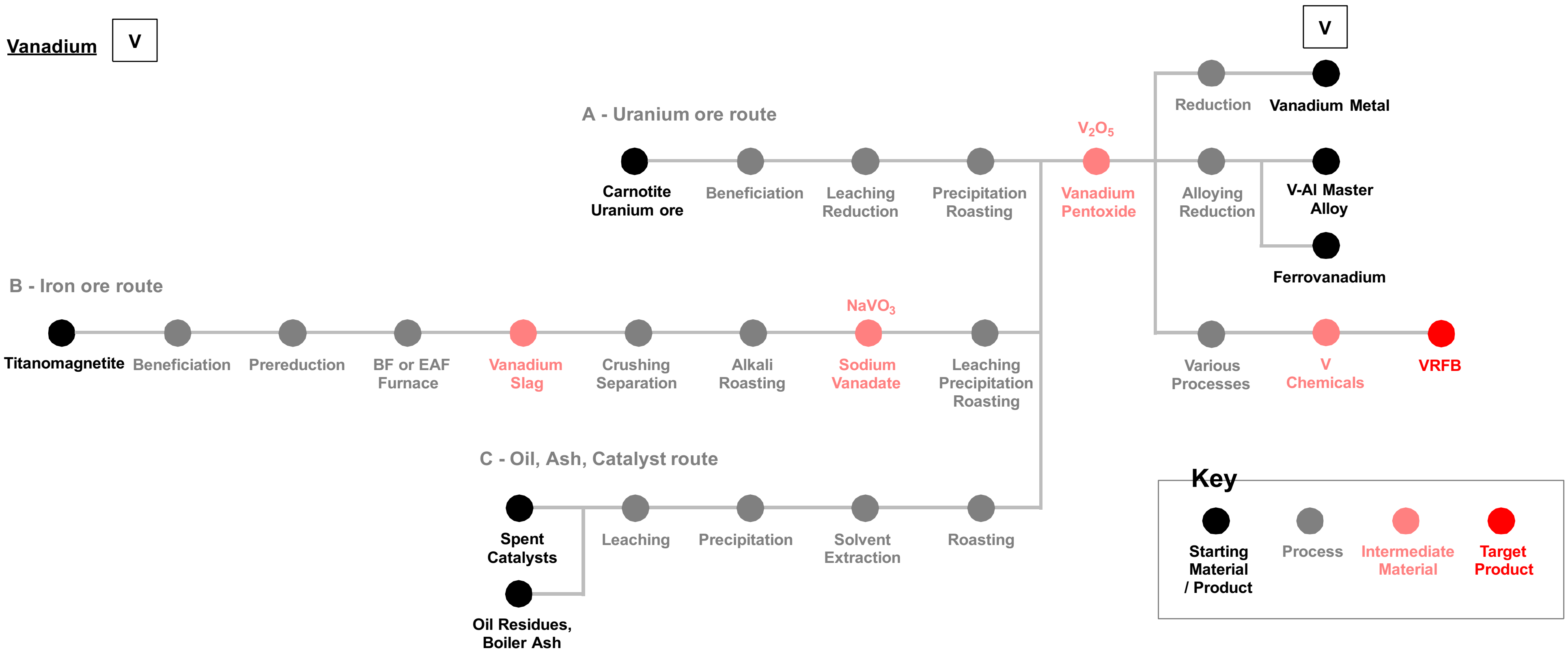


Figure 9.3.1 Simplified flowsheet of vanadium

9.3.1 The Different Types of Vanadium Ores

Vanadium is available under the form of **roscoelite** $K(V^{3+},Al,Mg)_2AlSiO_{10}(OH)_2$ or **carnotite** $K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$. Roscoelite is a vanadium-rich mica mineral typically found in low-temperature hydrothermal deposits. It is a secondary mineral associated with uranium ores. Carnotite is a uranium-vanadium ore occurring in sandstone-hosted deposits. Significant carnotite deposits are found in the Colorado Plateau in Utah and Colorado, where it was actively mined along with roscoelite for vanadium and uranium during the Cold War. Although these mines are largely inactive today, carnotite and roscoelite remain potential sources of vanadium if economic conditions favour its extraction.

Patronite VS_4 is a rare vanadium sulfide mineral historically mined in Peru, specifically at the Minas Ragra deposit. It was a primary vanadium ore during the early 20th century, but the deposit is now exhausted, and no active mining of patronite occurs today. See the section on the history of vanadium and its industry above for more details. **Vanadinite** $Pb_5(VO_4)Cl$ is a lead vanadate mineral found in the oxidation zones of lead ore deposits. It has been mined as a secondary vanadium source in Morocco, Namibia, and parts of Mexico. However, vanadinite is not a primary vanadium ore due to its lower vanadium content and association with lead.

Finally, **vanadiferous titanomagnetite** $Fe^{2+}(V^{3+},Ti^{3+})O_4$is a vanadium-bearing iron ore formed in igneous deposits. The trivalent ferric iron is sometimes replaced with either trivalent vanadium V^{3+}, or titanium Ti^{3+}. It is currently the main source of vanadium. It occurs in layered mafic intrusions and vanadiferous magnetite deposits. Prominent examples include the Bushveld Complex in South Africa, the Kachkanar Deposit in Russia, and the Largo Resources Maracás Menchen Mine in Brazil.

9.3.2 International Vanadium Production & Reserves

Table 9.3.1 Estimated reserves & production of vanadium by country in tonnes

Country	**Vanadium Mining Production in 2022**[a] (in tonnes)	**Country**	**Vanadium Reserves in 2024**[a] (tonnes x 10^3)
United States	/	United States	45
Australia	/	Brazil	120
Brazil	5,840	South Africa	750
South Africa	8,870	China	4,400
Russia	20,000	Russia	5,000
China	66,900	Australia	8,500
World Total	**102,000**	**World Total**	**19,000**

[a]Data from the 2024 U.S. Geological Survey.[421]

Vanadium is the 20th most abundant element on Earth's crust, averaging at 120 ppm (g/tonne).[153,319] This makes Vanadium relatively available, as, in comparison, it is twice as abundant as copper and six times as abundant as lithium. By this measure, it is one of the most abundant battery metals in the Earth's crust.[425] Considering the estimations and forecasted demand, vanadium availability will not be an issue, even in the most aggressive VRFB adoption scenario. Known global reserves are estimated at 22–24 Mt of vanadium, which could certainly accommodate the VRFB-driven IEA NZE scenario, where the average annual demand reaches 300 kt of vanadium during 2031–2040.[404,423] More globally, the total world resources are estimated to be over 63 Mt of vanadium.[421]As such, the expected bottlenecks are more likely to occur in the vanadium processing and electrolyte production segments of the value chain.

China is the world's top vanadium producer (66% of world V production in 2022), ahead of Russia (20%), South Africa (9%), and Brazil (6%), with a global output of 102 kt, according to the U.S. Geological Survey.[421] A different accounting for the same year by Vanitec estimated that almost 118 kt of vanadium was produced and that 116 kt was consumed.[426]

In 2023, 6.8% of the global vanadium consumption was for VRFB, and China accounted for 92% of this amount.[413]
However, alloying remains the main application for vanadium: the steel sector represented 92% of the total vanadium demand in 2021, with steel slag co-production being the major production pathway (73%), followed by extraction from primary resources (17%) and secondary sources (10%).[404]

9.3.3 Processing

9.3.3.1 From Uranium

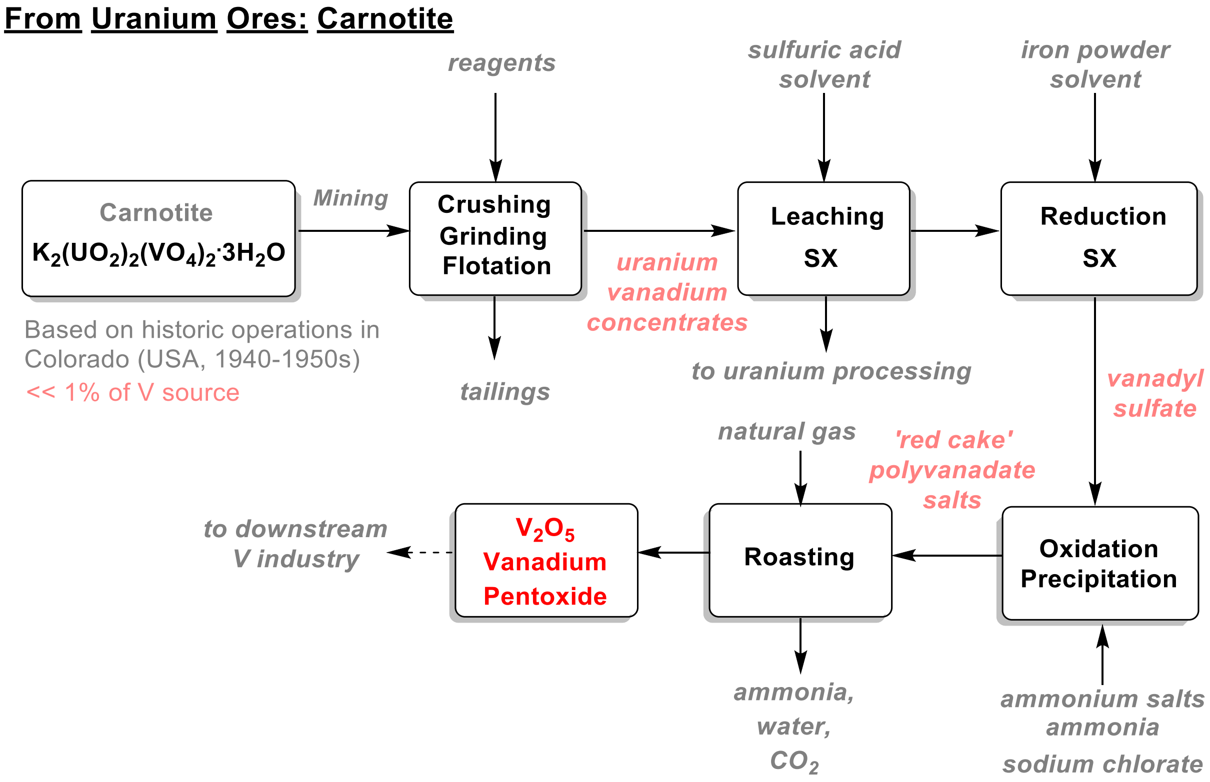


Figure 9.3.2 Flowsheet from uranium-vanadium resources to vanadium pentoxide

Vanadium extraction from uranium ores typically involves two main processes: sodium salt roasting or leaching and pressurized acid leaching.[427]

The **Sodium Salt Roasting-Leaching Process** method involves roasting uranium-vanadium minerals (e.g., carnotite) with sodium salts (commonly sodium carbonate or sodium chloride) at high temperatures (typically 800–850°C). The roasting converts vanadium and uranium into water-soluble **sodium vanadate** $NaVO_3$ and sodium uranyl carbonate. The roasted material is leached with water or an alkaline solution to dissolve the vanadium and uranium compounds. These elements are separated in the liquid phase using selective precipitation or solvent extraction. Vanadium recovery is 70–80%, and uranium recovery is 90–95%. While effective for uranium, the process leaves a portion of vanadium unrecovered in the residue due to incomplete reaction or structural inaccessibility. The later stages of this pathway follow the same route as the titanomagnetite pathway, starting from the leaching and filtration of sodium vanadate. See the appropriate section below for more details.

In the **Pressurized Acid Leaching Process**, in this method, finely ground uranium-vanadium ores are directly leached with sulfuric acid (H_2SO_4) at elevated temperatures (150–160°C) under oxygen pressure in an autoclave. Sulfuric acid is the primary leaching agent, and oxygen is supplied continuously to maintain oxidative conditions that favor the dissolution of uranium and vanadium. After leaching, vanadium and uranium are separated in the liquid phase using solvent extraction or ion exchange techniques. Uranium recovery reaches 90–94%, but vanadium leaching rates are typically lower at 65–72%, as the mineral structure resists complete dissolution. A **vanadyl sulfate** solution is the product. The high temperature and pressure enhance reaction kinetics, making it suitable for processing low-grade ores. This was also the main method used by industry.

In both processes, vanadium recovery is less effective than uranium, leaving untapped potential in the residues. The need to separate vanadium and uranium in the liquid phase adds operational challenges. Researchers have then focused on tailing to recover additional vanadium; in one instance, metallurgy used microbial processes to extract vanadium from tailings, achieving recovery rates of around 45%.

After the acid-leaching process, the vanadyl sulfate solution can be oxidized by using sodium chlorate at high temperatures. Then a subsequent addition of ammonia or ammonium salt precipitates the vanadium as '**red cake**', a mixture of **ammonium polyvanadate** (APV) and **sodium polyvanadate**. After roasting, ammonia is eliminated, and only alkali-containing **vanadium pentoxide** remains V_2O_5.[384]

9.3.3.2 From Titanomagnetite

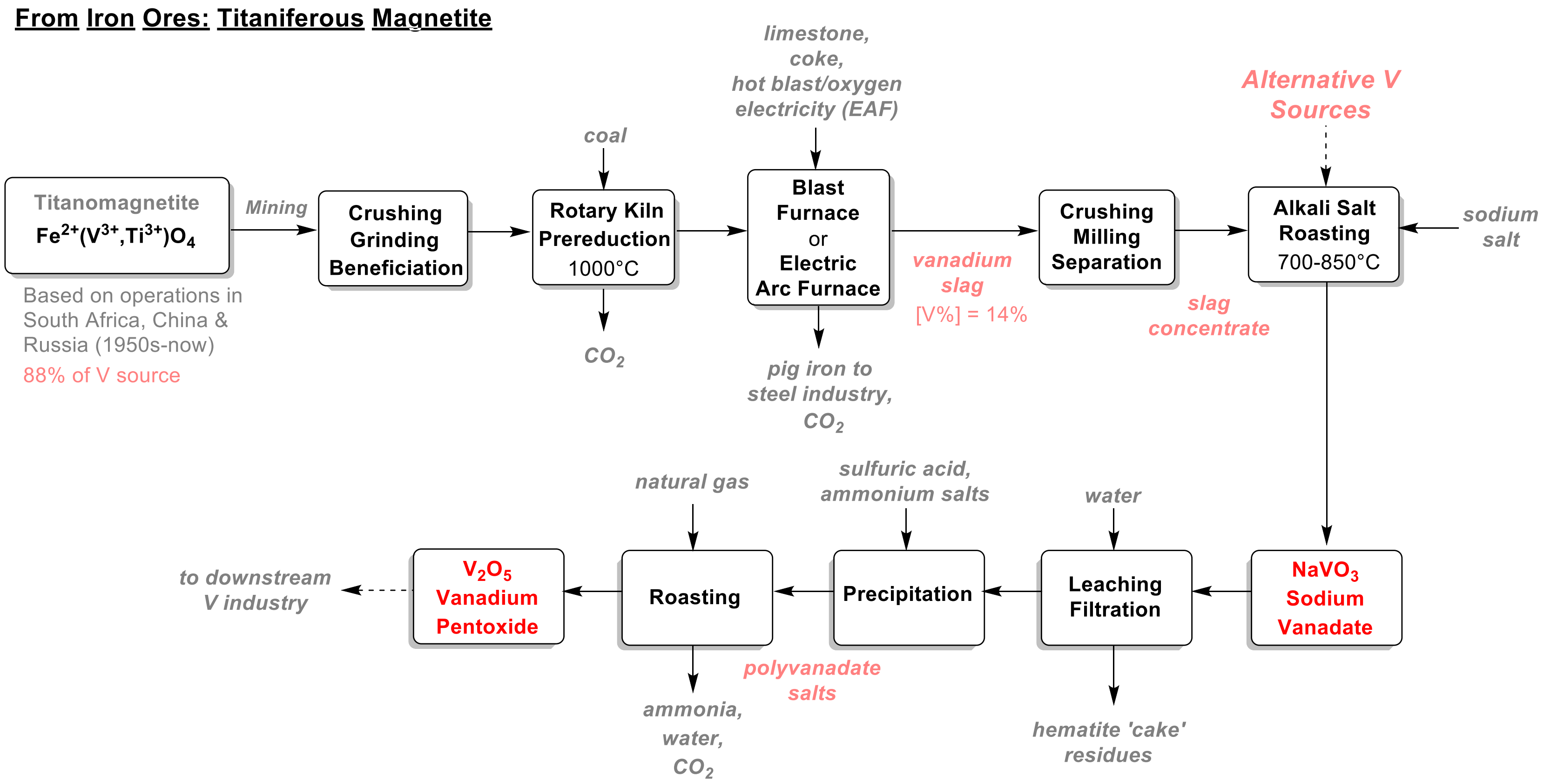


Figure 9.3.3 Flowsheet from titanomagnetite resources to vanadium pentoxide

Vanadium extraction from titanomagnetite ores (VTM) and vanadium slag involve a multi-step process to recover vanadium in vanadium pentoxide (V_2O_5), and it is often a by-product of iron and steelmaking plants. High-grade vanadium concentrates can be directly processed through direct extraction or direct reduction.

After beneficiation, titanomagnetite ore, typically containing 1.5–1.7% V_2O_5, is partially reduced with coal at approximately 1000°C in rotary kilns. The reduced ore is further processed in an electric arc furnace, producing pig iron with 1.4% V_2O_5 and vanadium-rich slag containing up to 25% V_2O_5 in South Africa (or 14% V) or 14–22% in China or Russia. Vanadium from pig iron can be transferred to the slag using a shaking ladle and oxygen lances. The slag also contains titanium dioxide.[384] The rotary kiln/EAF pathway is mainly used in South Africa, while a blast furnace is used in China and Russia

The slag is finely ground (<100 μm) and roasted with sodium salts (*e.g.*, Na_2CO_3 or NaCl) at 700–850°C in rotary kilns or multiple-hearth furnaces. This oxidizes vanadium into water-soluble **sodium vanadate** ($NaVO_3$). The roasted material is leached with water, dissolving sodium vanadate and leaving impurities behind. This produces a vanadium-rich solution. Calcium, magnesium and aluminum impurities form other vanadate salts that are insoluble in water, thus reducing the yield.

Ammonium salts (*e.g.*, NH_4Cl or $(NH_4)_2SO_4$) are added to the leachate to precipitate **ammonium metavanadate** (AMV) or **ammonium polyvanadate** (APV) at elevated temperatures and with sulfuric or hydrochloric acid. The AMV is calcined/roasted at 700°C to produce high-purity **vanadium pentoxide** V_2O_5, which is then melted and cooled into flake form for commercial use.

If the titanomagnetite ores have a vanadium content > 1%, they are eligible for alkali roasting directly after beneficiation, bypassing the pre-reduction or slag steps. The product obtained is also vanadium pentoxide and the process is similar to the one mentioned above. Companies in South Africa and Brazil can follow this method in an economically viable manner.[427]

In general, the sodium salt roasting process generates high-salinity wastewater and acidic gases. Improving environmental compliance includes replacing sodium salts with lime (calcification roasting), reducing harmful emissions, and recycling process water.

A newer Direct Alkaline Leaching method bypasses high-temperature roasting using highly concentrated alkaline solutions (40–60% NaOH) at 150–200°C under oxygen pressure, achieving over 90% vanadium recovery. However, it requires specialized corrosion-resistant equipment and is mainly suitable for high-grade vanadium slag. Other alternative routes include Microwave-Assisted Roasting; this innovation improves reaction kinetics, increasing vanadium extraction efficiency during leaching.

Vanadium slag is the world's primary raw material for vanadium production, with major producers in South Africa, China, and Russia. The slag pathway has a few advantages, with a small processing load for extraction, a high vanadium content in the slag, or iron as a by-product which can be used for steelmaking. However, global recovery rates from titanomagnetite remain low (~50%) due to inefficiencies at various stages.[427] The process must balance economic viability, resource conservation, and environmental sustainability with ongoing research into cleaner and more efficient extraction methods.

9.3.3.3 From Oil Residues and Spent Catalysts

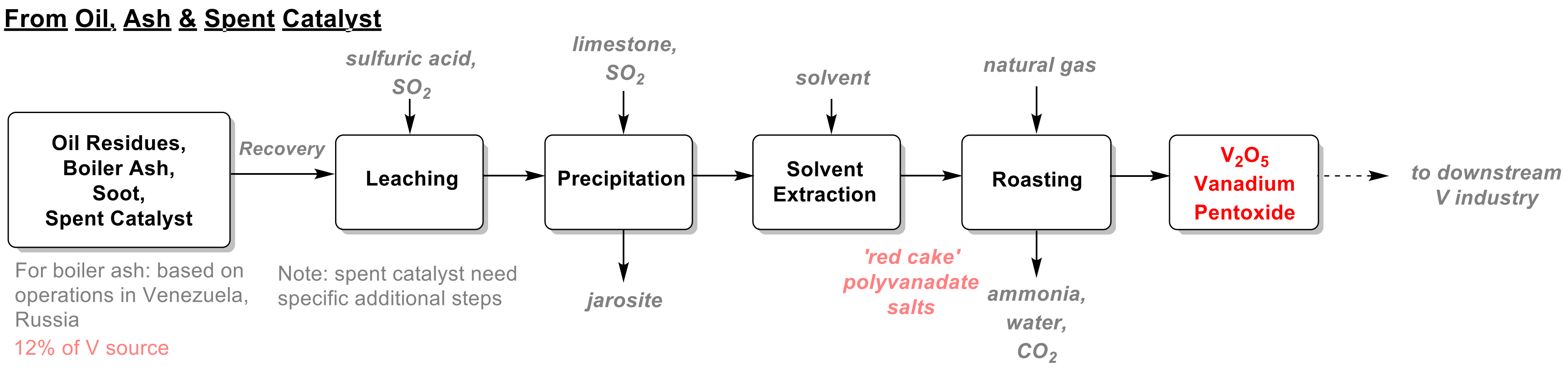


Figure 9.3.4 Flowsheet from petroleum-based vanadium and spent catalyst resources to vanadium pentoxide

Secondary vanadium can be extracted as a secondary raw material from oil and coal combustion residues, such as soot and ash from oil-fired boilers and oil refinery residues. These by-products, often containing significant vanadium content (sometimes exceeding 50% V_2O_5),[384] can be a source of vanadium, but it can come at a higher processing cost.[385] Coal ash has a lower vanadium content than petroleum fly ash. Ash is typically recovered in a collection system such as an electronic precipitator or a cyclone and has a high carbon content and includes a minor amount of non-ferrous metals.[428]

Heavy crude oils, such as those from the Orinoco Basin in Venezuela, Russian oil fields, parts of the Middle East and the tar sands of western Canada, can contain vanadium. In Venezuela, heavy asphalt-like oil deposits are emulsified with water and magnesium nitrate to create a fuel used in power stations, generating boiler ash rich in vanadium.

The process for extracting vanadium from these secondary sources typically involves a combination of roasting, leaching, and precipitation, similar to the methods used for vanadium titanomagnetite ores. The objective is also to produce **vanadium pentoxide** V_2O_5. However, additional steps, such as filtering, solvent extraction, and ion exchange, are required to handle complex waste streams.

Another important secondary source of vanadium is spent catalysts: spent hydrodesulfurization (HDS) catalysts for oil refining and selective catalytic reduction (SCR) catalysts for NO_x conversion (in incinerators, vehicles or power plants). Metals such as molybdenum, nickel, cobalt, and aluminum are also present and can be recovered during processing. A complete description of the different processes for secondary sources of vanadium can be found in the literature.[428]

9.3.3.4 From Vanadium Pentoxide to Different Vanadium Products

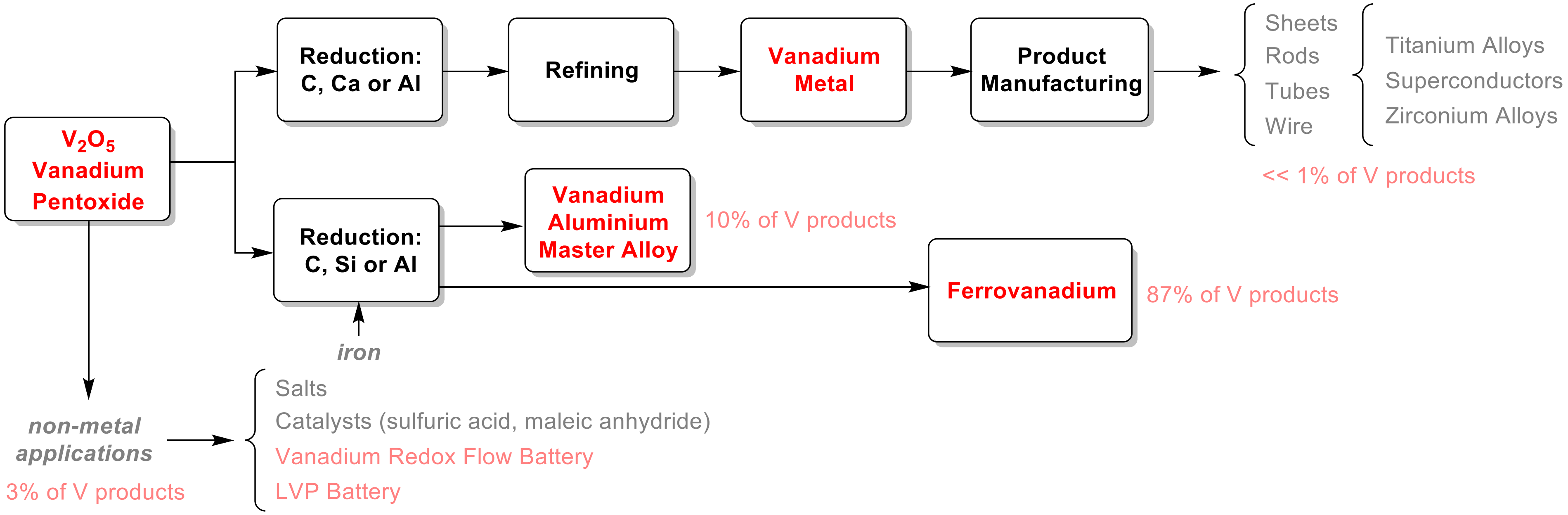


Figure 9.3.5 Flowsheet from vanadium pentoxide to finished vanadium products

Whether from titanomagnetite, carnotite, fly ash, or other secondary vanadium sources, the main chemical intermediate produced is **vanadium pentoxide** V_2O_5. Different processing routes link vanadium pentoxide to diverse vanadium products.

As the steel industry still accounts for most of the vanadium demand, products such as ferrovanadium make up most of the vanadium products. Ferrovanadium's most common grade is FeV80 (80% vanadium), but content can range from 35 to 85%. Ferrovanadium is mainly obtained from aluminum reduction, also known as **aluminothermic reduction**, a very exothermic reaction.[429] Vanadium oxide is mixed with aluminum, iron scrap, an initiating mixture and flux (such as lime) in an electric arc furnace. After initiation with the electric arc, the reaction is self-sustaining. The reaction is quick and only requires a few minutes while cooling the furnace can take several days. FeV60, 80, and even FeV90 can be produced this way.[384] Instead of aluminum, silicon or carbon can also be used for this reduction reaction, but the silicothermic reduction suffers from low yield and low profitability, while the carbothermic reaction will also form vanadium carbide, and has been supplanted by the other two methods. Other vanadium alloys can be obtained *via* similar processes.

Vanadium metal can also be obtained through a similar reduction of V_2O_5 in the absence of iron. Carbon, calcium or aluminum can be used as a reductant, although the carbothermic reaction is rarely used, while the aluminothermic method in inert a also seems to be preferred by the industry.[430] After the reduction, refining through either electron-beam melting or after crushing and heating in a vacuum can be performed to obtain high-purity vanadium ingots. Further refining methods include iodide refining (Arkel process), molten salt electrolysis or electro-transport. The Arkel process can notably yield 99.95% pure vanadium.

The vanadium electrolyte used for VRFB is usually a sulfuric acid solution containing vanadyl sulfate salts $VOSO_4$ and $V_2(SO_4)_3$. The original method to synthesize electrolytes developed by the Skyllas-Kazacos team was to dissolve the **vanadyl sulfate** $VOSO_4$ blue solid in sulfuric acid. However, $VOSO_4$ is expensive, and has to be prepared by reducing V_2O_5 with sulfur dioxide in aqueous sulfuric acid. Since then, methods using more inexpensive V_2O_5 directly (or vanadium trioxide V_2O_3) to prepare electrolytes were developed, amongst which: the dissolution of V_2O_5 in sulfuric acid and its subsequent reduction (using oxalic acid, ascorbic acid, *etc.*) to yield V(IV) electrolyte; or the electrolytic reduction of V_2O_5 in an electrolytic cell with sulfuric acid under direct current, producing V(IV) and V(III) electrolytes. Other methods completely bypassing the use of V_2O_5 have been proposed, such as the solvent extraction of vanadium-containing wastewater or leaching solution to produce $VOSO_4$ or even the leaching and solvent extraction of vanadium slag. More detailed descriptions of those processes can be found in the literature.[431–433]

9.3.3.5 Vanadium Circularity and Recyclability

The data on vanadium recycling is uncertain but generally appears low. In 2011, the UNEP estimated Vanadium's general End-of-Life recycling rate to be lower than 1%.[434] Similarly, the EU accounted for an end-of-life recycling input rate of 1% for the EU in 2022.[435] These old scrap analyses focus on recycled vanadium after usage, which is mainly spent catalysts and chemicals collected and treated to manufacture new catalysts. The U.S. Geological Survey's annual mineral commodity summaries stated that from the 2010s until 2022, the quantity of vanadium recycled from spent catalysts could account for as much as 40% of the total vanadium catalysts in the U.S. More recent summaries from the same institution disclose that the uncertainty for this figure was significant.[421]

Vanadium from alloys can be recycled by re-melting it into a similar alloy, especially in the case of tool steel scrap,[429] but as the V concentration in those alloys is low, it is not specifically collected, and the addition of different steel scrap feed will ultimately dilute vanadium.[417]

Vanadium in VRFB is easy to recycle; in 2021, U.S. Vanadium showed a 97% recovery rate when recycling electrolytes from decommissioned vanadium flow batteries. [436]

10 Conclusion

Canada has a unique opportunity to lead in critical mineral value chains essential for the clean energy transition. With abundant resources, industrial expertise, and a commitment to sustainability, Canada can become a dominant North American supplier of materials crucial for EVs, renewable energy systems, and advanced technologies. But there is a need to act now to build the missing midstream (chemical processing, metallurgy, pCAM & CAM) while supporting and accelerating more upstream operations (Mines and DLE extraction).

A bold strategy positioning Canada as the North American leader is required for nickel, copper and graphite.

For nickel, Canada can capitalize on its abundant resources to capture up to 35% of the North American EV market by 2030. Expanding mining and processing in Newfoundland and Labrador, Québec, Ontario, and Alberta, alongside building a large metallurgical facility in British Columbia, will enhance domestic refining capacity. Integrating black mass recycling and imported feedstocks will further support battery-grade nickel sulfate and precursor material production.

Copper remains a cornerstone of the clean energy economy. Addressing declining processing capacity by building a modern smelter in British Columbia and scaling up recycling initiatives will enhance Canada's competitiveness. Expanding mining operations in British Columbia will secure a steady supply of copper concentrates for domestic use and export.

Graphite represents a significant opportunity for Canada to dominate the North American EV battery supply chain. Expanding natural graphite mining in Québec and British Columbia, establishing coating and anode production hubs, and developing synthetic graphite facilities in Alberta will secure Canada's leadership. Supporting R&D for bio-based graphite production and methane carbon capture/clean hydrogen-derived alternatives will diversify production while driving innovation.

Lithium, phosphate, and vanadium require a more balanced approach. Canada has less opportunity to dominate the global market for those minerals, but a strong development approach is necessary to develop those strategic commodities and reach the mandated benchmarks. Iron is not likely to be a bottleneck, but the development of specific intermediates such as high-purity iron powder or iron sulfate for cathode is to be boosted.

In lithium, Canada should focus on integrating its extraction and processing capabilities. Direct lithium extraction (DLE) projects in Alberta and Saskatchewan should be paired with a dedicated research hub to scale up innovation and operations. Simultaneously, spodumene mining in Québec and Ontario must ramp up, with processing hubs such as the Bécancour lithium hydroxide facility in Québec converting concentrates into battery-grade materials.

Canada’s phosphate resources, particularly rare igneous deposits, position it to lead in battery-grade purified phosphoric acid (PPA) production for LFP batteries in North America. Developing 3–4 mining projects in Québec, British Columbia, and Ontario and processing hubs focused on PPA for battery applications will address bottlenecks in LFP cathode material production.

In vanadium, Canada has the potential to create a comprehensive value chain. Establishing a vanadium processing and redox flow battery (VRFB) manufacturing hub in Alberta, leveraging petroleum residues and fly ash, will ensure a steady vanadium supply. Expanding recovery from secondary sources and co-producing vanadium with iron, uranium, and aluminum mining operations will strengthen Canada’s critical mineral capacity.

For iron, Canada’s strength in high-purity iron ore and steelmaking can support the production of lithium iron phosphate (LFP) battery materials. Encouraging cleaner processes, such as using iron powder or iron oxide to bypass traditional sulfate routes, will improve sustainability. Leveraging operations like Rio Tinto’s Quebec facility for high-purity iron powder production can further integrate iron into the battery value chain.

Canada has the resources for rare earth elements (REEs), various public initiatives and facilities, and promising processing intellectual properties. However, it still lags behind China’s multi-decade expertise and scale or Australia and the U.S.’s more recent large-scale operational mines and processing projects. Canada can develop a centralized processing and magnet manufacturing hub in Saskatchewan, supported by increased mining in the Northwest Territories, Québec, Saskatchewan, and British Columbia. Building partnerships with manufacturers to produce magnetic powders and magnets will secure Canada’s role in advanced materials for EV motors and other technologies.

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