Life-Cycle Assessment of Critical Minerals from Mine to Active Material for Lithium-ion and Beyond

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Abstract

Life Cycle Assessment of Critical Minerals from Mine to Active Material

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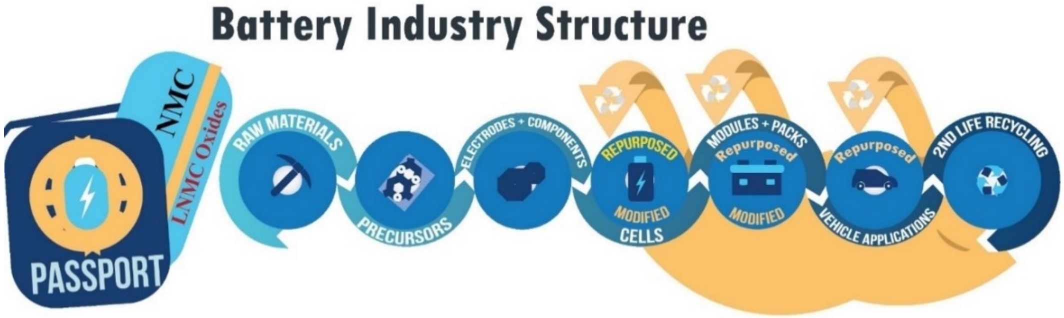
The rapid electrification of the global transportation sector has intensified the demand for lithium-ion batteries (LIBs), prompting an urgent need to establish sustainable, traceable, and regionally resilient supply chains for battery materials. This dissertation presents a comprehensive multi-material life cycle assessment (LCA) of three critical minerals, lithium, natural graphite, and nickel focusing on their extraction and processing in the province of Québec, Canada. The goal of this research is to quantify the environmental impacts of producing battery-grade cathode and anode materials while identifying opportunities for emissions reduction, process optimization, and circular economy integration across the LIB value chain. Given that approximately 85% of current cathode materials originate from Asia, the work addresses a significant data gap by providing robust, North American-specific LCA inventories and impact analyses for a region increasingly targeted by OEMs, policymakers, and investors under frameworks such as the U.S. Inflation Reduction Act (IRA) and Canada's Critical Minerals Strategy.



Graphical Abstract: Battery Industry Structure. (Vegh, 2023).

Acknowledgments

I would like to express my deepest gratitude to my supervisor, **Dr. Karim Zaghib**, for welcoming me into his battery research group within the Department of Chemical and Materials Engineering. His guidance, expertise, and unwavering support have been invaluable throughout the course of this work. In addition to sharing his extensive knowledge of EV lithium-ion batteries, Dr. Zaghib arranged several field visits including the Nouveau Monde Graphite mine and processing plant (Saint-Michel-des-Saints, QC), the CNETE electrochemistry laboratories (Shawinigan, QC), the National Research Council battery research laboratory (Boucherville, QC), and the NanoOne manufacturing facility (Candiac, QC). These experiences greatly enhanced my understanding of critical mineral extraction and the processing steps required to produce battery-grade materials.

I am also sincerely grateful to **Dr. Anil Kumar M R** for his thorough review of my manuscripts and his insightful suggestions that strengthened the final publication.

I am deeply fortunate to have benefited from **Dr. Ivan Kantor's** comprehensive analysis of the mining and processing plant data, as well as his significant contributions to the LCA modeling. I am equally appreciative of my life partner, **Dr**. **Sarah Sajedi**, for her meticulous review of the mining and processing plant data and her support with the *OpenLCA* modeling using the *Ecoinvent* database and manuscript review.

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Dedication

I like to dedicate my work to my wife, friend, and colleague who is the main inspiration to pursue my PhD. Her constant support, understanding, and patience was paramount in my research efforts and publications. Sarah has been a great believer in me and realized my passion for electric vehicle battery technology.

It was great that Sarah's passion for her own PhD, work spilled over to me. I am forever grateful for her being part of my life. We are both looking forward to taking our research work and lessons learned to go out a make a change with others around the globe.

I also would like to thank our two sons Seina and Paymon for their support during this doctorate degree. It is a challenge to return to school after almost 35 years of absence from academia. They both cheered along the side lines.

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Table of Contents

List of Figures

List of Tables

List of Symbols/Abbreviations/Glossary/Equations/Other

EV	electric vehicle
ICE	internal combustion engines
LIB	lithium-ion battery
NCA	nickel cobalt aluminum
NSH	nickel sulfate hexahydrate
NMC	nickel manganese cobalt
OEM	original equipment manufacturer
GWP	global warming potential
GHG	greenhouse gas
IEA	International Energy Agency
LCA	Life-cycle assessment
LCE	lithium carbonate equivalent
LCI	Life-cycle inventory
LHM	lithium hydroxide monohydrate
Mt	million metric ton
QC	Québec
tpy	metric ton per year
USGS	United States Geological Survey
AAM	anode active material
BAM	battery anode material
NG	natural graphite
SG	synthetic graphite

CHAPTER 1. INTRODUCTION

My interest in environmental issues dates back to the 1970s, when David Suzuki's *Here Come the Seventies*, broadcast on the Canadian Broadcasting Corporation (CBC), first shaped my awareness of the environmental challenges confronting modern society. This early awareness evolved into a research-oriented career that began with several environmentally focused projects at the Research Triangle Institute (RTI) in Research Triangle Park (RTP), North Carolina. I subsequently transitioned into private consulting, where I worked directly with industry on compliance related to the Clean Air Act Amendments (CAAA) of 1990. Responding to the growing complexity of environmental regulations, I developed an environmental software platform designed to support state- and federal-level recordkeeping and reporting requirements. In 1995, I founded ERA Environmental Consulting, Inc., which partnered with North Carolina State University (NCSU) to further advance the development of this platform. In 2011, my interests expanded into electric mobility, marked by the importation of a Chevrolet Volt into Canada for testing in Québec. While I have long been an advocate for electric vehicles, this experience also raised important questions about their true environmental impacts. These questions ultimately motivated the research presented in this thesis.

1.1 Problem Statement

The accelerated global transition toward electric mobility has dramatically increased the demand for LIBs, placing unprecedented pressure on existing supply chains for critical battery minerals. Currently, the majority of cathode and anode materials, particularly those used in NMC (nickel-manganese-cobalt) chemistries are produced in Asia, resulting in geographically concentrated and carbon-intensive supply networks. As governments and manufacturers in North America pursue supply-chain security and compliance with emerging policy frameworks such as the U.S. Inflation

Reduction Act (IRA); that was in place at the time of my review paper and Canada's Critical Minerals Strategy, there is an urgent need for transparent, region-specific, and environmentally robust life-cycle data for battery material production.

Despite this need, a significant knowledge gap persists: no comprehensive LCA currently exists for the extraction and processing of multiple critical minerals within Québec, a region with rapidly expanding resource-development activity and a uniquely low-carbon hydroelectric power grid. This gap limits policymakers, OEMs, and industry stakeholders from accurately assessing environmental impacts, identifying emission hotspots, or comparing Québec-based supply chains with established Asian production routes.

The problem is further complicated by the heterogeneity of battery materials. Production of lithium hydroxide monohydrate, natural graphite anode material, and nickel sulfate hexahydrate involves distinct extraction pathways, processing technologies, energy inputs, and waste streams each contributing differently to greenhouse gas emissions, and water consumption impacts. Without harmonized, region-specific LCA inventories, efforts to build sustainable, circular, and traceable North American supply chains remain hindered.

Therefore, there is a critical need to develop a rigorous, multi-material LCA framework that quantifies the environmental burdens associated with Québec-based production of lithium, graphite, and nickel battery materials, identifies key emission drivers, and evaluates opportunities for process optimization and circular-economy integration. Addressing this need will establish a foundational baseline for future battery-pack LCAs, support evidence-based policy and investment decisions, and inform strategies for developing a resilient, low-carbon North American battery ecosystem.

1.2 Research Objectives

My work with Dr. Karim Zaghib's battery group is to look at the environmental impact of critical minerals used in EV LIBs. This was done by conducting LCAs on selected critical minerals. These were selected from the province of Québec to help promote a local green EV battery. I realized after talking to Dr. Ivan Kantor, an LCA would have to be conducted on each critical mineral separately from mine to battery grade material. With the exponential growth of the EV market, there is also a need for more LIBs. The cathode is the most expensive component of EV batteries, and as the demand for EVs continues to grow, it is essential to develop sustainable and cost-effective processes for the supply chain, from mining to material. The main objective of this dissertation is to provide LCAs on critical minerals mined in the province of Quebec and processed into battery grade material. As part of this research an investigation into the environmental impact of battery grade material production was evaluated with respect to energy consumption (electricity, wind, solar, natural gas, diesel, gasoline, coal, and reagents), water usage, and air emissions in the form of carbon dioxide (CO_2) as the global warming potential (GWP). Transportation (truck, rail, and ship) was also considered based on the location of the mine and the process plant location to manufacture the final battery grade material.

It has been identified that there are large gaps in environmental impact data with regards to critical mineral production, especially for North America. Limited LCAs have been undertaken and most of the data has been from Asia since 85% of the EV LIB cathode material was produced mainly in China. This research focused on lithium, graphite, and nickel key critical minerals used in LIBs. As LIB chemistry continues to evolve, additional LCAs will be required. In the future, developing a comprehensive model of the entire battery pack will also be necessary to accurately evaluate the overall environmental impact of LIBs.

1.3 Thesis Outline

This thesis investigates the environmental performance of key LIB materials through a series of LCAs, with a particular focus on Québec-based supply chains. As LIB demand accelerates alongside the global energy transition, understanding the upstream environmental impacts of critical battery components and how these impacts vary by chemistry, geography, and production pathway has become increasingly important. While many LCAs still need to be conducted on the remaining components of LIBs before the true environmental footprint of a complete battery pack can be fully quantified, this research contributes meaningful progress toward that goal by establishing robust cradle-to-gate baselines for high-impact materials. The need for such analyses is underscored by the rapid emergence of new LIB chemistries and the diversification of global supply chain locations. The chapters that follow are structured to contextualize these evolving trends, present detailed LCAs for cathode, anode, and precursor materials, and synthesize findings that support future full battery pack assessments and next-generation battery technologies.

Chapter 1 Includes the introduction to the research topic, the problem statement, research objectives, and thesis outline.

Chapter 2 provides a broad assessment of the evolving NMC (nickel-manganese-cobalt) cathode landscape, highlighting how shifts toward higher-nickel, lower-cobalt chemistries (e.g., NMC622 and NMC811) influence environmental performance, material criticality, energy density, and safety. The chapter underscores that NMC cathode production contributes up to 50% of total LIB GHG emissions, driven largely by energy-intensive precursor production and the carbon intensity of regional power grids. It further identifies supply chains and in LCA datasets, particularly in Western supply chains, and examines the role of battery passports and blockchain-based traceability in building a transparent, low-impact critical mineral ecosystem.

Chapter 3 presents a cradle-to-gate LCA for LHM produced from Québec spodumene. Using *OpenLCA v2.3* and the *Ecoinvent v3.8* database, the study calculates that producing 1 ton of battery-grade LHM generates 5.46 tons of CO_2-equivalent emissions significantly lower than prior studies conducted for Australia and China. The dominant environmental hotspots include the natural gas-powered calcination and acid baking steps, while upstream co-products such as gypsum and sodium sulfate provide notable emissions credits. Water consumption and energy inputs likewise fall below international benchmarks, benefiting from Québec's hydroelectric grid and stringent environmental regulations.

Chapter 4 delivers a detailed LCA of natural graphite anode material (AAM), showing that Québec-based production emits approximately 1.44 tons CO_2-eq per ton of AAM, compared with 9.6 tons for natural graphite and nearly 30 tons for synthetic graphite produced in China. The analysis identifies purification and micronization as the most emission-intensive stages due to the use of natural gas and chemical processing requirements. A cluster-based environmental impact analysis further isolates process-specific interventions such as substituting natural gas with renewable electric heating, electrifying mining equipment, and optimizing closed-loop water systems that can reduce emissions by up to 40%.

Chapter 5 examines the unique environmental challenges associated with nickel sulfide ore mined in remote off-grid northern Québec and refined to nickel sulfate hexahydrate (NSH) in Norway. The study calculates an impact of 20.1 tons CO_2-eq per ton of NSH, with Smelter operations accounting for majority of the emissions. Sensitivity analyses show that replacing diesel with natural gas or hybrid wind-diesel microgrids could reduce emissions by up to 40% of CO_2, although Arctic conditions impose constraints. Water scarcity impacts were found to be highest in smelting and refining stages, while mine tailings treatment (via BioSulphide technology) demonstrated strong potential for reduced ecological harm.

Collectively, this research establishes the first comprehensive LCA baseline for Québec's critical mineral supply chain. It demonstrates that a localized, hydropower-driven, circular-economy-driven battery materials industry can substantially reduce GHG emissions compared with current Asian supply chains. The findings provide actionable insights for policymakers, OEMs, mining companies, and battery manufacturers seeking to scale North America's green battery ecosystem and lay the groundwork for full battery-pack LCAs and future integration of emerging chemistries.

CHAPTER 2. NORTH AMERICA’S POTENTIAL FOR AN ENVIRONMENTALLY SUSTAINABLE NMC BATTERY VALUE CHAIN

2.1 Background

The automotive industry is investing hundreds of billions of dollars (USD) in transitioning from internal combustion engine (ICE) vehicles to electric vehicles (EVs) platforms (IEA, 2020). Many countries have planned to ban the sale of ICE vehicles by 2035–2040 (Baars, 2007; Fallah & Fitzpatrick, 2023; Fallah et al., 2021; Vegh, 2023). This change in vehicle drivetrains is rapid, and every original equipment manufacturer (OEM) is engaged in this market (McGovern et al., 2023; Mohammadi & Saif, 2023) (Figure 1). Automotive manufacturers estimate that EVs will constitute 40–50% of the annual vehicle sales volume by 2030 (GM-News, 2023; IEA, 2023; McGovern et al., 2023; Reuters, 2021) thus increasing the need Li-ion batteries (LIBs) and the development of active materials. This shift in the automotive sector is considered the most dramatic change in the industry since the introduction of the assembly line by Henry Ford in Detroit, Michigan (Cimino et al., 2023). There is a long history of using batteries for energy storage, from the Alessendro Volta cell in the 1800s to the commercialization of LIB in 1992 (Julien et al., 2014; Reddy et al., 2020). The mining industry has a long history of providing hydrometallurgical processes (Schwich et al., 2020) dating back to pre-industrial times (Asare & Afriyie, 2021; Burkin, 2001; Shukla & Kumar, 2008).

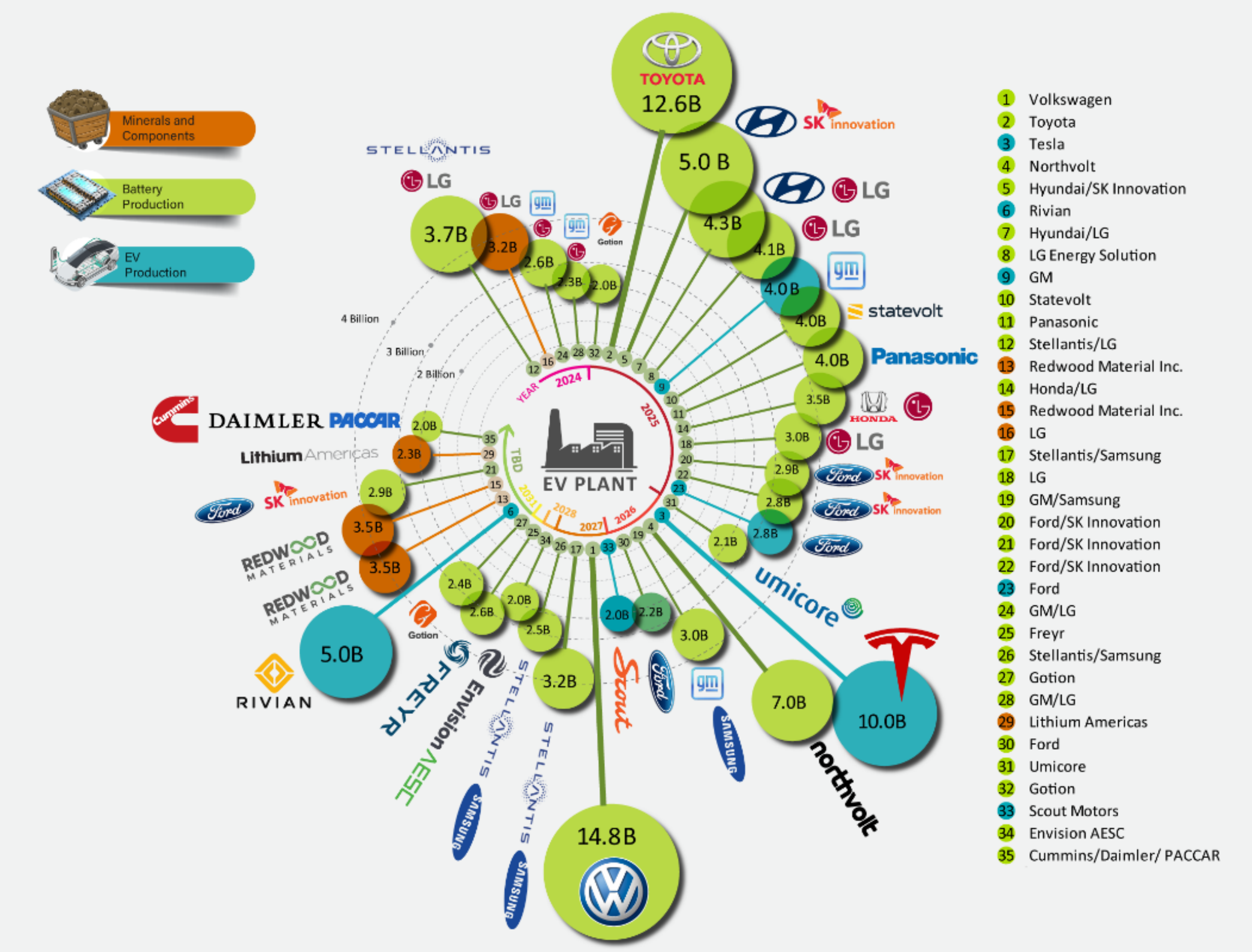


Figure 1: North American investments in the electric vehicle (EV) battery industry (U.S._DOE, 2024).

With this major change in the automotive industry, OEMs are seeking to secure a dependable and sustainable supply chain (Ballinger et al., 2019; Roelich et al., 2014) that considers the environmental impact. The United States Inflation Reduction Act (IRA) (Church et al., 2023; Grimm et al., 2023; U.S.DT, 2023) is a primary driving force providing strong incentives for using raw materials sourced from the US and free-trade partner countries (Morris, 2023). Canada has strong ties with the auto sector in the US via the North American Free Trade Agreement, which was enacted in 1994 (International Trade Administration) and is now referred to as the U.S.-Mexico-Canada agreement (USMCA) since July 2020 (Guzman-Anaya, 2023). Many US-based automotive OEMs consider Canada a major supplier of the important minerals used in the production of LIBs. Companies such as General Motors (GM), Ford, Tesla, and Northvolt are investing in critical minerals in Quebec (Canada-Service, 2022; Davis & P. Demopoulos, 2023; Gorachinova & Wolfe, 2023) to secure reliable sources for creating precursors that can be used in producing cells for LIBs in EVs (E&MJ, 2023; IBAT, 2024). Many companies in Canada have invested in the EV market in cathode active material (CAM) and EV battery plants (Bettenhausen, 2022) Stellantis and LG Energy Solutions are investing in an LIB facility in Windsor, Ontario, Canada. Figure 2 shows investments in Quebec and Ontario, which come from OEMs and chemical companies involved in key minerals. The GM/POSCO, BASF, and Umicore facilities will produce CAMs (BASF-Canada, 2022; Bettenhausen, 2022; GM-News, 2024; Umicore-Canada, 2024).

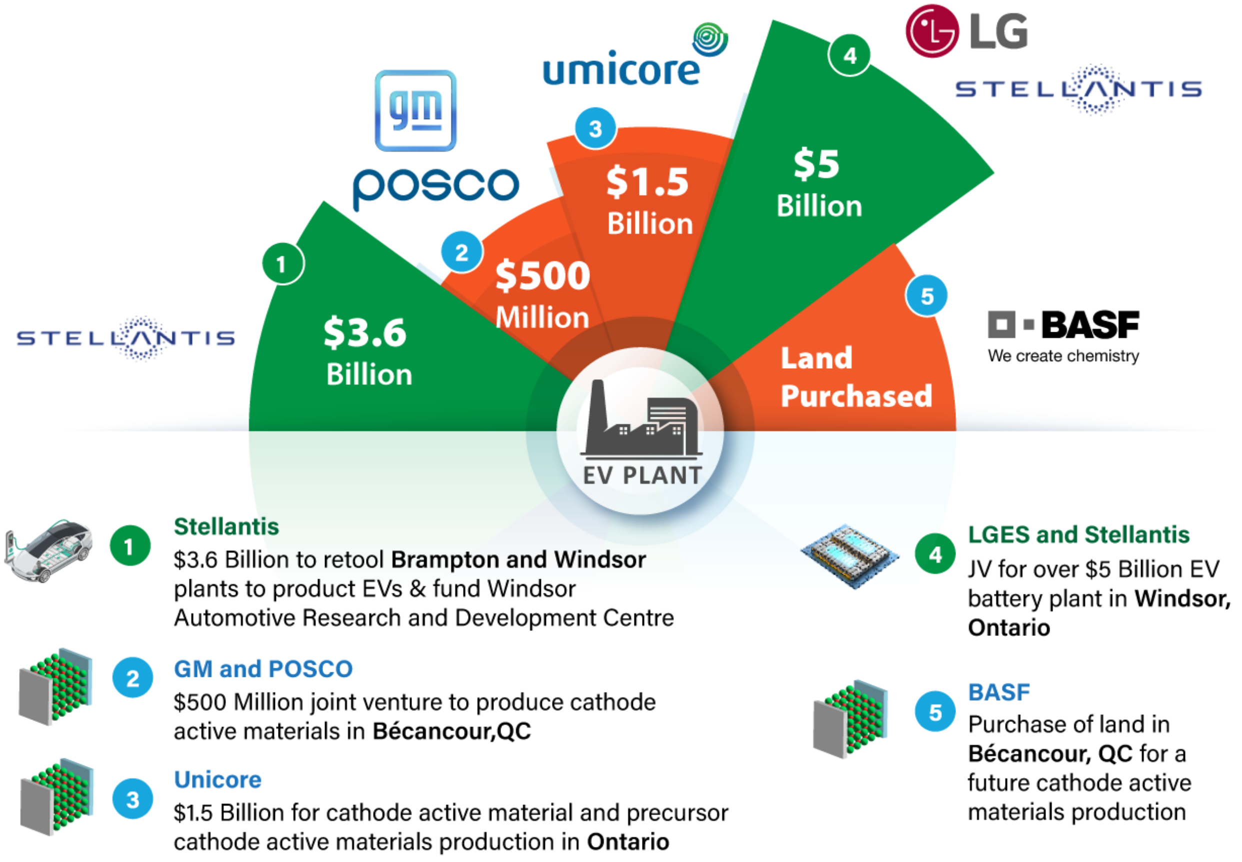


Figure 2: EV plant investments in Canada (Quebec and Ontario) (redesigned)

With the exponential growth of the EV market, more LIBs are urgently required (AMR, 2023; Z. Chen et al., 2019; Mohammadi & Saif, 2023). The following graph in Figure 3a depicts the global EV demands with respect to country (China, Japan, France, Germany, United Kingdom, and United States) from 2015 to 2040. According to these data, China has the highest growth versus Europe, the United States, and the rest of the world. This projection seems accurate as the global EV sales of China's BYD automotive company have surpassed those of Tesla (Khaleel et al., 2024; Pereira, 2024).

As the sales of EVs increase globally, LIB production must be increased. Figure 3b depicts the continuous growth in battery demand (GWh/year) for light-duty vehicles (LDEV) worldwide (total), in China, Europe, and the United States (Barman et al., 2023). With the availability of larger battery packs in the market, there has been a push to develop in R&D technologies in developing NMC cathodes with higher nickel content and lower cobalt (NMC111, NMC622, and NMC811) (Schulz-Mönninghoff et al., 2023). plays a major role, thus the industry focus on already commercialized NMC cathodes that have a high energy density. This also demonstrates how battery demand will increase with an increase in the EV platform sizes, specifically in North America because of the introduction of sports utility vehicles and pickup trucks into the EV market (Kampker et al., 2023).

A plot of battery demand is shown in Figure 3c, as battery demand (MWh) versus NMC cathode type (NMC111, NMC622, and NMC811). The evolution of LIBs has resulted in the quest for higher-density EV batteries based on available critical minerals (Diouf & Pode, 2015). Figure 4 depicts the history of the development of LIBs over time (Xiao et al., 2023). The idea of LIBs emerged in the 1970s, and the commercialization of lithium manganese oxide (LMO), lithium iron phosphate (LFP), and lithium nickel cobalt aluminum oxide (NCA) batteries occurred in the 1990s. In 2000, NMC, niobium titanium oxide (NTO), and graphite anodes were fabricated. The Li-rich cathodes and C-Si alloy anodes have been developed in the 2020s. Solid-state batteries are the next phase in battery development, with their predicted commercialization in the 2030s. The difference of a solid state battery versus a traditional LIB is that the electrolyte is solid instead of liquid which is designed to increase the safety in a more energy dense battery (Naz, 2024).

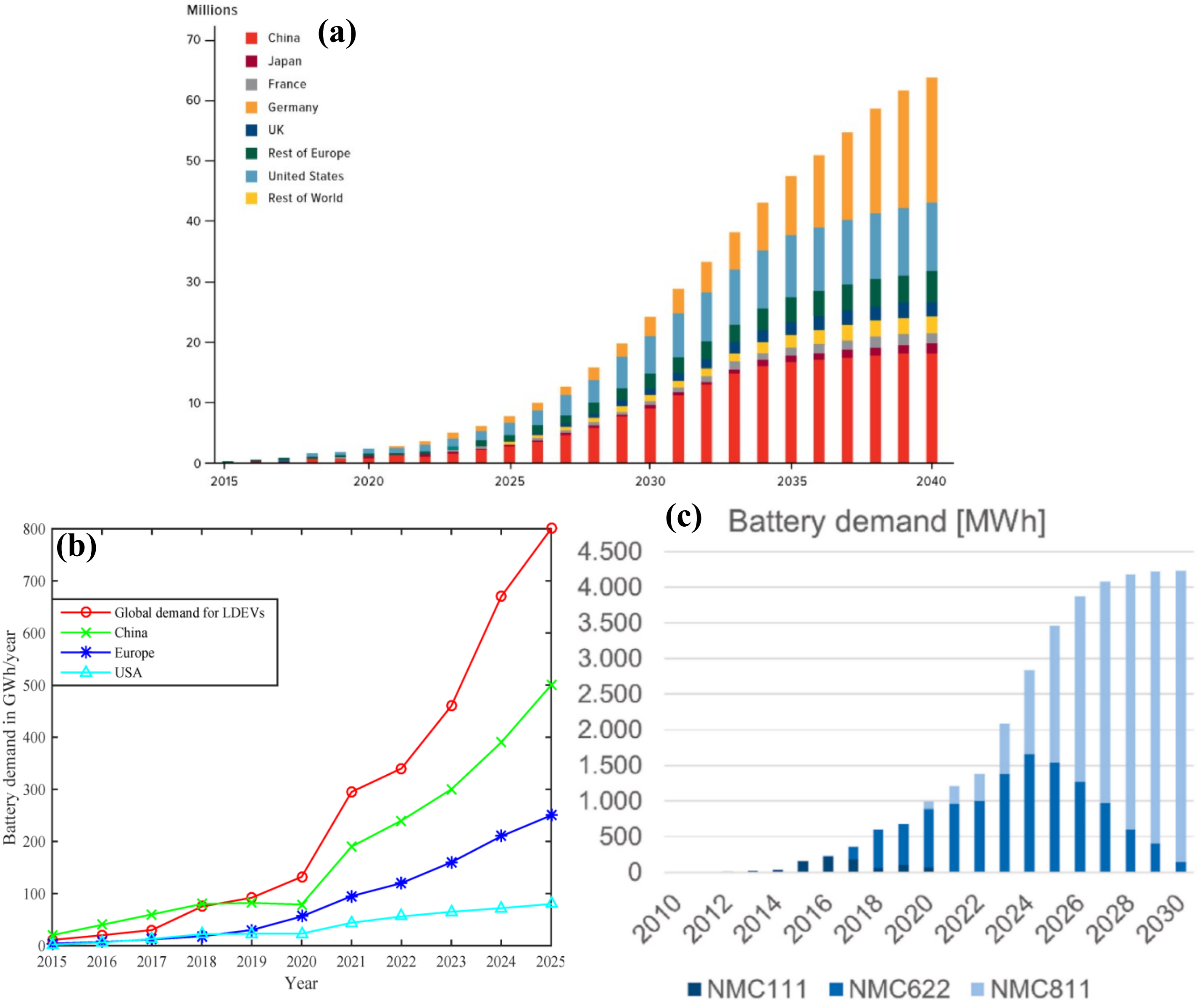


Figure 3: (a) Annual demand (millions) estimate for EVs worldwide (Mohammadi & Saif, 2023) (b) Global demand of batteries for light duty vehicles (Barman et al., 2023). (c) Increase in NMC111, NMC622, and NMC811 battery demand over time (Schulz-Mönninghoff et al., 2023).

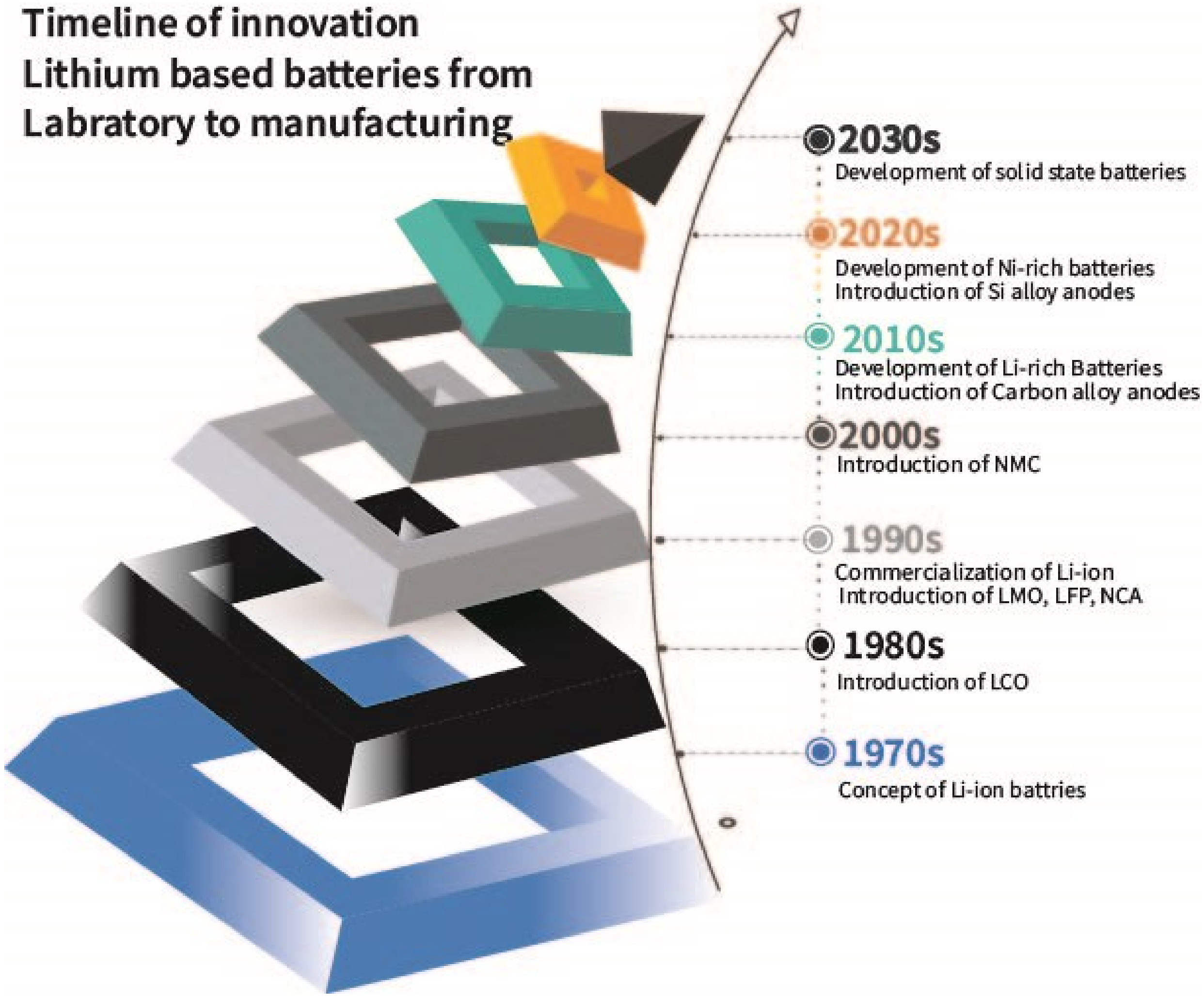


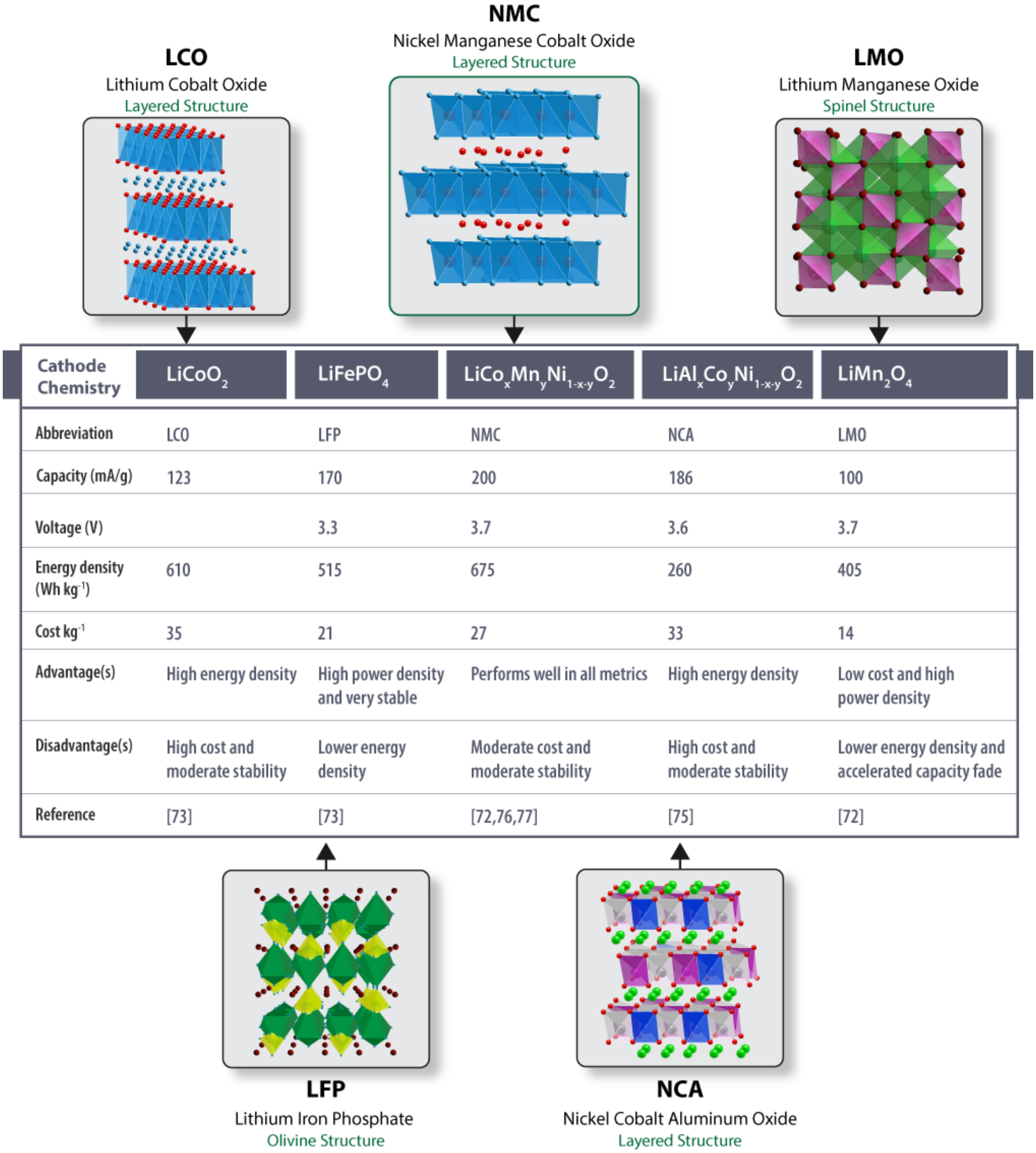
Figure 4: History of lithium-ion batteries (LIBs) (redesigned) (Xiao et al., 2023).

The availability of critical minerals in Canada (mainly the province of Quebec) and the United States will play an important role in the development of a North American sustainable LIB supply chain.

2.2 Changing battery chemistries

In developing high-energy-density, multi-cycling, fast-charging, low-cost, and safe LIBs, NMC cathode has been subjected to several modifications (Julien et al., 2014; Malik et al., 2022). Figure

5 shows the various cathode chemistries (namely, lithium cobalt oxide (LCO), LFP, LMO, NCA, and NMC). May be variations in the "Elements" or "Chemical compositions" of the cathode material (Chu et al., 2022) (as found in LCO/NMC), olivine, and spinel phases, which play an important role in the performances of these cathodes, must be determined. The structure of the cathode affects the energy capacity of the cathode, for example, NMC (layered) (200 mA g^{-1}) versus LFP (olivine) (170 mA g^{-1}) (Figure 5). These chemical structures also contribute to the energy densities of the cathodes (Wh kg^{-1}). Higher energy densities of NMC cathodes adversely affect the performances and safety of these cathodes (Hu et al., 2023) .The next stage in the development of LIBs is solid state batteries due to the intrinsic safety characteristics and high theoretical energy density (Li et al., 2019).



Cathode Chemistry	$LiCoO_2$	$LiFePO_4$	$LiCo_xMn_yNi_{1-x-y}O_2$	$LiAl_xCo_yNi_{1-x-y}O_2$	$LiMn_2O_4$
Abbreviation	LCO	LFP	NMC	NCA	LMO
Capacity (mA/g)	123	170	200	186	100
Voltage (V)		3.3	3.7	3.6	3.7
Energy density (Wh kg^{-1})	610	515	675	260	405
Cost kg^{-1}	35	21	27	33	14
Advantage(s)	High energy density	High power density and very stable	Performs well in all metrics	High energy density	Low cost and high power density
Disadvantage(s)	High cost and moderate stability	Lower energy density	Moderate cost and moderate stability	High cost and moderate stability	Lower energy density and accelerated capacity fade
Reference	[73]	[73]	[72,76,77]	[75]	[72]

Figure 5: Cathode chemical structures (redesigned) (Ding et al., 2019; Kiemel et al., 2021).

2.3 Battery Properties

2.3.1 Why NMC?

Cathode is one of the main components of a LIB. In the automotive industry, NMC cathodes are dominant transportation since it meets the industry requirements of battery range, charging, cost and safety (Fallah & Fitzpatrick, 2023). The NMC cathodes consist various stoichiometric ratios of Ni, Mn, and Co atoms (Stephan, 2020). In LIB, Mn stabilizes the structure, Ni determines the capacity, and Co increases the electrical conductivity, significantly influencing battery performance (Cheng et al., 2011; Xu et al., 2018) with respect to electrodes and is independent active material.

Stoichiometric ratios of these atoms affect different properties, including structural and chemical stabilities and charging capacity, of the NMC cathode (Jung et al., 2017) . NMC compounds can vary in size and crystal orientation, thereby leading to potential issues such as structural degradation, chemical destabilization, and heterogeneity of NMC (Stephan, 2020). Therefore, appropriate methods for material identification are required to ensure material quality, which significantly impacts LIB performance (Jones et al., 2023). Excellent performances of NMC cathodes are one of the primary reasons for the development of these cathodes. NMC cathodes are rapidly advancing, which has contributed to their widespread use in EVs and other high-demand applications (IEA, 2020; Nagmani et al., 2022). The cathode material used in the first commercial LIBs produced by Sony was $LiCoO_2$ (LCO), and NMC exhibits structural and chemical instabilities, which decreases cell the performance over time (Wood et al., 2019). Regulation of the crystallinity and size of the material are more difficult to control during cathode preparation, thus a complete understanding of NMC particle morphologies, crystal orientations, and grain boundaries is needed to optimize the performance of LIBs (Mohammadi & Saif, 2023). Higher energy densities and outstanding performances of NMC cathodes, particularly those with higher Ni contents, lead to superior energy densities when compared with those in the cases of other cathodes, for example, LFP cathodes. Ni-based cathodes are popular since they meet the requirement for application in higher-energy-capacity EV batteries (icct, 2024).

2.3.2 Cost

NMC cathode materials demonstrate advantages over traditional cathode materials such as LCO, in terms of cost. Despite its inferior chemical stabilities, NMC offers a higher capacity (160-200 Ah/kg^{-1}) and contains less amount of Co, reducing costs (since it does not have to be mined and imported from Africa). This is aligning with the industry shift toward cost-effective battery materials including LMO and changes to its LIB supply chain. Higher Ni content increases cation mixing; however, this may decrease structural stability (Li & Lu, 2020; T. Li et al., 2020). Although spinel oxides, such as $LiMn_2O_4$ and $LiNi_{0.5}Mn_{1.5}O_4$, exhibit high Li ion intercalation rates, they demonstrate some challenges, for instance, capacity fading caused by Mn dissolution in acidic media (Nie et al., 2018) $LiNi_{0.5}Mn_{1.5}O_4$ exhibits a specific capacity of 200 mAhg^{-1} and promising performance over a voltage range of 2.8-4.6 V (Nie et al., 2018). Polyanionic compounds, such as $LiFePO_4$, offer stability, safety, and low-cost advantages; nevertheless, they demonstrate low electrical conductivities. $LiFePO_4$ exhibits a stable redox potential of 3.5 V (vs. Li^+/Li) and high theoretical capacity of 170 mA·h·g^{-1}. ((Nie et al., 2018). NMC cathodes are solid solutions of $LiNiO_2/LiMnO_2/LiCoO_2$, which provide distinct advantages over other materials. These advantages include versatility in composition variations (e.g., NMC111, 532, 622, and 811) to tailor properties based on specific requirements and structural stability because of the Jahn–Teller inactivity of Mn^{4+} and energetic favourability of Ni^{2+} (Nie et al., 2018). NMC 111. For instance, demonstrates a specific capacity of 200 mA·h·g^{-1} within a voltage range of 2.8–4.6 V and a reversible capacity of 160 mA·h·g^{-1} (Nie et al., 2018). Coating NMC 811 with magnesium oxide (MgO) improves the coulombic efficiency of NMC811 because of less Ni and Li mixing within the NMC lattice (Ma et al., 2019). Additionally, MgO coatings improve the stability of NMC811 during potential cycling, reducing the resistance during Li^{+} insertion and extraction (Iriyama et al., 2004). Similar ionic radii of Mg^{2+} and Li^{+} lead to high structural stability as Mg^{2+} and Li^{+} attract adjacent layers in the cathode. Furthermore, decreasing the Co contents in NMC cathodes can mitigate the issues (such as high costs of raw materials, inferior performances, and low structural stabilities of these cathodes) related to Co. High-Co NMC formulations, for instance NMC111 have been replaced by lower-Co alternatives, such as NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$), and zero-Co alternatives, for example, spinel $LiNi_{0.5}Mn_{1.5}O_4$ and layered Ni-rich $LiNi_{1-x}M_xO_2$ (Z. Chen et al., 2019; Li et al., 2023; Lu et al., 2013; Zuo et al., 2017), Increasing the Ni content in NMC-type cathodes enhances the capacities of these cathodes; nevertheless, this also renders these cathodes more reactive and less stable in the presence of liquid organic electrolytes, moisture, and cracks (Z. Chen et al., 2019; Gong & Yang, 2011; Hu et al., 2013; Lu et al., 2013; Mao et al., 2019; Mizushima et al., 1981; Xu et al., 2018).

Widespread adoption of NMC in EVs and other applications is attributed to the balance between cost (Patry et al., 2015), capacity, and reduced Co content (Li & Lu, 2020) of NMC as compared to that in the case of LCO (Julien et al., 2014). Despite the inherent challenges related to the stability, performance, and cost of NMC, the material properties and potential for performance optimization render NMC an attractive cathode material (Malik et al., 2022) (Figure 6a and b).

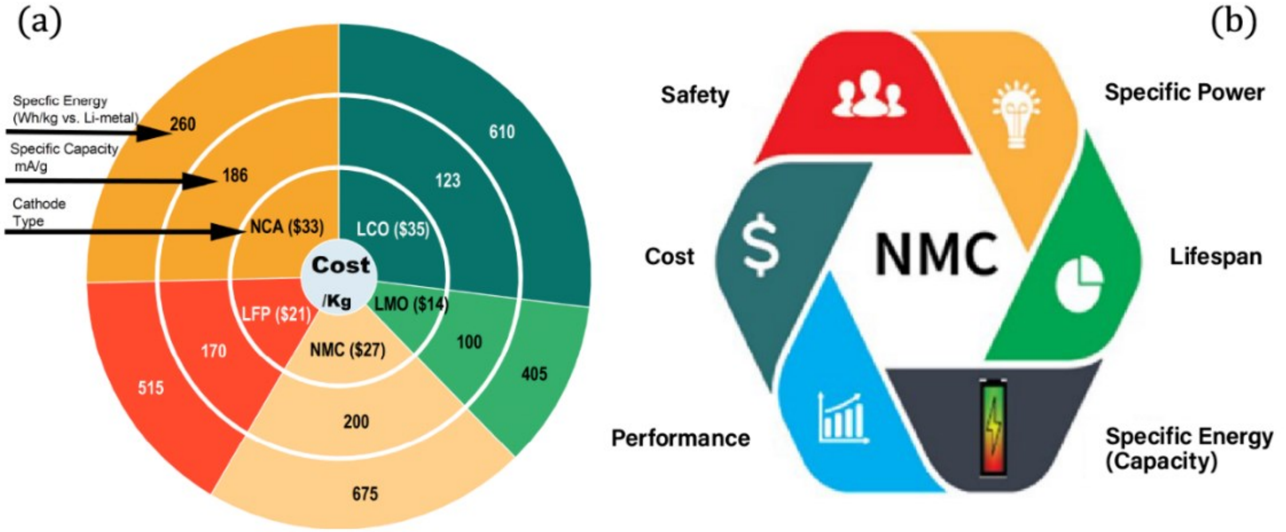


Figure 6: a) Graphical representation of Table 1: Specific capacity (mA g-1), specific energy (Wh kg-1), and cost/kg of LCO, LMO, NMC, LFP, and NCA cathodes (ANL, 2024; Chae et al., 2013; Kaur & Gates, 2022) (b) Important NMC parameters (Ahmed et al., 2017).

Table 1: Specific capacity (mAg-1), specific energy (Wh kg-1), and cost kg-1 of LCO, LMO, NMC, LFP, and NCA cathodes with advantages and disadvantages

Reference	Chemical formula	Abbreviation	Specific capacity (mA g^{-1})	Specific energy (Wh kg^{-1} vs. Li-metal)	Cost kg^{-1}	Advantages (s)	Disadvantage (s)
(Patry et al., 2015)	$LiCoO_2$	LCO	123	610	35	High energy density	High cost and moderate stability
(Mao et al., 2019)	$LiMn_2O_4$	LMO	100	405	14	Low cost and high-power density	Lower energy density and accelerated capacity fade
(ANL, 2024)	$LiNixMnyCo1-x-yO_2$	NMC	200	675	27	Performs well in all metrics	Moderate cost and moderate stability
(Patry et al., 2015)	$LiFePO_4$	LFP	170	515	21	High power density and very stable	Lower energy density
(ANL, 2024)	$LiNi_xCo_yAl_{1-x-y}O_2$	NCA	186	260	33	Energy density	High cost and moderate stability

Table 1 presents the advantages and disadvantages of various cathode chemistries, which support the use of NMC cathodes for LIBs in the automotive industry (ANL, 2024; Mao et al., 2019; Patry et al., 2015). These advantages and disadvantages are graphically shown in Figure 6a. The transition metals used in the cathodes play a significant role in determining the overall performance and costs of LIBs. NMC and NCA ($LiNi_xCo_yAl_{1-x-y}O_2$) cathodes (Kraft et al., 2021), which involve various ratios of Ni to other metal cations in different ratios, are pivotal in promoting the development of the automotive battery industry because of their high cycling and thermal stabilities (Ahmed et al., 2017; Lee et al., 2001). In addition to the environmental impacts, key parameters must be considered when producing NMC cathodes, including a) specific energy, b) cost, c) specific power, d) safety, e) performance, and f) lifespan must be considered during the synthesis of NMC cathodes (Gutsch & Leker, 2024; Kaur & Gates, 2022). Specific power and lifespan are optimized (Purwanto et al., 2024) in the NMC cathode which make it very attractive to the automotive industry. Cathodes contribute significantly to the production costs and environmental impacts of LIBs. Cathodes that substantially rely heavily on scarce metals such as Ni and Co, exhibit limitations owing to the limited reserves and high prices of these metals (S. Ziegler et al., 2021; Yang et al., 2022). Therefore, advancing LIBs using more sustainable cathode materials is essential to balance sustain abilities, cost, and performances of these batteries (Gutsch & Leker, 2024). Precursor preparation conditions (for example, sintering time, temperature, and atmosphere), morphology, and electrochemical performance, capacity retention, impedance, and cycle stability are also important for developing NMC cathodes (Hawley et al., 2023). Preparation techniques incorporated into the manufacturing of NMC cathodes are a significant factor that contribute to the overall costs of the materials (Nisa et al., 2022). In addition to the critical mineral costs of cathodes, the processes employed to develop the precursors can consume large amounts of water and generate waste (Tahmasebi et al., 2023). During the establishment of new LIB supply chains in Canada and the US, processes must be carefully selected to reduce the environmental impact and produce a “green battery” to be truly sustainable (Berry, 2023).

NMC cathode materials demonstrate advantages over traditional cathode materials, such as LCO, in terms of cost. Despite its inferior structural and chemical stabilities, NMC affords a higher capacity (160-200 Ah kg^{-1}) and contains less Co, which reduces costs and aligns with the industry shift toward cost-effective battery materials (Schöberl et al., 2024). NMC cathodes contribute to more than 20% of the costs of EV batteries (Ahmed et al., 2017). Approximately 4 kWh of energy and 15 L of water are required to produce 1 kg of NMC, and 50% of the cost of generating NMC is attributable to raw materials. Specific energy, cost, specific power, safety, performance, and lifespan are all drivers of the changing NMC cathode chemistry (Ahmed et al., 2017; Greenwood et al., 2021).

2.3.3 Performance

Understanding the relationships among the cathode performance, mechanical properties, and degradation are crucial for the appropriate functioning of LIBs (Stallard et al., 2022). With an increase in the demand for LIBs by the automotive industry, the requirement of NMC cathode with higher performance, which are dependent on the crystallinity, morphology characterization (Celeste et al.), and other parameters during the synthesis of these NMC cathodes has increased (Malik et al., 2022). Charge/discharge cut-off voltages play an important role in the development of high-performance LIB, as shown in (Figure 7a, c, and e). Although layered oxides, including $LiCoO_2$ and $LiNiO_2$ exhibit outstanding conductivities, they demonstrate structural instabilities during charge cycling (Nie et al., 2018). $LiCoO_2$ provides a reversible capacity of 140 $mA \cdot h \cdot g^{-1}$ at

4.2 V, whereas $LiNiO_2$ can achieve a capacity of 240 $mA \cdot h \cdot g^{-1}$; however, they experience structural changes compromising their thermal stabilities (M. Chen et al., 2019; Z. Chen et al., 2019). These cathodes are highly sensitive to the mechanical pressure exerted on the cell, which can affect their performances and cycling life (Kaboli et al., 2020; Li et al., 2023; Sun et al., 2023).

2.3.4 Specific Energy

NMC811 exhibits a specific energy of over 600 $Whkg^{-1}$, indicating its potential for realizing high energy density (Heenan et al., 2020; Jung et al., 2017; Zhao et al., 2017). It demonstrates favorable rate capabilities, with an electronical conductivity of ~2.8×10^{-5} S cm^{-1} and Li^+ diffusivity (McClelland et al., 2023) of 8-9 cm^2s^{-1}. These characteristics support the potential of NMC811 for achieving high reversible capacities (>200 mAh $gNMC^{-1}$) and desirable rate capabilities (Jung et al., 2017) (Figure 7b). Figure 7d shows discharge capacity $mAhg^{-1}$versus current density

mAg^{-1}. Despite the challenges related to Ni-rich formulations, such as oxygen release and structural instabilities associated with Ni-rich formulations, research efforts have aimed to understand and mitigate the degradation mechanisms of NMC811. Studies have suggested that defects, including within NMC811 particles, can occur because of electrochemical expansion/contraction, grain orientation, and structural changes during cycling (Heenan et al., 2020; Li et al., 2023; Zhao et al., 2017). NMC cathodes exhibit a charge rate (C-rate) ranging from 0.7 to 1C at 4.20 V (Figure 7a, c), whereas the discharge rates (C-rate) at 1C and 2C can be attained for certain cells, with a cut-off voltage of 2.50 V. This cathode chemistry achieve a balance between the strengths of Ni and Mn, thereby ensuring stable performance (Mayyas et al., 2023) (See Figure 7).

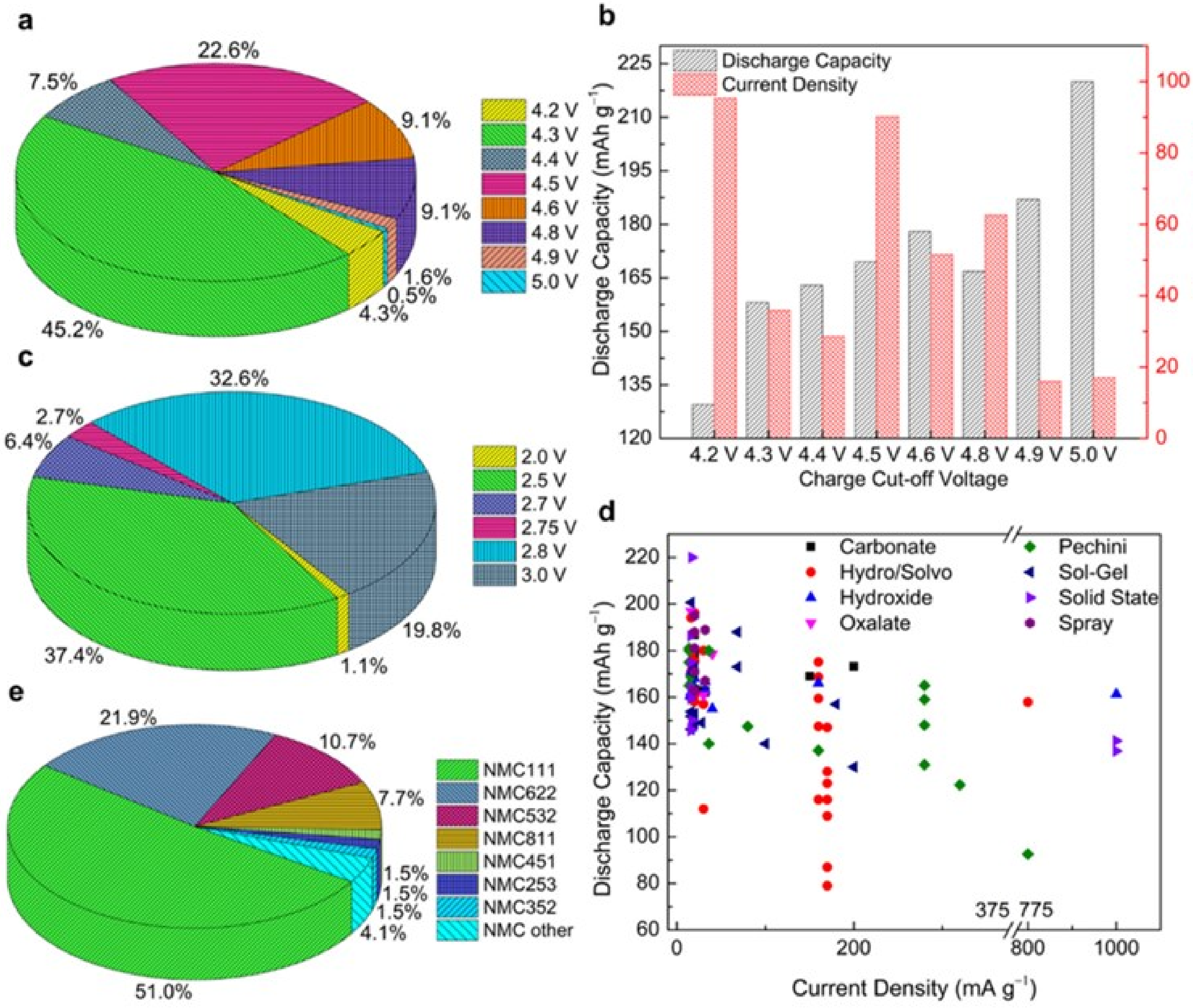


Figure 7: (a,c and e) Summary of the charge and discharge cut-off voltages and current density and (b) their effects on the discharge capacity of the $\text{LiNixMnyCo1-x-yO}_2$ cathode material (Malik et al., 2022)

2.3.5 Safety

Safe operation of the cathode is a crucial characteristic of LIBs. Table 2 lists the safe operating parameters of the NMC cathode (Kaur & Gates, 2022).

Nevertheless, NMC cathodes demonstrate high stabilities during cycling, higher reversible capacities, and better thermal stabilities in charged states as compared to those of LCO cathodes, which renders them promising candidates for LIBs (Julien et al., 2014; Yabuuchi & Ohzuku, 2003).

Safety issues associated with LIBs due to their physical/chemical natures support the need for suitable characterization (Tiozzo et al., 2024) of NMC cathode materials. NMC cathodes suffer from many challenges including 1) solvent co-interaction and graphite exfoliation, 2) structural disordering, 3) particle cracking, 4) internal short-circuit, 5) solid electrolyte interphase decomposition and precipitation, 6) binder decomposition/contact loss, 7) dendrite formation, and 8) transition metal dissolution (Kaur & Gates, 2022), 9) corrosion of current collectors as shown in (Figure 8). These challenges can lead to side reactions that decrease the battery performance (White et al., 2020), resulting in reduced battery life and power capacity (Kaur & Gates, 2022). Dendrites are formations across the separator that cause short circuits and result in thermal runaway (Aslam et al., 2021).

Table 2: Safe operating parameters for the NMC cathode (Kaur & Gates, 2022).

NMC cathode operating parameters	
Operation	2–4 V
Charging	0–45 °C
Discharging	−20–55 °C
Electrolyte decomposition	70 °C
Solid phase electrolyte (SEI) decomposes	90–120 °C
Production of flammable gases	> 120 °C
Separator melts	130 °C
Cathode material decomposes	150 °C
Thermal runaway (self-heating)	10 C/min* 11

*When a cell is under thermal runaway, temperature increases at a rate of 10°C per minute.

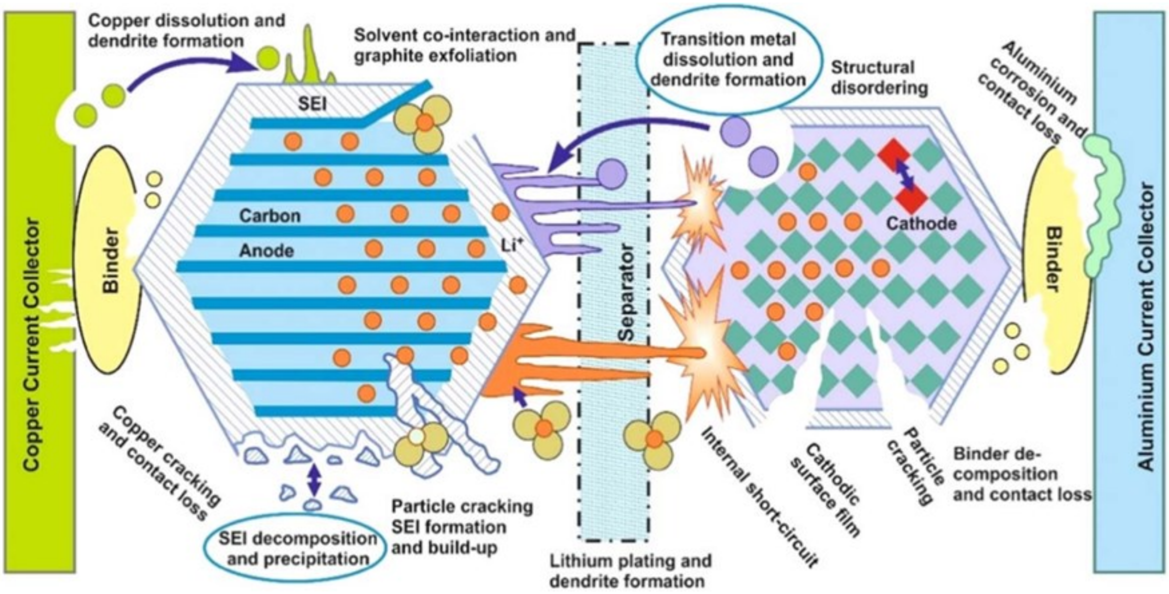


Figure 8: Dendrite formation based on material properties and different chemistries (Kaur & Gates, 2022).

Moreover, other limiting factors such as cell performance, cost, manufacturing capabilities, supply chain, and logistics, must be considered during the production of NMC cathodes (Wentker et al., 2019). Several parameters of NMC cathodes and desired properties of the cathode are important in

developing the synthesis method with respect to cathode properties (Malik et al., 2022), (Figure 9), have been modified to realize high energy densities, multi-cycling capabilities, fast charging rates, cost-effectiveness, and safety of these cathodes in LIBs (Hu et al., 2021).

Electrochemical performance is a crucial aspect of lithium-ion EV batteries and is directly related to the crystal structures (Garcia et al., 2017) of materials, for example, the NMC cathode (Kaur & Gates, 2022; Para et al., 2023). In addition to electrochemical performance, safety is an area of concern for LIBs considering previous failures reported for Samsung phones (2016), Boeing 787 aircraft (2013), and Tesla model S vehicles (2019) (Kaur & Gates, 2022) Goodenough. Yazami, and Yoshino were awarded the 2012 Institute of Electrical and Electronics Engineers Medal for Environmental and Safety Technologies for their work on LIBs (Deng, 2015). Specific energy is a driving force in the development of LIBs, and automotive battery manufacturers are dedicating significant efforts to eliminate the use of Co (R. Zhang et al., 2023), Figure 10 shows the evolution of battery chemistry using a recursive model that represents the average Co content (g/kWh), average Co content per LIB, and average LIB size (kWh) (Mayyas et al., 2023; Xiao et al., 2023).

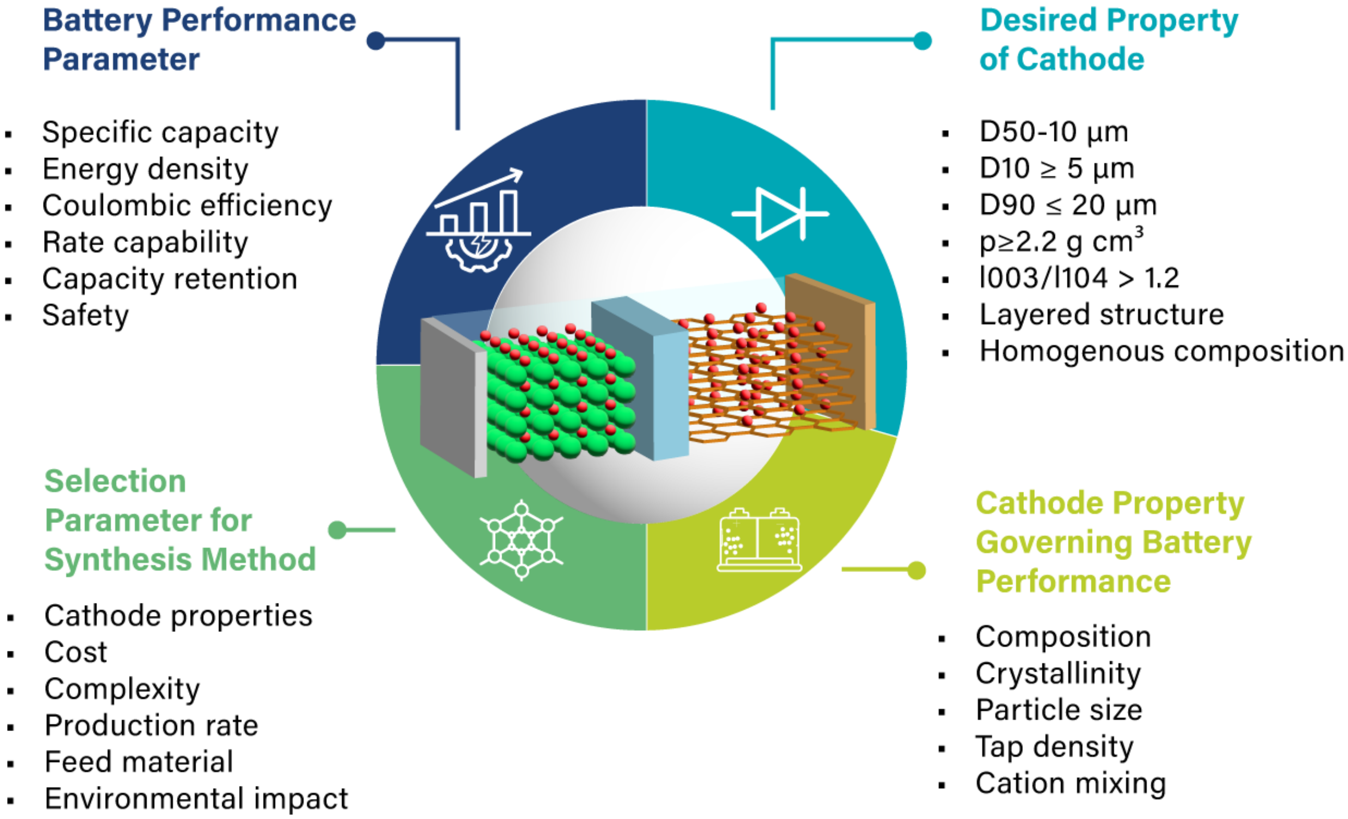


Figure 9: Review on the synthesis of LiNixMnyCo1-x-yO2 (NMC) cathodes for LIBs (redesigned) (Malik et al., 2022).

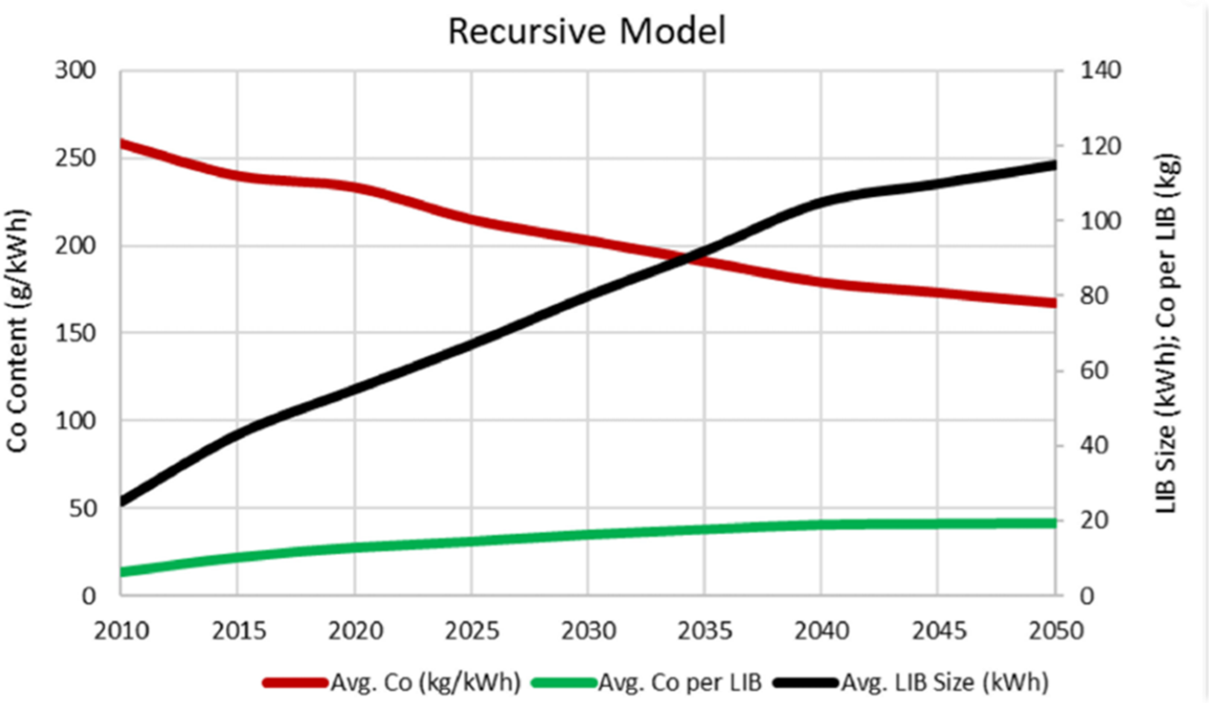


Figure 10: Evolution of battery chemistry using a recursive model of average Co content (g/kWh) and average LIB size (kWh) (Mayyas et al., 2023).

Assumptions of the recursive model demonstrating cathode evolution, LIB size and estimated Co content in kg kWh^{-1}. Upon examining the recursive model, we observed a gradual increase in LIB size (kWh) from 2010 to 2050 (Figure 10 and Table 3). Average Co used (kg kWh^{-1}) is decreasing with time; however, the average Co used in LIBs is increasing gradually and becoming steady despite the increase in LIB size by almost 2.5 times (50-120 kWh) (Mayyas et al., 2023). Furthermore, Ni is becoming an issue for EV makers, and therefore, fabricating a LIB with very low Ni and Co contents that maintains a high specific energy and stable system is challenging (R. Zhang et al., 2023). Overall, these properties such as cost-effectiveness, safety, performance, and specific energy make NMC cathodes a preferred choice for LIBs in EVs. Their balanced properties address the key requirements of high-performance and safe battery systems needed for widespread adoption of electric mobility in the automotive industry.

Table 3: Assumptions of recursive model for the evolution of the NMC cathode. (Mayyas et al., 2023).

Cathode	2010	2015	2020	2025	2030	2035	2040
NMC	NMC111 (45%)	NMC 111 (35%)	NMC 111 (40%)	NMC 111 (20%)	NMC 111 (10%)		
	NMC 532 (55%)	NMC 532 (50%)	NMC 532 (30%)	NMC 532 (50%)	NMC 532 (35%)		
		NMC 622 (205)	NMC 622 (25%)	NMC 622 (30%)	NMC 622 (35%)		
		NMC 811 (<5%)	NMC 811 (<5%)	NMC 811 (10%)	NMC 811 (20%)		
kg Co per battery	6.34	10.8	13.39	15.17	14.68		
Battery size kWh (extrapolated) *	25	43	55	67	80	92	105
NCA**	83% Nickel (Ni) (100%)	83% Ni (100%)	83% Ni (48%)	83% Ni (40%)	83% Ni (25%)		
			87% Ni (52%)	87% Ni (45%)	87% Ni (40%)		
				90% Ni (15%)	90% Ni (35%)		
Recovery Rate			46.50%	50%	70%	75%	80%
Collection Rate ***			20%	50%	60%	75%	85%

*As forecast in Aviceene report. ** Based on EIA 2020. *** Fraction of spent batteries obtained for recycling in year t.

2.4 Mining

2.4.1 Availability of Critical Minerals

A considerable supply of critical minerals is essential to meet the growing global demand for LIBs. Currently, over 85% of LIBs components are acquired from Asian countries, mainly China (Moores, 2021). In North America, particularly in the US and Canada, a recent shift towards establishing a local green supply chain for the critical minerals used in LIBs is occurring (Figure 11). The Biden administration in the US is encouraging LIB growth under IRA (Prina Cerai, 2024) to ensure the availability of jobs in America (Trost & Dunn, 2023).

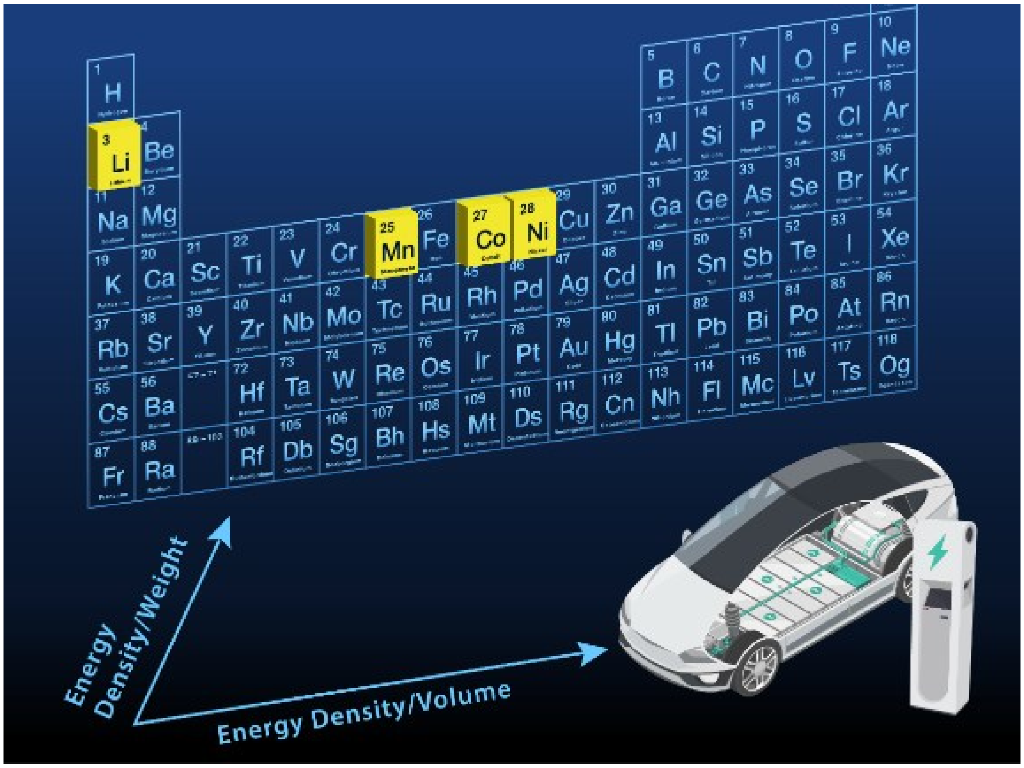


Figure 11: Critical minerals (Li, Mn, Co, and Ni) used in NMC cathodes.

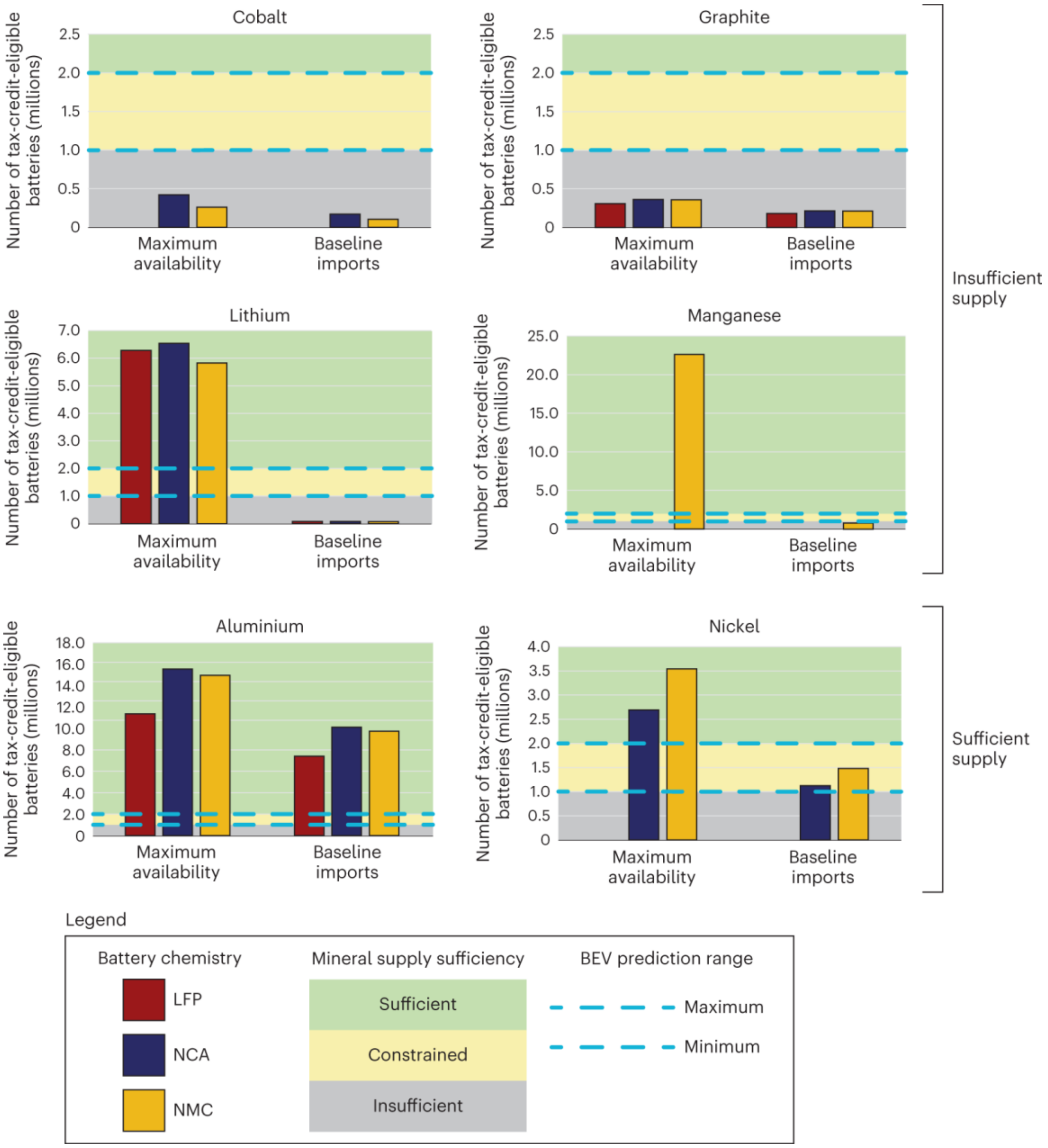


Figure 12: Critical mineral supply based on battery chemistry (Trost & Dunn, 2023) with NMC, NCA, and LFP chemistries are represented by blue, yellow, and rust-colored bars, respectively Bars that fall within areas that are shaded in grey, yellow, or green, respectively, represent inadequate, limited, and sufficient mineral supply.

Figure 12 depicts critical mineral supply chains based on various battery chemistries (namely LFP, NCA, and NMC). These data indicate an insufficient supply of critical minerals for NMC, which is another driver for the development of a North American supply chain. Critical minerals' mass target or market value at the battery level are not taken into consideration in this analysis. It suggests that the supply of nickel and aluminum eligible for Inflation Reduction Acts (IRAs) is plenty. Notably, though, under either scenario of availability, there is not enough graphite or cobalt to meet demand. The supply of manganese is likewise limited. Regarding plug-in hybrid electric vehicles (PHEVs), the only minerals that show inadequate supply of other IRA-eligible minerals are cobalt and lithium. These minerals would enable the production of sufficient batteries to fulfill demand. Lithium supply is adequate for battery electric vehicles (BEVs) in the maximum-availability scenario, but it is insufficient at normal import levels. With supply chains adapting to a shifting policy environment, the US may increase its share of qualifying minerals, such as lithium (Survey_U.S.G, 2020).

2.4.2. Lithium (Li) Sources

Lithium can be found in different parts of the world. Australia leads the global Li production with several mines, and there are brine operations have been reported in Chile, Argentina, and Bolivia (lithium triangle), with the remaining Li mining conducted in China (IBAT, 2024). Spodumene mines and salt brine water are the two primary global sources of Li (IBAT, 2024). Li projects range from traditional hard rock mining to unconventional sources, including salt brines and industrial wastewaters (IBAT, 2024). Extracting lithium from ores involves resource-intensive processes such as calcination, roasting, and purification, which consume more energy. Its environmental impact largely stems from emissions linked to fossil fuel use, which can be 9.3-60.4 times higher than lithium extraction from brine (Gao et al., 2023).

Spodumene are hard rock clusters of crystals containing lithium that are mined using “traditional” mining processes. These processes are complicated and expensive and exhibit significant environmental impacts because of the consumption of large volumes of chemicals, production of considerable amounts of waste, and involvement of processes that necessitate extensive maintenance. General Li compounds are synthesized in numerous forms, which include lithium carbonate (Li_2CO_3), lithium oxide (Li_2O), and lithium hydroxide (LiOH) (Burkin, 2001; NRC, 2024b). Li_2CO_3 and LiOH are key components of EV batteries. Hard rock extraction of spodumene is performed via open-pit mining using sulfuric acid, and the subsequent processing of spodumene comprises the use of sulfur acid and water to transform α-spodumene to β-spodumene via roasting to obtain Li_2CO_3 (Song et al., 2019) (Figure 13 a-c).

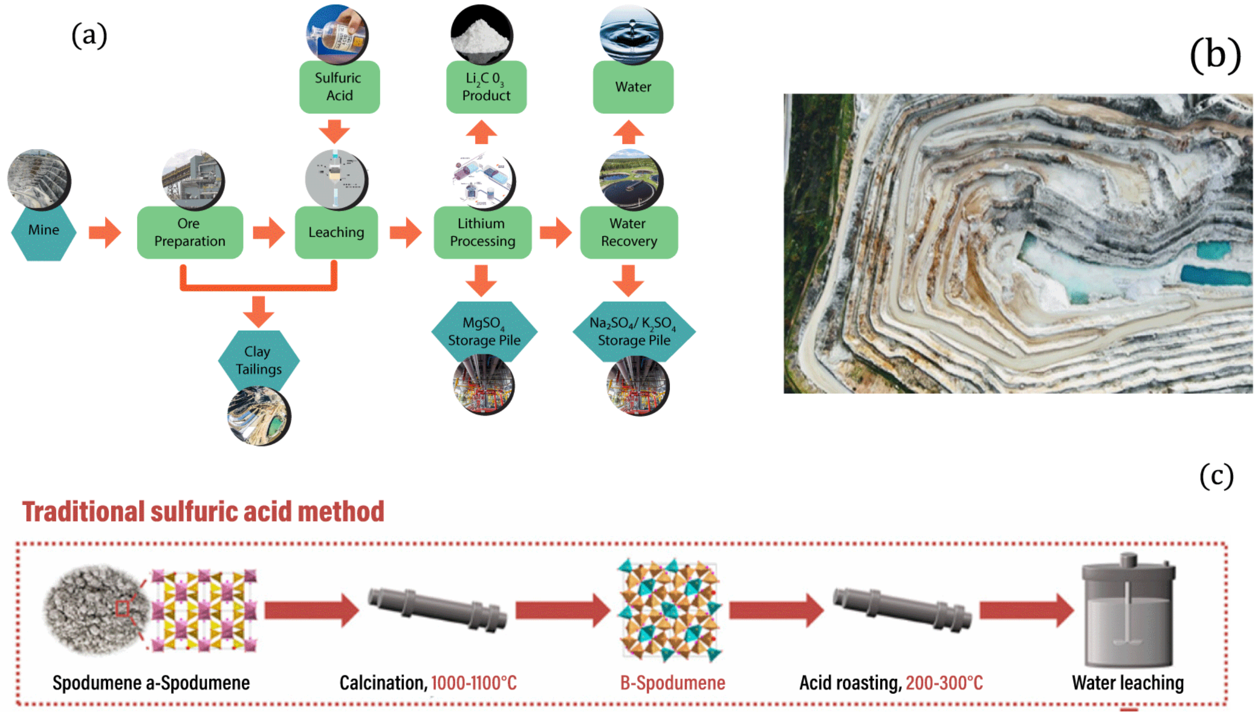


Figure 13: a): Spodumene (hard rock ore mining) (redesigned) (Song et al., 2019) b): Open pit hard rock mining of α-spodumene (Survey_U.S.G, 2020). c) Transformation of lithium from α-spodumene to β-spodumene via roasting to achieve Li_2CO_3 (Song et al., 2019).

Lithium is extracted from salar brine water in South American countries such as Argentina, Bolivia, and Chile (IBAT, 2024). Direct impact of this type of traditional salar brine processing involves the heavy consumption of groundwater, which affects local residents by leaving large salt piles, and this processing demonstrates with very low Li recovery rates. Figure 14(a, b.1, b.2) shows the typical extraction of Li from salar brine to produce Li_2CO_3 (Flexer et al., 2018).

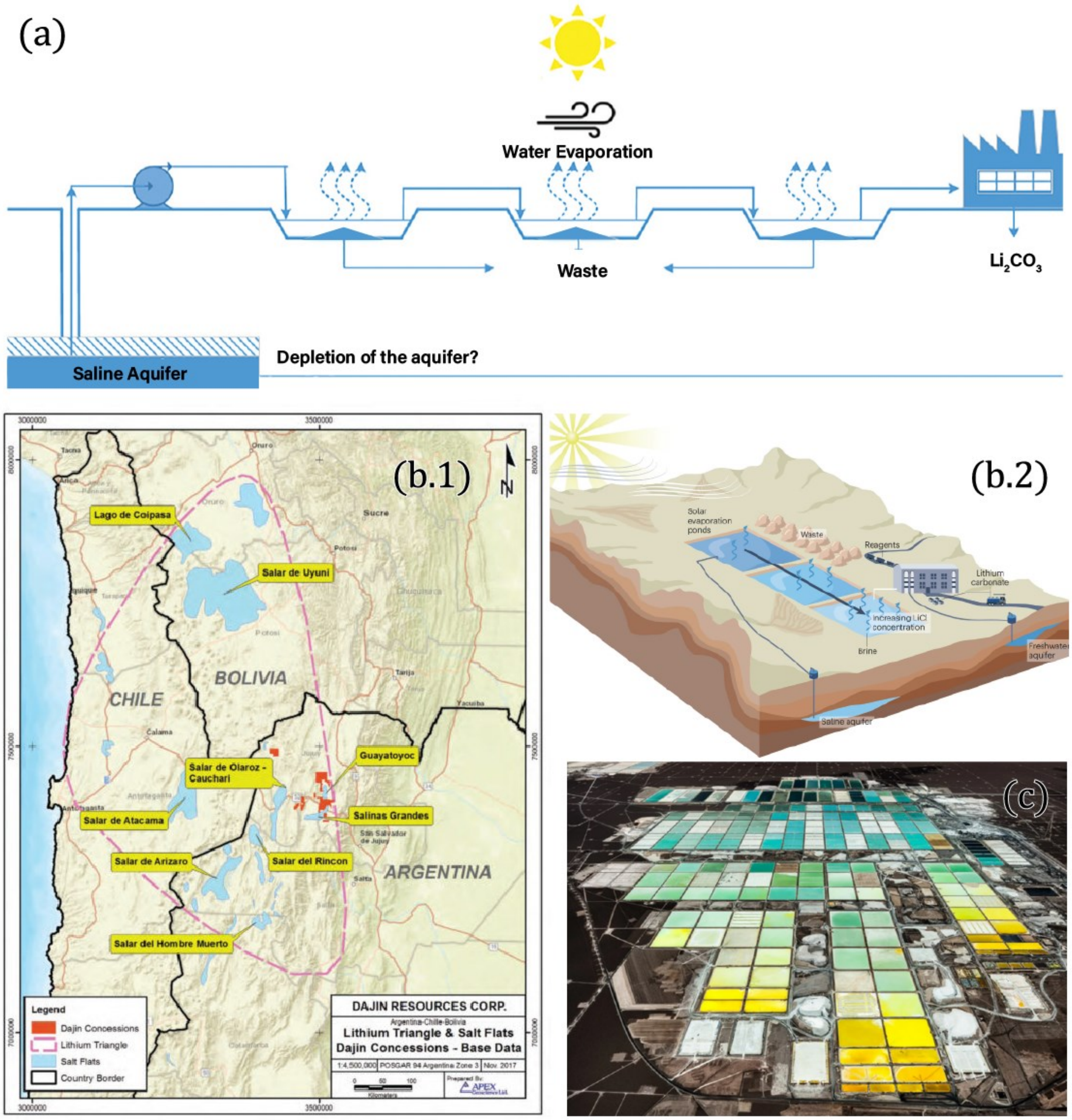


Figure 14: a) Traditional Li extraction from salt brine lakes (Flexer et al., 2018) b.1) "Lithium triangle" in South America World map of lithium brine deposits and b.2) Direct Li extraction from brines (Vera et al., 2023) c) Li salt brine extraction in South America (euronews, 2022).

Extraction of Li_2CO_3 requires large quantities of water and is a time-consuming process (Al-Jawad et al., 2024). Salar brine deposits represent over 50% of the global Li resources (Munk et al., 2016);

and these deposits may become more important to the LIB supply chain as the demand for Li is forecasted to increase by 40% according to the International Energy Agency (IEA, 2021). Figure 14 (b.1) depicts the Li triangle area in South America (Chile, Bolivia, and Argentina) and the solar evaporation ponds leading to concentrated lithium carbonate. Multicolored ponds, in Figure 14(c) suggest visual representations of various concentrations of Li as water is evaporated by the sun over time (Flexer, 2018).

Researchers have been investigating other sources of Li because of the globally increasing demand for Li. Extracting from seawater (Figure 15) via pulsed electrochemical intercalation is another possible method of Li extraction (Liu et al., 2020), which is an interesting method to explore, as the amount of Li in seawater is 5,000 times the combined amount of Li in ore (hard rock) and brine based resources (Liu et al., 2020). Intercalation chemistry naturally offers high selectivity for Li owing to the higher structural activity of Li in $FePO_4$ and faster ion diffusion (Dixit et al., 2015; Zhu et al., 2013).

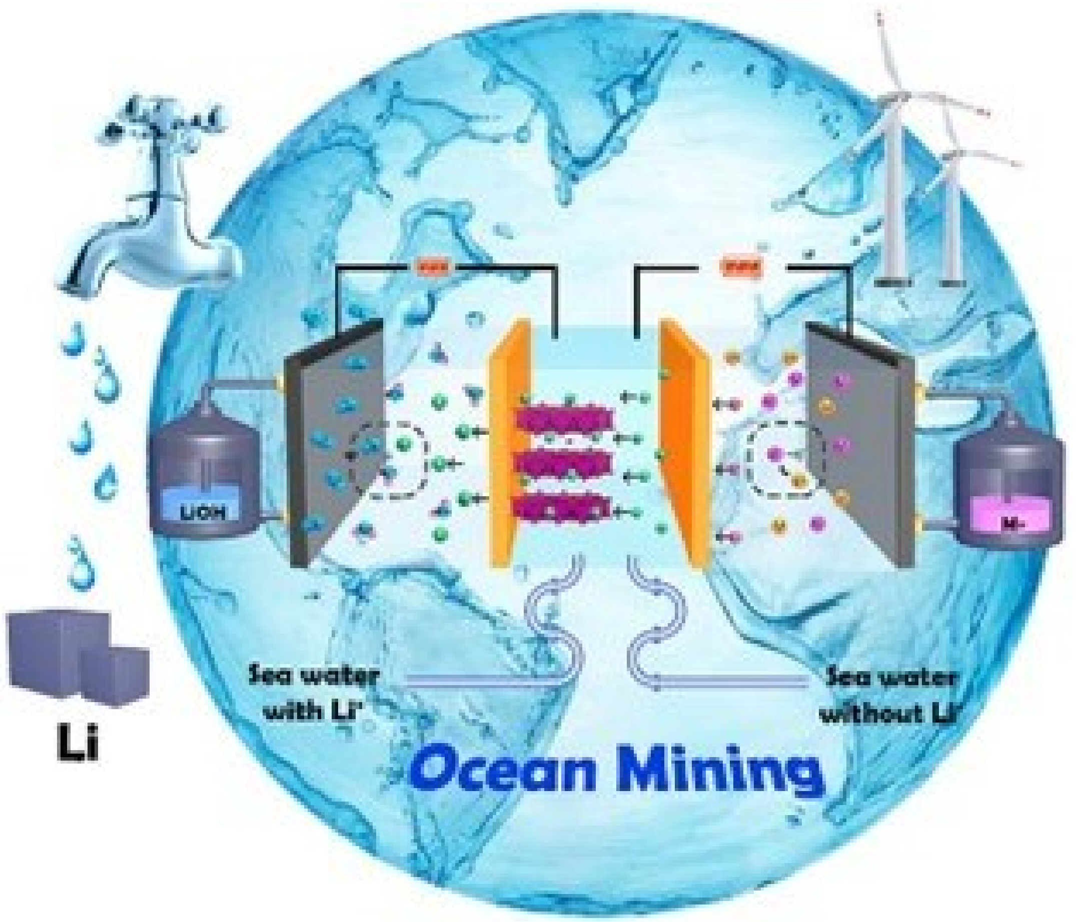


Figure 15: Extraction of lithium from sea water (purple equals sea water with Li+ and without Li+1) (Yu et al., 2020).

Canada is rich in the critical minerals, for instance, Li, Ni, Mn, Co, and graphite used in the synthesis of LIBs (Canada-Service, 2022). Canada is estimated to comprise 2.9 million tons of Li resources (Canada-Service, 2022) (Figure 16). Advantageously, Canada is a part of the USMCA signed in July 2020 (IBAT, 2024). Under this agreement, the North American automobile sector can obtain critical minerals and low-cost hydro-electric power from Canada, specifically from Quebec (E&MJ, 2023; Ibarra-Gutiérrez et al., 2021). In Quebec, Nemaska Lithium produced its first spodumene concentrate at the Whabouchi Mine in 2017. In early 2018, the Nemaska mine shipped spodumene concentrate to refineries in China for this concentrate processing into Li_2CO_3.

Analyzing lithium extraction relative to other critical minerals like nickel, cobalt, manganese, and aluminum is crucial for understanding Canada's evolving mining landscape, particularly in regions such as Quebec. While traditional mining activities have long centered around minerals like nickel, cobalt, manganese, and aluminum, the emergence of lithium mining presents both opportunities and challenges. In Quebec, specifically, the exploration and development of lithium deposits have accelerated in recent years, driven by the province's rich mineral reserves and supportive government policies. Quebec's abundant hydroelectric resources also provide a clean energy advantage for lithium extraction operations, further enhancing the region's appeal for investment in the lithium sector.

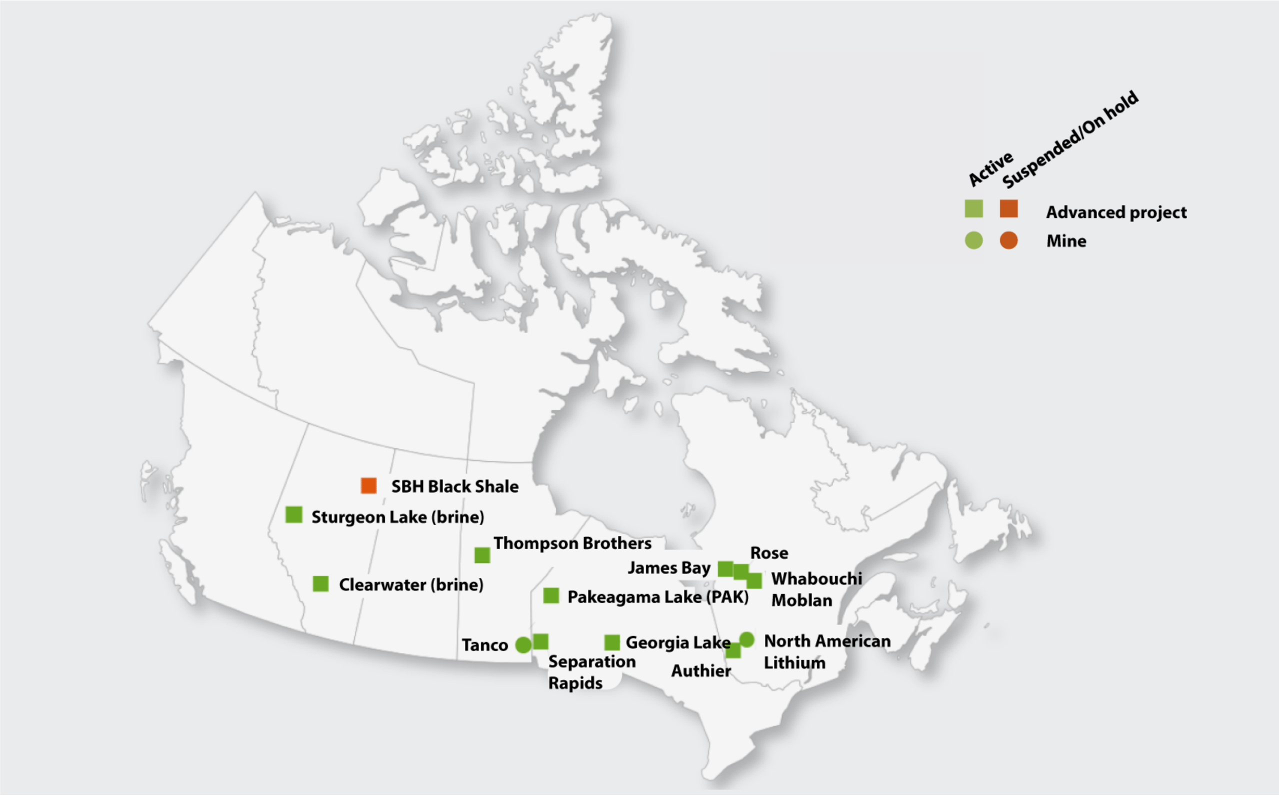


Figure 16: Canadian Li projects during, 2021-2022 (IBAT, 2024).

2.4.3 Nickel (Ni) Sources

Battery-grade Ni used in Ni cathode chemistries such as NMC and NCA (Campagnol et al., 2017) is in the form of nickel sulfate ($NiSO_4$) and can be generated from high-purity Ni (Class I; 99.8% Ni), which is mainly found in Canada, Russia, and China (USGS, 2024c). Class I Ni represents 70%, whereas the other 30% comes from lower-purity Ni as matte and mixed sulfide precipitate. Lattice ore is another form of Ni and is found in countries including Indonesia, Philippines, and New Caledonia (USGS, 2024c). Among 186 Ni mines operating globally, (Dixit et al., 2015) 19 are located in Canada (Carmen, 2022). Canada produced 134,000 metric tons of Ni in 2021, ranking sixth in global Ni production (NRC, 2018).. In addition to Ni, Canada has other critical minerals, including Mn, Co, graphite, and Al (Canada-Service, 2022) (Figure 17).

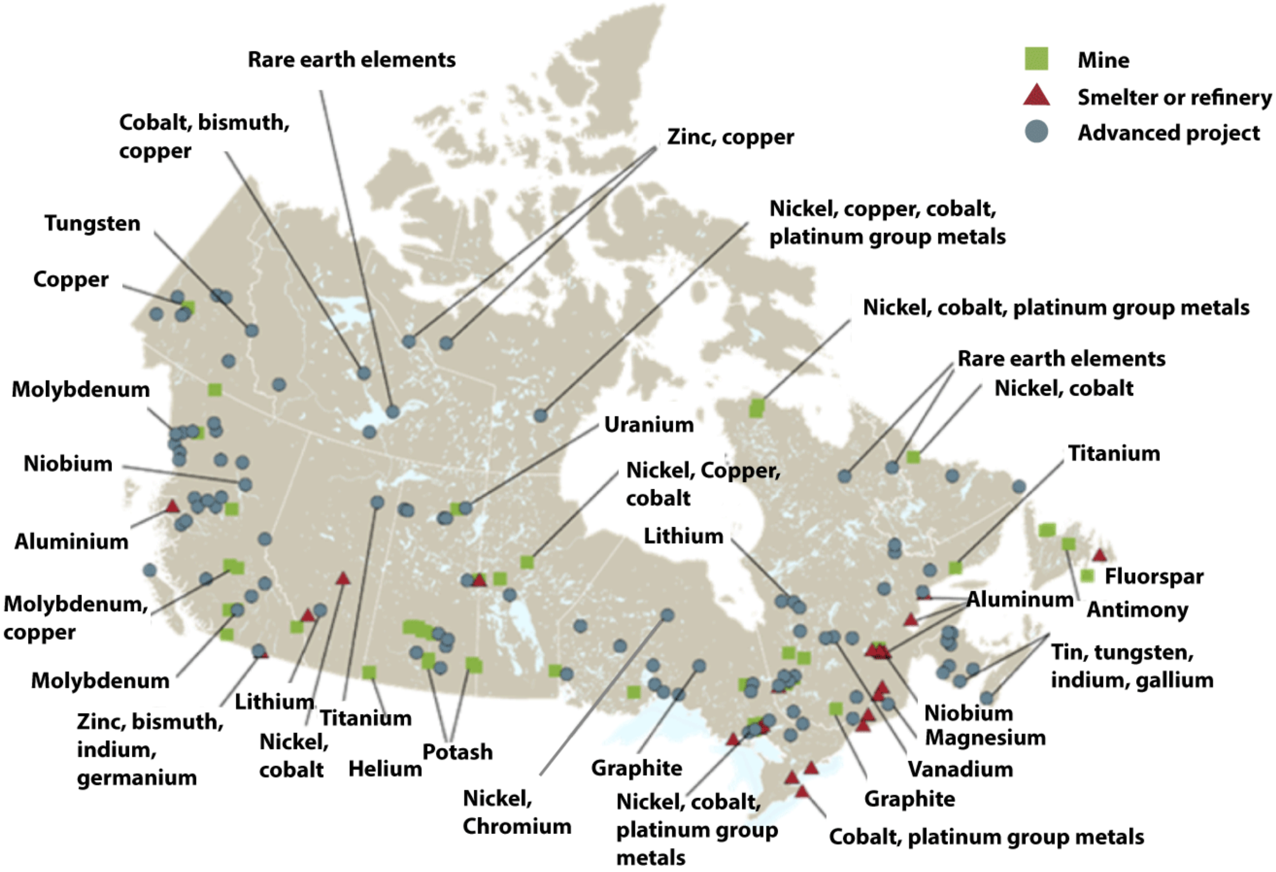


Figure 17: Critical mineral rich regions of Canada (Canada-Service, 2022).

2.4.4 Manganese (Mn) Sources

According to the US Geological Survey (USGS) (Survey, 2020), the largest Mn resources are located in South Africa (Survey_U.S.G, 2020) accounting for 74% of the global Mn resource, along with reserves in Ukraine and Brazil (Jones et al., 2022). Other countries with Mn ores include Australia, the Republic of Korea, and Mexico. China currently constitutes for over 50% of Mn processing and produces 70 and 86% of cathodes and anodes globally (Ren et al., 2024) . Mn is a part of the Canadian government's critical minerals list (Canada-Service, 2022), (Figure 18). The LIB cathode consists of manganese sulfate ($MnSO_4$) (Kelly et al., 2020).

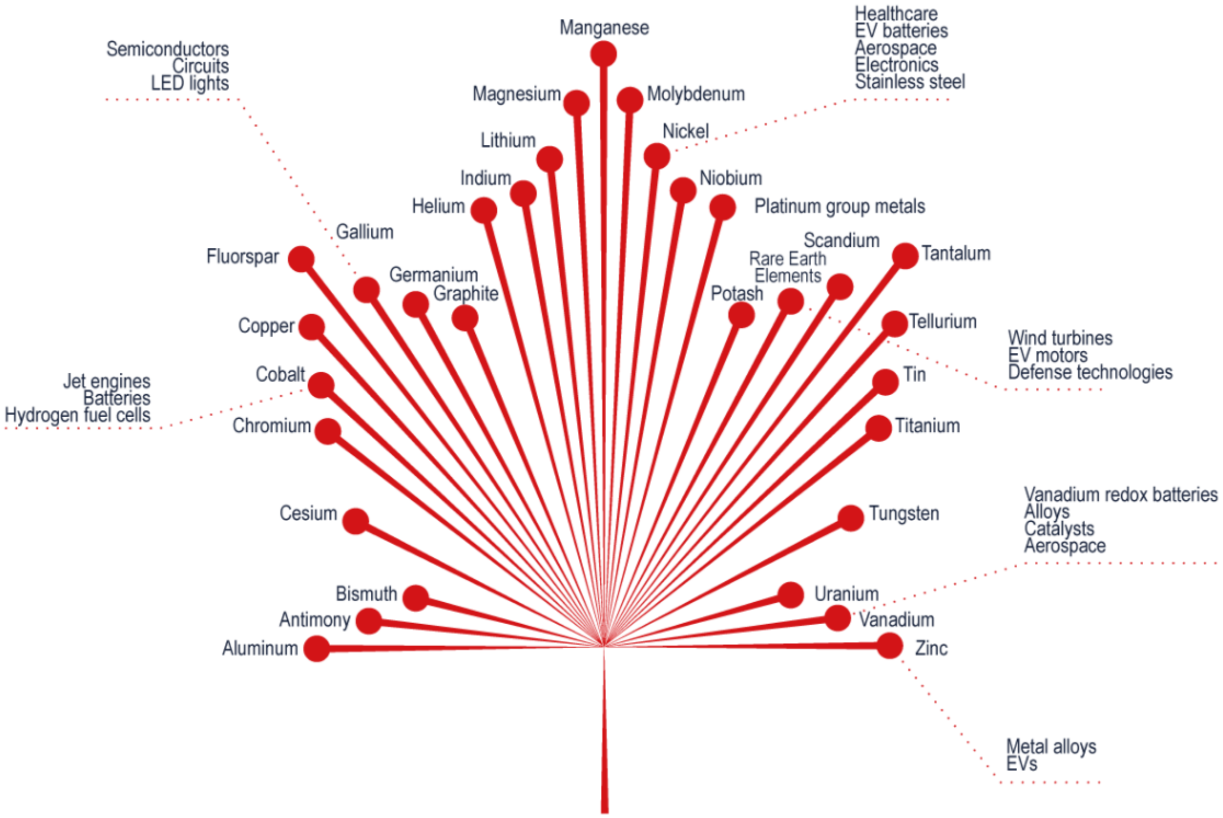


Figure 18: Canadian government critical mineral list (Canada-Service, 2022).

Although Mn is extensively used in steel making, the demand for Mn is growing because of the popularity of the NMC cathode used in LIBs for EV (Clarke & Upson, 2017).

2.4.5 Cobalt (Co) Resources

Cobalt resources is mined mainly in the Democratic Republic of Congo (DRC), and according to the USGS, it represents 70% of the global production of LIBs (Winjobi et al., 2022), following Indonesia, Russia, Australia, and the Philippines (Natural-Resources-Canada, 2023). NMC LIBs utilize cobalt sulfate ($CoSO_4$), primarily generated in China, which account for 80% of the global production (Winjobi et al., 2022). Finland produced the remaining 20% in 2020. Moreover, Cobalt ores are mined in Canada, with 40% coming from the province of Ontario and the remainder from Newfoundland, Labrador, Manitoba, and Quebec (Natural-Resources-Canada, 2023) (Figure 19) .

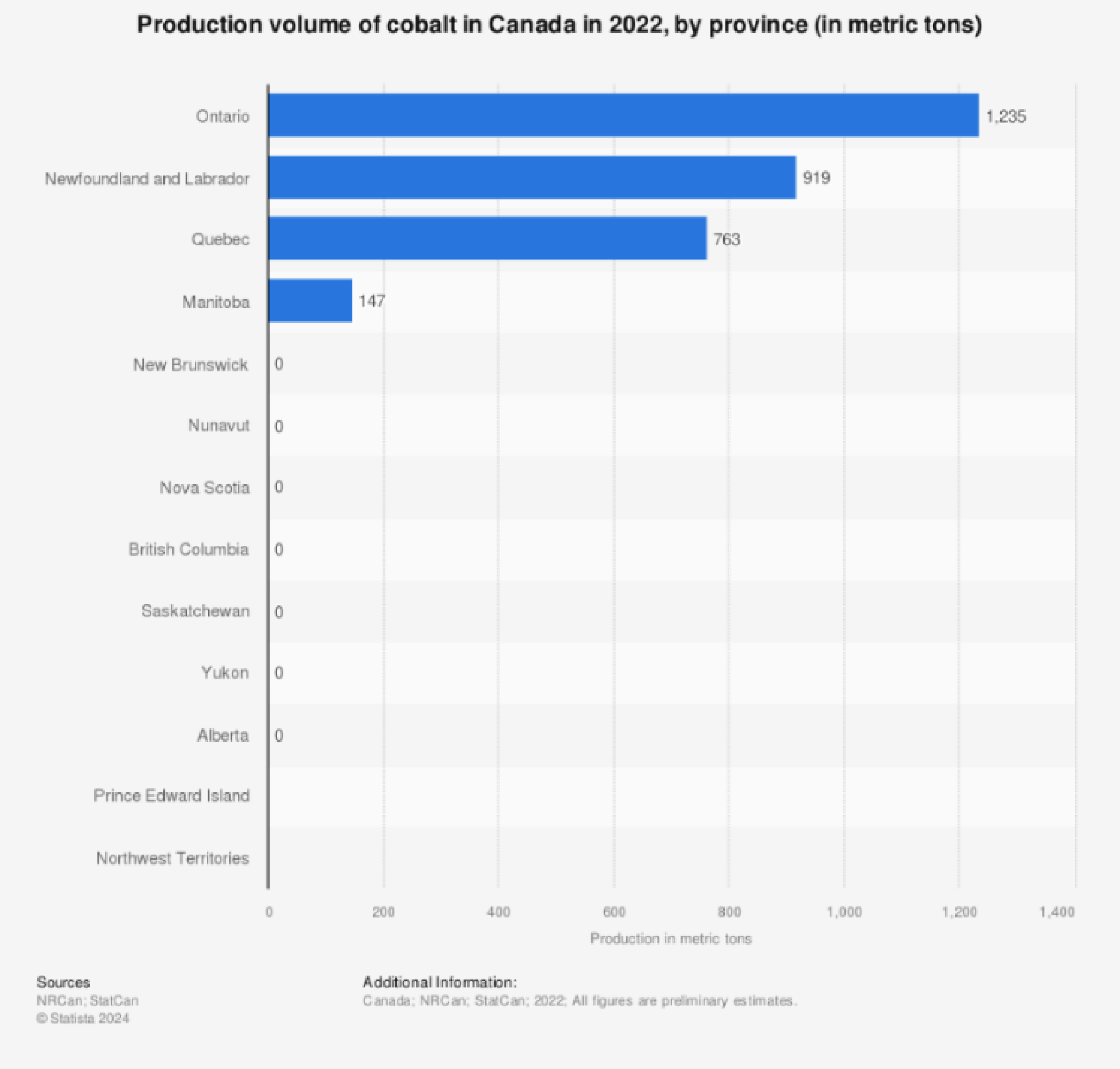


Figure 19: Cobalt production in Canada by province (Statista, 2022).

2.4.6 Aluminum (Al) Sources

NMC LIBs utilize 17-18% Al because Al represents several components (Sadeghian & Iqbal, 2022) in the battery (Winjobi et al., 2022). Al reserves are mainly present in Canada, Mexico, China, and Russia (USGS, 2024a). Canada produced 3 million metric tons of primary Al in 2022, with plants primarily situated in Quebec (AAC, 2024) (Figure 20). Currently, Canada is the fourth largest manufacturer of Al following China, India, and Russia (NRC, 2024a).

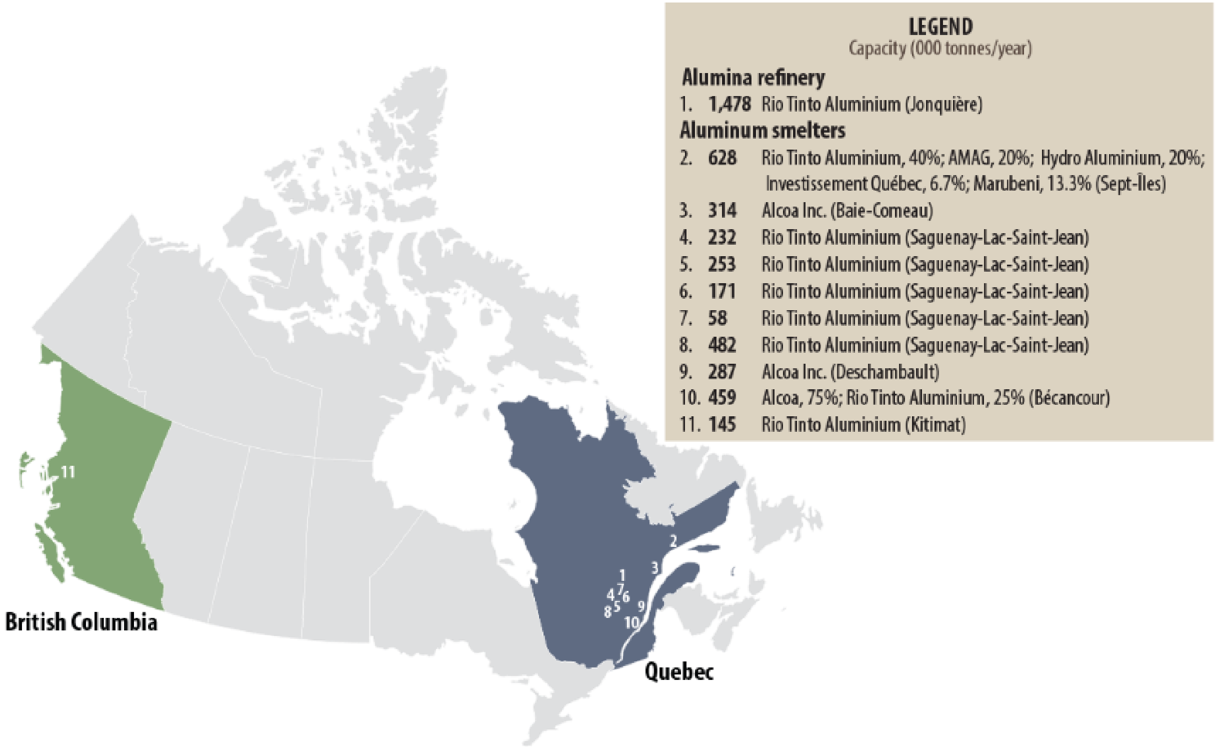


Figure 20: Alumina refinery and smelters located in Canada (NRC, 2024a).

2.5 Manufacturing NMC Cathodes from Materials to Cells

Thermal runaway is an important drawback of LIBs that has led to further research on finding more stable CAMs that can operate under the charging and discharging conditions required for modern EV batteries (Gong & Yang, 2011).

Figure 21 reveals the 1) Equivalent electrons simultaneously move from the cathode to the anode via an external circuit to maintain charge neutrality 2) During discharging, the cell releases electric energy to appliances 3) During charging, when an external voltage is applied, Li ions transfer from the cathode to the anode via the electrolyte and intercalate into the anode 4) Chemical potential for the anode indicating electric energy storage 5) During discharging, Li ions move from the anode to the cathode 6) Separator is a microporous membrane that enables Li^+ migration and prevents short circuiting.

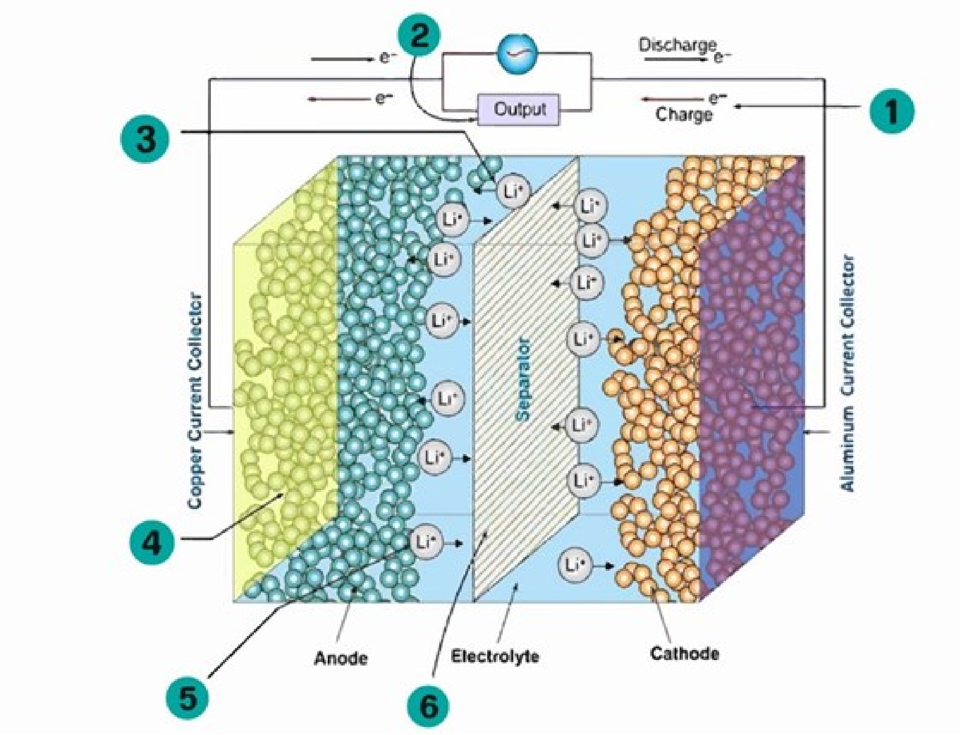


Figure 21: Basic functionality and mechanism of a LIB (redesigned) (T. Li et al., 2020).

During charging, when an external voltage is applied, Li ions transfer from the cathode to the anode via the electrolyte and intercalate into the anode. Chemical potential for the anode indicating electric energy storage. During discharging, Li ions move from the anode to the cathode.

Construction of NMC cathodes requires material acquisition, transportation, distribution, and final battery assembly. Safe operations of cells and packs in LIBs are important aspects for selecting battery chemistry. High-quality LIBs with uniform capacities, safety, and long cycling life can be developed by reducing the electrolyte wetting, formation, and aging times associated with LIB (Wood et al., 2019). Another aspect of new production facilities is reducing manufacturing costs: wetting and formation may take 3-7 days, and aging may need up to an additional 2 weeks. Figure 22 depicts the full process from material acquisition (mining) to final battery assembly.

All NMC cathodes necessitate processing from the mined material (ore mining) because they contain various minerals (including Ni, Mn, and Co). Figure 23 shows a schematic of standard manufacturing process of an NMC cathode (ANL, 2024). Sulfuric acid is used to prepare various sulfates (for example Ni, Mn, and Co sulfates). Na in the salt brine is transformed into NaOH via electrolysis. Drying process utilizes NH_4OH and heat.

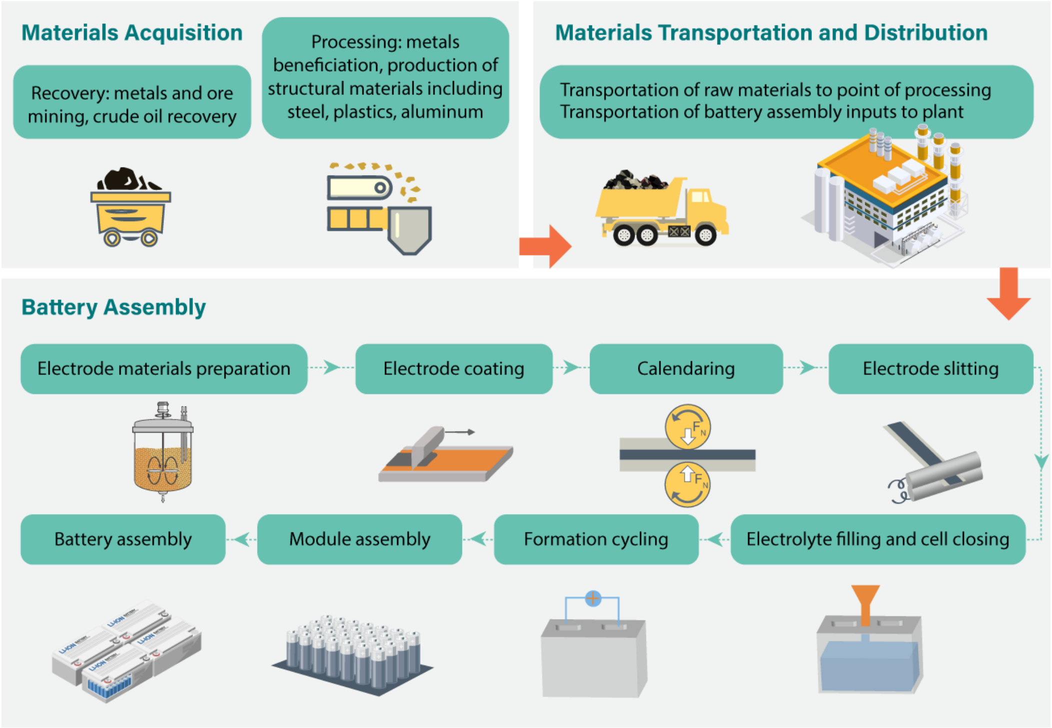


Figure 22: Battery cradle-to-gate schematic (redesigned).

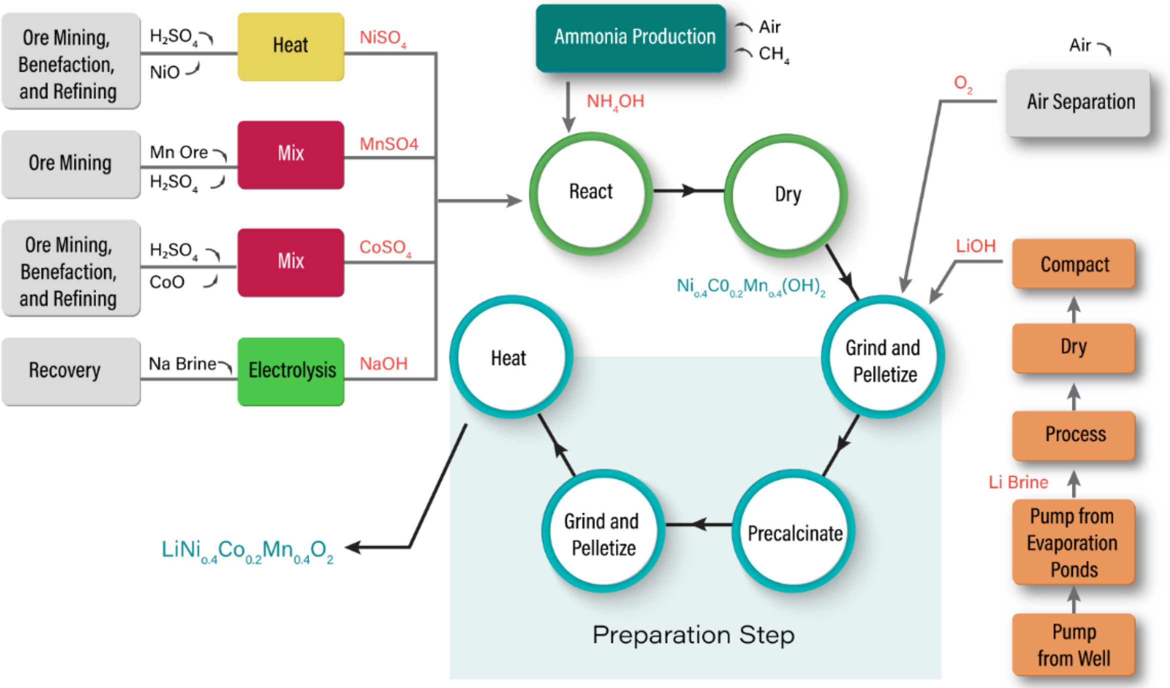


Figure 23: NMC cathode manufacturing (redesigned) (ANL, 2024).

2.5.1 Lithium-ion and NMC Cathode Materials

Crystal structure, particle size, morphology, surface chemistry, and electrochemical properties play crucial roles in the construction of the NMC cathodes (Figure 24). Single crystal structure and high truncation (planes) lends to higher ion transfer in NMC cathodes (Hu et al., 2023). Storage of Li ions and adsorption of the electrolyte solution are the main functions of CAMs (Long et al., 2016) (Figure 24).

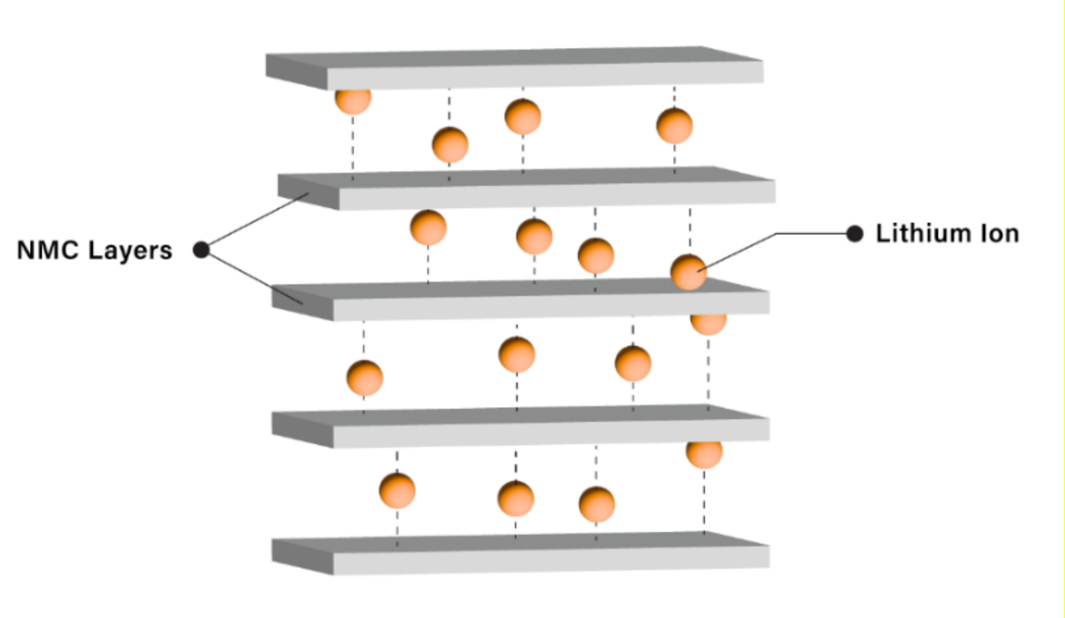


Figure 24: Li-ion transfer on NMC cathode layers.

2.5.2 Cell Production Mechanism

Synthesis of the Ni-Mn-Co cathode material is the first step in the preparation of NMC cathode materials and NMC cathodes are fabricated by creating a homogeneous low-viscosity black slurry (Hawley et al., 2023). Production of NMC cathodes requires Ni, Co, Mn salts and a Li source (Malik et al., 2022).

Typical cell manufacturing includes three processes: 1) electrode manufacturing, 2) cell assembly, and 3) cell formation. Research on NMC cathodes in the laboratory starts with coin cell assembly (Figure 25) to minimize material usage at the bench stage. After the coin cells are produced, their performances must be evaluated (Kendall et al., 2024). Voltage profiles, specific capacities, and electro chemical stabilities are the standard parameters that need to be analyzed (S. Chen et al., 2019; Marks et al., 2010).

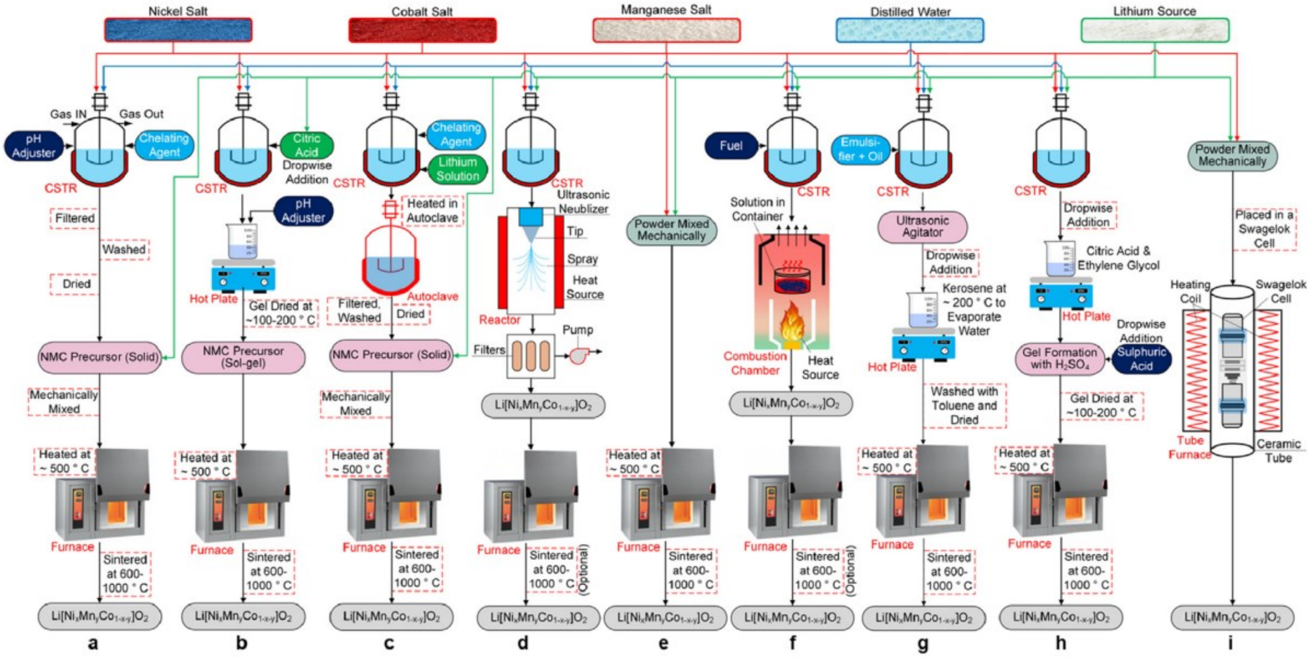


Figure 25: Synthesis of NMC cathode precursors from Ni, Co, and Mn salts (Malik et al., 2022).

Pouch cell production has been reported in a recent study by GM regarding quality verification during EV LIB manufacturing (McGovern et al., 2023). Basic fabrication processes of cathodes comprise mixing the raw materials to form a slurry, coating and drying the slurry, calendaring, and cell assembly using a CAM, for instance, NMC for pouch cells (McGovern et al., 2023) (Figure 26).

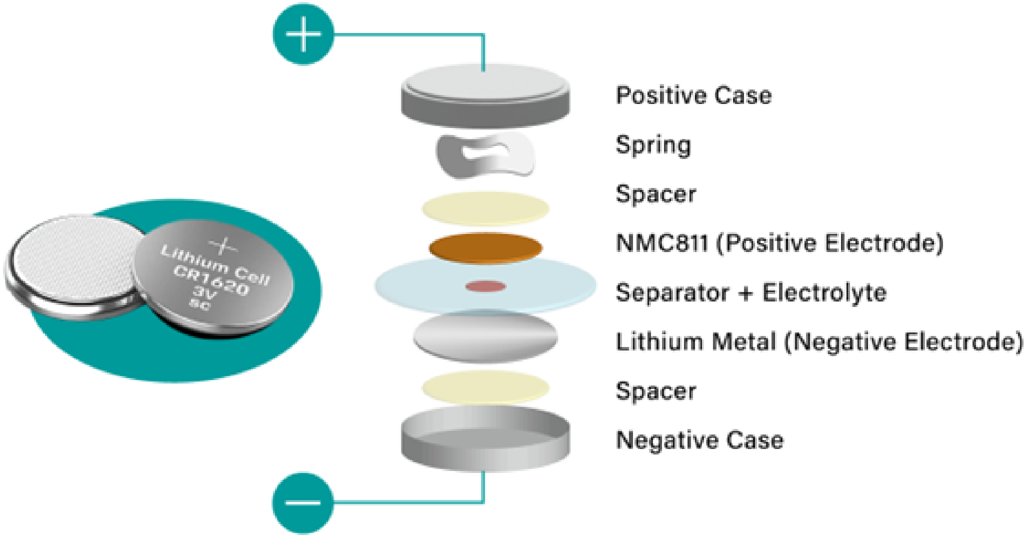


Figure 26: Schematic of a typical coin cell assembly.

The processes for extracting and processing critical minerals in North America must be developed carefully with the shifting of the critical mineral supply chain of LIBs from Asia to North America, Zero-waste (Gohlke et al., 2021) processes must to incorporated zero waste into the extraction and processing of critical minerals (Yang et al., 2022) (see Figure 27).

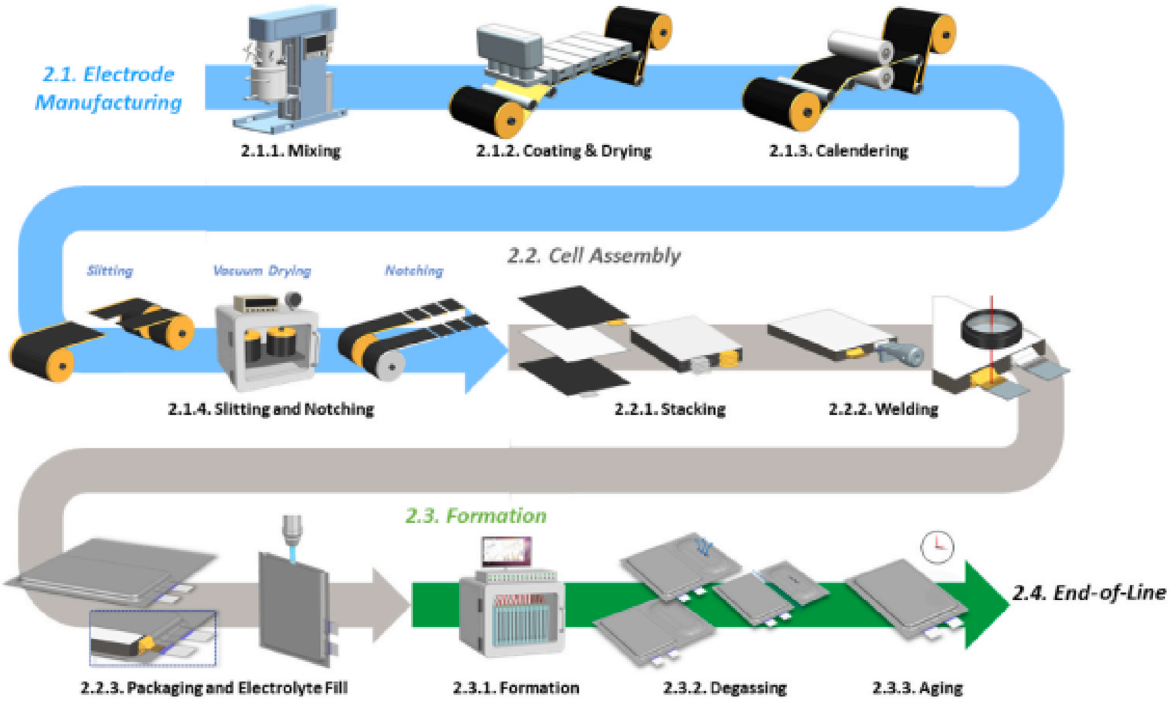


Figure 27: Typical Li-ion pouch cell manufacturing process (McGovern et al., 2023).

Incorporating zero-waste processes into the extraction and processing of critical minerals is essential for minimizing environmental impact and maximizing resource efficiency. Zero-waste principles aim to eliminate or reduce waste at every stage of production, from extraction to processing and beyond. By implementing innovative technologies and practices, such as recycling and reuse of materials, energy recovery, and efficient water management, it's possible to significantly reduce the environmental footprint of mineral extraction and processing operations. The type of NMC cathode dictates the amount of critical minerals since several types of cathode chemistries require different amounts of Li, Co, Ni, and Mn (Jones et al., 2023) (Figure 28).

In Quebec, there has been a movement towards extracting and processing critical minerals with zero waste and this has been started in Montreal. On March 7, 2023, St. Georges Eco-Mining Corp. (CSE:SX) (OTC:SXOOF) (FSE:85G1) announced that it has filed a provisional patent covering a new breakthrough in spodumene processing and lithium hydroxide production technologies (Insidexploration, 2023). St-Georges Eco-Mining Corp. claims that it uses nitric acid (HNO_3) to extract Li from α-spodumene; with 92% of the acid being recirculated in the hydrometallurgy process and creating zero waste (Insidexploration, 2023). This company declares 98% recovery of Li from spodumene with a 99% purity of lithium hydroxide (LiOH). This company also claims that it can produce 99.99% pure LiOH in one step after the novel treatment of Li in the solution using an electrowinning method, thereby omitting the need to ship Li concentrates to a third party for refining and reducing greenhouse gases (GHGs) generated by shipping raw materials to Asia.

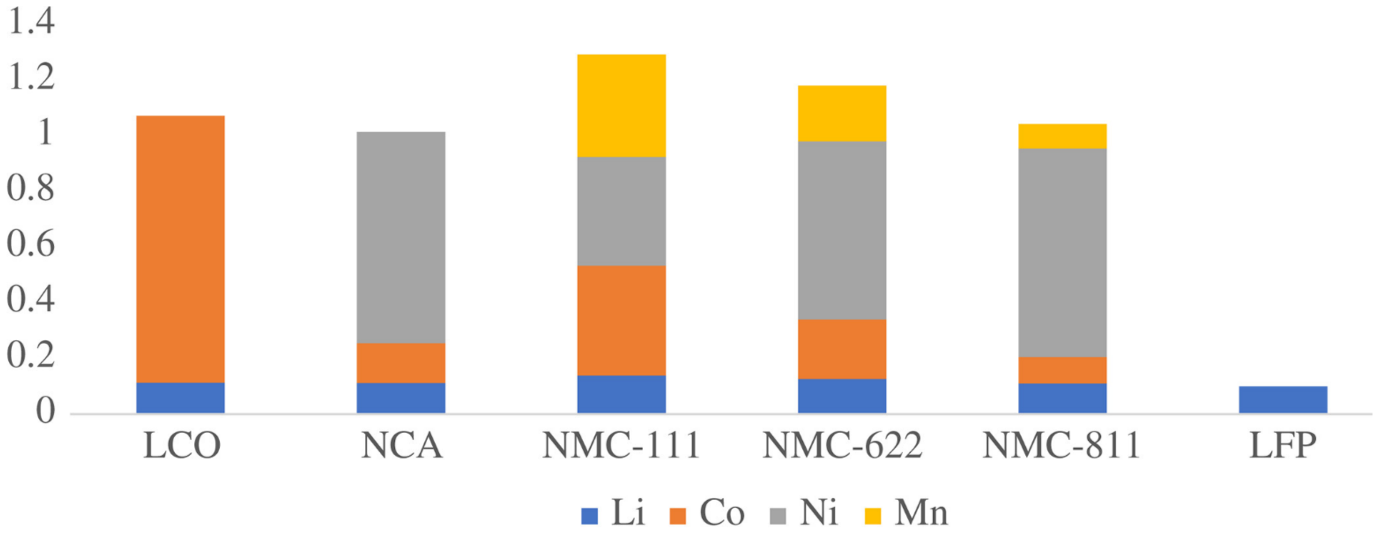


Figure 28: Amount (kg kWh-1) of Li, Co, Ni, and Mn required by various cathode chemistries (Jones et al., 2023).

2.5.3 Reuse/Recycling

A circular economy is essential for developing a critical mineral supply chain. Reuse and recycling (Qian et al., 2022) of NMC cathodes play an important role in the supply of LIBs (Marchese et al., 2024). The automotive lead-acid battery closed-loop recycling (Do et al., 2022) program has been very successful in North America and can serve as a model for emerging LIBs (ECO-Canada, 2024). Figure 29 depicts the recycling of LIBs from EVs for creating a circular economy.

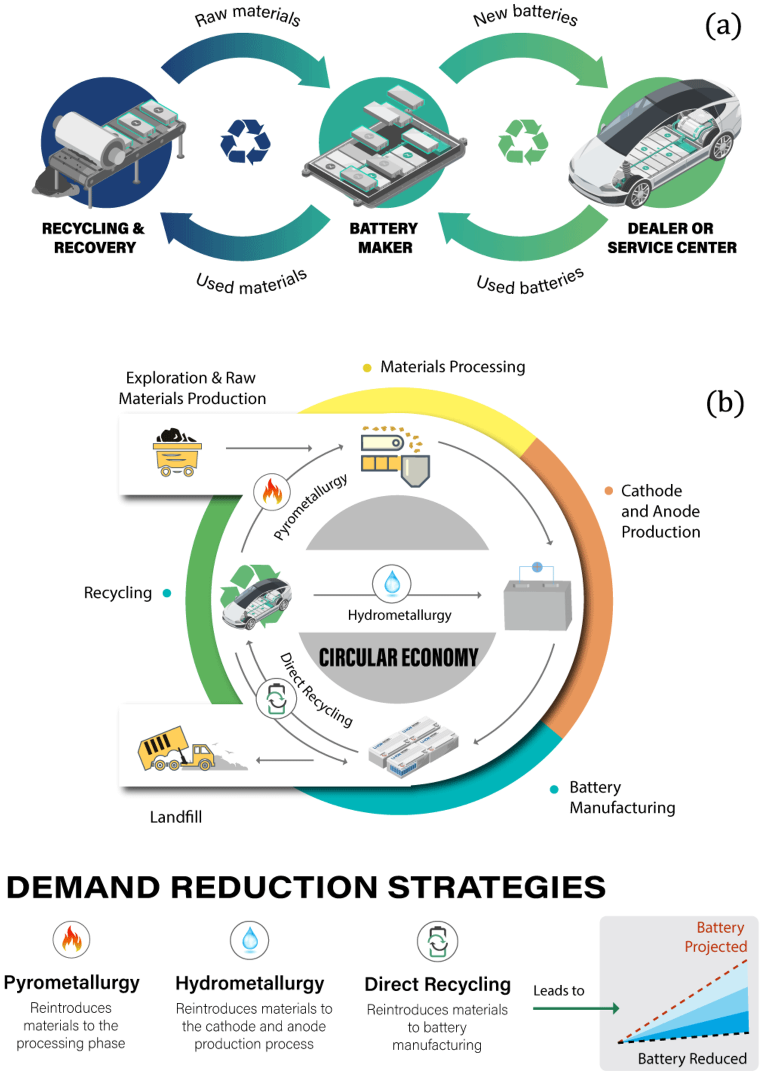


Figure 29: Model for closed-loop recycling (redesigned) and typical methods for LIB recycling.

Several governments, such as the United States and European Union, have placed critical minerals on high importance for national security. Figure 30 shows common recycling methods for LIBs. Hydrometallurgy, pyrometallurgy, and direct recycling are the primary methods for LIBs recycling that can help achieve a circular economy (Gaines et al., 2011; Qiao et al., 2024).

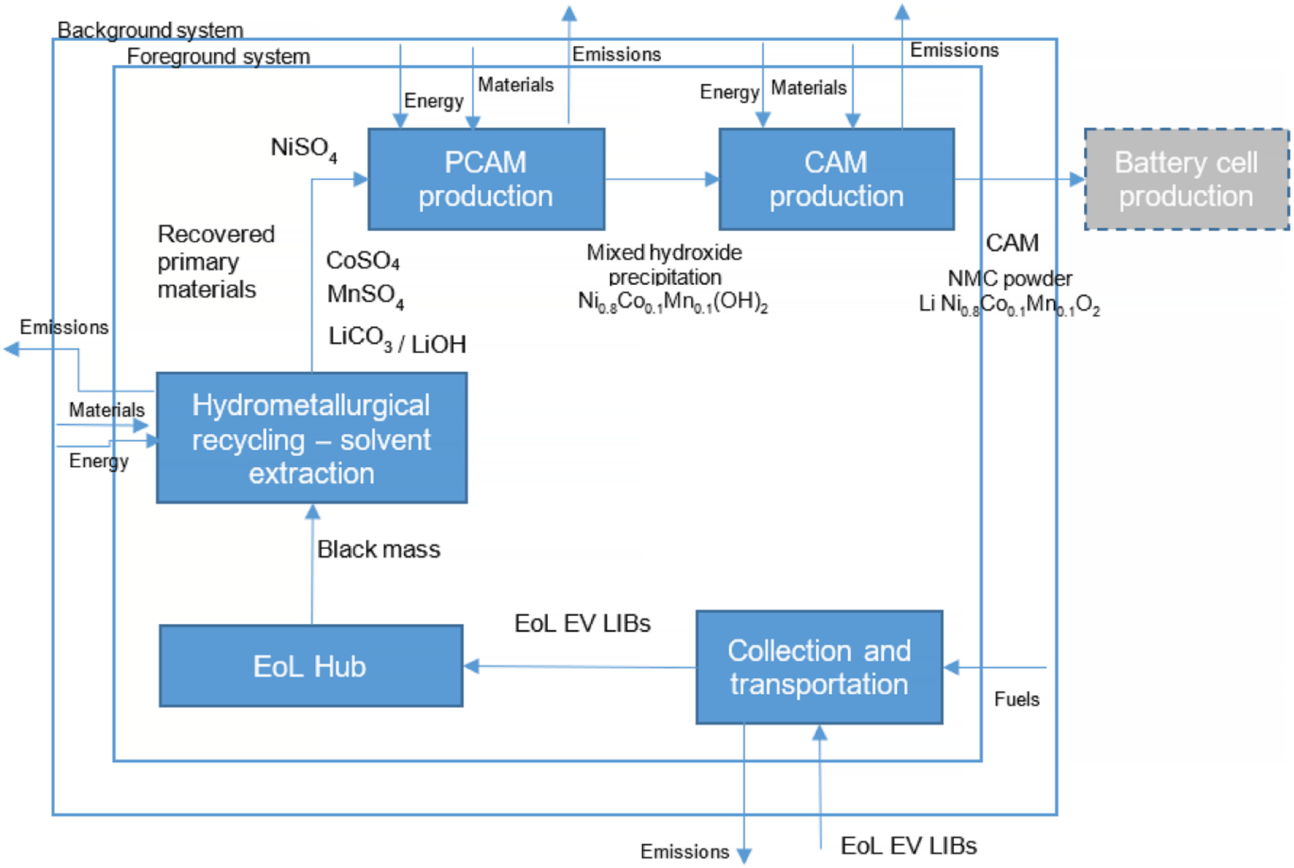


Figure 30: Standard process of NMC cathode material recycling (Gonzales-Calienes et al., 2023).

Recycling LIBs requires energy and produces emissions (Dai et al., 2019) during the creation of precursor cathode active materials (PCAMs) and cathode active materials (CAMs) from black masses (Figure 30). These environmental impacts should be considered during the evaluation of a sustainable LIB supply chain.

2.6 Creation Of New Production Facilities

With the construction of numerous battery plants in the US, Canada, and Europe, supply of precursors, including those entering the NMC cathode, is needed. Several investments have been made in North America, setting its path to become the fastest-growing battery manufacturing hub (Gohlke et al., 2021) Figure 31a and b depict an updated geography of the North American second-life battery, sorted EOL, battery, black mass (Co, Ni, C, and Li powder), metal sulfate ($CoSO_4$, $NiSO_4$, and $MnSO_4$), cathode precursor material, and other metal (Al and Cu) facilities that are presently operating or being planned or whose status is unknown (Kendall et al., 2024).

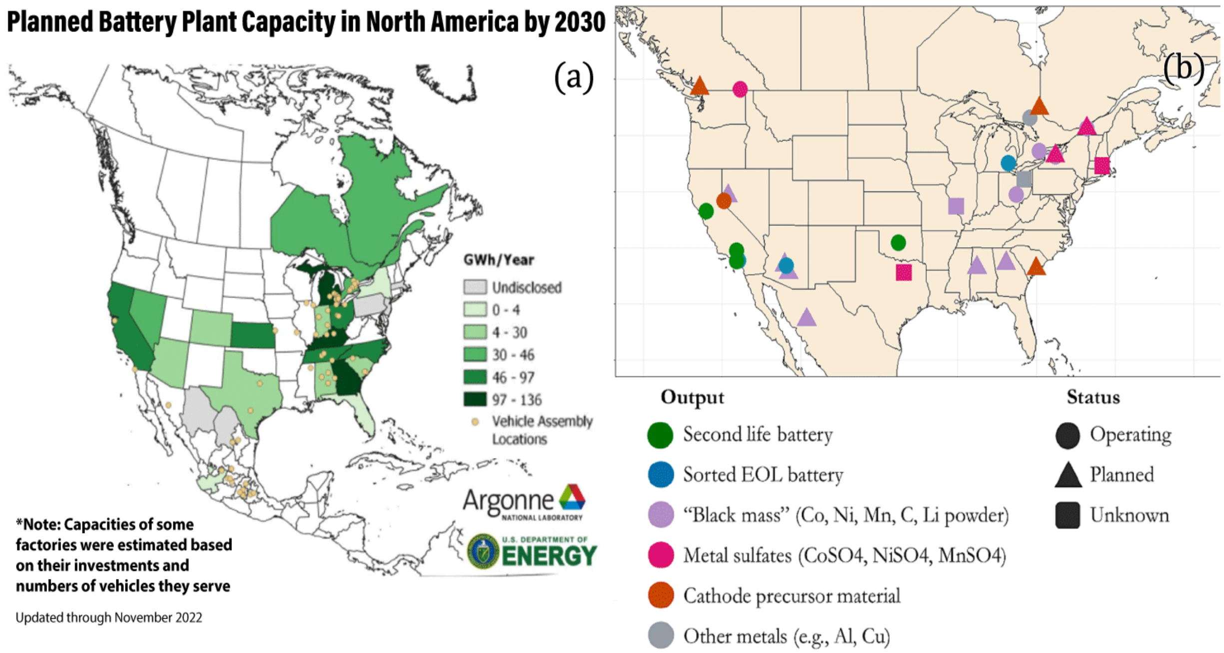


Figure 31: a) Planned battery plant capacity based on state/province in 2030 GWh year-1, as of November 2022 (Gohlke et al., 2021). b) North American LIB recycling facilities (Klier & Rubenstein, 2022).

The Argonne National Laboratory (ANL) and the US Department of Energy (DOE) have complied a map of battery plant capacity (GWh year^{-1}) in North America until the year 2030 (Gohlke et al., 2021). Since November 2022, many automotive companies have announced various battery pack plants in North America (Klier & Rubenstein, 2022). These plants are presented according to the battery company, location, automotive company, and production start date in Table 4.

Table 4: North America's rapidly growing electric vehicle market: Implications for the geography of automotive production (Klier & Rubenstein, 2022).

Battery pack plants in North America, operating and announced since November 2022			
Battery company	**Location**	**Automaker customer**	**Production start year**
CATL	Ciudad Juárez, Chihuahua, Mexico	Ford, Tesla	TBD
CATL	Big Rapids, Michigan	BMW, Ford	2026
Envision AESC	Bowling Green, Kentucky	Mercedes	2025
Envision AESC	Smyrna, Tennessee	Nissan	2012
Envision AESC	Woodruff, South Carolina	BMW	TBD
iM3NY	Endicott, New York	TBD	2022
LG Chem	Queen Creek, Arizona	TBD	2024
LG Chem	New Castle, Indiana	GM	TBD
LG Chem	Lansing, Michigan	GM	2024
LG Chem	Holland, Michigan	GM	2011
LG Chem	Lordstown, Ohio	GM	2022
LG Chem	Jeffersonville, Ohio	Honda	2025
LG Chem	Windsor, Ontario, Canada	Stellantis	2024
LG Chem	Spring Hill, Tennessee	GM	2023
Mercedes	Woodstock, Alabama	Mercedes	TBD
Microvast	Clarksville, Tennessee	TBD	2022
ONE	Van Buren Township, Michigan	TBD	2024
Panasonic	De Soto, Kansas	Tesla	2025
Panasonic	Sparks, Nevada	Tesla, others	2016
Panasonic	TBD, Oklahoma	Tesla	TBD
Samsung	Kokomo, Indiana	Stellantis	2025

SKI	Commerce, Georgia	Ford, VW	2022
SKI	Glendale, Kentucky	Ford	2025
SKI	Glendale, Kentucky	Ford	2026
SKI	Stanton, Tennessee	Ford	2025
Tesla	Fremont, California	Tesla	2022
Tesla	Austin, Texas	Telsa	TBD
TBMNC	Liberty, North Carolina	Toyota	2025
VinFast	Sanford, North Carolina	VinFast	2023
VW	Chattanooga, Tennessee	VW	2022
		VW	2022

2.7 Current Environmental Data on the Production of NMC cathodes

Several variables, including but not limited to a) the availabilities of critical minerals, b) extraction techniques, c) creation of new production facilities, e) changing battery chemistry, d) regulatory changes, e) geopolitical forces, f) reuse/recycling, g) consumer demand, and f) climate change, must be considered during the examination of environmentally sustainable NMC cathodes from mines to chassis.

Exploration and development of mines represent the “upstream” process in the EV LIBs supply chain (Brinn, 2023) (Figure 32). Mining is the main source of the critical minerals used to produce LIBs; the processes of this industry have historically been detrimental to the environment and raised human rights issues (Brinn, 2023). The mining law in the United States was established in 1872, and with the demand for localized critical minerals in the US and Canada, the interagency working group helped reform the outdated mining law. Efforts are currently being devoted to reducing the negative influences of the mining industry in both the United States and Canada (Ibarra-Gutiérrez et al., 2021). In the US, the Federal Land Policy and Management Act of 1976 and the U.S. Forest Service have been provided authority over hard rock mining.

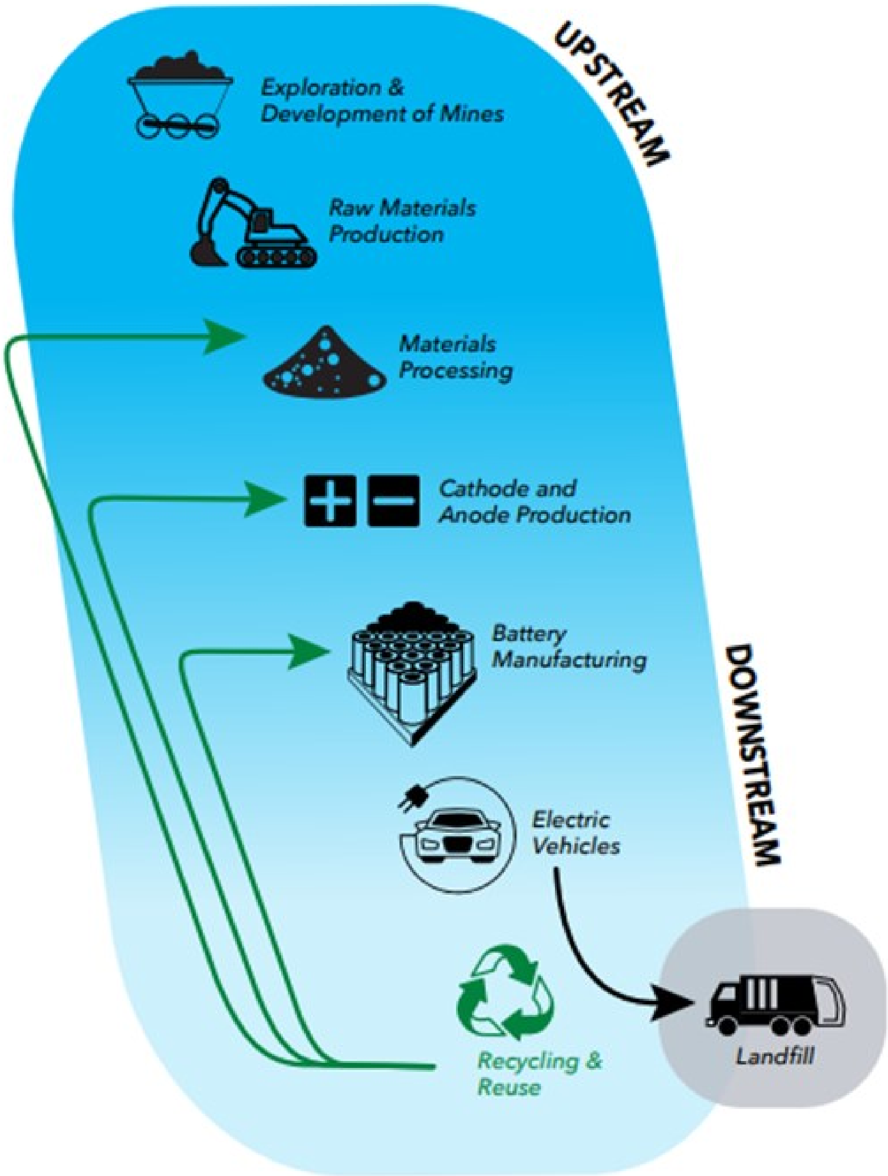


Figure 32: Mine (upstream) to electric vehicle (downstream) material flow (Brinn, 2023).

The EV industry is a multi-stakeholder industry with agencies working on the definitions of waste, reuse, and manufacturing (Brinn, 2023). Accessing critical minerals such as nickel (Ni), cobalt (Co), manganese (Mn), and lithium (Li) in an environmentally sustainable manner (Chandrasekharam et al., 2024) is challenging.

Examining the environmental effects of the adoption of EV platforms is important with the shift of our society from traditional ICE vehicles to EVs. Materials presently employed in LIBs are obtained from outside of North America, and 74% of these materials are acquired from China, Africa, and Latin America (Mayyas et al., 2023). Environmental impacts of LIBs have been investigated in the current supply chain with respect to water use, energy consumption, and emissions of criteria pollutants, for example, carbon dioxide (CO_2), sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM).

NMC cathode production accounts for 50% of the GHG emissions of NMC LIBs (Winjobi et al., 2022). Synthesis of the active material for an NMC cathode (NMC111 LIB) constitutes 40% of the water consumption (Winjobi et al., 2022). During the evaluation of the environmental effects of NMC cathode production, the focus should be on CAM (Ni, Co, or Li precursor). Reduced water consumption has been observed for a higher-Ni cathode because Co processed in DRC is treated using hydroelectric power (Winjobi et al., 2022). Cell production and battery pack assembly powered by hydroelectric power increase the water consumption by 43, 36, 26, and 23% for NMC111, NMC532, NMC622, and NMC811, respectively (Winjobi et al., 2022). NMC811 may be more sustainable with regards to water consumption as shown in Table 5. Although electricity from Hydro-Quebec is renewable, the amount of water used should still be evaluated. ANL utilizes a life-cycle assessment model, called GHGs, regulated emissions, and energy use in technology (GREET), for analyzing the environmental impact of LIB (Winjobi et al., 2022). NMC cathodes significantly reduce the reliance on Co to minimize the dependency on scarce metals, which is essential as Co faces supply challenges owing to its concentrated manufacture in a few countries, mainly DRC (Das et al., 2024). Application of cathodes that are Ni-rich and Co-free has gained attention for alleviating concerns related to cost, C emissions during production, and ethical issues associated with Co mining (B. Dunn et al., 2015; Yang et al., 2022). Various other metal cations have been explored to replace Co in Ni-rich cathodes for maintaining the stabilities of cathodes while reducing the dependency on Co (B. Dunn et al., 2015; Kim & Amine, 2002).. Increased cost may be associated with higher nickel content due to the addition of clean room, infrastructure and energy (Kim et al., 2018).

Transition from NMC111 to higher-Ni lower-Co cathodes (including NMC532, NMC622, and NMC811) results in high energy densities and wide driving ranges for batteries, thereby rendering these cathodes industry-preferred choices. This transition demonstrated reductions in GHG emissions ranging from 0.3 to 7.5% as compared to those in the case of NMC111, whereas SO_x emission levels substantially increased by 130-142% because of the production pathway of the Ni precursor (Bibra et al., 2021; Dai et al., 2019; Gaines, 2018; Winjobi et al., 2022). Higher Ni content is correlated with considerable SO_x emissions. Higher specific energy associated with high Ni content reduces GHG emissions despite higher GHG emissions from $NiSO_4$ generation (Dai et al., 2019; Emilsson & Dahllöf, 2019; Kelly et al., 2020; Lewrén, 2019; Winjobi et al., 2022). With the transition of batteries to higher-Ni batteries, SO_x emissions have significantly increased, particularly from the production of $NiSO_4$, which accounts for a substantial amount of SO_x emissions. However, no distinct trend has been noticed for NO_x emissions during this transition (Bibra et al., 2021; Kelly et al., 2020; Winjobi et al., 2022). The increase in Ni content leads to high SO_x emissions; with the use of a Ni precursor exclusively synthesized from mixed hydroxide precipitate (MHP) instead of Class I Ni lowers SO_x emissions (Dai et al., 2019; Emilsson & Dahllöf, 2019; Kelly et al., 2020; Lewrén, 2019; Winjobi et al., 2022). With an increase in the Ni content of the batteries (for instance, NMC532, NMC622, and NMC811 batteries), water consumption consistently decreased during battery production as compared to those in the cases of lower-Ni batteries (NMC111 LIBs) (Bibra et al., 2021; Lampert et al., 2016; Winjobi et al., 2022). Limited data are available on the environmental effects related to air emissions and water use for NMC (virgin raw material and CAM), which are provided in Table 5.

Table 5: Sample CO_2 emissions from different processes.

Reference	**Process parameter**	**CO_2 emissions (kg CO_2 Eq/kg)**
(Kaboli et al., 2020)	NMC emissions (Virgin raw material)	8.9
(NRC, 2018)	$CoSO_4$ (Cathode active material; (pCAM)	6.73
(NRC, 2018)	$NiSO_4$ (pCAM)	8.61
(Liu et al., 2020)	Electricity power (concentration plant) to produce LiOH monohydrate (raw material) from spodumene	0.00254
(Liu et al., 2020)	Electricity power (electrochemical plant) to produce LiOH monohydrate (raw material) from spodumene	0.01095
(Liu et al., 2020)	Natural gas (electrochemical plant) to produce LiOH monohydrate (raw material) from spodumene	1.861

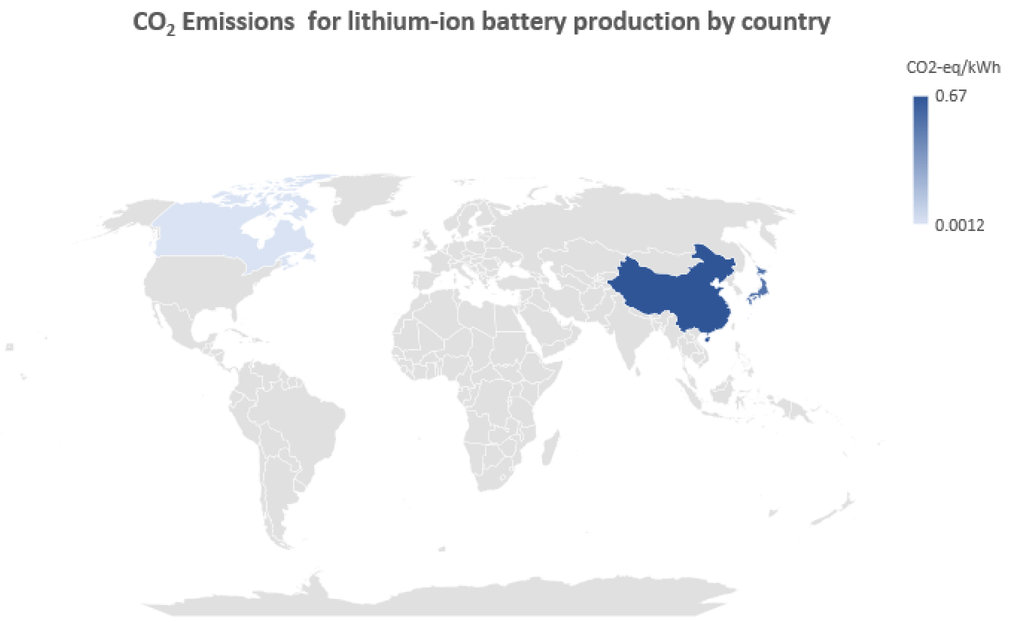
Table 6 Presents the data for CO_2, SO_x emissions, and water consumption for various types of NMC cathodes (NMC111, NMC532, NMC622, and NMC811) (Kaboli, 2020; Liu, 2020; Canada). The water consumption of LIB production using NMC111 is 43% higher than that using LFP.

Table 6: CO_2, SOx, and water consumption

Reference	Process parameter	CO_2 emissions kg CO_2 Eq Kwh^{-1}	CO_2 emissions kg	SO_X emissions increase relative to NMC111	Water consumption	Overall emissions
(NRC, 2018) (Liu et al., 2020)	NMC811 Assembly of single lithium-ion battery	55.1	141.5	142%	12%	
(NRC, 2018)	NMC111	59.1			44%	
(NRC, 2018)	NMC532			130%	28%	
(NRC, 2018)	NMC622			130%	27%	
(Liu et al., 2020)	(LIB)		141.5			
(Kaboli et al., 2020)	NMC cathode (recycling; hydrometallurgy)					> 23%
(Kaboli et al., 2020)	NMC cathode (recycling; pyrometallurgy)					0%

Comparison of CO_2 emissions generated from LIB production in China, Japan, Korea (Winjobi et al., 2022), and Canada (Quebec) (Ibarra-Gutiérrez et al., 2021) indicates that the source of energy affects GHG emissions. Quebec exhibits the lowest CO_2-eq kWh^{-1}, which is understandable considering that its main source of electricity generation is hydropower (Figure 33).

Quebec comprises one of the world's largest spodumene (hard rock Li mineral) deposits and is adequately positioned to become the hub of the critical mineral supply chain for the EV battery industry (Ibarra-Gutiérrez et al., 2021). As of 2021, four Li projects have been established in Quebec: 1) Whabouchi, 2) Authier lithium, 3) Quebec lithium, and 4) Rose Li-Ta. GHG emissions for different processes (concentration and electrochemical plants) have been evaluated for the Whabouchi mine project; Table 7 (Ibarra-Gutiérrez et al., 2021).



Electricity grid profile	China	Japan	Korea	Canada (Quebec)
CO_2-eq/kWh	0.67	0.53	0.55	0.0012

Figure 33: CO_2 emissions generated from LIB production based on country Campagnol 2017; NRC Canada Cobalt Facts.

Table 7: GHG emissions with respect to process in the production of lithium hydroxide monohydrate ($LiOH \cdot H_2O$) from spodumene in the Whabouchi mine, Quebec (Ibarra-Gutiérrez et al., 2021).

GHG emissions to produce 1 ton lithium hydroxide monohydrate from spodumene		
Process	Amount	Emissions
Spodumene concentrate	5.81 t	
Lithium sulfate	0.054 t	
Electricity power (concentration plant)	7,610 MJ	2.54 kg CO_2
Electricity power (electrochemical plant)	32.85 GJ	10.95 kg CO_2
Natural gas (electrochemical plant)	36.35 GJ	1,861.14 kg CO_2
Total	69.21 GJ	1,874.63 CO_2

2.8 Regulatory Changes

Recently, the EU enacted compulsory critical mineral recycling content in the construction of new EV batteries to protect the environment and secure a steady supply of essential minerals (Jacob et al., 2024). The US and Canadian governments are seeking to establish new regulations governing the transportation, storage, and fabrication of LIBs in the automotive industry (Slattery et al., 2024).With the introduction of more EVs into the market, the US government is working to set stricter standards for the qualities, safety, and performances of LIBs (Brinn, 2023).

2.9 Consumer Demand

Consumers are starting to adopt EVs over traditional ICE vehicles because of the low costs, high driving ranges, and less charging times of EVs. Energy densities are an important parameter of LIBs, which determine the driving ranges of EVs. Interestingly, the majority of passenger vehicle trips in the US are less than 31 miles (Figure 34); nevertheless, the consumers remain focused on the EV battery range (Osaka, 2023).

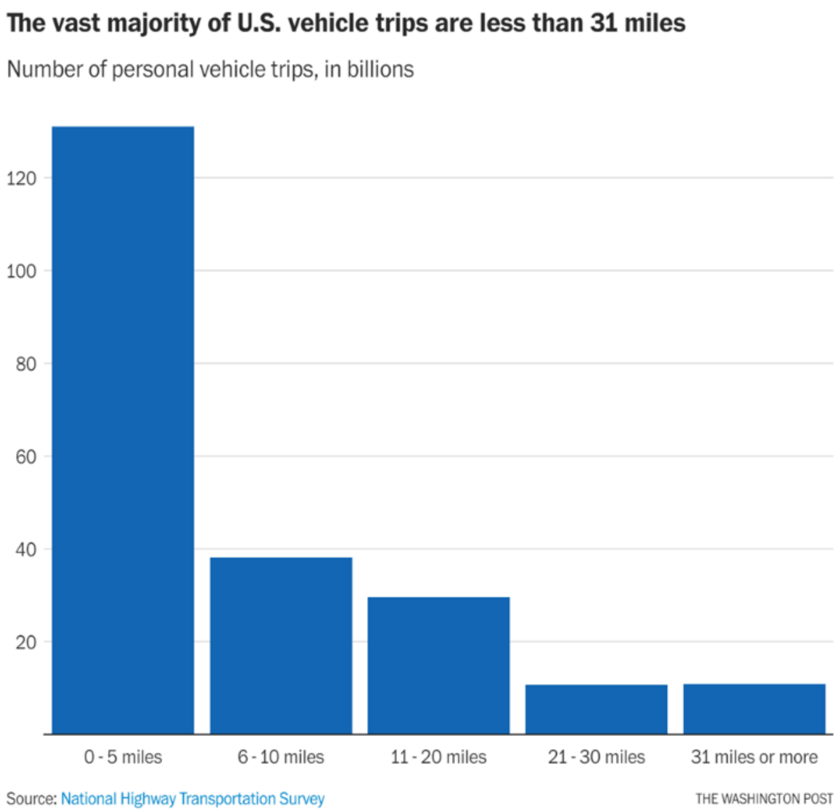


Figure 34: Average vehicle trips in the US (Osaka, 2023).

Automotive manufacturers continue to promote the production of vehicles with higher driving ranges, which in turn affects battery chemistry. Figure 35 shows the all-EV driving ranges for the cars sold in the US.

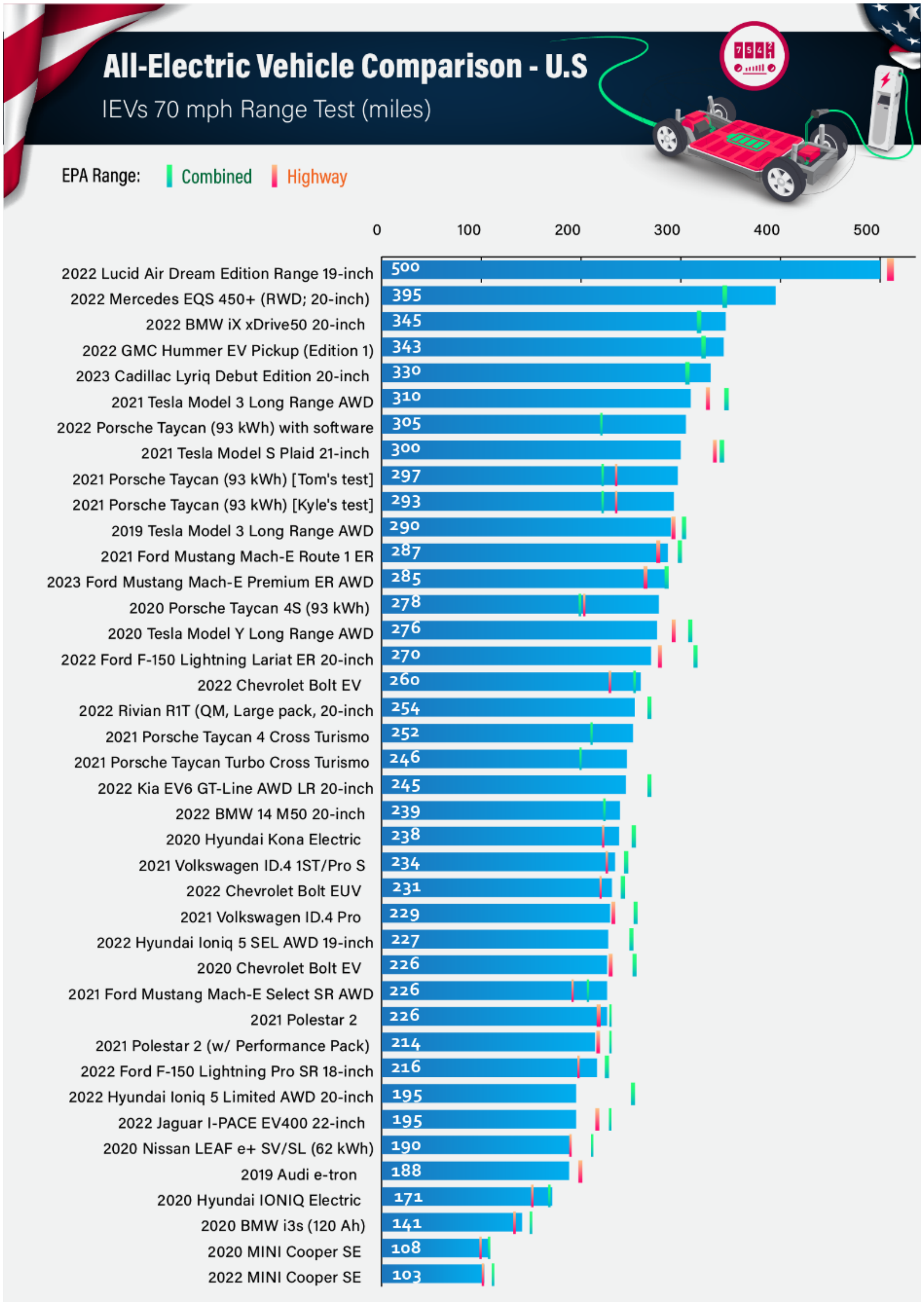


Figure 35: Driving range of electric vehicles currently being sold in the US (redesigned) (Moloughney, 2023)

2.10 Climate Change and Sustainability

Climate change is another major driver of the EV market as countries all over the world are attempting to decarbonize their emissions from mobile sources (Yee, 2023). Many parts of the world have set climate change targets to reduce GHG emissions via EV adoption (Neshat et al., 2023). The shift from ICE vehicles to EVs is a means of decarbonizing the transport sector (Rasbash et al., 2023). However, the current challenge is that with the movement of the automotive sector away from ICE drivetrains, LIBs have become the power sources and mining has become the primary source of critical minerals. Numerous mines in Canada are a part of renewable energy and decarbonization efforts, and ways to render these mines more sustainable are being investigated (Issa et al., 2023). Table 8 provides the initiatives undertaken in Canadian mines via the adoption of fully electrified vehicles.

Table 8: Canadian mines that have adopted a fully electrified vehicles (Issa et al., 2023).

Project	Operator/Owner	Fleet Description
Borden Lake, Ontario	Goldcorp	Canada's first fully electric underground mine (fully electric fleet)
Macassa Mone in Kirkland Lake, Ontario	Agnico Eagle	Twenty-two battery electric scoops with 6 X Z50 trucks (a 50 tonne-battery-powered haul truck)
Onaping Depth Nickel-Copper Project, Ontario	Glencore Canada	An entire fleet of Epiroc battery-electric mining equipment (scoop tram loader, Mine truck hauler, Boomer fac drilling rig, Cabletec rock bolting rig and drill rig)
Lamaque Gold Mine, Quebec	Eldorado Gold	Two Sandvik TH550B battery-electric trucks
NMG open-pit, Quebec	Nouveau Monde Graphite	One X 40-tonne Western Star 6900XD
Brucejack Mine, British Columbia	Newcrest Mining	12 electric haul trucks
Mcllvena Bay Project, Saskatchewan	Foran Mining Corporation	Fleet of 20 BEVs, including trucks, loaders, and drill
BHP Jansen Potash Project, Saskatchewan	BHP Group	Ten underground battery electric loaders and one electric tethered loader

2.11 Environmental Impacts of NMC Cathode Production

With the shift of society from traditional ICE vehicles to EVs, close examination of the environmental effect of switching to EV platforms is important (Shang et al., 2024). Presently, the materials employed in LIBs are obtained from outside North America, with 74% of these materials originating from China, Africa, and Latin America (Mayyas et al., 2023). Environmental influences of LIBs have been investigated in the current supply chain with respect to water use, energy consumption, and emissions of pollutants such as CO_2, SO_x, NO_x, and PM (Sankar et al., 2024).

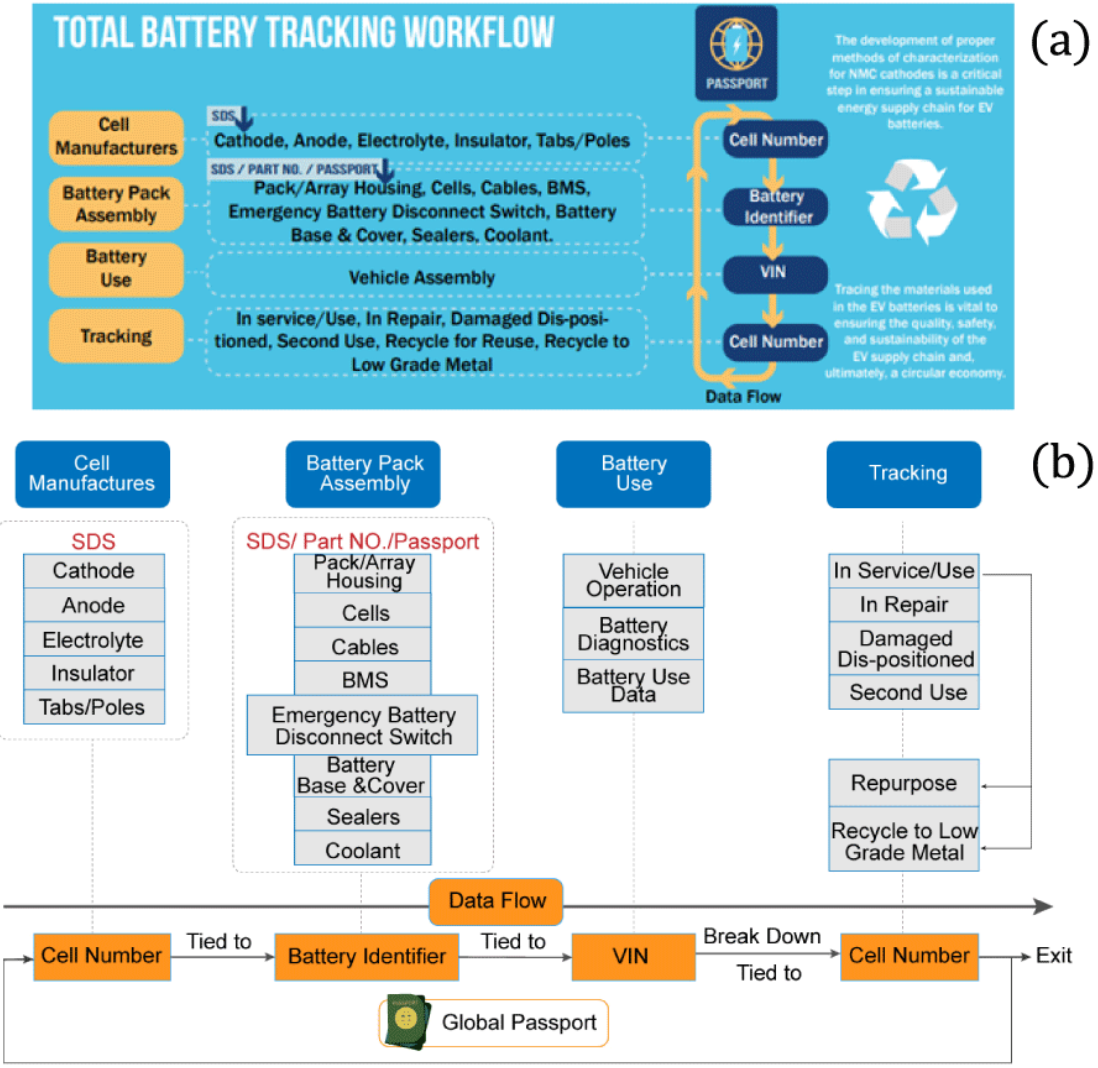
The North American automotive industry is committed to a local supply chain, and the abovementioned environmental parameters must be analyzed, mainly in the US and Canada (Jannesar Niri et al., 2024). In Canada, considerable emphasis is being placed on the acquisition of a "green battery" constructed in Quebec (Aubertin et al., 2024). To establish a sustainable LIB supply chain, various environmental parameters must be considered (Niu et al., 2024). The following table presents the historical data of these environmental parameters for China, Japan, and Korea (Winjobi et al., 2022). NMC cathode preparation accounts for 50% of the GHG emissions of an NMC LIB (Winjobi et al., 2022). Production of the active material for an NMC cathode (NMC111) constitutes 40% of the total water consumption (Winjobi et al., 2022).

Ni, Co, and Li precursors as CAMs should be considered during the evaluation of the environmental effects of NMC cathode production (Gutsch & Leker, 2024). Reduced water consumption was detected for a higher-Ni cathode because Co processed in DRC is treated using hydroelectric power (Winjobi et al., 2022). This should be considered during the analyses of the environmental effects of battery components manufactured by mines (raw material) and processing plants (steel/aluminum and cathode/anode/separator manufacturing) in Quebec using 100% hydroelectric power. Recently, Northvolt announced the construction of the new battery plant

“Giga factory” (Bellan, 2023) in Quebec. The Northvolt project was correct at the time of the review paper (2024), but this has changed now with the publication of this thesis (April 2026).

2.12 Battery Passport (Future Perspective)

With the global increase in demand for critical minerals, the development of a system that recovers EV LIB materials is crucial (Jannesar Niri et al., 2024). Many recommendations have been made to develop a circular economy (Gu et al., 2024) by the recovery of LIB critical minerals and other materials and to create a battery passport (Global_Battery_Alliance, 2019). The idea of a battery passport is to facilitate the tracking of several components of LIBs and LIB packs (Figure 36).



The development of proper methods of characterization for NMC cathodes is a critical step in ensuring a sustainable energy supply chain for EV batteries.

Tracing the materials used in the EV batteries is vital to ensuring the quality, safety, and sustainability of the EV supply chain and, ultimately, a circular economy.

Figure 36: Battery traceability "passport" portion of the poster presented (Vegh, 2023).

Suggested flows (cell-to-pack-to-vehicle-to-end-of-life) have been presented to the North American automotive industry (Kellen, 2020) (Figure 37). These flows break the cell down into components, for instance, the cathode, anode, electrolyte, insulator, and tabs/poles, to identify the specific chemistry of the cell(s). Additionally, to track the entire battery pack, individual cells are tracked because they may change during the life of the battery. Tracking cells and packs offers an accurate battery profile, which is vital for material traceability. Linking the pack to the vehicle identification number (VIN) provides a unique number during the life of the vehicle and battery.

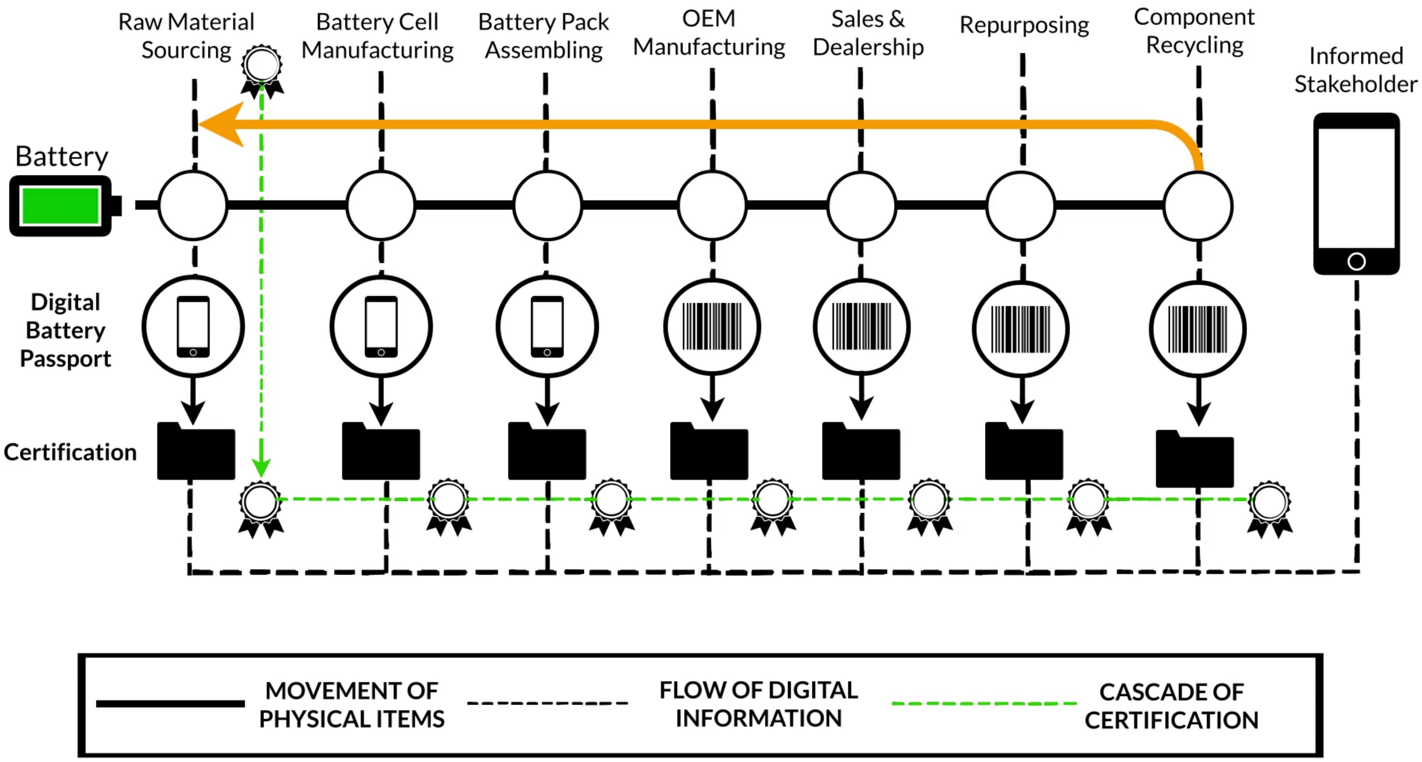


Figure 37: Proposed method for digitizing the LIB cell data “Big data” via blockchain.

Considering the volume of information (big data of individual cells/pack), digitization of data via blockchain (Shahzad et al., 2024) has been recommended as a format to track LIB materials (SP_Battery_Group, 2024) (Figure 37).

2.13 Summary

Presently, hundreds of billions of dollars are being globally invested by the automotive industry (IEA, 2020). Much of this investment is being made in North America, mainly the US and Canada because of the building of Giga factories and EV assembly plants. With the growth of the EV market in North America, more critical minerals that are used in LIBs are needed. Because the North American automotive industry is committed to a local supply chain, environmental parameters must be investigated, primarily in the US and Canada. Canada emphasizes the acquisition of a “green battery” constructed in Quebec with zero waste. We must consider various environmental parameters to establish a sustainable LIB supply chain. With the production of larger EV platforms, battery size is increasing. Several NMC cathode coating chemistries must be understood to provide standards that can be employed in the automotive industry. Demand for higher-energy-density and faster-charging LIBs has created a challenge in designing a safe, cost-effective, and sustainable cathode coating (Ahmed et al., 2017). NMC cathodes have proven to be superior in terms of performance. Environmental data are lacking for North American countries, namely, the US and Canada, Numerous studies have been discussed the increase in Li extraction in Australia and China; however, hard-rock mines in the US and Canada are not considered in these studies.

With a shift in the dependency of the supply chain in the automotive industry on Asia (mainly China), North American environmental data are crucial to the development of a sustainable supply chain. As critical mineral extraction, PCAMs, CAMs, cell, pack, and vehicle assembly are established in North America, environmental impacts must be evaluated in this new circular economy supply chain to ensure a sustainable “green” battery. Moreover, various studies have examined specific energy using the GREET model based on an 84-kWh LIB as the automobile sector produces larger vehicle platforms in North America. Many studies are focused on the “cradle-to-gate” concept and do not consider the “cradle-to-cradle” concept, which is a gap as the EV market demand drives the growth in the recycling of LIB materials. New regulations, as implemented in Europe, require the recycling of critical minerals in new EV batteries, thereby indicating the importance of this aspect in LIB production. With the construction of numerous giga factories in the US and Canada and several new LIB recycling facilities, environmental effects must be analyzed during the evaluation of the NMC cathode supply chain emissions. An updated list of LIB recycling plants is important for evaluating the potential of a circular economy to stabilize the supply chain of LIBs and achieve zero waste. With this shift from ICE vehicles to EVs, appropriately planned processes must be investigated and implemented to ensure that we are reducing tailpipe emissions without creating other environmental problems via the processing and use of critical minerals such as those employed in NMC cathodes.

CHAPTER 3. LIFE-CYCLE ASSESSMENT OF LITHIUM HYDROXIDE MONOHYDRATE (LHM) FROM SPODUMENE IN QUÉBEC, CANADA (MINE-TO-MATERIAL)

3.1 Background

3.1.1 LCA of Lithium Hydroxide Monohydrate (LHM) Critical Minerals in Canada

The purpose of this study was to conduct an LCA on the critical mineral lithium. Lithium can be found in different parts of the world, including Canada (NRC, 2024b). Spodumene mines and lithium brines are the two primary global sources of lithium. While Australia leads the global lithium production with several mines, large-scale brine operations have been reported in Chile, Argentina, and Bolivia (lithium triangle), with the remaining lithium mines in China (IBAT, 2024). Apart from the conventional sources of lithium, academia and industries have also focused on other sources such as industrial wastewaters (NRC, 2024b). The urgency to investigate other sources also comes from the growing lithium demand coinciding with the production of electric vehicles (EVs) (IEA, 2024). The automotive industry is expanding its EV production in North America; mainly in the United States and Canada with retooling of the existing facilities and building of new active material, battery, and assembly plants (IEA, 2024). With this increase in production, there is an increased need for the supply of critical minerals required for the manufacturing processes (Jones et al., 2023). According to Bloomberg, Canada has claimed the top position among thirty countries in the supply chain of lithium-ion battery (LIB) (Yakub, 2024). Canada has many critical minerals, including cobalt, graphite, lithium, nickel, and rare earth metals for battery production (ECO-Canada, 2024). The growing demand for lithium is being supported by the province of Québec, which has some of the largest spodumene ore deposits (Ibarra-Gutiérrez et al., 2021). Notably, a driving force for the automotive industry to have factories located in the United States and Canada has been the Inflation Reduction Act (IRA) (Grimm et al., 2023), which provides financial incentives based on the origin of the materials incorporated into

EV batteries. Furthermore, according to the US Geological Survey (USGS) (USGS, 2024b), Canada has an abundance of minerals, evident by Canadian Critical Minerals Strategy (Government_Canada, 2025a) map, presented in Figure 38.

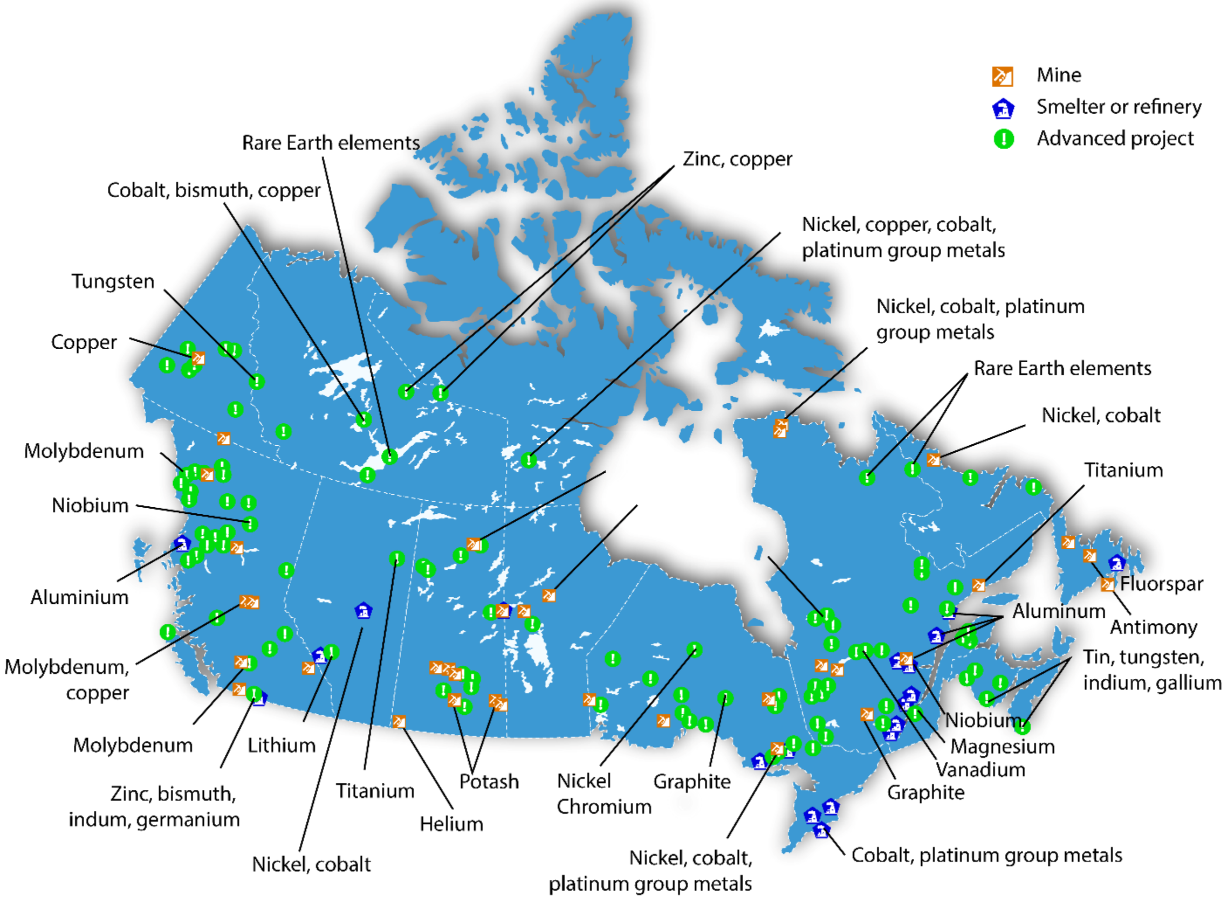


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Figure 38: Critical minerals in Canada (Government_Canada, 2025a)

Conventionally, critical minerals used in LIBs have mainly been sourced from Asia, particularly China (Barman et al., 2023). With the introduction of the IRA, there is a growing need that the critical minerals are being sourced and developed in the United States and Canada in a sustainable manner (Church et al., 2023). The province of Québec is notably rich in critical minerals (Ibarra-

Gutiérrez et al., 2021; Quebec_Government, 2022) necessary for the production of LIBs, as shown in Figure 39. With the availability of critical minerals in the province of Québec, many LIB related businesses have started the upstream, midstream, downstream, and research/service sectors (NREL, 2025) besides which, Québec is home to a diverse range of mining projects for various minerals~~.~~

There are the following projects:

- 11 graphite projects
- 8 nickel, copper, cobalt, and platinum group element projects
- 2 niobium projects
- 7 titanium and vanadium projects
- 6 lithium projects
- 7 rare earth element projects
- 4 zinc and copper projects

- This extensive mining activity highlights Québec's significant contributions to the extraction and production of critical minerals and metals.

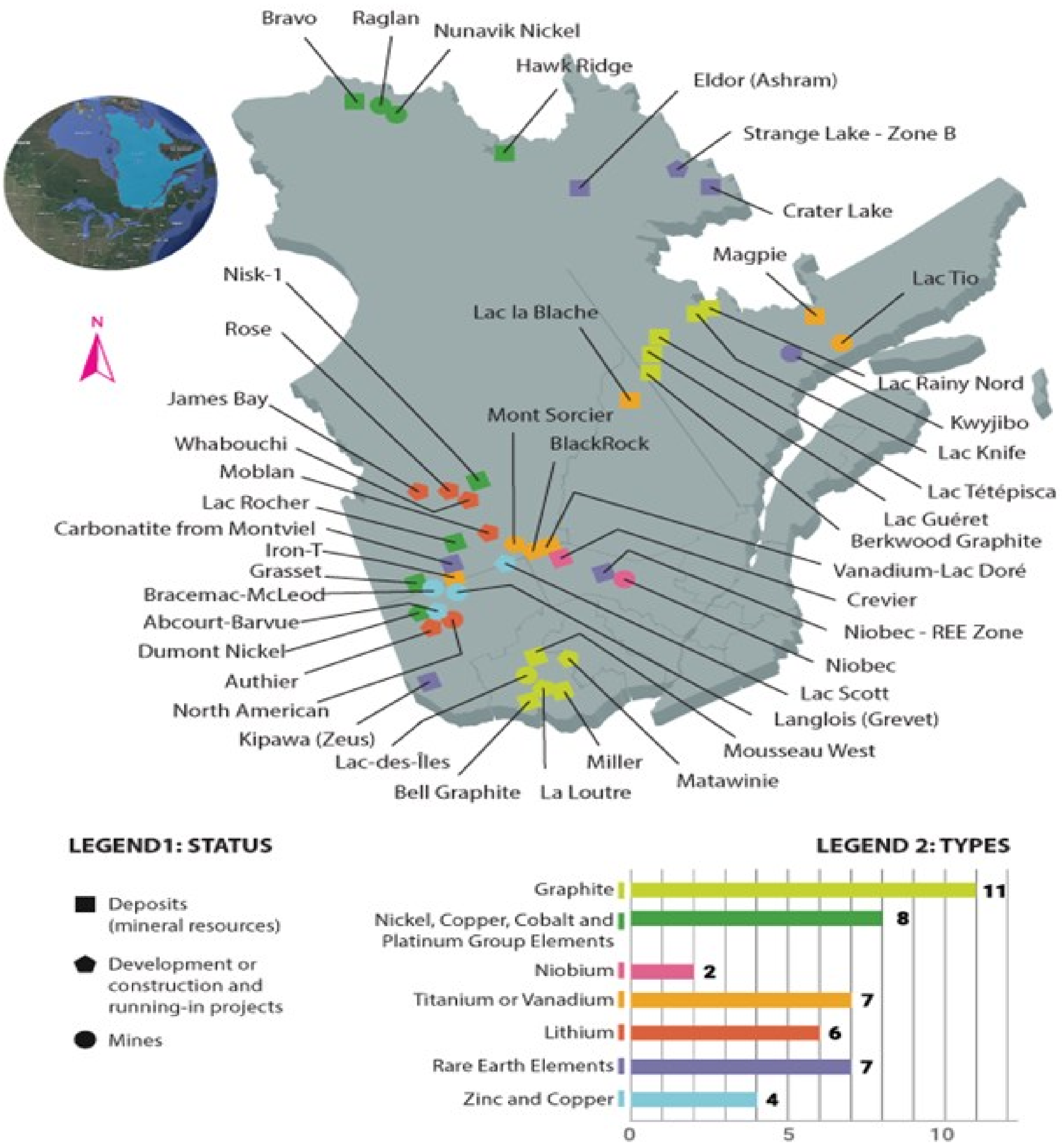


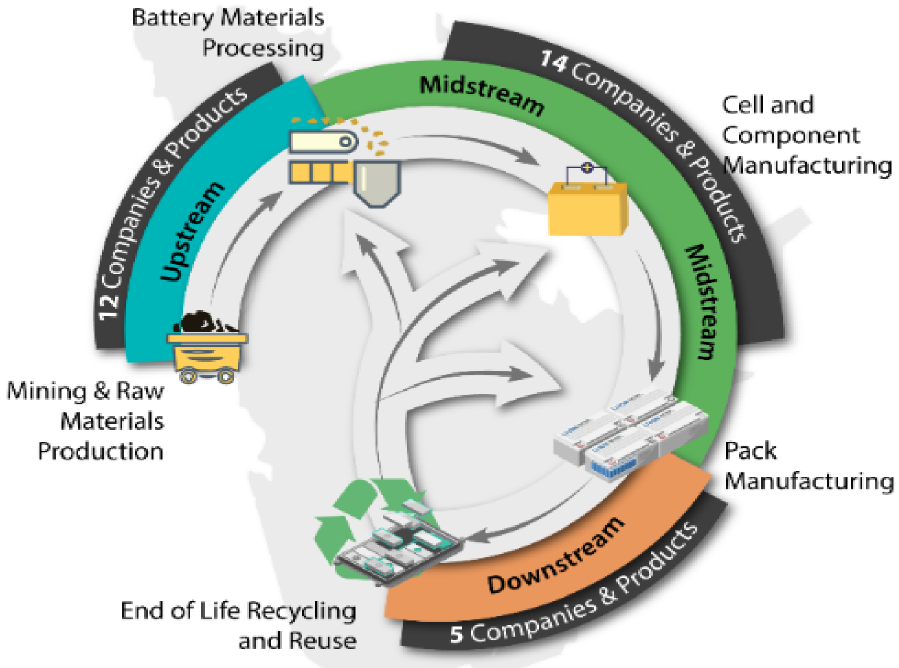
Figure 39: Critical minerals in Québec (Quebec_Government, 2022).

Figure 40 lists the EV supply chain projects currently active in Québec (NREL, 2025). Québec hosts a robust ecosystem of EV battery companies, categorized into various facility types. There are twelve upstream companies focused on extracting and processing raw materials essential to battery production, fourteen midstream companies involved in manufacturing and assembling battery components, and five downstream companies dedicated to the final assembly and integration of batteries into EVs. Additionally, Québec is home to four companies specializing in research, service, and repair, as well as product manufacturing and recycling, ensuring a comprehensive approach to the lifecycle management of EV batteries (NREL, 2025). This diverse range of facilities highlights Québec's significant role in the EV battery supply chain and the commitment to sustainable practices. One of the fundamental phases in looking at the environmental impacts of this new LIB supply chain is to perform an LCA (Notter et al., 2010). Completing this assessment requires collecting data on the inventory of flows associated with the production of cell materials, starting from the mining of the critical minerals (cradle-to-gate) (Hawkins et al., 2012). LCAs have been conducted in the past for critical minerals used in LIBs for EU and Asia, but not recently for the United States and Canada (Das et al., 2024; Kelly et al., 2021; Porzio & Scown, 2021). Consequently, the focus of this study is to conduct LCA on the most important critical mineral needed to produce LIBs lithium. The source of lithium in LIBs is either lithium carbonate or LHM.

This research focused on the production of battery grade LHM from the mine/concentrator and process plant. The data is based on primary industrial data (Engels et al., 2022) and a cradle-to-gate approach has been used to calculate the global warming potential (GWP) (Gutsch & Leker, 2024; Kolahchian Tabrizi et al., 2024).

UPSTREAM
12 Companies & *Products*

New Nemaska Lithium
Spodumene concentrates
Patriot Battery Metals
Spodumene concentrates
Corporation Lithium Éléments Critiques
Lithium hydroxide - crude
Manganese X Energy Corp.
Natural graphite
Arcadium Lithium
Spodumene concentrates
Northern Graphite Corp.
Graphite concentrates
Glencore
Cobalt concentrates
Nickel concentrates
NION Nickel Inc
Lithium carbonate - crude
Sayona Mining Limited
Spodumene
Mason Resources
Natural graphite
Nouveau Monde Graphite
Graphite ore
Sayona Quebec Inc.
Lithium carbonate - crude
Spodumene concentrates
Spodumene



EV Battery Company In Quebec and Product types

MIDSTREAM **14 Companies** & *Products*

Vale Canada Limited
Nickel sulfate
LION Electric
Lithium iron phosphate
Britishvolt
Other/ Unknown
Northvolt
Nickel manganese cobalt
Ultium CAM JV
Unknown
Targray Technology International Inc.
Liquid electrolyte
Synthetic graphite
Lithium cobalt oxide
Nickel manganese cobalt
Lithium-ion manganese oxide
Lithium nickel cobalt aluminum oxide

Blue Solutions Canada Inc.
Lithium iron phosphate
Nano One Materials Corp.
Lithium iron phosphate
BASF Canada
Unknown
Volta Energy Solutions
Copper
Stromvolt
Other/ Unknown
Nouveau Monde Graphite
Synthetic graphite
New Nemaska Lithium
Lithium hydroxide
EcoPro CAM Canada LP
Lithium nickel manganese cobalt

DOWNSTREAM **5 Companies**
& Products

Lithion Recycling
Mixed metal intermediates - alloy/ salts/ sulfates/ mattes
Blue Solutions Canada Inc.
Packs
UgoWork
Packs
LION Electric
Packs
Britishvolt
Packs

OTHER - RESEARCH SERVICE & REPAIR **4 Companies** & *Products*

Calogy Solutions
Battery thermal characterization and analysis
Sudano Consulting Inc.
Engineering Analysis

SolidVert Renewable Energy Technology Inc.
Analysis
Université de Montréal
Research of Electrode and electrolyte materials

Figure 40: Electric Vehicle Supply Chain Projects in the Province of Québec, Canada (NREL, 2025).

Growth of the LIB industry has prompted an LCA to be conducted on LHM from spodumene ore, although the majority of the data have originated from Australia and China (Kelly et al., 2021). Previously, studies have been conducted to compare the LCA of the battery pack with internal combustion engines (ICE) (Ellingsen et al., 2013) and examine the potential environmental impact in the Québec lithium mining industry focusing on greenhouse gas emissions (GHGs) (Ibarra-Gutiérrez et al., 2021). In the available literature, LCA on the Québec lithium mining industry has not been performed in the past two years, since, conventionally, this is not the main geographic area for the supply of battery grade LHM. To cater the anode side, Engels et al. published an LCA for natural graphite production (Engels et al., 2022) using industrial primary data and the *Ecoinvent* database. In this study, the industrial graphite mining data were acquired from a mine/process facility and an LCA was carried out. A similar study was conducted by Kelly et al. (2021) (Kelly et al., 2021) on lithium extraction from brine and ore (spodumene) with analysis of energy, greenhouse gas, and water. In the LCA conducted on spodumene from Australia, diesel consumption was 4,500 MJ per ton of LHM and electricity (Chinese grid mix) consumption was 12,600 MJ per ton of LHM (Kelly et al., 2021). According to Chordia et al. (2022), in Australia, electricity is generated primarily using diesel (Chordia et al., 2022). Furthermore, Chordia et al. calculated climate change impacts of 9.66 tons of CO_{2eq} for 1 ton of LHM from spodumene mined in Québec based on *Ecoinvent v3.8* database. Fresh water usage was at 5.88 m^3 per ton of concentrated LHM (Kelly et al., 2021). In the Québec study by Ibarra-Gutierrez et al (2021) on GHG emissions, the concentration and electrochemical plants required a total of 69.21 GJ per ton of LHM (heat and electricity), of which 36.35 GJ was fulfilled from natural gas combustion and 32.86 GJ from electricity. This GHG emission study, based on process emission factors, not on LCA, calculated a total of 1,875 kg CO_{2eq} per ton of LHM produced at a Québec mine/concentrator and electrochemical plant (Ibarra-Gutiérrez et al., 2021). Current LCA studies conducted in the years 2021 to 2025 have been compared with respect to various parameters (water, electricity, diesel, coal, and natural gas) and the results are presented in Table 9.

Table 9: Comparison of water and energy consumption from Australia/China and Canada

Energy Flow per ton of $LiOH{\cdot}H_2O$				
Parameter	Australia/China (Kelly et al., 2021)	Canada (Québec) (Ibarra-Gutiérrez et al., 2021)	Canada (Québec) (Chordia et al., 2022)	Canada (Québec) (2025) Current research
Water	69.00 m^3	NA	5.66 m^3	3.48 m^3
Electricity	12,600 MJ	40,460 MJ	15,372 MJ	7,729 MJ
Diesel	4,500 MJ	NA	NA	8,935 MJ
Coal	71,343 MJ	No coal	No coal	No coal
Natural Gas	21,000 MJ	36,350 MJ	20,700 MJ	40,717 MJ

The literature review revealed varying results as indicated above. With the critical mineral supply chain shifting to North America, many automotive OEMs are looking to secure enough material to meet the needs for their production of EVs. The purpose of this study is to provide an up-to-date LCA on LHM from Québec and thereby provide a more accurate assessment of LIB cathode material.

3.1.2 Cost Analysis of LHM

LHM is a critical precursor for high-nickel cathode chemistry in lithium-ion batteries, and its production cost significantly influences the overall cost of battery-grade active materials. Typically derived via causticization of lithium carbonate (Li_2CO_3), the conversion process involves the reaction of Li_2CO_3 with a causticizing agent (e.g., $Ca(OH)_2$), followed by an energy-intensive evaporative crystallization step (Liu & Azimi, 2022).

According to the London Metal Exchange, the current spot price for battery-grade LHM (purity greater than 56.5%) is approximately US$ 8,250 per tonne (LME, 2025). Cost structures for LHM production vary significantly depending on the origin of the feedstock, the degree of integration, and the technology employed. For instance, Piedmont Lithium's integrated spodumene mining and conversion facility in the US reports a low operating cost of US $2,943/t, making it one of the most competitive producers globally (Piedmont_Lithium, 2025). Similarly, Zinnwald Lithium PLC in Germany, which employs a co-production model yielding both LHM (12,011 t/a) and potassium sulfate (K_2SO_4; 56,887 t/a), estimates an OPEX of US $6,200/t for LHM (Zinnwald_Lithium, 2022).

Emerging technologies offer further opportunities for cost reduction. Bipolar membrane electrodialysis (BMED), a novel electrochemical route for base recovery, has been demonstrated to produce LiOH at US$2.94/kg (US $2,940/t), offering an energy-efficient alternative to the conventional method (Wei et al., 2024). On the other hand, a techno-economic analysis of LHM production from brine-based Li_2CO_3 shows that additional costs arise from the need to manage precipitated $CaCO_3$, excess reagents, operator labor, and specialized capital equipment, resulting in an OPEX of US $3.04/kg (US $3,040/t) and CAPEX of US $7.4 million (Huang et al., 2021).

While LHM production is inherently more costly than Li_2CO_3 due to the added conversion step, its use is preferred in advanced cathode materials such as NMC, where LiOH ensures better lithiation kinetics and improved electrochemical performance. Thus, despite a higher production cost, LHM remains economically justified, given its superior compatibility with high-energy-density battery chemistries. Moreover, the gap between production cost (US$ 2,900-6,200/t) and market price (US$ 8,000-8,500/t) indicates strong profitability potential, reinforcing its competitiveness in both the current and projected battery materials markets.

3.1.3 Chemical Analysis of the state-of-the-art LHM

LIB technology, currently the most advanced electrochemical storage solution, relies heavily on high-purity lithium compounds to meet demanding performance criteria. Given that battery manufacturers are continuously developing newer chemistries to achieve cheaper, lighter, and more energy-dense batteries, the quality of LHM plays a critical role in ensuring optimal energy density, cycling performance, and safety. LIBs already operate within a broad temperature range (-50 °C to 125 °C), offer low self-discharge, and deliver long lifespans, but advancing these metrics further demands consistent material quality (Abu et al., 2023).

As LIB demand surges due to electric vehicles and mobile technology, lithium resource constraints and price volatility have become increasingly relevant concerns. Therefore, aligning chemical analysis with the specifications of state-of-the-art LiOH is vital not only for performance but also for enabling cost-efficient, sustainable production of next-generation batteries amid supply uncertainties.

Chemical analysis should be reported against the specifications of state-of-the-art lithium hydroxide (LiOH), as the quality and purity of LiOH directly impact on the performance, safety, and cost efficiency of lithium-ion batteries (LIBs). As the battery industry advances, particularly with the shift toward high-voltage, nickel-rich, and cobalt-free cathode materials, the demand for high-purity, low-impurity lithium hydroxide (LiOH) becomes increasingly critical. Impurities in LiOH can negatively affect electrode stability, electrolyte compatibility, and ultimately battery cycle life and energy density (Y. Liu et al., 2021) .

Given that LIB manufacturing remains a complex, multi-stage process and still accounts for roughly 25% of the total battery cost, optimizing every input material-including LiOH is essential.

Comparing chemical analysis results to state-of-the-art specifications ensures that materials meet the performance and reliability standards required for modern LIB applications such as electric vehicles and grid storage, where high energy density and long cycle life are paramount. By aligning material specifications with the latest industry standards, manufacturers can better control variability, reduce failure rates, and support the continued advancement and competitiveness of LIB technologies.

3.2 Methods and Materials

3.2.1 Lithium Ore Extraction and Processing in Québec

Lithium ore processing (spodumene to concentrated lithium) is presented in Figure 41 and LHM process plant in Figure 42. Québec spodumene contains about 1.2% lithium and the ore is concentrated to 5.5% at the mine site (Nemaska_Lithium, 2019). The concentration of lithium was achieved by several beneficiation steps: crushing, grinding, sorting, and flotation, as illustrated in Figure 41. The concentrated spodumene was then transported to a process plant where it was converted into battery grade LHM. In this LCA, the extraction of lithium was achieved by the calcination of the ore followed by leaching. The leachate was further purified, neutralized, and crystallized to obtain battery grade LHM. This process resulted in the generation of co-products aluminum silicate, gypsum, and sodium sulfate, which were subsequently used as raw material in other industrial sectors (Livent_Nemaska_Lithium, 2023; Nemaska_Lithium, 2019). In this LCA study, The CO_2 emission from the production of these co-products was deducted from the overall LHM CO_2.

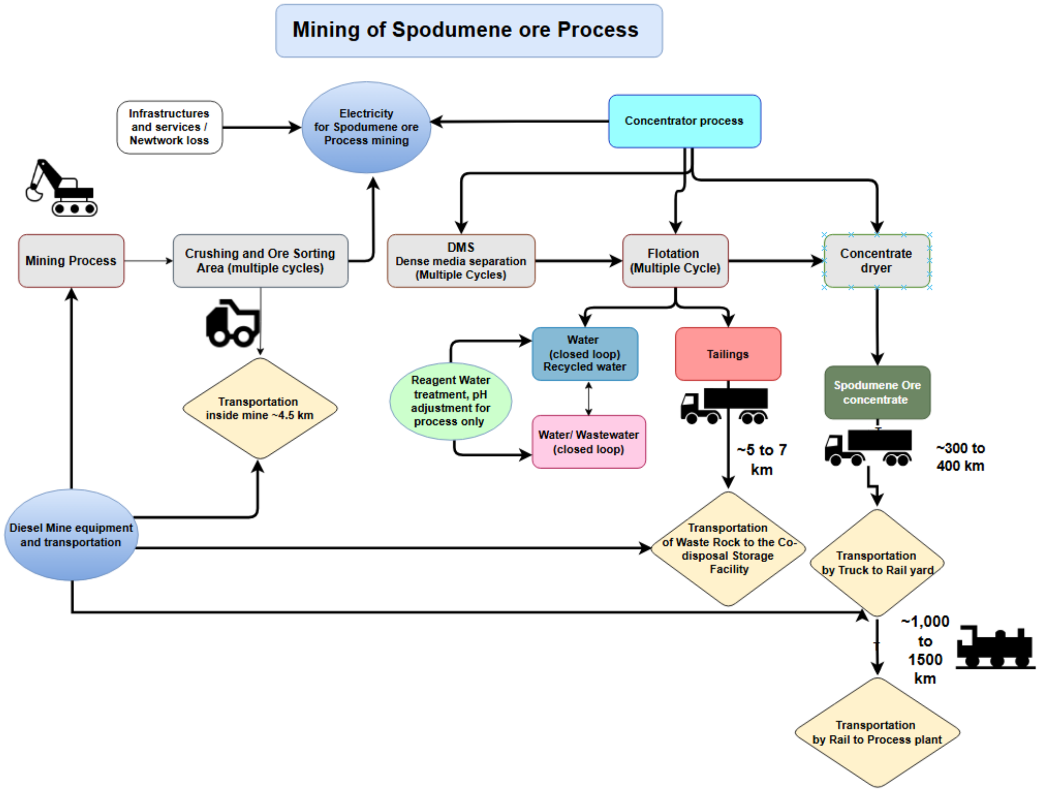


Figure 41: Extraction of spodumene ore at mine and concentration of material in Québec

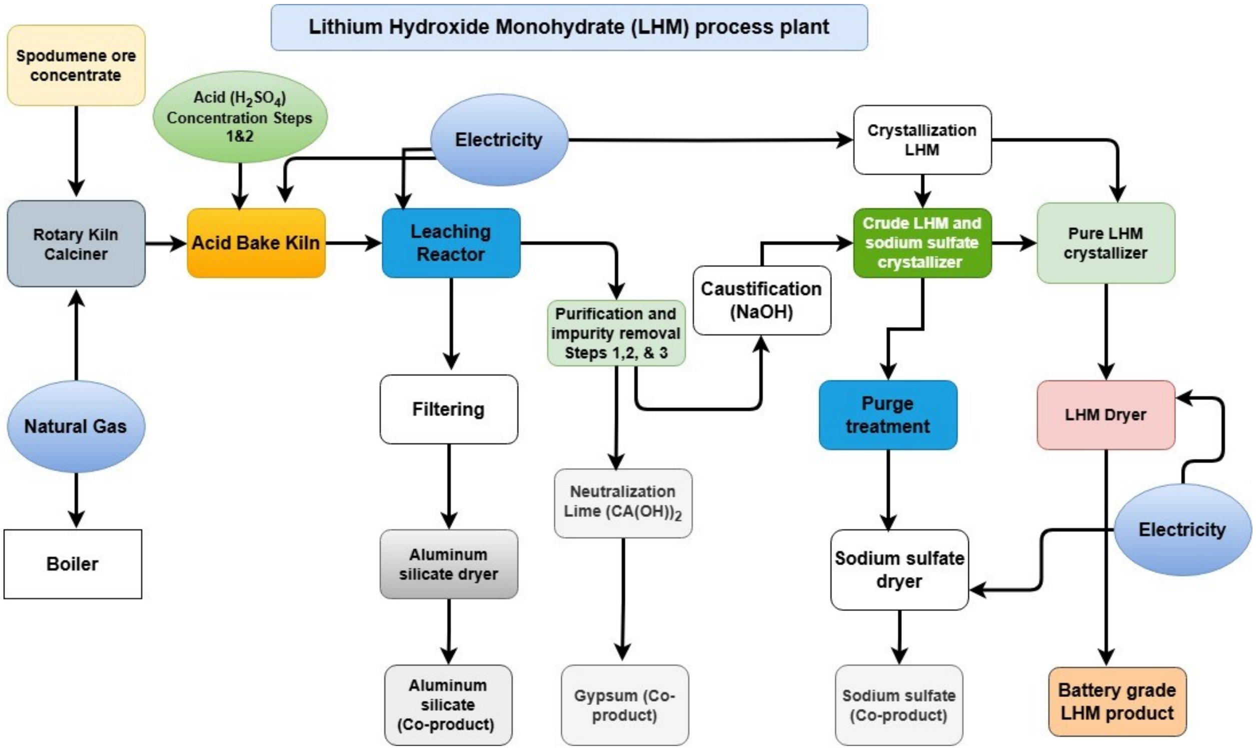


Figure 42: Concentrate to LHM Process Plant (LiOH• H2O)

3.2.2 Review of LCA Datasets and Data Analysis

To conduct the LCA of battery-grade LHM, we utilized *OpenLCA (v2.3)* in conjunction with the *Ecoinvent database (v3.8)* the most comprehensive and widely used inventory database for LCA studies currently (Ellingsen et al., 2013). These datasets provided detailed information on the extraction and processing of spodumene ore, enabling a thorough assessment of the environmental impacts associated with LHM production. Midpoint impact assessments were conducted using *Impact World + midpoint v2.0.1*, an impact assessment method that evaluated a range of environmental indicators. In this study, the focus was primarily on the global warming potential (GWP). An attributional LCA was performed to quantify the environmental burdens directly associated with the production of battery-grade LHM, without considering the broader system-wide effects such as market dynamics or indirect emissions from secondary processes. This approach provides a clear and structured evaluation of the environmental footprint of LHM production, focusing on energy use, greenhouse gas emissions, and resource consumption.

Figure 42 illustrates the data analysis workflow used in this study, outlining the cradle-to-gate LCA process for LHM production in Québec. This assessment specifically focused on evaluating the environmental impact of producing battery-grade LHM from spodumene (hard rock) ore mined within the province of Québec, Canada.

The LCA workflow for battery-grade LHM followed a systematic sequence of steps to ensure a precise and reliable evaluation of environmental impacts. The process began with the collection of raw data from the lithium mine and the process plant, including key inputs such as energy consumption, material usage, emissions, and waste generation. The collected data was then manually processed using MS-Excel to validate and prepare it for integration into the LCA model. Once verified, process flows for the lithium mine and plant (Québec) were established in *OpenLCA* *v2.3* to accurately represent all the relevant life-cycle stages. The model was executed by running the processes in *OpenLCA v2.3*, enabling the calculation of environmental impacts across various impact categories. Subsequently, an in-depth data analysis was conducted to identify key impact drivers, resource-intensive stages, and opportunities for improvement. The study proceeded to generate midpoint and endpoint reports, providing a detailed assessment of environmental burdens across different levels of impact characterization. In the final stage, the conclusions and recommendations were drawn, providing key insights and suggesting potential strategies for enhancing sustainability, optimizing processes, and mitigating impacts. Such a structured approach ensured a comprehensive and transparent evaluation of the environmental footprint associated with LHM production.

3.2.3 Goal and Scope Definition

The LCA framework defines the system boundaries, inventory inputs, and impact assessment methodology. The functional unit for this study was set as the production of 1 ton of LHM to ensure comparability with the existing LCA studies and industry benchmarks. By employing a cradle-to-gate approach, the LCA herein captured all major environmental impacts from raw material extraction to the final production of LHM, offering valuable insights into key areas for potential process optimization and sustainability improvements in lithium refining operations.

The LCA framework utilized the International Standard ISO14040. (ISO, 2006a) Using a set of elementary processes as a model, this study was designed to evaluate the cradle-to-gate LCA of active cathode material derived from critical minerals produced in Québec for use in automotive lithium-ion batteries. The goal and scope of the study focused on assessing the environmental impacts associated with the extraction and processing of these materials, covering all stages from raw material acquisition to the production of battery-grade material. The inventory analysis included both foreground data collected directly from the lithium mine and production plant and background data sourced from the *Ecoinvent v3.8* database to ensure comprehensive and reliable modeling. The impact assessment examined key environmental categories, including air emissions, water consumption, waste generation, transportation impacts, and by-products, providing a holistic view of the environmental footprint of the material. This structured framework allowed for a detailed evaluation of the sustainability and potential areas for improvement in the production of critical minerals for battery applications. An overview of the methods and materials used in conducting the LCA and a summary of the goal, scope, and impact assessment of this research are presented in Table 10.

Table 10: Overview of methods and materials for LCA research

Goal	Cradle-to-gate LCA of the extraction and processing of spodumene (hard rock ore)
Scope Definition Functional Unit	1 ton of battery grade lithium hydroxide monohydrate (LHM)
Product Technology	Battery grade LHM used in EV batteries
Background data	Spodumene mine and processing facility in Québec
Background database	Ecoinvent database (v3.8),
Cut-off criteria	No explicit cut-off criteria. All information on energy, materials, and emissions compiled from industry-specific technical documents
Impact Assessment Categories	Global warming potential (GWP); mainly CO_2

3.2.4 Processes, Intermediary Flows, and System Boundary

Several sources of data were used such as environmental impact assessments, technical reports, and other sources (Nemaska_Lithium, 2019), and the data were rigorously reviewed by the Québec mining company (Table 11 and 12) (Ellingsen et al., 2013; Nemasaka_Lithium, 2022, 2023a, 2023b; Nemaska_Lithium, 2019).

Table 11: LHM processes, intermediary flows, and sub processes

Processes	Intermediary flows (sub processes)
Mining	Spodumene ore with waste rock
Concentrator (Spodumene ore Concentrate)	Pre-concentration and dense media separation
	Crushing/ore sorting areas (electricity)
	DMS removal, grinding, wet magnetic separation (electricity)
	Dry magnetic separation (electricity)
	DMS concentrate dryer (electricity)
Flotation	Reagents total mass in tons/day
	Reagents systems (electricity)
	Floatation water treatment (de-sliming, attrition, & spodumene) (electricity)
	Tailings (waste)
	Tailing (electricity)
	Waste water (closed loop system) small amount of wastewater
LHM production plant	Concentrated spodumene received from mine
Spodumene Ore concentrate Reagents	Acid bake kiln _(H_2SO_4)
Spodumene Ore concentrate Leaching	Leach reactor
Spodumene Ore concentrate Purification	Filtering
	Filtrate liquid
	Impurity removal
	Neutralization lime ($Ca(OH)_2$)
LHM process Co- Products	Filtrate solid
Aluminum silicate process	Aluminum silicate dryer
LHM process Co-Products	
Crystallization and packaging of Lithium Hydroxide	Caustification using (NaOH) reagent
	Crude LHM crystallizer
	Purge treatment
	Sodium sulfate dryer
LHM process By Products	Pure LHM crystallizer
	LHM dryer drying
	Packaging
LHM Product	

Table 12: Energy and transportation at Mine and Process Plant

Energy/Transportation	
Electricity	**(Mining)** Mine general area (electricity) utilities—air and water services + fire water **(Mining)** Monitoring station (ABB) **(Mining)** Power distribution (ABB) **(LHM production plant)** Facility wide electricity demand includes all process activities
Diesel Fuel	**(Mining)** The diesel fuel required for both the drilling and blasting service contracts
Gasoline Fuel	**(Mining)** Other light duty trucks
Natural Gas	**(LHM production plant)** Natural gas is used as a fuel throughout the facility, with the large users being the flash calciner, the acid bake kiln, the aluminum silicate dryer and the boilers. (Natural Gas heat used in process) Cost incurred in dollars has been used to calculate volume (m^3)
Transportation Delivery to Cathode active material (CAM) facility	**(Mining)** Transport-in plant **(LHM production plant)** Transport by truck- to production plant **(LHM production plant)** Transportation by rail to production plant

Once the processes, elementary, and intermediary flows were identified, a product system was created as shown in Figure 43 (process tree). In this study, energy usage was from electricity, diesel, gasoline, and natural gas. Water consumption, reagents, and transportation were considered for both the extraction/concentration of lithium and processing to LHM at the process plant.

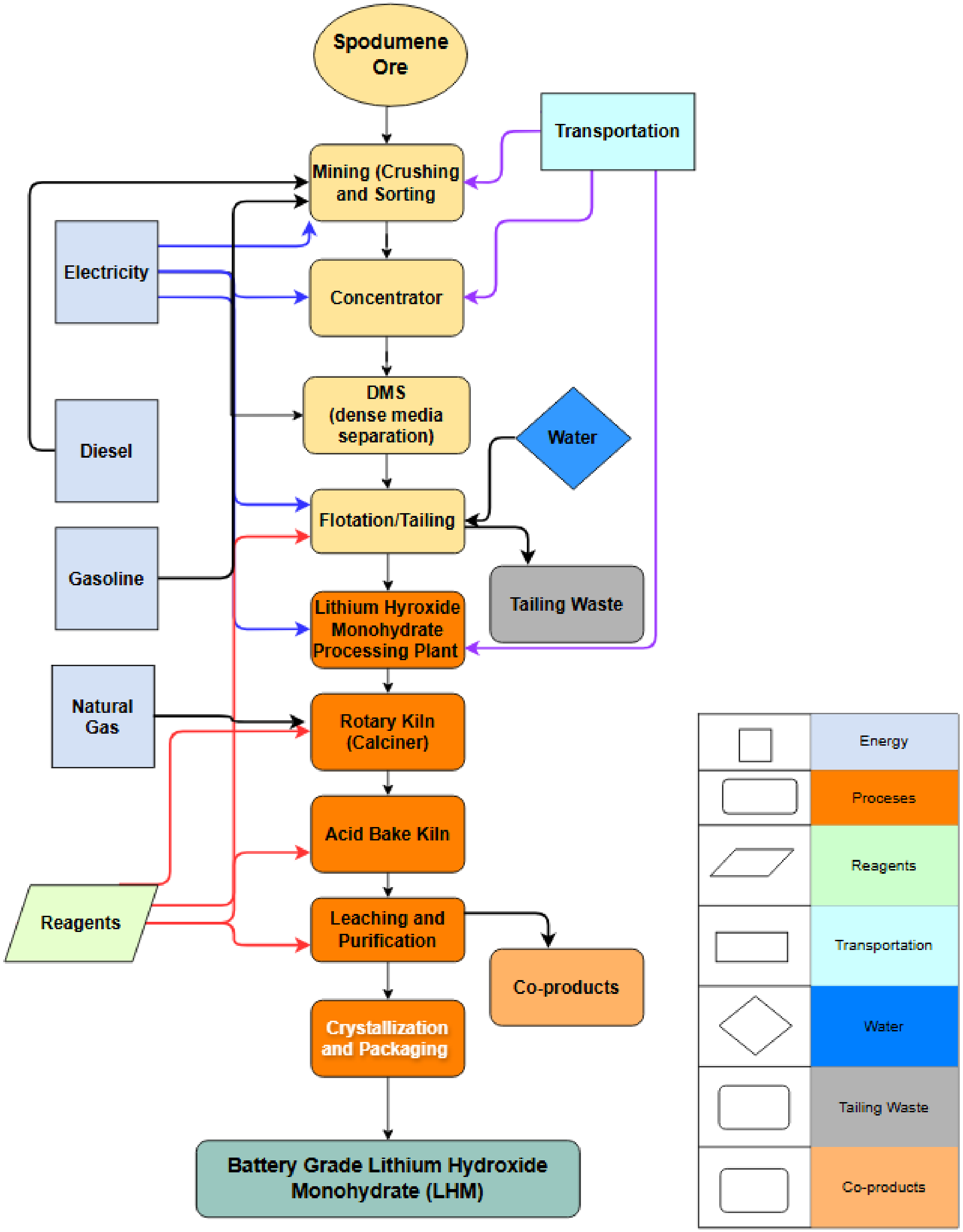


Figure 43: Process Tree (mine-to-material; LHM Québec Mine extraction/concentrator and process plant)

To conduct a proper LCA, it was essential to collect accurate and representative data to ensure the reliability of the environmental impact assessment. Environmental process data was obtained from multiple sources, including environmental impact assessment (EIA) reports mandated by the Québec government and Technical and Feasibility reports from the mining industry. These reports provided critical information on resource extraction, energy consumption, emissions, water usage, and waste generation associated with lithium mining and processing operations. The EIA reports were particularly valuable as they included regulatory assessments, environmental monitoring data, and mitigation strategies implemented by mining operations to comply with provincial and federal environmental standards. Additionally, technical and feasibility reports from the mining industry offered detailed insights into operational efficiencies, material flows, and process optimization efforts. By integrating current data from both regulatory and industry sources, this work provides an updated and detailed assessment for specific operations of extraction and LHM production in Québec.

3.3 Results & Discussion

The research case study for spodumene mining, concentration, and processing in Québec was reviewed and verified by the mining company and multiple LCA researchers and a comparative analysis was conducted against a recent LCA by (Chordia et al., 2022).

A Sankey diagram was created using *OpenLCA v2.3* based on the processes found in mine-to-concentrator and LHM production plant in Québec, as shown in Figure 44.

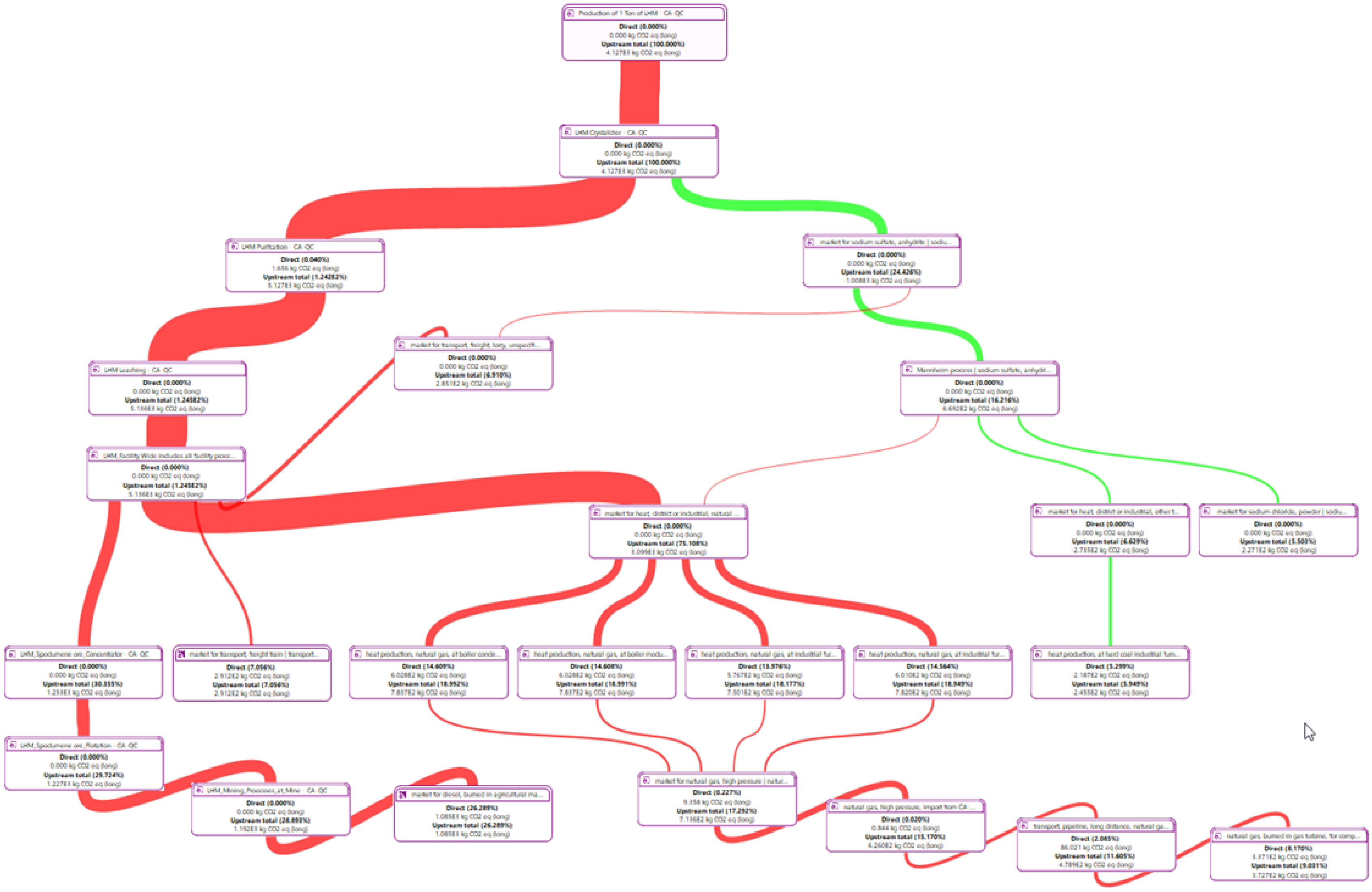


Figure 44: Sankey diagram to produce one ton of LHM in Québec. Red line represents CO_2 emissions and green lines represents CO_2 credits from by-products

3.3.1 Environmental Impact

The Sankey diagram in *OpenLCA v2.3* is a visual representation used to illustrate the flow of emissions within the system. It shows the twenty-five upstream processes involved in the extraction/concentration and processing of one ton of LHM in Québec, how resources move through different stages of a process (extraction at the mine and process at the plant), and the most significant flows. The data presented highlights the direct and upstream CO_2 emissions associated with various processes and markets in the production and transportation of LHM and related products. For example, the production of 1 ton of LHM and processes like crystallizer and leaching involve upstream CO_2 emissions, with leaching and facility wide exhibiting substantial upstream CO_2 emissions of 5.14 tons each, making up significant proportion of their total emissions. While the market for transport, freight lorry, and the LHM spodumene ore concentrator contribute lesser emissions, significant volumes still arise in certain categories like the market for diesel burned in agricultural machines, with a direct CO_2 emission of 1.08 tons. The calciner accounts for most of the natural gas emissions at the production plant. Other processes, like the production of sodium sulfate anhydrite, exhibit negative emissions, indicating carbon capture or sequestration. However, such emissions are avoided when these co-products are used as raw materials in other markets.

3.3.3 Upstream Emissions

Overall, upstream emissions consistently account for the majority of CO_2 emissions in industrial activities. The CO_2 emissions details from the Sankey diagram presented in Figure 45, as direct and upstream emissions.

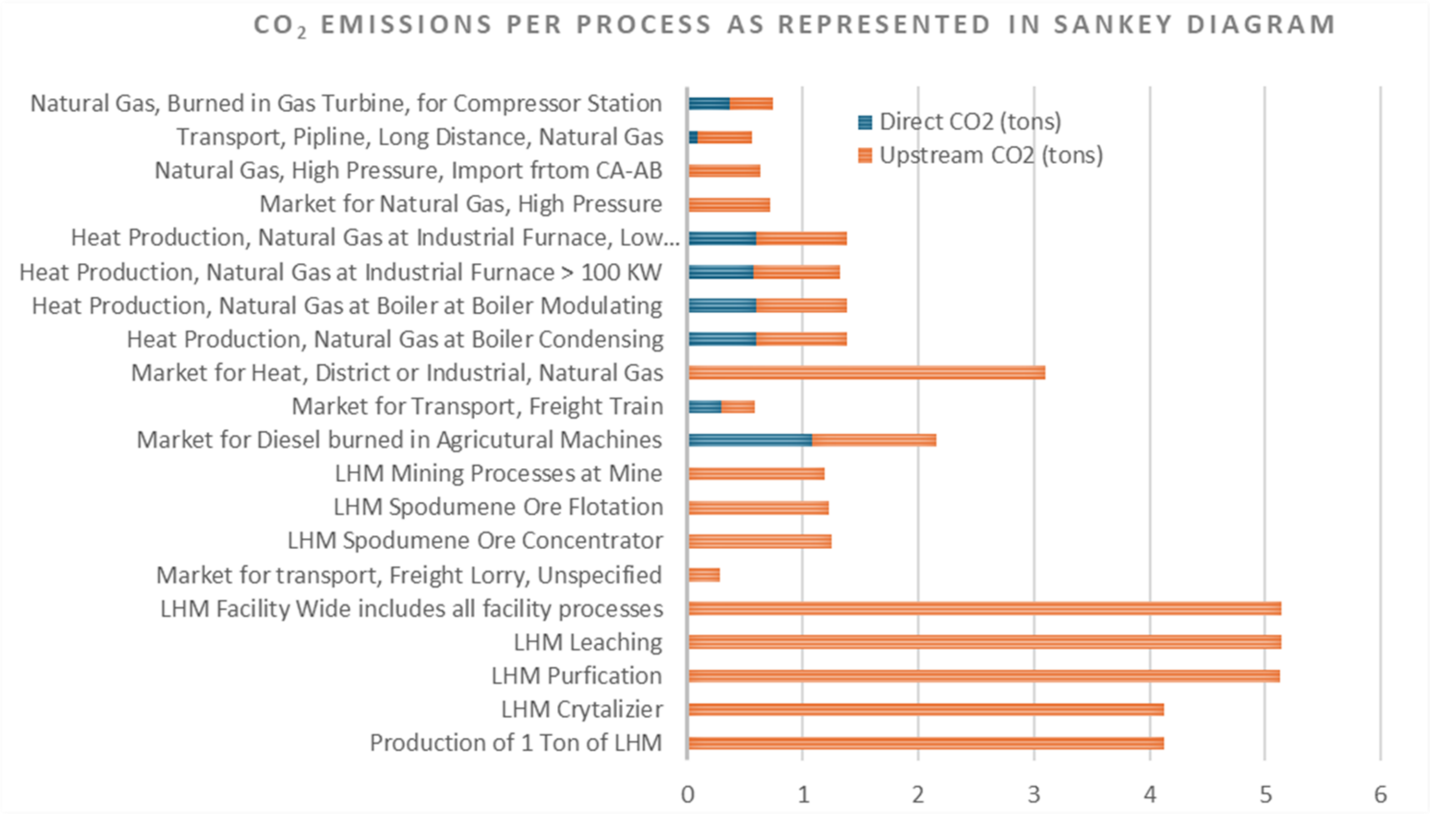


Figure 45: Direct and upstream CO2 emissions from LHM extraction/concentrator and process plant in Québec

The comparison between the present study, being conducted in 2025 (current research), and that conducted by Chordia et al. (2022) highlights key differences in material inputs, categorization (see Table 13), and market choices for LHM production. In the mining/concentrator phase, this study replaces blasting and grinding media with rock crushing, owing to the unavailability of data for blasting. The provider in *Ecoinvent v3.8* was as follows: market for blasting (cutoff, U), grinding media (market for steel, low alloyed market for forging steel), market for electricity (medium voltage, CA-QC), diesel mining (market for diesel, burned in agricultural machinery), freshwater (water, lake, CA), and tailing (market for non-sulfidic tailing, offsite), based on supplementary data from (Chordia et al., 2022). Notably, in the current research, sodium hydroxide is classified as a neutralizing agent, and energy inputs shift to high-voltage electricity and Cutoff-

S diesel, whereas the 2022 study used medium-voltage electricity. Additionally, water sourcing also differs, with the present study replacing lake water with market tap water, and explicit transport modes (conveyor belt and rail freight), absent in the 2022 study, are introduced. In the process plant phase, while sulfuric acid remains unchanged, calcium hydroxide is omitted, and sodium hydroxide is assigned to the updated classification. Energy inputs shift from district/industrial natural gas to low-pressure natural gas. Furthermore, there are significant changes in the waste by-products; the 2022 study represents aluminum silicate using waste foundry sand, while the present study initially substitutes sodium silicate but deems it unsuitable because of excessive CO_2 credits. Gypsum, modeled as waste gypsum in 2022 study, is considered as gypsum mineral production, while sodium sulfate anhydrite is explicitly accounted for as a byproduct in the present study. These refinements improve the specificity and relevance of LCA modeling, potentially altering impact assessments by modifying system boundaries and credit allocations. Figure 46 shows the long/short term impacts of climate change, reported in kilograms of CO_2 emitted during the production of LHM. Since sodium sulfate was used instead of aluminum silicate, no credit was applied to the short/long-term CO_2 emissions. However, a small by-product credit was calculated for gypsum mineral production (1.65 kg CO_2 for both long term and short term). Production of sodium sulfate had the largest by-product credit (1,007.95 kg CO_2 long-term and 1,062.04 kg CO_2 short-term), as presented in Figure 46. Impacts on water scarcity (m^3) were also calculated for each process. The impact on water scarcity is highest in the concentrator, attributed to flotation a part of LHM production process requiring large volumes of water (Livent_Nemaska_Lithium, 2023; Nemaska_Lithium, 2019). It can be seen from the graph that water has the highest impact, despite taking the by-product credit. The negative values for gypsum (mineral) and sodium sulfate are the credits based on CO_2 emissions, which may be avoided by using these by-products as raw materials in other industries. Notably, the by-products, aluminum silicate (Al_2SiO_5), gypsum, and purge solution were considered waste and no CO_2 credit was taken in their overall emission calculations in the study by Chorida et al.(2022).

Table 13: Comparison of current research (2025) versus the Chordia et al. (2022) for provider and category for a Québec LHM

Chordia et al (2022)			**Current Research (2025)**		
Provider material input	Provider in ecoinvent	Category	Provider material input	Provider in ecoinvent	Category
Mining/Concentrator			Mining/Concentrator		
Mining activity input					
Spodumene ore		Resource/ in ground			
Blasting	Market for blasting | blasting | Cutoff, U	GLO			
Grinding media	Market for steel, low-alloyed market for forging, steel	GLO			
			Spodumene-ore concentrator	Market for rock crushing | rock crushing | Cutoff, U	GLO
			LHM Spodumene-ore Flotation		
Chemical and reagent input					
Sodium hydroxide	Market for NaOH, without water, in 50% solution state	GLO	Neutralizing agent, sodium hydroxide	Sodium hydoxide to generic market for neutralizing agent | neutralizing agent sodium hydroxide equivalent | Cutoff , S	GLO
Energy input					
Electricity	Market for electricity, medium voltage	CA-QC	Electricity	Market for electricity, high voltage | Cutoff_S |	CA-QC
Diesel, mining	Market for diesel, burned in agricultural machinery	GLO	LHM Mining Processes at Mine	Market for diesel, burned in agricultural machinery | Cutoff, S	GLO
Freshwater	Water, lake, CA	Resource/ in water	Tap water	Market for tap water tap water | Cutoff, S	CA-QC
Tailing	Market for non-sulfidic tailing, off-site	GLO			
Water, sedimentation pit	Water, lake, CA	Resource/ in water	Tap water	Market for tap water tap water | Cutoff, S	CA-QC
Transportation					

Chemical and reagent input					
Sulfuric acid (H_2SO_4)	Market for sulfuric acid	RoW	Sulfuric acid	Market for sulfuric acid | sulfuric acid | Cutoff U	RoW
Calcium hydroxide $CA(OH)_2$	Market for quicklime, milled packed	RoW			
Sodium hydroxide (NaOH)	Market for NaOH, without water, in 50% solution state	GLO	Neutralizing agent, sodium hydroxide	Sodium hydoxide to generic market for neutralizing agent | neutralizing agent sodium hydroxide equivalent | Cutoff , S	GLO
Energy input					
Electricity	Market for electricity, medium voltage	CA-QC	Electricity	Market for electricity, high voltage | Cutoff_S |	CA-QC
Heat (natural gas)	Market for heat, district or industrial, natural gas	CA-QC	Natural gas, low pressure	Market for natural gas low pressure | natural gas low pressure | Cutoff, S	RoW
Waste (by-products)					
Aluminum silicate (Al_2SiO_5)	Market for waste foundry sand	GLO	Sodium silicate, solid	Market for sodium silicate solid | sodium silicate, solid | Cutoff U	RoW
Gypsum ($CaSO_4.2H_2O$)	Market for waste gypsum	RoW	Gypsum fiberboard	Market for gypsum fiberboard production | gypsum production } Cutoff, S	RoW
Sodium sulfate (Na_2SO_4)			Sodium sulfate, anhydrite	Market for sodium sulfate anhydrite | sodium sulfate anhydrite | Cutoff, S	RoW

GLO = global **CA-QC = Quebec, Canada** **RoW = Rest of the World**

The parameters in Table 13 were applied in *OpenLCA v2.3 using Ecoinvent v3.8* and *Impact World+ Midpoint v2.0.1* to assess long- and short-term CO_2 impacts and water scarcity. As can be seen from Table 14, the present study calculated 5.46 tons of CO_2 per ton of $LiOH \cdot H_2O$ from spodumene ore, as compared with 9.66 tons estimated by Chordia et al. (2022) and 15.7 tons by Kelly et al. (2022) using the Argonne National Laboratory (ANL) *GREET LCA* model. The GREET model, which includes inventory data for lithium-ion battery (LIB) production, differs from OpenLCA as it is tailored to U.S. transportation data, whereas *Ecoinvent v3.8* provides a more global perspective. The variation between the two *OpenLCA*-based studies is primarily owing to the differences in provider markets and linked production processes. The present study is focussed on the operations at a Québec-based mine and production facility, ensuring relevance for North American battery manufacturing.

Table 14: CO_2 emissions from (Québec) LHM production

Tons CO_2 per ton $LiOH \cdot H_2O$ Spodumene ore mined/processed		
		Current research (2025)
[26]	[19]	
9.66	15.70	5.46
Ecoinvent v3.8 (LCA)	GREET (LCA)	Ecoinvent v3.8 (LCA)

The climate change long/short term CO_2 emissions (kg) and water scarcity (m^3) for spodumene ore extraction and the processing of LHM in Québec are shown in Figure 46. The updated LCA results indicate that the production of battery-grade LHM has notable environmental impacts, particularly in climate change and water scarcity. The long-term climate change impact of LHM production is 5,110 kg CO_2-eq, but reductions from avoided by-products, mainly sodium sulfate (-1,007.95 kg CO_2-eq), bring the overall impact down to 4,100.75 kg CO_2-eq. Similarly, the short-term climate change impact starts at 5,459.10 kg CO_2-eq, with by-product contributions reducing the final impact to 4,395.42 kg CO_2-eq. Water scarcity is also a key concern, with an initial impact of 10,772.97 m^3 world-eq, which decreases to 9,422.31 m^3 world-eq after accounting for sodium sulfate recovery. These findings emphasize the significance of by-product utilization in mitigating the environmental footprint of LHM production and highlight opportunities for sustainability improvements.

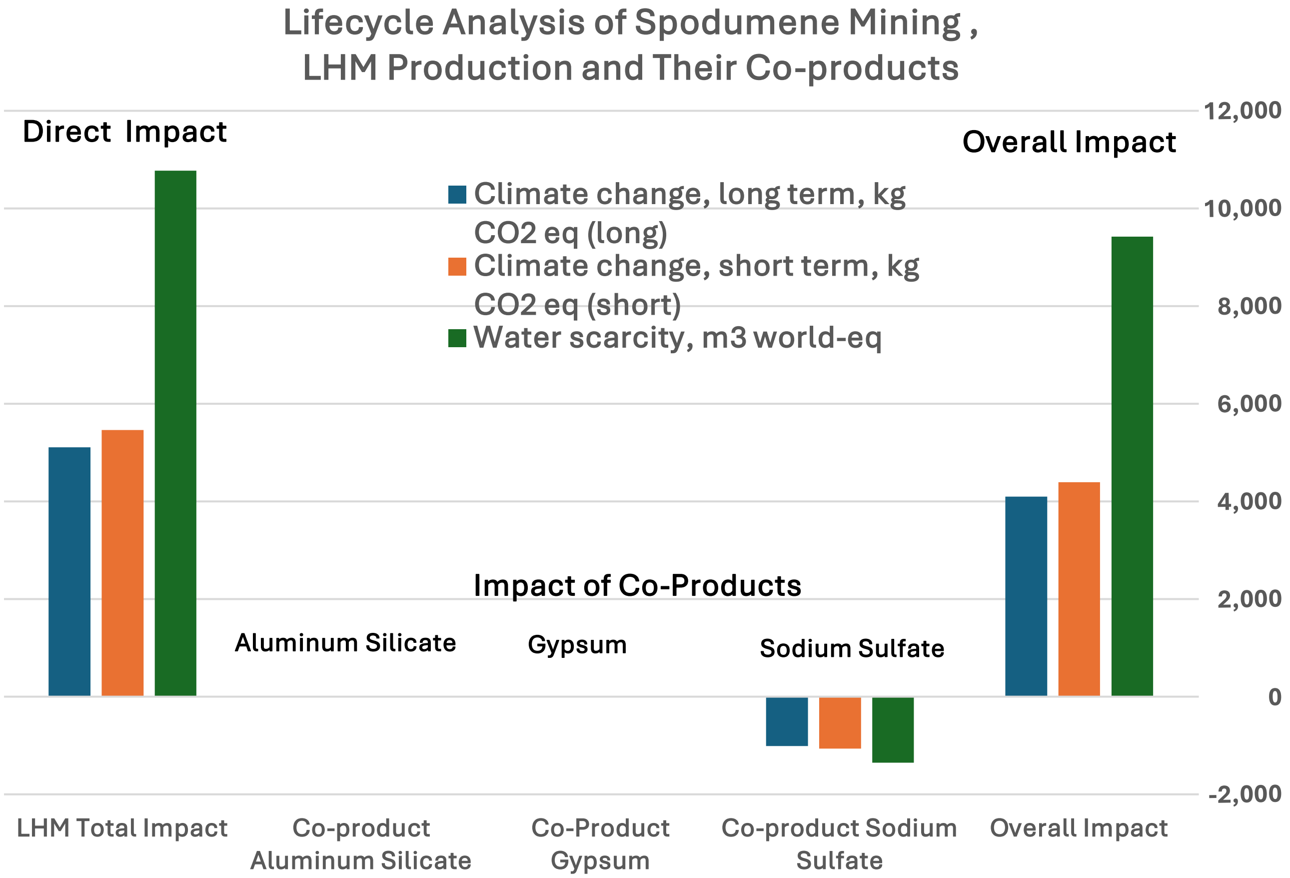


Figure 46: CO_2 emissions (long/short term) and water scarcity from the extraction and production of LHM in Québec

A cradle-to-gate LCA of LHM production is presented in Figure 47 for each process as a percentage of long/short term CO_2 and water scarcity. The spodumene ore concentrator and the spodumene ore flotation had the highest water usage, which was logical considering the operational requirements of those processes. The LHM purification process had one of the highest CO_2 emissions (long/short term), which reflected the energy usage from natural gas (rotary kiln calciner) at the LHM process plant.

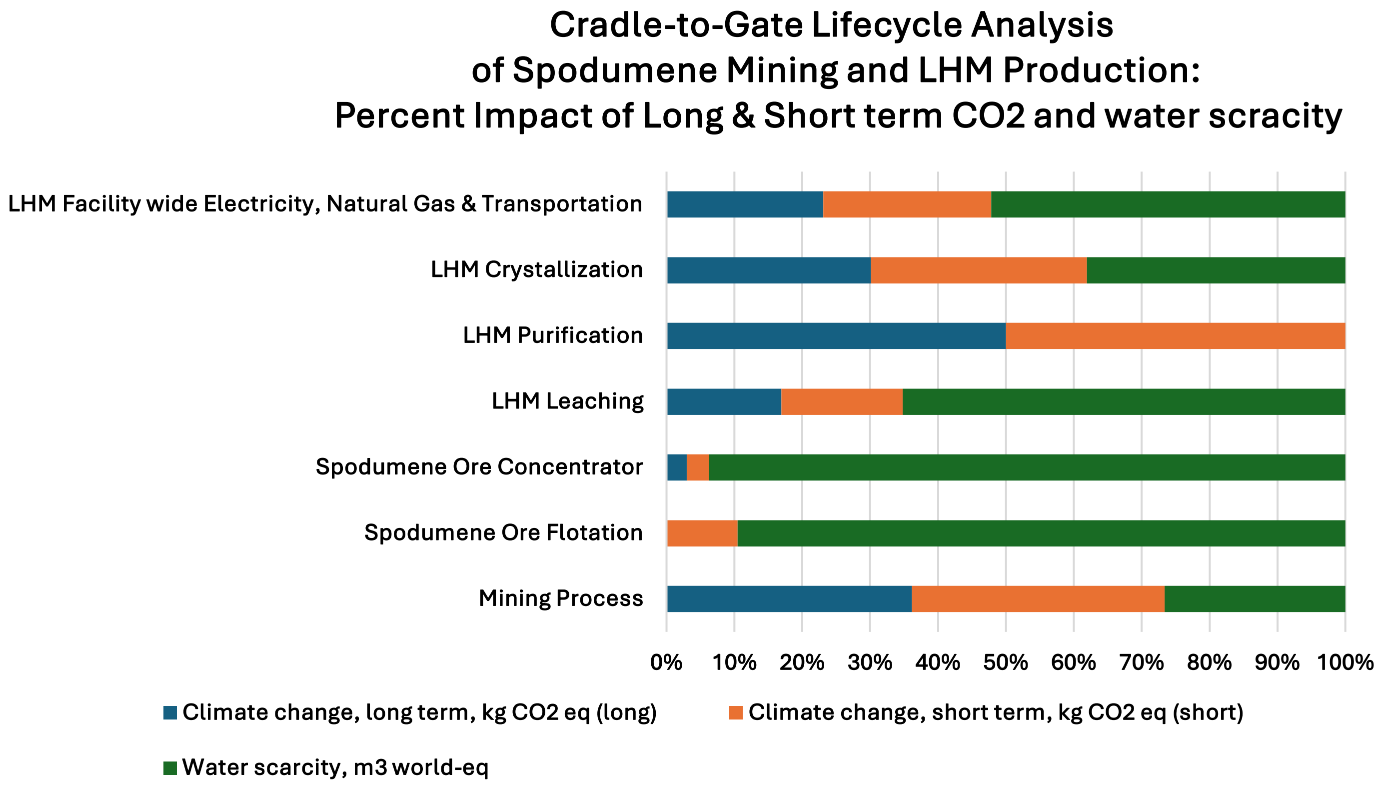


Figure 47: Cradle-to-gate LCA of spodumene mining and LHM production as percent of long- and short-term CO2 and water scarcity

The LCA results highlight the environmental impact of various stages in the production of LHM, with the facility-wide electricity, natural gas, and transportation (concentrate shipped via truck and rail to process facility) contributing the most to both climate change and water scarcity. The corresponding impact of LHM production in Québec varies significantly across different process stages. Mining and ore processing contribute a notable share to the total CO_2 emissions, with the mining process alone accounting for 1,228.09 kg CO_2-eq (short-term). The spodumene ore flotation and concentrator stages add relatively minor emissions, totaling to 60.30 kg CO_2-eq (long-term) and 64.52 kg CO_2-eq (short-term). Most emissions arise from LHM production facility-wide processes, responsible for 3,883.05 kg CO_2-eq (long-term) and 4,157.07 kg CO_2-eq (short-term), making up the largest share of total climate impact. Water scarcity impact is similarly dominated by facility-wide processes, which account for 8,760.26 m^3 out of the total 10,772.97 m^3 world-eq. While individual process stages contribute incrementally, these findings emphasize that optimizing facility-wide operations is key to reducing the overall environmental footprint of LHM production. Facility wide emissions are comprised of that from electricity, natural gas, reagents, and co-products. The long/short term CO_2 emissions by each process involved in the mine/concentrator and LHM process plant in Québec are presented in Table 15 and 16.

Table 15: Climate change long/short term impacts by process for LHM production in Québec

Impact category	**Mining process**	**Spodumene ore flotation**	**Spodumene ore concentrator**	**LHM leaching**	**LHM purification**	**LHM crystallization**	**LHM production facility wide processes**	**LHM total impact**
Climate change, long term, kg CO_2 eq (long)	1,192.30	34..30	26.00	0.03	1.66	7.32	3,883.05	5,110.35
Climate change, short term, kg CO_2 eq (short)	1,228.09	36.44	28.08	0.03	1.66	7.74	4,157.07	5,459.10
Water scarcity, m3 world-eq	878.27	312.10	812.99	0.10	0.00	9.26	8,760.26	10,772.97

Table 16: Climate change long/short term avoided impacts for by-products of LHM production in Québec

Impact category	LHM production total impact	By product aluminum silicate	By product gypsum	By product sodium sulfate	Overall impact
Climate change, long term, kg CO_2 eq (long)	5,110.35	0.00	-1.65	-1007.95	4,100.75
Climate change, short term, kg CO_2 eq (short)	5,459.10	0.00	-1.65	-1062.04	4,395.42
Water scarcity, m^3 world-eq	10,772.97	0.00	0.00	-1350.66	9,422.31

By-products play a crucial role in reducing the overall environmental impact of LHM production. While aluminum silicate does not contribute to impact reductions, avoided production of gypsum and sodium sulfate provide significant CO_2 and water scarcity credits. For long-term climate change impact, LHM production initially accounts for 5,110.35 kg CO_2-eq, but sodium sulfate reduces this by 1,007.95 kg, bringing the total to 4,100.75 kg CO_2-eq. Similarly, short-term climate change impact decreases from 5,459.10 kg CO_2-eq to 4,395.42 kg CO_2-eq, primarily because of sodium sulfate. In terms of water scarcity, LHM production requires 10,772.97 m^3 world-eq, but sodium sulfate offsets 1,350.66 m^3, reducing the final impact to 9,422.31 m^3 world-eq. These findings highlight the importance of accounting for by-product credits in life-cycle assessments, as they significantly lower the total environmental burden of LHM production.

3.4 Summary

The main environmental impacts of producing one ton of LHM arise from energy consumption (including electricity, diesel, gasoline, and natural gas), water usage, waste generation, and by-products. These impacts were assessed for a mine and processing plant located in the province of

Québec, Canada. A cradle-to-gate LCA was conducted, covering the process from mining to battery-grade material. Impacts were calculated using *OpenLCA v2.3, Ecoinvent v3.8* database and the *Impact World+ Midpoint v2.0.1* method, based on data from a spodumene mine and LHM production plant in Québec, Canada. Given that Australia is one of the world's largest suppliers of lithium from spodumene, with processing occurring in China, the results from Québec were compared with those from Australia, China, and previous LCAs conducted on Québec LHM mine/process plant. The highest CO_2 emissions observed in the Québec mine and process plant were noted to arise from the natural gas used in the process plant. In the Australia/China operations, diesel was used not only for extraction of the spodumene ore at the mine, but also to generate electricity. This case study has shown that even though Québec has lower GWP linked to renewable hydroelectric power, electrification of the process calciner can help to lower the CO_2 generation at the process plant. Additionally, electrification of mining equipment (excavators, dump trucks, graders etc.), and the replacement of fossil fuel vehicles to electric models could eliminate the impact from fuel consumption. This work demonstrates that an LCA can be helpful in identifying hotspots and opportunities for improvement of products, herein, battery grade LHM, that are critical to a sustainable future. The province of Québec continues to work towards a "green battery" with zero waste and performing LCA on critical mineral extraction and processing in the province is a necessary step providing valuable information and insights for the decision-makers and ensure progress toward this goal.

CHAPTER 4. TOWARD SUSTAINABLE ANODE MATERIALS: LCA OF NATURAL GRAPHITE PROCESSING IN QUÉBEC

4.1 Background

Sales of electric vehicles continue to increase in North America (*Electric Vehicles - North America*) even with the economic fluctuations in both the United States and Canada. According to Bloomberg, global EV sales are projected to reach approximately 24.3 million units by 2026 (Bloomberg_NEF, 2026).There is also a change in the lithium-ion battery (LIB) supply chain for critical minerals that were originally coming from Asia, mainly China (Barman et al., 2023) but now being sourced from the United States and Canada (NREL, 2025). Canada has reserves many critical minerals, including cobalt, graphite, lithium, nickel, and rare earth metals for battery production (Government_Canada, 2025a).

Graphite has dominated the anode materials market, accounting for up to 98% of market share, while $Li_4Ti_5O_{12}$ represents only about 2% (Julien & Mauger, 2024). Silicone anodes have been researched over the past several years due to the high theoretical capacity, availability and low cost, but issues like volume expansion and reliability have hindered commercialization for EV anodes (Toki et al., 2024). Graphite, which can make up 20% of a LIB cell, is a critical mineral used in the anode of the LIB. Graphite sourced from natural ores; natural graphite (NG) generally has lower production costs but also lower purity and quality. Its anisotropic crystal structure can hinder performance in lithium-ion batteries, even though the larger domain sizes often allow for higher capacities. This advantage, however, typically comes with reduced cycle life. In contrast, synthetic graphite (SG) produced from carbon precursors such as petroleum coke or coal tar pitch is more costly to manufacture but offers much higher purity and consistency, but had a higher market share (59.09%) by revenue in 2025 (Mordo_Intelligence, 2026). Its isotropic crystal orientation provides better thermal stability, lower thermal expansion, and faster lithiation/delithiation kinetics. As a result, it delivers stronger overall battery performance and longer cycle life, despite usually having lower capacities due to smaller domain sizes or a greater number of interdomain boundaries (Rijo, 2024).

The widespread use of graphite is attributed to its low cost, natural abundance, high energy and power density, and long cycle life, making it a highly favorable choice for lithium-ion battery anodes (Zhang et al., 2021). According to the International Energy Agency (IEA), achieving net-zero emissions by 2050 would require global demand for graphite to reach approximately 16 million tons by 2040 (IEA, 2024). The production of NG used in LIBs requires 230 to 260 MJ of energy per kg graphite, with China burning mainly coal as a source of electricity, thus causing a high environmental impact (Engels et al., 2022). China is working on developing green energy for critical mineral processing. An example of this effort is the Sunstone facility in Inner Mongolia that operates its graphitization furnaces on 100% renewable electricity, making it an early commercial example of fully renewable-powered anode-material processing (Han & Li, 2025).

SG is preferred due to the lack of natural graphite sources for LIB applications (Kulkarni et al., 2022). In a recent study by Pandey et al. (2025) in the United States found that the production of battery anode active material (BAAM) from synthetic graphite produced 29.7 CO_2 -eq per kg BAAM. The hotspot was found in the graphitization step and total energy use was at 580 MJ kg^{-1} (Pandey et al., 2025). To address this challenge, researchers have explored methods to reduce the energy required for synthetic graphite production, including electrochemical graphitization. The Acheson process transforms soft amorphous carbons, such as petroleum coke, into graphite at high temperatures up to 3200 °C (Kulkarni et al., 2022).

Engels et al. (2022) conducted a LCA of natural graphite production for battery-grade anodes using industrial primary data from China. The study reported total greenhouse gas emissions of 9,616 kg

CO_2-eq per 1,000 kg of natural graphite, with the coating process identified as the primary contributor to these emissions (Engels et al., 2022). In another study, Zhang et al. (2018) found that the purification process accounted for most of the environmental impact (60%), followed by surface modification (18%). This study reported an energy consumption of 100.46 MJ per kg of natural graphite anode, with electricity identified as the dominant contributor, accounting for 50% of the overall environmental impact (Zhang et al., 2018). Additionally, Gao Si et al. (2018) reported that producing 1 ton of natural graphite anode resulted in 112.48 GJ of energy consumption and 5,315.91 kg CO_2-eq of emissions (Gao et al., 2018).

High-purity graphite is required by EV manufacturers for their anode material. Many original equipment manufacturers (OEMs) have signed contracts with graphite mines located in Québec (Nouveaux_Monde_Graphite, 2025). With this new North American graphite supply chain, OEM's are requiring LCA from the mines as part of their sustainability objectives. It was noted that there are no recently published articles for LCAs on graphite extraction and processing in Asia and Europe. There is no recent LCA published in the literature for graphite extracted from Québec. Many previous studies found in the literature focused on carbon fiber-thermoplastic, fuel cell, and the crystallization of carbon atoms in Acheson furnaces (Kulkarni et al., 2022).

4.2 Cost Analysis of Natural Graphite

Graphite comprises roughly half the mass of a lithium-ion battery anode, with roughly 1.2 kg of graphite required per kWh of cell capacity. Driven by EV and energy-storage demand, natural flake graphite is projected to gain market share relative to synthetic graphite, rising from about 224,538 tons today to roughly 3.08 million tons by 2030 (Nouveaux_Monde_Graphite, 2023a). Natural graphite undergoes mining, flotation, purification, spheroidization, and heat treatment to achieve battery-grade quality (>99.95% C). This process is notably wasteful, as up to 70% of feedstock is lost during conversion to spherical form (Mining_Market_Watch, 2025). According to research by the German institute, anode material made from natural graphite is priced between \$4-\$8 per kg. In contrast, synthetic graphite-based anode material costs \$12-\$13 per kg (Government_Canada, 2025b). Meanwhile, synthetic graphite is produced via high-temperature graphitization (exceeding ~2,800 - 3,000 °C) of petroleum or needle coke, an energy-intensive method responsible for 50-60% of total production costs and heavily affected by electricity pricing (Fastmarkets, 2022; PWCCERC, 2025). On an energetic basis, given graphite's specific capacity (~360 mAh/g), this equates to an energy-material cost of approximately \$8-\$12/kWh for natural graphite and higher for synthetic. However, the precise values can vary depending on process efficiencies and regional energy costs. Notably, synthetic graphite's higher carbon footprint (up to 20 kg CO_2e/kg) makes natural graphite more environmentally favorable, offering a 60-90% reduction in emissions CO_2 (J. Zhang et al., 2023).

Studies have been conducted to reduce the energy consumption needed to produce synthetic graphite via electrochemical graphitization (Engels et al., 2022; Kulkarni et al., 2022). The techno-economic analysis shows that natural graphite is the lowest-cost pathway for producing battery-grade anode material, with total production costs typically in the range of \$2,000-3,000 per ton, driven mainly by purification chemicals, electricity use, and spheronization. In contrast, synthetic graphite is significantly more expensive, approximately \$4,000-10,000 per ton because high-temperature graphitization (2,500-3,000 °C) dominates both energy demand and capital expenditure. Northern Graphite has indicated that producing battery-grade natural graphite commercially in Canada would require sale prices of approximately \$8,000-\$10,000 per ton, whereas equivalent material sourced from China was available for about \$6,000-\$7,000 per ton in 2024. In addition, a recent comparative economic assessment of Chinese and U.S. graphite reported natural graphite prices of \$4.34/kg for China and \$7.99/kg for the United States (Gorman et al., 2025). Overall, the significant factors influencing cost include energy consumption, chemical purification reagents, feedstock quality, and equipment capital costs, with graphitization energy being the single most significant contributor to synthetic graphite production (Kadivar et al., 2025). Recent studies demonstrated practical, industry-relevant anode-material manufacturing routes, particularly those based on industrial by-products and waste-derived carbon sources, for processes of spheronization, carbon coating, and graphitization in an attempt to reduce process cost.

4.2.1 Spheronization

Recent results indicate that graphite waste (GW) produced via the Acheson furnace constitutes a technically robust and scalable precursor route for the development of low-cost, environmentally benign anode materials for LIBs(Yang et al., 2024).

4.2.2 Carbon Coating

Another study reported that commercial high-density polyethylene (CPE) and waste high-density polyethylene (WPE) can be effectively regenerated into anode-grade materials for LIBs (Jin et al., 2025). Because polyethylene (PE) undergoes rapid thermal degradation at elevated temperatures, it was first subjected to a thermal stabilization step to facilitate controlled carbonization. After stabilization, the material was graphitized at 3000 °C, producing PE-derived graphite with crystallinity surpassing that of conventional commercial anode materials (CAM).

4.2.3 Graphitization

High-purity graphite was produced from steel manufacturing waste through the successful conversion of emission control system (ECS) dust a carbon-rich by-product generated during steel processing into anode-grade material for LIBs (Choi et al., 2025). The ECS dust first underwent a purification step to remove metallic contaminants and non-carbonaceous phases. It was then subjected to thermal stabilization to mitigate premature decomposition during subsequent high-temperature processing. After stabilization, the material was carbonized and graphitized at temperatures approaching 3000 °C, promoting the development of highly ordered graphitic domains. This integrated sequence of purification, stabilization, and high-temperature graphitization enabled the production of graphite exhibiting structural and electrochemical characteristics on par with, or superior to, those of conventional commercial anode-grade graphite.

4.2.4 Availability of Graphite in Canada

The province of Québec in Canada is notably rich in critical minerals, including graphite (Ibarra-Gutiérrez et al., 2021; Quebec_Government, 2022). Currently, there are graphite projects in three Canadian provinces (Québec, Ontario, and British Columbia) (NREL, 2025) as shown in Figure 48. The purpose of this research is to evaluate the environmental impact of graphite mined in Québec via LCA. A cradle-to-gate process-based attributional analysis was performed on AAM produced in Québec. Our objective was to compare LCA results from AAM originating in China and material from Québec, Canada. This study encompassed the processes of ore extraction at the open pit mine, drilling/blasting, metrophoric rock out of the ground, flotation, spheronization, purification, and coating. The production of co-products was also considered in this LCA (Nouveaux_Monde_Graphite, 2023b, 2025).

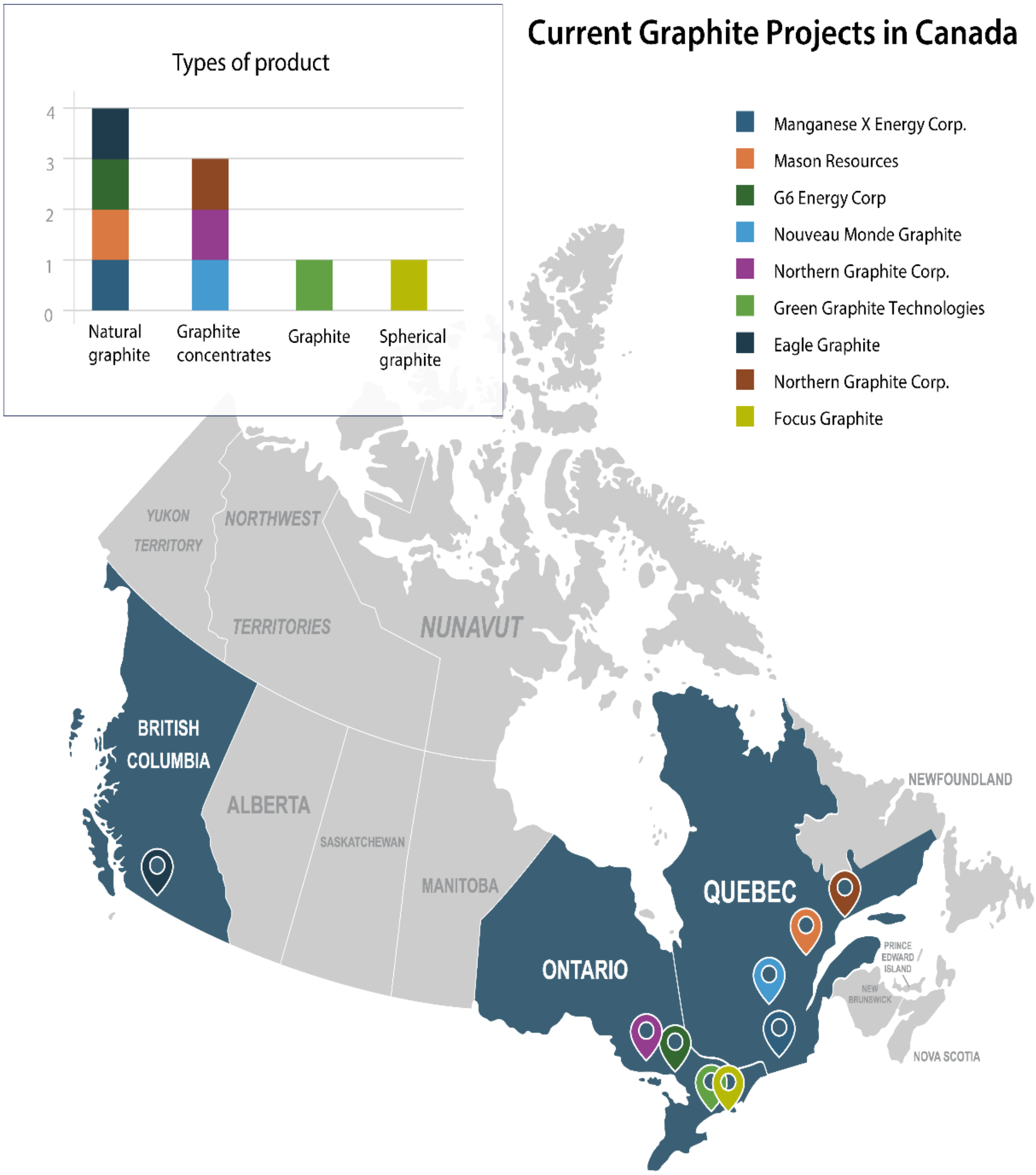


Figure 48: Graphite projects in Canada (NREL, 2025).

4.3 Methods and Materials

4.3.1 Graphite Ore Extraction and Processing in Québec

Canada is home to several critical minerals used in lithium-ion batteries, including graphite, a commonly used anode material currently being mined in Québec. Figure 49 represents typical mining and extraction of natural graphite from ore.

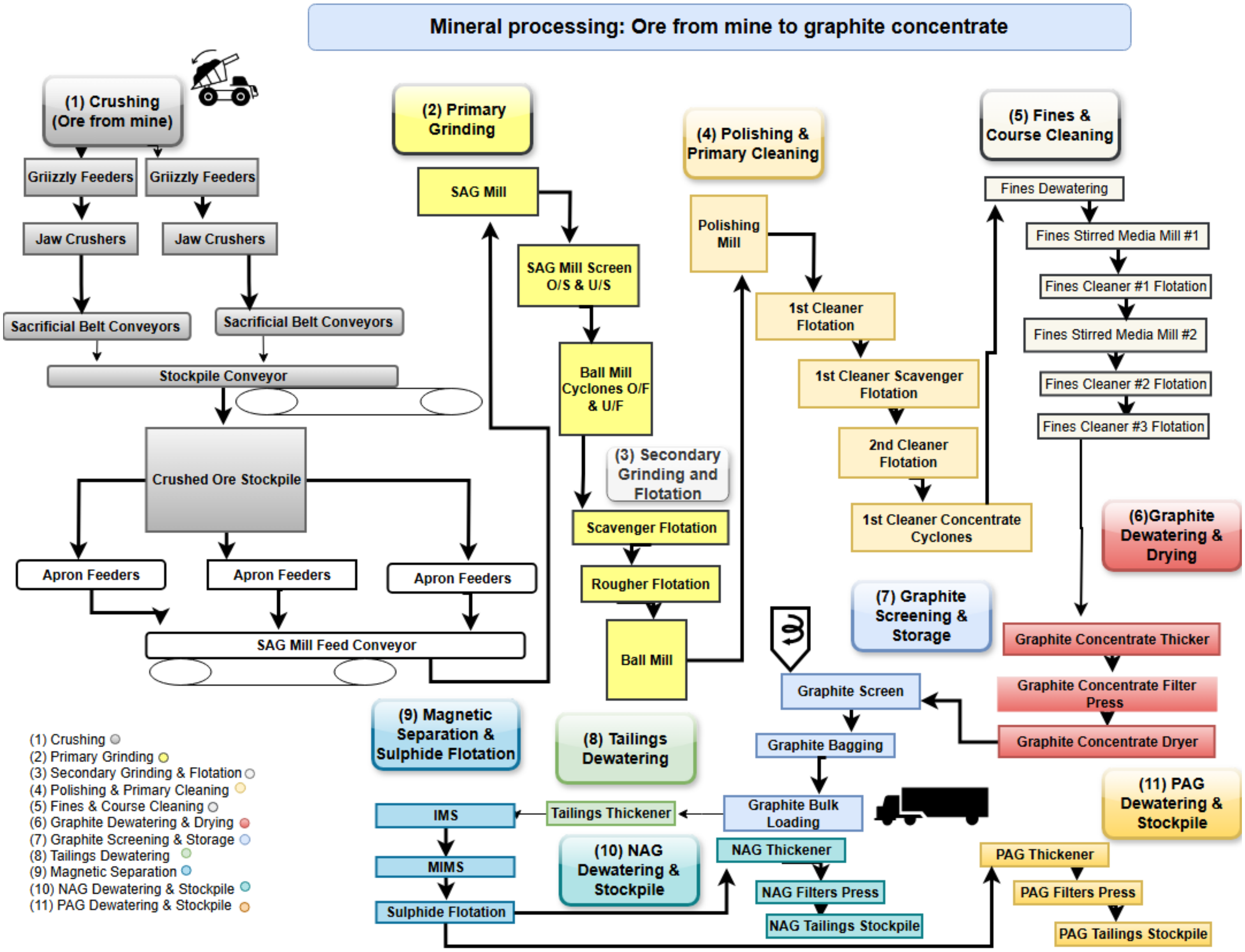


Figure 49: Extraction of graphite and processing to concentrated graphite at a Québec mine.

The extraction of natural graphite from ore in Québec involves a series of complex beneficiation steps designed to produce high-purity graphite concentrate suitable for battery applications. These steps typically include crushing and grinding to reduce the particle-size, followed by polishing and primary cleaning to remove impurities. The material then undergoes fines and coarse cleaning, dewatering, drying, and screening before being stored. Additional processes such as magnetic separation and sulfide flotation are used to eliminate metallic contaminants. Waste management is also a critical component of the operation, with non-acid generating (NAG) waste being dewatered and sorted for safe disposal, while potentially acid-generating (PAG) waste is carefully managed to prevent environmental contamination, as illustrated in Figure 50. The graphite concentrate is then transported to the process plant to create AAM used in LIBs.

In a typical anode material processing plant, three primary steps are involved: micronization and spheronization, purification, and coating as seen in Figure 50. During the micronization step, concentrated graphite is micronized to achieve optimal particle size. This is followed by spheronization, in which the particles are shaped into spherical forms to enhance tap density, improving packing efficiency and electrode performance.

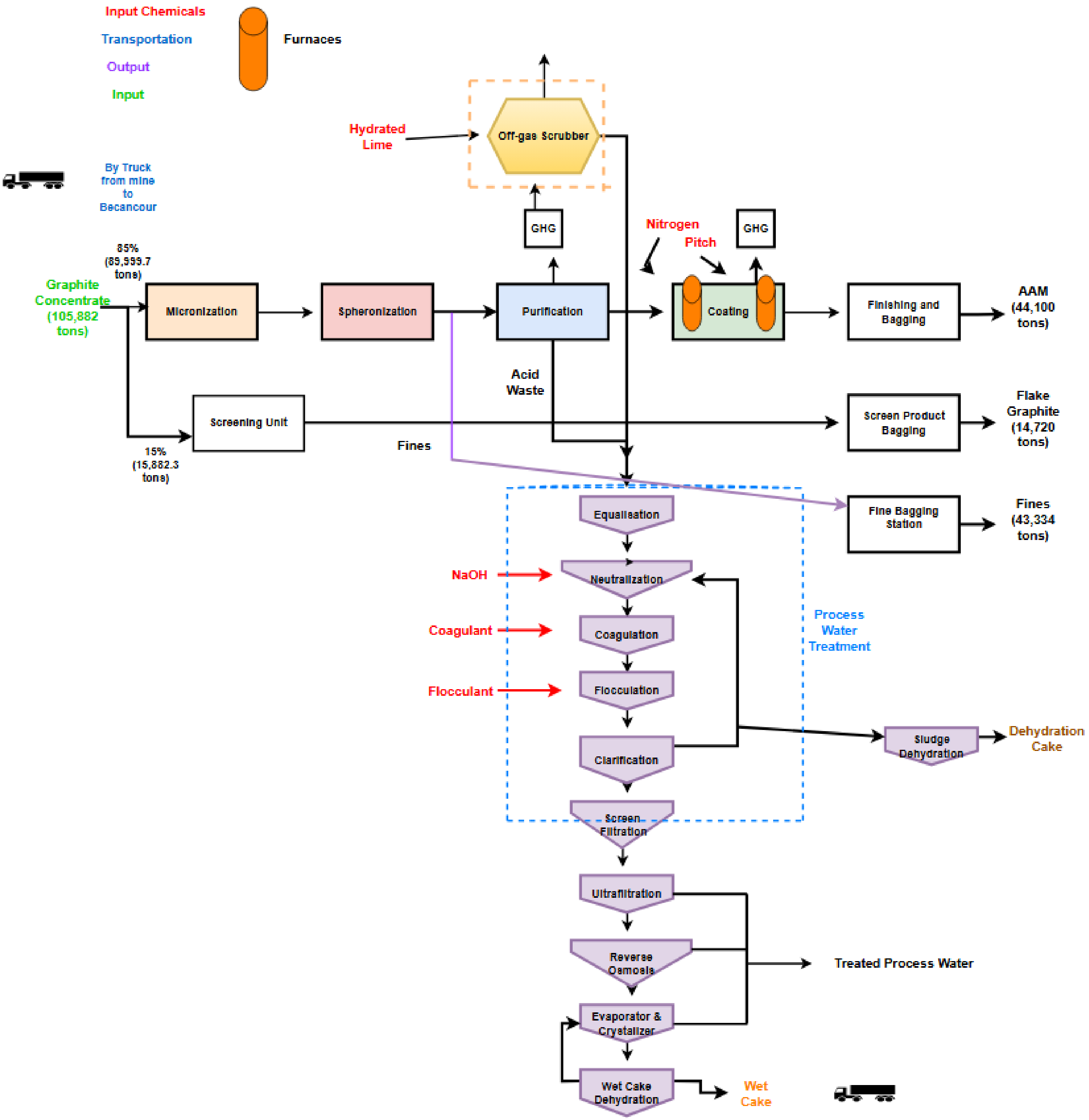


Figure 50: Graphite process plant flowchart for Québec case study.

The purification step can employ either hydrometallurgical or pyrometallurgical methods. In the hydrometallurgical route, acid-based leaching techniques are applied, commonly using hydrofluoric acid (HF), which is highly effective but associated with significant environmental impacts due to the toxicity and corrosivity of HF (Microlit, 2023; Nouveaux_Monde_Graphite, 2025). Alternatively, pyrometallurgical purification involves chlorination roasting, where impurities react with chlorine to form volatile chlorides that are subsequently removed. This method can achieve a purification efficiency of up to 98% (Microlit, 2023). Another technique under exploration is high-temperature purification, in which graphite is heated to elevated temperatures to vaporize impurities with low boiling points (Barma et al., 2019). In this study, we focus on acid-based leaching, as it is a widely adopted purification technique, particularly in Chinese graphite processing facilities (Engels et al., 2022). The final stage is coating, wherein the purified, spheronized graphite is coated with a nanometric carbon layer. This coating improves the electrical conductivity, structural stability, and overall performance of the anode material.

To compile a comprehensive dataset of input parameters reflecting the mining, concentration, and processing of AAM in Québec, data was sourced from a range of technical documents published in 2022 (Nouveaux_Monde_Graphite, 2022), 2023 (Nouveaux_Monde_Graphite, 2023b), and 2025 (Nouveaux_Monde_Graphite, 2025). A data gap was also identified in locating *Ecoinvent (v3.8)* entries for certain reagents utilized in both the concentrator plant and the AAM process facility. Where feasible, proxy chemicals were selected based on available datasets within the *Ecoinvent (v3.8)* database. Co-products were also considered in the process of plant operations and credit given on CO_2 emissions.

Table 17 lists the processes, intermediary flows, and subprocesses that were setup in the *OpenLCA v2.3* program that represents the Québec case study. The main areas were the (mine) concentrator, mining crusher/concentrator, flotation, (AAM production plant) process plant micronization spheronization**,** purification, coating, process facility wide (example one number provided for total plant wide natural gas consumption), finishing/bagging, and AAM production.

Table 17: Flows (detailed) in current research and from Engels et al (Engels et al., 2022) per ton of AAM

Processes	Intermediary flows (sub processes)
Mining	Natural graphite with waste rock
Concentrator (natural graphite concentrate)	Mine NAG non acid generating waste
	Mine PAG potential acid generating waste
	Mine_Diesel_Equipment
	Mine (electricity) mining equipment
	Mine (electricity) water services
	Mine transport crusher concentrator to process plant
Mining crusher concentrator	Mine transport waste rock and tailings to co-disposal facility
	Crusher concentrator electricity crusher
	Concentrator NAG tailing dewatering and stockplie
	Concentrator PAG tailing dewatering and stockplie
	Concentrator water
	Crusher_Concentrator (electricity) concentrator process
	Crusher concentrator (electricity) HVAC and aux system
	Concentrator reagent flotation fuel oil
	Crusher concentrator reagent methy isobutyl carbinol MIBC
Flotation	Concentrator reagent flocculant
	Concentrator reagent lime
	Concentrator reagent potassium amyl xanthate
AAM production plant	Concentrated natural graphite received from mine
Process plant micronization spheronization	Process micronization and spheronization (electricity)
	Process by product fines (by product)
Process plant purification	Process purification reagent hydrochloric acid

	Process purification reagent hydrofluroic acid
	Process purification reagent nitric acid
	Process purification reagent sodium hydroxide
	Process purification reagent nitrogen
Process plant coating	Process coating (electricity)
	Process coating reagent nitrogen purge
	Process by product purified jumbo flakes (by product)
	Process purification (electricity)
	Process water
Process facility wide	Process natural gas
	Mine transport in plant mine ore to crusher plant
Process plant finishing bagging	Process finishing and bagging (electricity)
AAM production	AAM produced

4.3.2 Reagent Substitution and Justification

While analyzing the AAM data for both the concentrator and process plant, several reagents were identified as missing from the *Ecoinvent v3.8* database. To address these gaps and maintain the continuity and completeness of the LCA, alternative reagent datasets were selected. This substitution strategy is widely recognized as a valid and practical approach in LCA modeling, particularly when direct inventory data is unavailable. According to Fantke et al. (2020) (Fantke et al., 2020), life-cycle-based alternatives assessment (LCAA) supports the use of functionally equivalent substitutes to ensure consistent environmental modeling while avoiding unacceptable trade-offs. Similarly, Meron, Blass, and Thoma (2020) (Meron et al., 2020) propose a proxy selection methodology that enables accurate approximation of environmental impacts when site-specific data is lacking. These approaches align with best practices in LCA and ensure that reagent-related impacts are represented transparently and scientifically.

In the absence of a dedicated dataset for Methyl Isobutyl Carbinol (MIBC) in the *Ecoinvent* database, butanol can be used as a representative substitute for modeling flotation reagents in graphite production. This substitution is justified by the chemical and functional similarities between the two compounds. Both MIBC and butanol are alcohol-based frothers commonly used in mineral beneficiation processes, particularly in froth flotation. MIBC is known for its superior frothing efficiency, bubble stability, and selectivity in mineral separation (Alsafasfeh et al., 2024; Xu et al., 2022). However, butanol shares key structural features and exhibits similar behavior in stabilizing air bubbles, which is essential for effective flotation performance (Xue & Li, 2024).

Moreover, butanol is readily available in the *Ecoinvent v3.8* database with comprehensive environmental impact data, making it a practical and defensible proxy for LCA purposes. Studies have demonstrated that butanol can serve as a primary frother in flotation systems, influencing bubble size and stability in a manner comparable to MIBC. While MIBC may offer enhanced performance in certain applications, the use of butanol allows for consistent environmental modeling without compromising relevance to industrial flotation practices. This approach ensures methodological transparency and supports the robustness of environmental assessments in the absence of specific data for MIBC (Pereira et al., 2015; Xue & Li, 2024) that can have both upstream and downstream impacts.

Hydrofluoric acid (HF), a highly reactive and hazardous chemical, is widely used in industrial applications such as metal treatment, glass etching, and uranium processing. Although HF is not explicitly listed as a standalone entry in the *Ecoinvent v3.8* database, hydrogen fluoride its gaseous form and molecular equivalent are available and serves as a scientifically valid proxy for environmental modeling. Chemically, hydrofluoric acid is simply hydrogen fluoride dissolved in water, and both forms share the same molecular formula (HF), properties, and industrial uses

(NIOSH, 2017) (*Hydrofluoric Acid vs. Hydrogen Fluoride – What's the Difference?*, 2025) (*Hydrofluoric Acid vs Hydrogen Fluoride: Detailed Comparison and Applications*, 2024).

Ferric sulfate ($Fe_2(SO_4)_3$) and ferric chloride ($FeCl_3$) are both iron-based coagulants commonly used in purification processes, but they exhibit notable chemical and operational differences (X. Liu et al., 2021). Ferric chloride is more acidic and corrosive than ferric sulfate, which can influence equipment durability and necessitate more robust handling protocols. The two compounds also differ in the nature of their byproducts: ferric chloride generates chloride-rich waste, while ferric sulfate produces sulfate-based residues, each carrying distinct implications for environmental emissions and wastewater treatment. In terms of effectiveness, their performance in graphite purification varies depending on the specific impurities targeted, with ferric sulfate often showing superior results due to its favorable precipitation characteristics. Ferric III chloride was chosen as a substitute for ferric sulfate since data was available in the *Ecoinvent v3.8* database as a coagulant.

To estimate reagent consumption in the purification stage of AAM production, plant-specific data were unavailable, so data from Engels et al. (2022)(Engels et al., 2022) were used as substitute. A process flowsheet was developed to trace input, output values across production stages, revealing that 1010 kg of purified spherical graphite is needed to produce 1 ton of coated spherical graphite. Since the purification stage yields 1 ton of purified graphite, a scaling factor of 1.01 (1010/1000) was applied to adjust reagent quantities accordingly. Using this factor, the required amounts of hydrochloric acid, hydrofluoric acid, nitric acid, and sodium hydroxide were calculated and converted to tons per year (tpy), ensuring consistency with the functional unit of 1 ton of coated spherical graphite.

4.3.3 Review of LCA Datasets and Data Analysis

To perform the LCA of battery-grade AAM, we used *OpenLCA v2.3* together with the *Ecoinvent v3.8* database, one of the most comprehensive and widely applied LCA inventory datasets available. Background data from *Ecoinvent v3.8* were incorporated to represent specific processes and feedstocks where primary, context-specific data were unavailable. This ensured a robust evaluation of the environmental impacts associated with graphite production. Midpoint impact results were generated using *Impact World+ midpoint v2.0.1*, which assesses a broad set of environmental indicators. In this study, the primary focus was on global warming potential (GWP), expressed as CO_2 emissions, and water use.

An attributional LCA approach was applied to quantify the direct environmental burdens associated with producing battery-grade AAM. This method excludes broader system-level considerations such as market effects or indirect emissions, enabling a clear and structured assessment of the energy use, greenhouse gas emissions, and resource demands of AAM production.

The LCA workflow was designed to ensure reproducibility and comprehensive quantification of environmental impacts. Primary data were collected from the graphite mining operation and downstream processing facility in Québec. These data included key operational parameters such as energy consumption profiles, raw material inputs, direct emissions, and solid and liquid waste outputs. All raw data were preprocessed and validated to ensure consistency and suitability for LCA modeling.

After validation, system boundaries and process flows were defined in *OpenLCA v2.3*, with individual unit processes representing each step of graphite extraction and refinement. A complete life-cycle inventory (LCI) was assembled to capture all relevant environmental exchanges. The model was then executed to calculate life-cycle impacts across multiple environmental categories using the selected impact assessment method.

4.3.4 Goal and Scope Definition

The LCA framework employed in this study was structured in accordance with ISO 14040 standards (ISO, 2006a), encompassing the definition of system boundaries, LCI inputs, and impact assessment methodologies. The functional unit was defined as the production of one metric ton of AAM, selected to ensure comparability with existing LCA studies and industrial benchmarks. A cradle-to-gate approach was adopted, thereby encompassing all relevant environmental impacts from raw material extraction through to the final production of AAM. An overview of the methods and materials used in this LCA are shown in Table 18.

The life-cycle inventory included primary (foreground) data obtained directly from operations at the graphite mine and associated processing facilities, complemented by secondary (background) data from the *Ecoinvent v3.8* database to ensure completeness and model fidelity. The life-cycle impact assessment (LCIA) focused on key environmental indicators, including atmospheric emissions, freshwater consumption, solid waste generation, transportation-related impacts, and co-product flows. These impact categories were analyzed to provide a comprehensive assessment of the environmental footprint and identify opportunities for sustainability improvements.

Table 18: Overview of methods and material for LCA research

Goal	Cradle to gate life cycle assessment of the extraction and processing of graphite
Scope Definition Functional Unit	1 ton of battery grade anode active material (AAM)
Product Technology	Battery grade AAM used in EV batteries
Background data	Graphite mine and processing facility in Québec
Background database	Ecoinvent database (v3.8),
Cut-off criteria	No explicit cut-off criteria. All information on energy, materials, and emissions compiled from industry-specific technical documents
Impact Assessment Categories	Global Warming Potential (GWP); mainly CO2

4.3.5 Processes, Intermediary Flows, And System Boundary

Several sources of data were used such as environmental impact assessments, technical reports (Nouveaux_Monde_Graphite, 2022, 2023b, 2025) and other sources. Once the processes, elementary, and intermediary flows were identified, a product system was created as shown in Figure 51 (process tree). In this study, energy was supplied by electricity, diesel, and natural gas. Water consumption, reagents, and to AAM at the process plant. transportation was considered for both the extraction/concentration of graphite and processing.

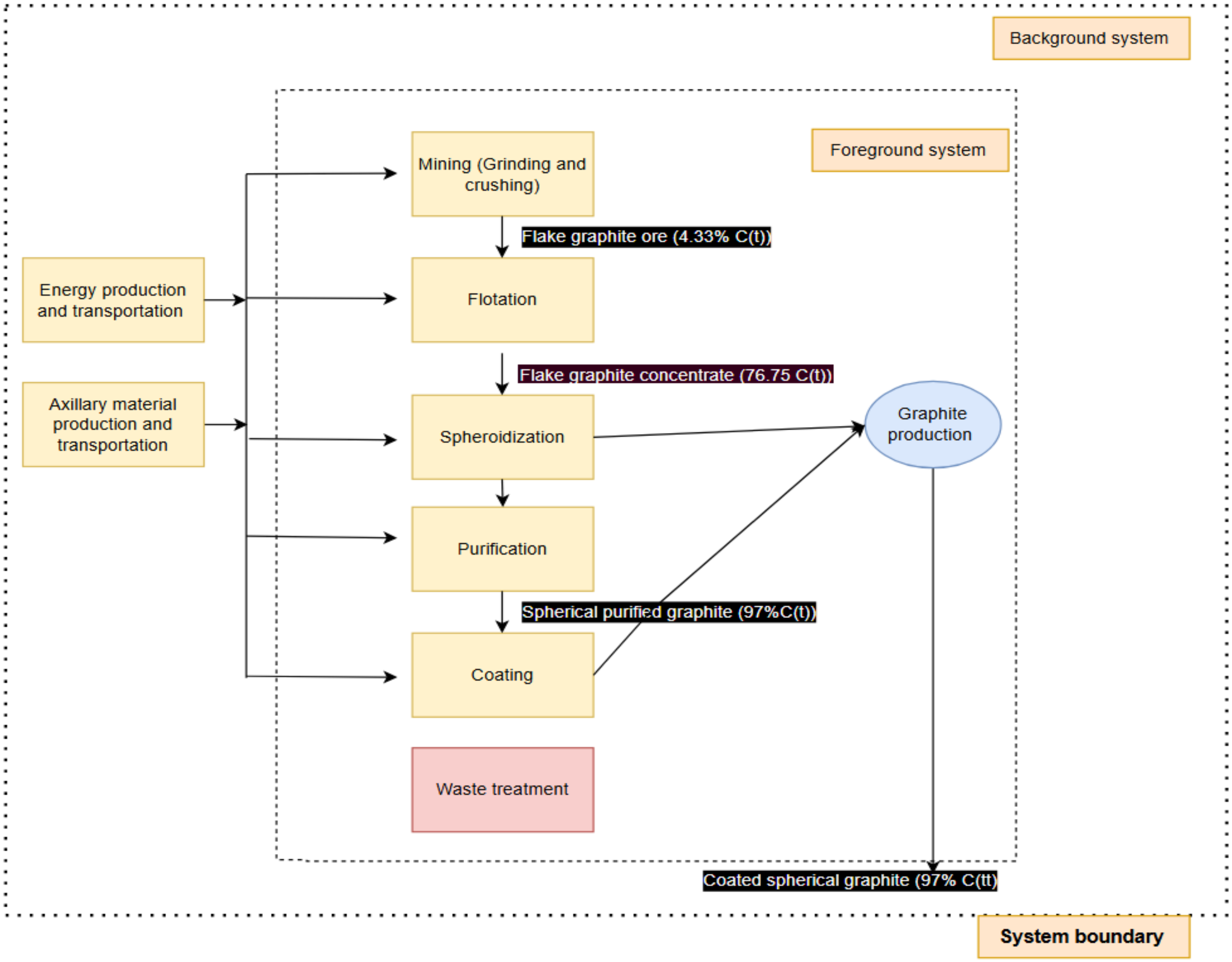


Figure 51: System boundary for graphite extraction and processing to AAM.

To carry out an LCA of graphite extraction and processing in Québec, it was crucial to collect accurate, site-specific, and representative data. This data was essential to ensure the reliability of the environmental impact assessment across all stages of the graphite supply chain. Environmental process data were gathered from multiple sources, including environmental impact assessment (EIA) reports mandated by the Québec government, as well as technical and feasibility reports from the mining industry (Nouveaux_Monde_Graphite, 2022, 2023b, 2025). These documents provided key information on resource extraction, energy consumption, emissions, water usage, and waste generation associated with graphite mining and processing activities.

The EIA reports were particularly valuable, as they included regulatory evaluations, environmental monitoring data, and mitigation strategies implemented by mining operations to comply with both provincial and federal environmental standards. In addition, technical and feasibility reports from the mining sector offered detailed insights into operational efficiencies, material flows, and efforts to optimize processing methods. By integrating updated data from both regulatory and industry sources, this assessment delivers a comprehensive and current evaluation of graphite extraction and AAM production operations in Québec, which can serve as a foundation for a more comprehensive LCA. Some assumptions had to be made such as the case of reagents substitution to conduct a multifunction system.

4.4 Results & Discussion

Several gaps have been identified in the literature regarding the comprehensive LCA of natural graphite mining and the subsequent processes involved in manufacturing AAM. Many studies, including Engels et al. (2022), rely on alternative process assumptions rather than modeling the actual steps performed in graphite extraction and processing. The production of battery-grade AAM typically involves a sequence of operations: mining natural graphite, flotation, spheronization, purification, coating, and final finishing. The current LCA was developed using a combination of data from 2022, 2023, and 2025 specific to graphite mining and processing activities in Québec (Nouveaux_Monde_Graphite, 2022, 2023a, 2023b, 2025).

To contextualize and validate the findings, a comparative analysis was conducted using the cradle-to-gate LCA presented by Engels et al. (2022) (Engels et al., 2022), which focused on natural graphite-based AAM produced in China for automotive lithium-ion batteries. Table 19 presents a detailed comparison of key input parameters between Engels et al. (2022) study and the current Québec-based assessment, covering both the concentrator and process plant stages.

Table 19: Flows (detailed) in current research and from Engels et al., (2022) per ton of AAM

Flow	Current Research (2025)	Engels et al (2022)
Diesel (at mine)	156.6 kg/ton	2.24 kg/ton
Electricity (mine/mining processes)	2137 KW/ton	8.7 kWh/ton
Process water	37 m^3/ton	47 m^3/ton
Fuel oil (flotation) (Reagent) Pitch	92 kg/ton	50 kg/ton
Lime	1.93 kg/ton	400 kg/ton
Electricity Process Plant Micronization & Spheronization	5519 kWh/ton	506 kWh/ton
Fines (by-product)	0.9826 ton/ton	1.22 ton/ton
Electricity Process Plant Purification	3070 kWh/ton	305 kWh/ton
Purification Hydrochloric Acid	0.20 ton/ton	0.02 ton/ton
Purification Hydrofluroic Acid	0.1818 ton/ton	0.1818 ton/ton
Purification Nitic Acid	0.100 ton/ton	0.100 ton/ton
Natural Gas	295.84 MJ	1,050 MJ

A summary of various parameters is shown in Table 20 including water, electricity, diesel, and natural gas consumption were compared with data from (Engels et al., 2022) on graphite mining and processing for one ton of AAM. Water usage in Engel's study was higher at 47 m^3 compared to 37 m^3 in our Québec case study mine, which employed a closed-loop water system. Electricity consumption was also significantly lower in Engel's study at 7,470 kWh compared to 17,100 kWh per ton of AAM in Québec. In contrast, diesel usage was higher at the Québec mine, reaching 156.6 kg per ton of AAM, compared to only 4.15 kg in Engels' findings. Natural gas consumption was higher in China at 1,050 MJ (Engels et al., 2022) compared to 295.84 MJ in Québec. Higher diesel consumption may be attributed to the detailed data obtained for the Québec mining equipment which was not presented in the Engels' study. The Québec study had higher electricity consumption which reduced the natural gas usage versus that in China.

Table 20: Summary comparison of graphite production

Comparison of graphite production Water and Energy flow per 1 ton of AAM		
	Current research (2025)	Engels et al (2022)
Parameter		
Water	37 m^3	47 m^3
Electricity	17,100 kWh	7,470 kWh
Diesel	158 kg	4.15 kg
Natural gas	295.84 MJ	1,050 MJ

The long-term CO_2 per ton of AAM in the Québec case study was 1.44, compared with 9.60 for China's natural graphite and 29.70 for synthetic graphite, as shown in Table 21. The data indicates that natural graphite production generates far lower CO_2 emissions than synthetic graphite production, and that Québec's natural graphite industry has a substantially smaller environmental footprint compared to natural graphite production in China.

Table 21: Long-term CO_2 for one ton of graphite in recent studies

Tons CO_2 per ton graphite mined/processed		
Engels et al. (2022)	Pandey et al (2025)	Current research (2025)
9.60 (natural)	29.70 (synthetic)	1.44 (natural)
Ecoinvent v3.8 (LCA)	GREET (LCA)	Ecoinvent v3.8 (LCA)

4.4.1 Natural Gas Consumption

One of the most significant differences observed between the Québec-based LCA and the study by Engels et al. (2022) (Engels et al., 2022) lies in natural gas consumption. Engels et al., (2022) reported a usage of 1,050 MJ per functional unit, whereas the Québec mine and processing plant recorded a substantially lower figure of 295.84 MJ. This discrepancy highlights regional variations in energy sourcing and process efficiency.

In the Québec LCA, natural gas was identified as the primary contributor to CO_2 emissions during the purification and coating stages of AAM production. These stages require extremely high temperatures often exceeding 2,500 °C to achieve the necessary material properties (Engels et al., 2022; Falcon Energy Materials, 2025). The lower natural gas consumption in Québec may reflect differences in technology, energy integration, or operational optimization, which contribute to a reduced environmental footprint in compared to the Chinese operations modeled by Engels et al., (2022) (Engels et al., 2022).

4.4.2 Electricity Consumption

In the Québec case study of producing AAM from natural graphite, the highest electricity consumption was observed during the micronization/spheronization, purification, and coating stages at the process plant (see Figure 52).

These stages micronization, spheronization, purification, and coating are particularly energy-intensive due to the mechanical and thermal demands required to transform graphite concentrate into battery-grade AAM. Micronization and spheronization involve high-speed milling and shaping of graphite particles into spherical forms, which improves tap density, reduces surface area, and enhances electrochemical performance in lithium-ion batteries (Fischer et al., 2023). Purification typically requires temperature treatment, often exceeding 2,500 °C, to achieve the necessary purity levels above 99.95% carbon content, which is essential for battery performance (Tan et al., 2025) (Lähde et al., 2024). The coating process further adds to the energy demand, as it involves applying a carbon layer to the graphite surface to improve conductivity, stability, and rate capability under fast-charging conditions (Kazyak et al., 2021). These steps are critical for producing high-performance AAM, but they also represent the most resource-intensive phases of the graphite refinement process.

Despite the high electricity demand in these stages, the environmental impact of electricity use in Québec is significantly lower than in many other regions. This is primarily due to Québec's electricity grid being powered almost entirely by renewable sources, particularly hydropower. Over 99% of Hydro-Québec's electricity generation comes from renewable energy, with hydropower alone accounting for approximately 94.3% of the province's electricity supply (Hydro-Québec, 2025). As a result, Québec's grid has one of the lowest greenhouse gas (GHG) emission intensities in North America, averaging just 2.48 kg CO_2e/MWh (Hydro-Québec, 2023). The use of clean electricity in both mining and critical mineral processing makes Québec a strategic location for developing a low-carbon supply chain for battery materials. This positions the province as a key contributor to the production of "green batteries" in North America, supporting broader climate and sustainability goals. Figure 52 shows the electricity consumption at the Québec case study by process for the mine/concentrator, and process plant.

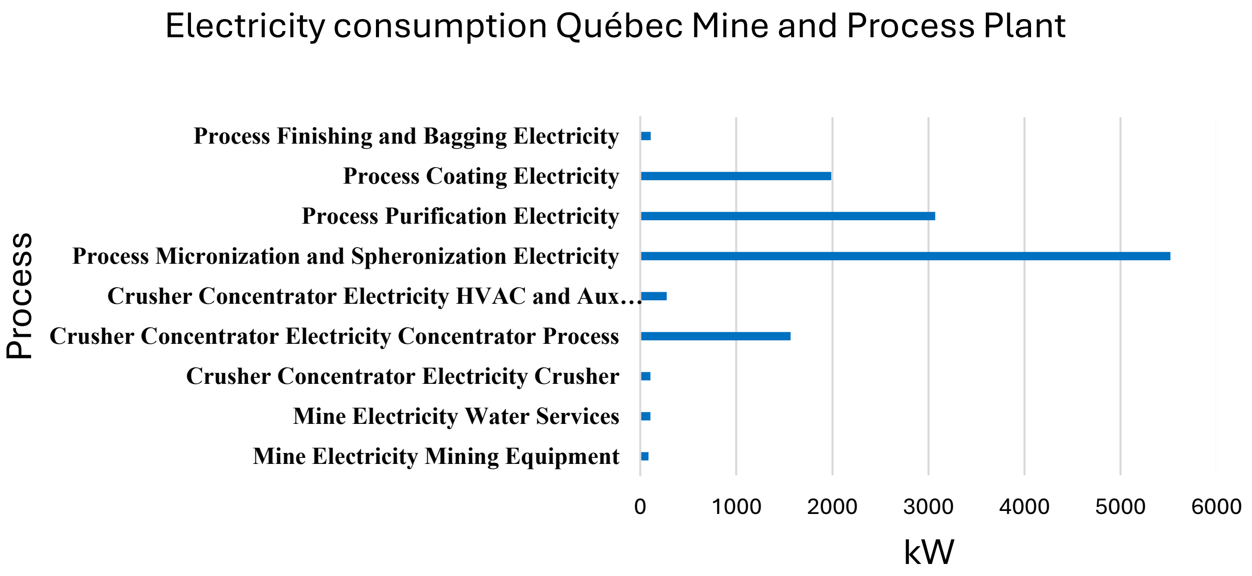


Figure 52: Electricity consumption at Québec mine/concentrator and AAM process

4.4.3 Water Consumption

Water plays a critical role throughout the graphite production process, both at the mine site and the downstream processing plant. At the concentrator located at the mine site, water is primarily used for ore beneficiation, including crushing, grinding, and flotation to separate graphite from gangue minerals (CarbonScape, 2022). In the subsequent refining stage, water is essential for converting graphite concentrate into battery-grade AAM, which requires multiple chemical and thermal treatments (Pandey et al., 2025).

Our Québec case study implemented a closed-loop water management system to minimize freshwater withdrawal and reduce environmental impact (Nouveaux_Monde_Graphite, 2022). This system recycles process water, significantly reducing demand for external water sources and mitigating stress on local ecosystems. Additionally, a dewatering system was installed to manage surface runoff, precipitation (rain and snowmelt), and groundwater infiltration, ensuring that excess water does not compromise operational efficiency or cause contamination (Nouveaux_Monde_Graphite, 2022, 2025).

To further safeguard water quality, a wastewater treatment facility was integrated at the process plant. This facility treats effluents generated during chemical purification and other processing steps, removing suspended solids, chemical residues, and potential contaminants before discharge or reuse (Beowulf_Mining, 2024). These measures collectively aim to conserve water resources, maintain compliance with environmental regulations, and reduce the overall water footprint of graphite production (CarbonScape, 2022; Pandey et al., 2025).

4.4.4 Diesel Consumption

Diesel consumption in the Québec case study was primarily associated with two key activities: excavation of natural graphite ore and transportation of ore and waste rock to the concentrator. To estimate diesel usage, detailed operational data for each piece of mining equipment was collected, including equipment model, payload capacity, gross horsepower (Club), number of units, and annual operating hours (Nouveaux_Monde_Graphite, 2025). These parameters were combined with manufacturer specifications for diesel consumption rates (liters per hour) to calculate the total liters of diesel per ton of AAM produced as shown in Table 22.

The calculation process involved multiplying the diesel consumption rate of each equipment type by the total operating hours for all units of that type. For example, the haul trucks (CAT 775G) had a consumption rate of 172.2 L/hr and operated for a combined total of 33,036 hours annually across 12 units, resulting in approximately 5.69 million liters of diesel consumed by haul trucks alone. Similar calculations were performed for hydraulic excavators, wheel loaders, drills, dozers, graders, water trucks, and support vehicles. The aggregated total across all equipment was 8,297,882 liters per year. To normalize this figure for LCA purposes, the total diesel consumption was divided by the annual production of AAM, yielding 188.2 liters per ton of AAM. This metric provides a clear basis for comparing diesel-related impacts across different production scenarios.

For integration into the LCA, diesel volumes were converted into energy units (megajoules, MJ) using the standard energy content of diesel fuel (38.6 MJ/L). This conversion ensures consistency in energy flow analysis and allows diesel-related impacts to be assessed alongside other energy sources such as electricity and natural gas.

The analysis revealed that haul trucks were the dominant contributor to diesel consumption, accounting for approximately 68% of the total fuel use. This reflects the energy-intensive nature of ore transportation compared to other mining activities. Excavation equipment such as hydraulic excavators and wheel loaders also consumed significant amounts of diesel, while auxiliary operations like drilling, grading, and water hauling represented smaller but still notable shares. Overall, the high reliance on diesel-powered equipment underscores its role as a major contributor to the energy footprint and greenhouse gas emissions of graphite production. These findings highlight the importance of targeting haulage and excavation processes to improve efficiency and of exploring alternatives, such as electrification or hybrid technologies, to reduce environmental impacts.

Implications for Sustainability: Reducing diesel consumption through fleet optimization, electrification of mining equipment, or hybrid technologies could substantially lower the carbon footprint of graphite production. Additionally, improving haulage efficiency and implementing advanced route-planning could further reduce fuel consumption.

Table 22: Mining equipment used to calculate liters of diesel per ton of AAM

Equipment Name	Model	Payload (tons)	Horsepower (Gross)	No. of Units	Operating Hours (hr/yr)	Total No. of hours for all the units run (hr/yr) (G*F)	Diesel consumption (L/hr)	Total diesel consumption for total units run hour (L/yr) (I*H)
Haul Truck	CAT 775G	60	812	12	2,753	33,036	172.2	5,688,040.6
Hydraulic excavator	CAT 395	94	543	2	2,592	5,184	115.1	596,628.0
Wheel Loader	CAT 988	12	580	1	2,753	2,753	122.9	338,460.3
Production Drill	Epiroc D65	23	540	2	2,248	4,496	114.5	514,583.5
Track Dozer	CAT D8T	38	359	2	2,753	5,506	76.0	418,687.7
Road Grader	CAT 14M	24	259	2	2,753	5,506	54.8	301,840.2
Water/Sand Truck	CAT 740		447	1	2,753	2,753	94.7	260,756.7
Utility Excavator	CAT 336	37	306	1	2,592	2,592	64.8	167,947.4
Transport Bus	GMC		276	1	187	187	58.4	10,937.7

4.4.5 LCA CO_2 And Water Scarcity Analysis

The LCA for producing one ton of graphite AAM for EV batteries demonstrates that environmental impacts are distributed across three major stages: mining, concentration, and processing, with each stage contributing differently to climate change, water scarcity, and resource use. A cradle-to-gate analysis was carried out for the Québec mine, concentrator, and process plant. The results showed long-term CO_2-equivalent emissions of 1.438 tons, short-term CO_2 and emissions of 1.252 tons, as presented in Figure 53. Co-products produced during the processing of graphite concentrate included jumbo flake and fine graphite. Water-scarcity impact of 14.271 m^3, was normalized by process against CO_2 long and short term as presented in Figure 54.

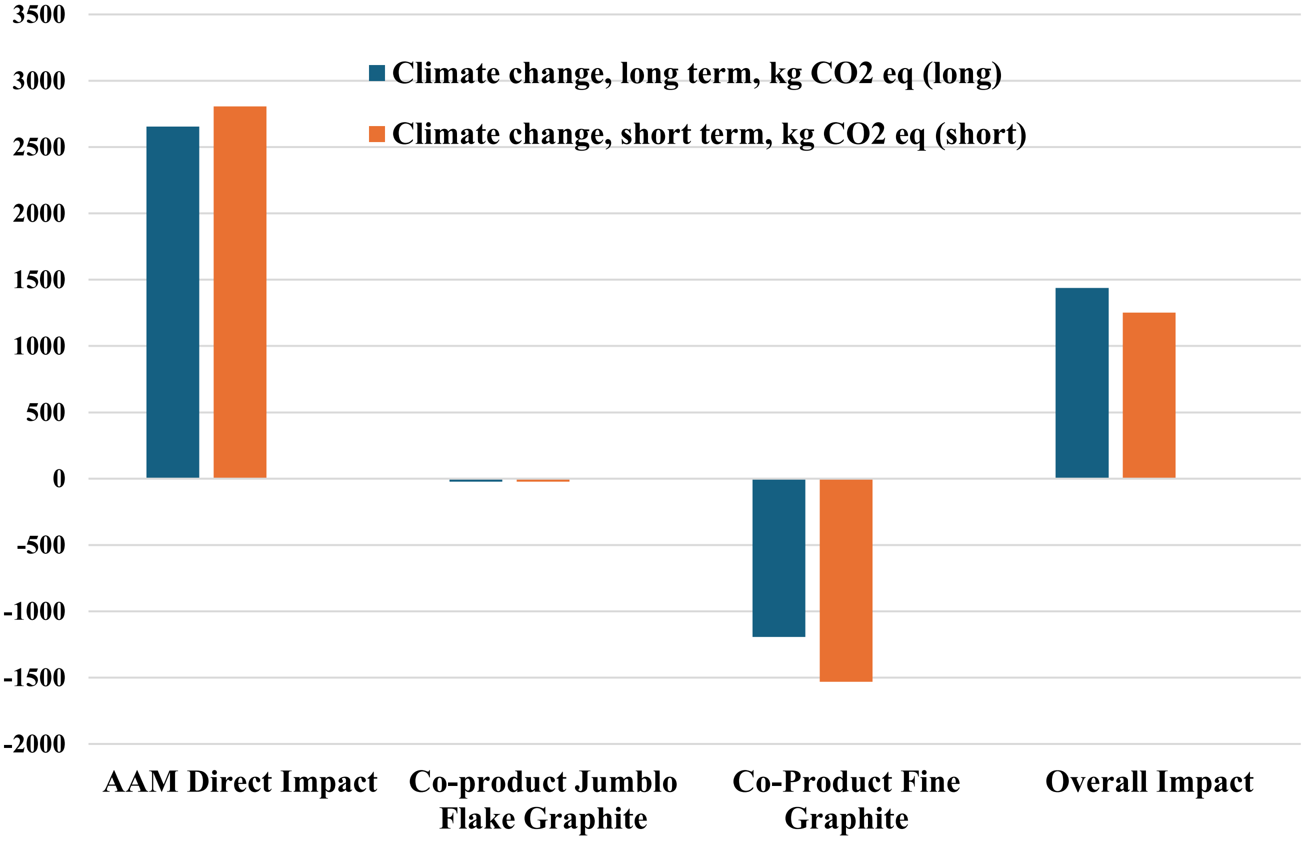


Figure 53: Long and short-term CO2 impact for Québec natural graphite case study

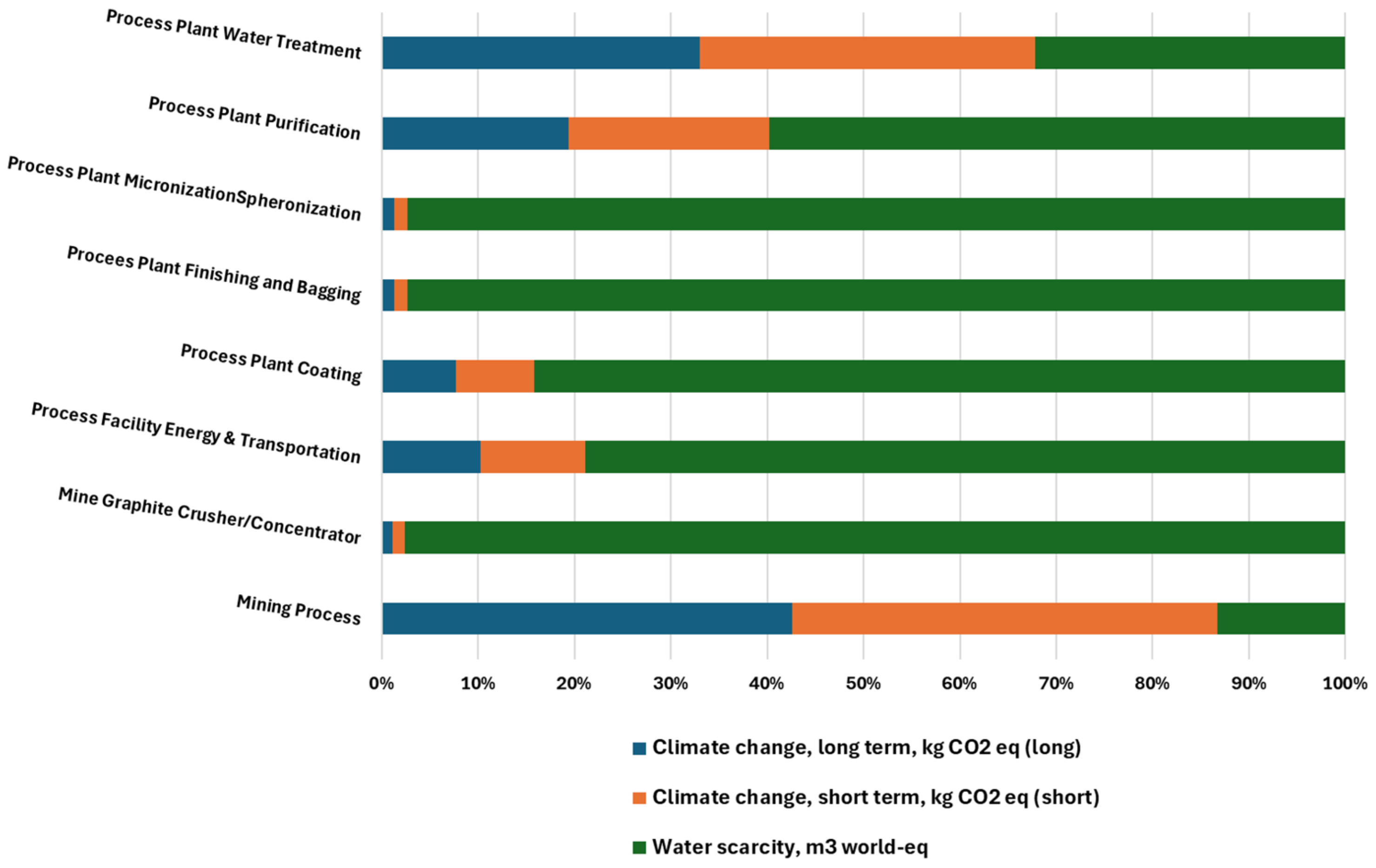


Figure 54: Water scarcity normalized to CO_2 long and short-term emissions by process

The mining stage is the foundation of the supply chain and is highly resource intensive. The extraction of rock from the ground alone accounts for 58 tons of material movement for one ton of AAM, generating 1,064 kg CO_2-eq (long-term) and 1,101 kg CO_2-eq (short-term) emissions. Diesel-powered equipment dominates energy consumption at 7,263 MJ, making it the largest single contributor to greenhouse gas emissions in this stage. Transportation of ore and waste adds further burdens, with over 110 ton-kilometers for ore movement and 130 ton-kilometers for waste disposal. While electricity use for mining equipment is relatively minor, the cumulative effect of blasting, drilling, and material handling amplifies the overall footprint. Water scarcity impact is also significant at 332.85 m^3 world-equivalent, primarily due to dust suppression and water services. The concentration phase introduces additional complexity through mechanical and chemical processes. Electricity demand for crushing and flotation is notable, with 1841.3 kW for concentrator operations and smaller loads for auxiliary systems. Water use spikes dramatically to 44.27 m^3, reflecting the need for slurry preparation and tailings management. Chemical reagents such as lime, potassium amyl xanthate, and methyl isobutyl carbinol (MIBC) are essential for flotation, adding toxicity and resource depletion concerns. Climate change impacts for this stage range between 42 - 46 kg CO_2-eq, but water scarcity impact is disproportionately high at 3,597 m^3 world-equivalent, signaling that water recycling and treatment should be a priority.

The processing plant is the most energy- and chemical-intensive stage. Purification processes consume 1,988.7 kW of electricity and use aggressive reagents such as hydrochloric, hydrofluoric, and nitric acids, which pose environmental and safety risks. This stage alone contributes 1,276 - 1,366 kg CO_2-eq and 3,935 m^3 world-equivalent in water scarcity, making it the single largest hotspot in the LCA. Coating operations add further emissions, with electricity use linked to 164-176 kg CO_2-eq, while micronization and spheronization processes consume 5,519.3 kW, resulting in 61-68 kg CO_2-eq. Finishing and bagging, though less impactful, still require energy and generate waste streams. The input and output (climate change long/short-term, and water scarcity) parameters used in this LCA are shown in Table 23.

Table 23: Input and output for Québec LCA case study natural graphite mine and process plant

Process	Parameter	For 1 ton AAM Battery Grade material	Final Converted Unit Per ton of AAM	Climate change, long term, kg CO2 eq (long)	Climate change, short term, kg CO2 eq (short)	Water scarcity, m3 world-eq	Reference
Mining Process	Mine Rock Out of Ground	58.13	ton	1064.64	1101.10	332.85	(Nouveaux_Monde_Graphite, 2025)
	Mine NAG non acid generating waste	50.32	ton				(Nouveaux_Monde_Graphite, 2025)
	Mine PAG potential acid generating waste	14.94	ton				(Nouveaux_Monde_Graphite, 2025)
	Mine Diesel Equipment	7263.00	MJ				(Nouveaux_Monde_Graphite, 2025)
	Mine Electricity Mining Equipment	84.66	kW				(Nouveaux_Monde_Graphite, 2025)
	Mine Electricity Water Services	105.82	kW				(Nouveaux_Monde_Graphite, 2025)
	Mine Transport Crusher Concentrator to Process plant	110.46	tkm				(Nouveaux_Monde_Graphite, 2025)
	Mine Transport Waste Rock and tailings to co disposal facility	130.52	tkm				(Nouveaux_Monde_Graphite, 2025)
	Mine Transport Overburden To Stockpile	34.01	tkm				(Nouveaux_Monde_Graphite, 2025)
	Mining Blasting Explosives	0.03	ton				(Nouveaux_Monde_Graphite, 2025)
	Mine Drilling Depth Max	0.00	m				(Nouveaux_Monde_Graphite, 2025)

Process	Parameter	For 1 ton AAM Battery Grade material	Final Converted Unit Per ton of AAM	Climate change, long term, kg CO2 eq (long)	Climate change, short term, kg CO2 eq (short)	Water scarcity, m3 world-eq	Reference
Mining Crusher Concentrator	Crusher Concentrator Electricity Crusher	0.02	kW	42.39	46.62	3597.21	(Nouveaux_Monde_Graphite, 2025)
	Concentrator NAG Tailing Dewatering and Stockplie	50.32	ton				(Nouveaux_Monde_Graphite, 2025)
	Concentrator PAG Tailing Dewatering and Stockplie	14.94	ton				(Nouveaux_Monde_Graphite, 2025)
	Concentrator water	44.27	m3				(Nouveaux_Monde_Graphite, 2025)
	Crusher Concentrator Electricity Concentrator Process	1566.14	kW				(Nouveaux_Monde_Graphite, 2025)
	Crusher Concentrator Electricity HVAC and Aux System	275.13	kW				(Nouveaux_Monde_Graphite, 2025)
	Concentrator Reagent Flotation Fuel Oil (pitch)	0.00	L				(Nouveaux_Monde_Graphite, 2025)
	Crusher Concentrator Reagent Methyl Isobutyl Carbinol MIBC	0.00	L				(Nouveaux_Monde_Graphite, 2025)
	Concentrator Reagent Lime	0.00	ton				(Nouveaux_Monde_Graphite, 2025)
	Concentrator Reagent Potassium Amyl Xanthate	0.01	ton				(Nouveaux_Monde_Graphite, 2025)
Process Facility Wide	Process water	5519.27	Ton	38.70	40.82	296.54	(Nouveaux_Monde_Graphite, 2025)
	Process Natural Gas	0.98	MJ				(Nouveaux_Monde_Graphite, 2025)

Process	Parameter	For 1 ton AAM Battery Grade material	Final Converted Unit Per ton of AAM	Climate change, long term, kg CO2 eq (long)	Climate change, short term, kg CO2 eq (short)	Water scarcity, m3 world-eq	Reference
Process Plant Coating	Mine Transport In Plant Mine Ore to Crusher plant	0.33	tkm	164.64	176.02	1808.79	(Nouveaux_Monde_Graphite, 2025)
	Process By Product Purified Jumbo Flakes	3070.29	ton				(Nouveaux_Monde_Graphite, 2025)
	Process Coating Electricity	0.20	kw				(Nouveaux_Monde_Graphite, 2025)
	Process Coating Reagent Nitrogen Purge	0.18	ton				(Nouveaux_Monde_Graphite, 2022)
	Process Coating Reagent Carbon precursor Pitch	0.10	ton				(Nouveaux_Monde_Graphite, 2022)
Process Plant Finishing Bagging	Process Finishing and Bagging Electricity	0.40	ton	1.22	1.36	92.23	(Nouveaux_Monde_Graphite, 2022)
	Process Finishing and Bagging Electricity	0.40	kw				(Nouveaux_Monde_Graphite, 2025)
Process Plant Micronization Spheronization	Process Micronization and Spheronization Electricity	5519.2744	kw	61.83	68.78	4678.69	(Nouveaux_Monde_Graphite, 2025)
	Process BY Product Fines	108.84	ton				(Nouveaux_Monde_Graphite, 2025)
Process Plant Purification	Process Purification Electricity	1988.66	kw	1276.49	1366.84	3935.77	(Nouveaux_Monde_Graphite, 2025)
	Process Purification Reagent Hydrochloric Acid	0.27	ton				(Barman 2023)
	Process Purification Reagent Hydrofluroic Acid	0.09	ton				(Barman 2023)
	Process Purification Reagent Nitric Acid	0.11	ton				(Barman 2023)

Process	Parameter	For 1 ton AAM Battery Grade material	Final Converted Unit Per ton of AAM	Climate change, long term, kg CO2 eq (long)	Climate change, short term, kg CO2 eq (short)	Water scarcity, m3 world-eq	Reference
	Process Purification Reagent Sodium Hydroxide	6.76	ton				(Barman 2023)
	Process Purification Reagent Nitrogen	295.84	ton				(Nouveaux_Monde_Graphite, 2022)
Process Plant Water Treatment	Process Water Treatment Reagent Ferric Sulphate coagulant	448.98	ton				(Mahmoud, 2019)
Production of 1 Ton of AAM Graphite	Graphite active anode material (AAM) for EV battery	1.00	ton				(Nouveaux_Monde_Graphite, 2025)

4.5 Cluster-Based Environmental Impact Analysis of Graphite AAM Production Processes

The polar heat map (Figure 55) provides a visually compelling representation of environmental impacts across various graphite processing stages. Each radial segment corresponds to a process or co-product, while the color intensity reflects the magnitude of key sustainability metrics long-term climate change potential, short-term climate change potential, and water scarcity. This visualization immediately highlights the stark contrasts between processes, enabling rapid identification of hotspots.

Comparative observations showed that processes such as Process Plant Purification and Micronization/Spheronization dominate the outer rings with high radial values, indicating significant contributions to CO_2 emissions and water usage. Purification alone shows a mean long-term climate impact exceeding 2,193 kg CO_2 eq, far surpassing finishing and bagging, which averages only 31.6 kg CO_2 eq. Similarly, water scarcity impacts are concentrated in micronization and purification, suggesting these stages are resource-intensive and prime candidates for optimization. In contrast, co-products like jumbo flake graphite and fine graphite exhibit negative values, reflecting potential credits of -16.42 to -1065.22 kg CO_2 in life-cycle accounting. The heat map reveals a contracting pattern for low-impact processes clustered near the center, such as water treatment and finishing, while high-impact processes expand outward. These radial spread underscores the uneven distribution of environmental loads, reinforcing the need for targeted interventions rather than uniform strategies. For example, reducing energy intensity in purification could yield disproportionately large sustainability gains compared to marginal improvements in coating or bagging.

Insights from dendrogram analysis indicate that hierarchical cluster diagrams, both angular and radial, complement the polar heat map by grouping processes based on similarities in their environmental profiles. Angular clustering reveals that low-impact processes tend to merge early, forming tight clusters at very small distances, indicating strong similarity. In contrast, purification and micronization remain isolated until much later in the clustering sequence, which confirms their distinct and severe impact profiles. Radial dendrograms further demonstrate how clusters progressively aggregate, with climate change metrics exerting a stronger influence on separation than water scarcity. The final stages of clustering highlight the dataset's pronounced heterogeneity. This structural insight is critical for decision-making because clusters can guide modular sustainability strategies, allowing similar processes to share mitigation technologies, while outliers require tailored solutions.

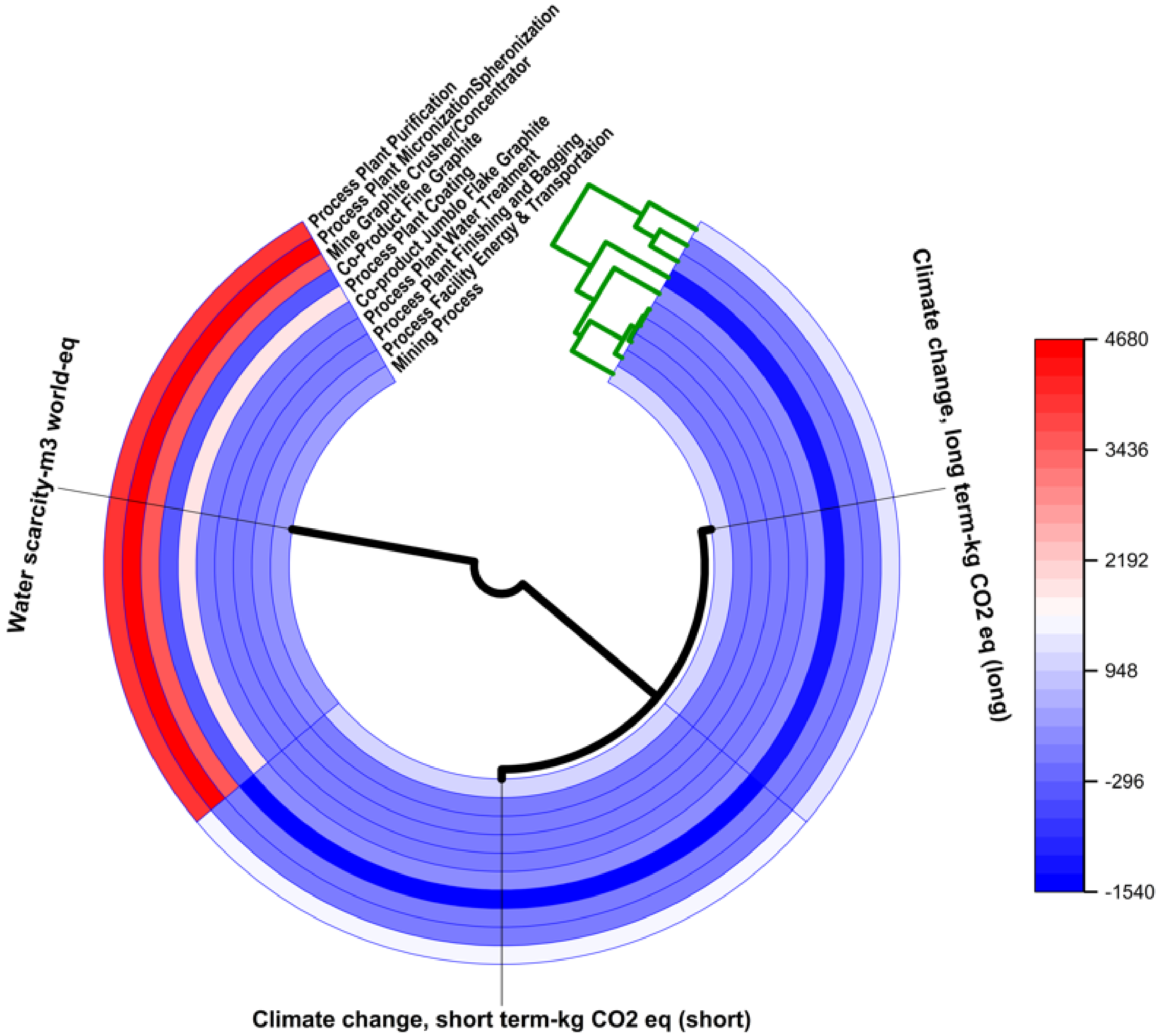


Figure 55: Polar Heat Map of Environmental Impact Metrics Across Graphite Processing Stages. This visualization displays the relative magnitude of key LCA indicators long-term climate change potential (kg CO_2 eq), short-term climate change potential, and water scarcity (m^3 world-equivalent) for each process and co-product in the graphite production chain. Radial positions represent individual processes, while color intensity indicates the severity of environmental impacts. The outer rings highlight high-impact stages such as purification and micronization, whereas inner rings correspond to low-impact processes like water treatment and finishing.

The combined interpretation of polar heat maps and dendrograms suggests a dual approach to improving sustainability performance across graphite processing stages. First, cluster-based optimization should be applied to processes that share similar environmental profiles, such as finishing and water treatment. These processes can benefit from common efficiency measures, reducing resource consumption without requiring major structural changes. Second, hotspot intervention is essential for outlier processes like purification and micronization, which exhibit disproportionately high impacts on climate change and water scarcity. These stages demand advanced technologies or complete process redesign to achieve meaningful reductions. Some of the changes could be at the mine with electrification of mining equipment and reduction of natural gas usage at the process plant. By integrating these two strategies, organizations can balance broad efficiency gains with targeted improvements, ensuring both cost-effectiveness and significant environmental benefits. A large focus in Québec is to reduce GHG’s and not so much on water consumption.

4.6 Summary

Following the analysis, a detailed interpretation phase was undertaken to assess impact contributions, identify environmental hotspots, and determine the stages with the highest resource intensity and emission profiles. This analysis facilitated the generation of midpoint impact indicators, enabling a comprehensive, multiscale evaluation of environmental burdens. The LCA conducted for this Québec case study on natural graphite mining and processing to AAM revealed that natural gas consumption contributed the most to CO_2 emissions, followed by diesel and electricity consumption. The study concluded with an integrated synthesis of findings, providing targeted recommendations for process optimization, emission reduction, and overall sustainability improvement. This systematic and transparent methodology ensured a robust assessment of the environmental performance of battery-grade AAM production. Despite the substantial decrease in CO_2 emissions compared to graphite mining and processing in China, the research highlights further opportunities for improvement, particularly through electrifying mining equipment to reduce diesel use and minimizing or substituting natural gas consumption during the purification and coating stages at the process plant.

CHAPTER 5. LIFE-CYCLE ASSESSMENT CASE STUDY: NICKEL SULFIDE ORE IN REMOTE NORTHERN QUÉBEC (OFF-GRID CONTEXT)

5.1 Background

Nickel sulfide ore is mined and processed into Class I nickel for EV batteries and Class II nickel for stainless steel via a metallurgical route (Kinnunen et al., 2024; Mistry et al., 2016). NSH is a common component of LIBs used in the automotive industry (Choi & Azimi, 2023). Nickel is an important critical mineral common in high energy density cathode like nickel-manganese-cobalt (NMC) and nickel-cobalt-aluminum (NCA) (W. Li et al., 2020; Vegh et al., 2024). The demand for nickel is increasing as more EV models are being produced globally (Dong et al., 2026; Maisel et al., 2023). Currently the major source of NSH has been from China (Wang et al., 2022). With this critical mineral interest comes the need to develop a local sustainable supply chain (Dou et al., 2023). Many automotive original equipment manufacturers (OEMs) are investing in nickel mines in Canada for their EV battery production (The Metallurgy and Materials Society of CIM; The Society for Mining, 2025). Some of these nickel mines are located in the far north of the province of Québec, Canada (Tardy et al., 2025). Northern Québec's komatiitic Raglan Horizon hosts one of the largest komatiite-associated magmatic sulfide deposits globally (Li & Mungall, 2022).

A recent study by Valencia et al. (2025) reported greenhouse gas emissions of 6.72 kg CO_2-eq per kilogram of NSH produced in Canada and Norway (Valencia et al., 2025). By contrast, production in Indonesia and China resulted in substantially higher emissions, at 36.8 kg CO_2-eq (Bartzas & Komnitsas, 2024) and 86.35 kg CO_2-eq per kilogram of $NiSO_4 \cdot 6H_2O$ (Valencia et al., 2025), respectively. The objective of the present work was to develop a detailed LCA of nickel sulfide ore mined underground in Northern Québec, subsequently concentrated and smelted into Class 1 nickel matte with the removal of iron and copper sulphide via precipitation in a metallurgical process (Kinnunen et al., 2024). This Canadian production route was then integrated with the refining of nickel matte in Norway to produce class 1 nickel. Class I nickel can then be further processed to battery grade NSH (Kinnunen et al., 2024).

5.1.2 Cost Analysis of Nickel Sulfate Hexahydrate

NSH production costs are shaped largely by volatile nickel feedstock prices, rising purification and crystallization expenses, and increasing energy, labor, and environmental-compliance requirements (Sloan, 2025; Kinnunen, 2024). Growing and accelerating demand for electric vehicles further amplifies these pressures, as high-purity nickel sulfate is a critical input for manufacturing nickel-rich cathode materials used in long-range lithium-ion batteries (ISO, 2024). Supply-chain risks including concentrated nickel reserves, export controls, and limited global refining capacity add additional cost and price instability. As a result, constrained feedstock availability, the need for highly precise processing, and the rapid expansion of the EV sector make NSH both cost-intensive and strategically important through the coming decade (Iyer et al., 2023).

Based on current compound annual growth rate (CAGR) estimates, the NSH market is projected to grow at 6.7%, increasing from USD 6.51 billion in 2026 to USD 9.67 billion by 2034. Market data from mid-2024 to mid-2025 indicates that nickel sulfate hexahydrate an essential precursor for high-nickel cathode chemistries typically trades between USD 3,000 and 5,000 per metric ton. In the U.S. specifically, the price was reported at USD 3,630 per metric ton in June 2025 (Markets, 2026). Amanyazova et al (2026) studied various crystallization techniques to remove impurities like magnesium to aid in the process of generating NSH. Nickel remains an essential mineral for lithium-ion batteries used in electric vehicles, and the production pathway plays a major role in determining overall manufacturing costs. Ongoing research is focused on improving purification and crystallization processes to help drive these costs down such as the removal of magnesium and other impurities like sodium and chlorine. The automotive industry demands high-purity nickel content for its LIBs (Amanyazova et al., 2026).

5.1.3 Availability of Nickel Sulfide Ore in Canada

In 2023, Canada produced a total of 158.7 kt of nickel concentrate with about 39% from the province of Ontario, 27% from Québec, 27% from Newfoundland/Labrador, and 7% from Manitoba (Government_Canada, 2026), Figure 56. Canada's top nickel-producing mines include Raglan Mines in Québec, an underground operation owned by Glencore that produced 20.51 kt of nickel. Also operated by Glencore, the Sudbury Area Mine in Ontario yielded 18.59 kt. Voisey's Bay Mine in Newfoundland and Labrador, owned by Vale, contributed 13.5 kt, while Vale's Coleman Mine in Ontario's Sudbury region added 10.36 kt. Rounding out the list is the Nunavik Nickel Project in Quebec, a combined surface and underground operation owned by Jin Horoc Nonferrous Metal Group, which produced 9.22 kt (Mining, 2024).

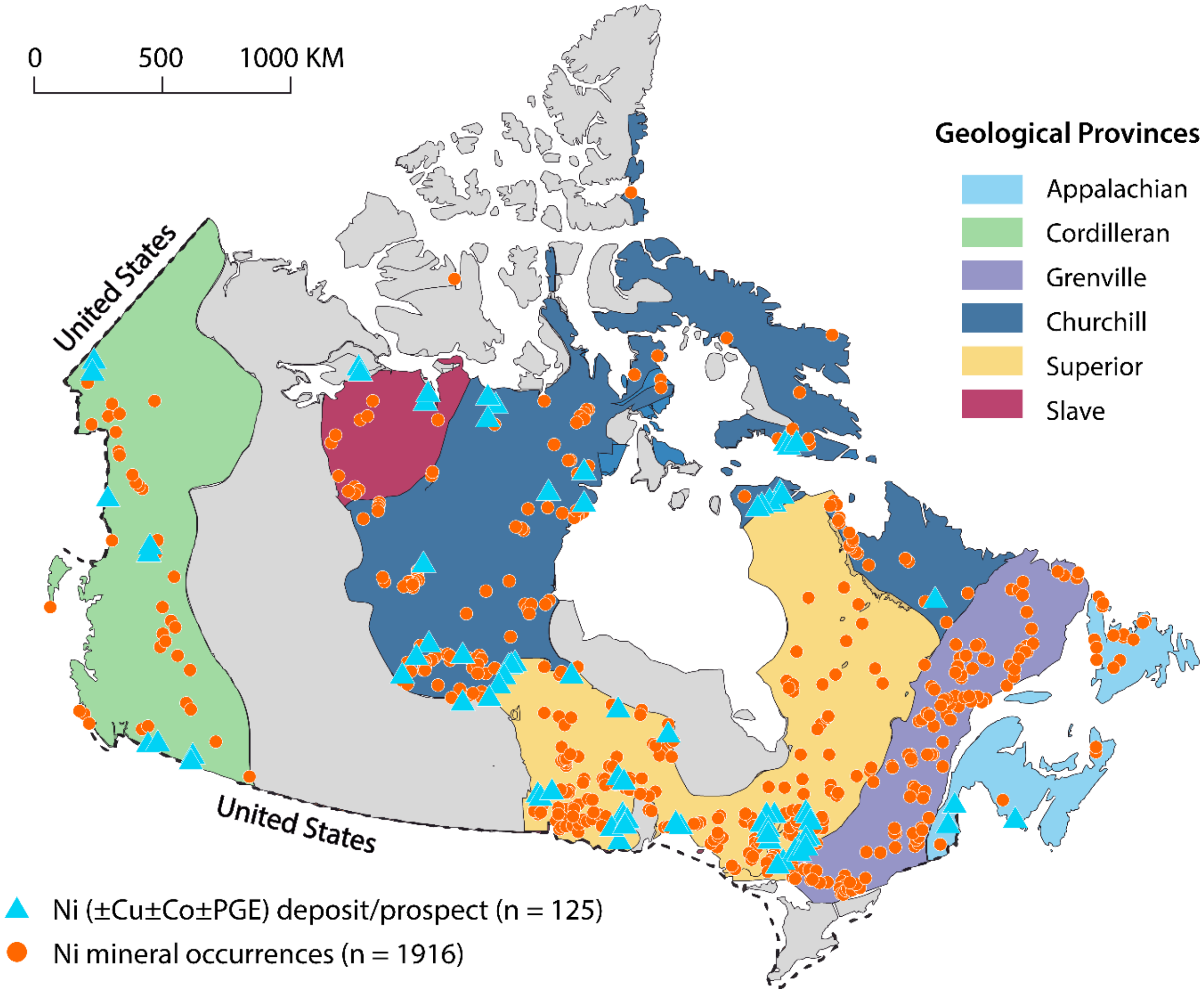


Figure 56: Availability of nickel in Canada by geological provinces (Lawley et al., 2021)

Despite growing interest in establishing low-carbon nickel supply chains, detailed cradle-to-gate LCAs that integrate Canadian sulfide mining with European refining pathways remain limited. This study addresses this gap by presenting a high-resolution LCA of an integrated Canadian European sulfide nickel supply chain, with particular emphasis on the environmental implications of off-grid mining operations and low-carbon refining routes.

The case study focuses on the production of nickel sulfide concentrate for battery-grade nickel derived from underground mining in Northern Québec, Canada. Québec hosts one of the world's eight most significant Nickel-Copper-Platinum Group Element (Ni-Cu-PGE) provinces, characterized by high-grade sulfide lenses associated with ultramafic rocks (SGS, 2014). The region presents distinct operational and environmental challenges due to its remoteness and severe climatic conditions, including an average annual temperature of approximately -10 °C and some of the harshest Arctic weather encountered in global mining operations (Sika, 2014).

In addition to emissions performance, off grid Arctic nickel production plays a strategic role in resource security by supporting geographically diversified, politically stable supply chains for battery-grade materials. Understanding the environmental intensity of such systems is therefore essential for balancing decarbonization objectives with supply resilience and critical mineral availability.

This study demonstrates that spatial aggregation and grid average energy assumptions can substantially underestimate the carbon intensity of sulfide-based nickel supply chains when mining occurs in off grid Arctic environments. By resolving energy use, transportation, and process flows at the off grid mine, smelter, and refinery levels, this work provides a more realistic benchmark for life-cycle assessments of critical mineral production. The results contribute actionable insight for resource system modeling, comparative LCA studies, and policy discussions on low-carbon battery material supply chains.

5.2 Methods and Materials

5.2.1 Nickel Ore Mining and Smelting in Canada with Downstream Refining to Class I Nickel and Nickel Sulfate Hexahydrate in Norway

The nickel production chain begins at mining operations in Northern Canada, where nickel–copper sulfide ore is extracted primarily through underground mechanized cut-and-fill mining, supplemented by limited open-pit operations. The off-grid mined ore typically contains 1.25-2.55 wt.% nickel and is processed on-site through crushing and grinding to liberate nickel-bearing minerals. Froth flotation is then applied to separate sulfide minerals from waste rock, followed by dewatering, filtration, and drying. This beneficiation sequence yields a nickel-copper concentrate containing approximately 16-18 wt.% nickel, alongside economically valuable by-products such as copper, cobalt, and platinum group metals (PGMs) (Kinnunen et al., 2024; PEMC, 2009; The_Commission, 2017).

The nickel sulfide concentrate is transported to Sudbury, Ontario, where it undergoes flash smelting to produce a nickel-copper sulfide matte. During smelting, iron is selectively oxidized and removed as iron-silicate slag, while sulfur is partially oxidized to sulfur dioxide and recovered for sulfuric acid production. The furnace matte is subsequently converted to remove additional iron and sulfur, increasing the nickel content to approximately 70-75 wt.% nickel, with copper largely reporting to the matte phase (Glencore, 2026; Nickel-Institute, 2024). This pyrometallurgical upgrading stage produces a high-grade nickel matte suitable for downstream hydrometallurgical processing.

High-grade nickel matte derived from Canadian sulfide ore is refined at the Nikkelverk facility in Kristiansand, Norway, using established hydrometallurgical processes including leaching, solvent extraction, and electrowinning to produce Class I nickel metal (Valencia et al., 2025). The resulting high-purity nickel (>99.8%) is further processed into battery-grade NSH through controlled dissolution, purification, concentration, and crystallization. This refining route benefits from integrated sulfuric acid recovery, efficient heat management, and access to low-carbon hydropower, resulting in high chemical efficiency and reduced environmental intensity (Iyer et al., 2023; Nickel_Institute, 2020). The final NSH product is used in the manufacture of NMC and NCA cathode materials for electric vehicle batteries.

5.2.2 Raw Data Inputs and Disaggregation Methodology for the Life-Cycle Assessment

To support a robust and credible LCA of nickel sulfide extraction and processing in Québec, the collection of accurate, site-specific, and representative data was essential. Such data ensured the reliability of the environmental impact assessment across all stages of the class 1 nickel and NHS supply chain. Environmental process data were sourced from a combination of Environmental Impact Assessments (EIA), reports mandated by the Québec government and technical and feasibility reports produced by the mining industry (Glencore, 2026; SGS, 2014; The_Commission, 2017). These documents provided critical information on resource extraction, energy use, emissions, water consumption, and waste generation associated with nickel sulfide ore mining and processing. The EIA reports were particularly valuable because they included regulatory evaluations, environmental monitoring results, and details on mitigation measures implemented by mining operations to comply with provincial and federal environmental requirements (SGS, 2014; SNC_Lavalin, 2007; The_Commission, 2017). Complementing these, technical and feasibility reports offered detailed insights into operational performance, material flows, and ongoing efforts to enhance processing efficiency. By integrating current data from both regulatory and industry sources, this assessment delivers a comprehensive and up-to-date evaluation of nickel sulfide extraction, class 1 nickel and NSH production activities in Norway, providing a strong foundation for a more extensive LCA.

Figure 57 illustrates a comprehensive overview of the raw data inputs and material flows considered in the LCA of nickel production, spanning sulfide ore mining in Canada, smelting to nickel matte, and final hydrometallurgical refining to battery-grade NSH in Norway. The system boundary encompasses all major upstream and midstream processes, including mining, beneficiation, transportation, smelting, refining, and by-product handling. The assessment explicitly accounts for energy inputs (diesel, electricity, natural gas, wind, and hydroelectric power), processing water, chemical reagents, and multimodal transportation (truck, rail, and marine shipping).

At the off grid mine site, large volumes of nickel sulfide ore are extracted using mechanized mining operations that require diesel for mobile equipment, electricity for material handling and ventilation, explosives for blasting, process water, and heat. Ore extraction generates both a valuable mineral stream and significant quantities of waste rock. Inventory data for the concentrator capture energy and material inputs associated with crushing, grinding, and froth flotation, as described in Section 2.1. This beneficiation stage is energy-intensive, relying primarily on electricity and processing water, and results in the production of one ton of nickel concentrate as the primary intermediate product.

For LCA modeling purposes, the mass and energy flows are disaggregated by processing stage to enable accurate allocation of upstream burdens to downstream products. In the pyrometallurgical stage, the nickel concentrate is transported by truck, rail, and ship to the smelter. As illustrated in Figure 57, 3.75 tons of nickel concentrate are required to produce one ton of nickel matte. The smelting process consumes substantial amounts of electricity, natural gas, water, and fluxing agents, including limestone, lime, silica, and sulphuric acid. Iron is removed as slag, and sulfur is partially oxidized, generating sulphuric acid as a recoverable by-product. This stage represents a major energy and material hotspot within the life-cycle due to high thermal demands and supporting infrastructure requirements.

The refined nickel matte is subsequently transported over long distances to the refinery in Norway, further contributing to cumulative transportation impacts. In the refinery stage, the matte undergoes hydrometallurgical processing to produce battery-grade NSH. The LCA model reflects the second level of disaggregation, wherein 3.2 tons of nickel matte are required to produce one ton of NSH. Refining relies heavily on electricity, supplemented by natural gas and process water, and uses a diverse set of chemical reagents, including sulphuric acid, sodium hydroxide, hydrochloric acid, calcium carbonate, and ammonia (Nickel-Institute, 2024; Nickel_Institute, 2020). Co-products such as copper, cobalt, ammonium sulphate, and nickel oxide are also generated and accounted for within the inventory.

The final functional output of the system, shown in Figure 57 as 1 ton of NSH, represents the aggregation of all upstream material inputs, energy consumption, emissions, and transportation activities. By explicitly disaggregating the production chain from concentrate to matte and from matte to NSH, the LCA captures the true material intensity of nickel processing and ensures that environmental burdens are correctly attributed across each transformation stage. This approach provides a transparent and robust basis for evaluating the cumulative impacts of nickel production for electric vehicle battery applications.

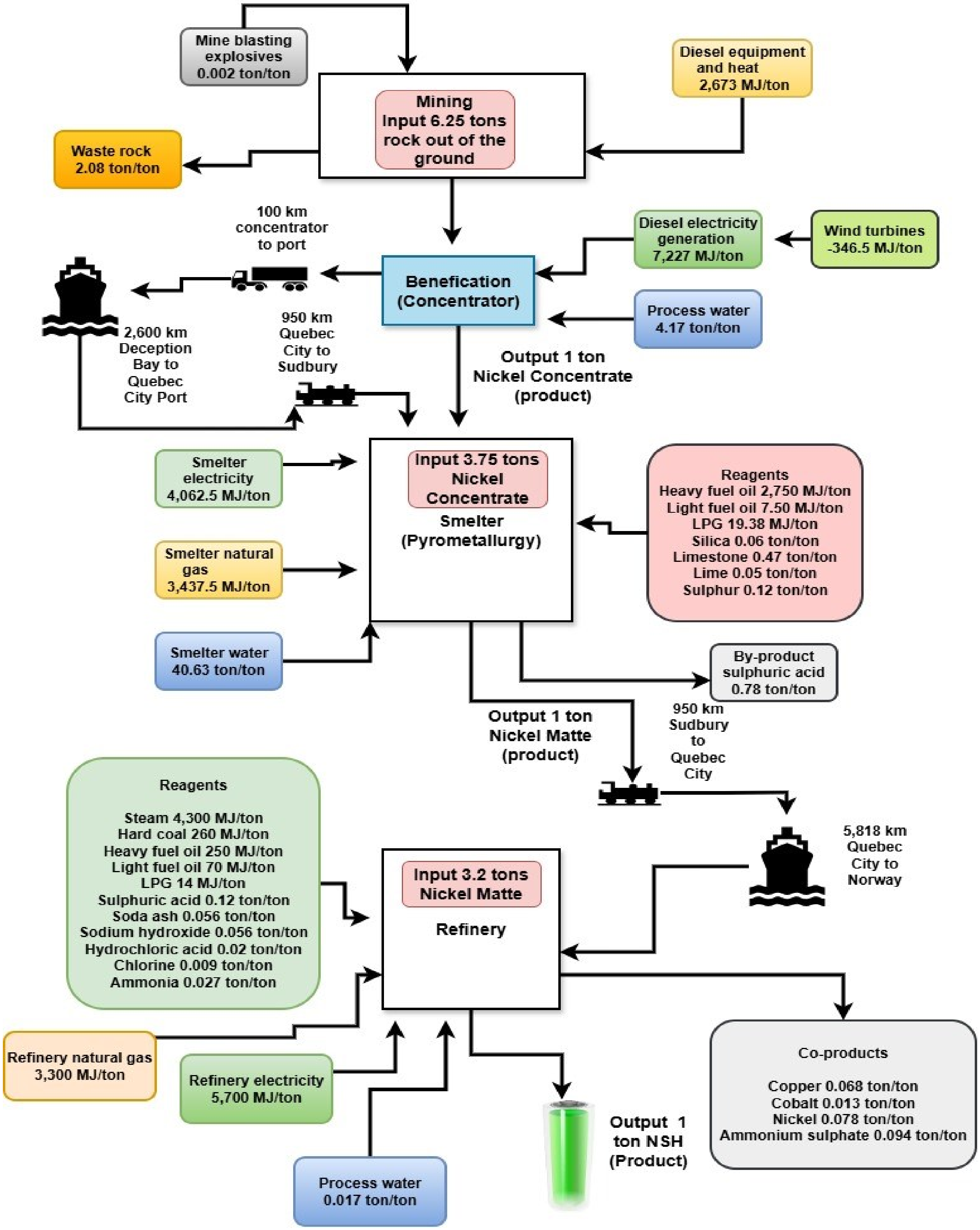


Figure 57: Life cycle inventory data flow for nickel production, showing mining and concentration in Québec, smelting in Ontario, and downstream refining to battery-grade nickel sulfate hexahydrate in Norway.

complemented by some open-pit operations. The process begins with crushing and grinding to liberate nickel minerals, followed by froth flotation to separate sulfide minerals from waste rock. The resulting concentrate undergoes dewatering and filtration to remove excess water, then drying to produce a nickel-copper concentrate containing approximately 16-18% nickel; Figure 57. The final output includes nickel concentrate along with valuable by-products such as copper, cobalt, and platinum group metals (PGMs) (Kinnunen et al., 2024).

This concentrate is transported to Sudbury, Ontario, where it is flash-smelted to produce a nickel-copper matte; iron and sulfur are oxidized and removed as slag, and further converting raises the matte's nickel content to about 70–75%(Glencore, 2026); Figure 57. The high-grade matte is then refined at the Nikkelverk facility in Kristiansand, Norway, using hydrometallurgical techniques such as pressure leaching, solvent extraction, and electrowinning to produce Class 1 nickel metal or nickel sulfate (Valencia et al., 2025). The final battery-grade NHS ($NiSO_4 \cdot 6H_2O$) is used in manufacturing nickel, manganese, cobalt (NMC) and nickel, cobalt, aluminum (NCA) cathode materials for electric-vehicle batteries.

Once the unit processes and associated elementary and intermediary flows were identified, the product system was modeled as a disaggregated set of system boundaries, as illustrated in Figure 58. Consistent with the process descriptions provided in Section 2.1, the nickel production chain was divided into three geographically and technologically distinct subsystems mining and concentration, smelting, and refining which were modeled independently at the inventory level. Material and energy flows linking these subsystems were explicitly defined to preserve continuity of the overall production system while enabling stage-specific life-cycle inventory development and analysis.

By presenting the system as disaggregated boundaries, Figure 58 makes clear which processes, resources, and emissions are attributed to each stage of the nickel production chain. This structure enhances transparency, allows for stage-specific impact assessment, and supports sensitivity or scenario analysis by enabling individual subsystems (e.g., mining, smelting, or refining) to be modified or analyzed independently without altering the integrity of the full supply chain model.

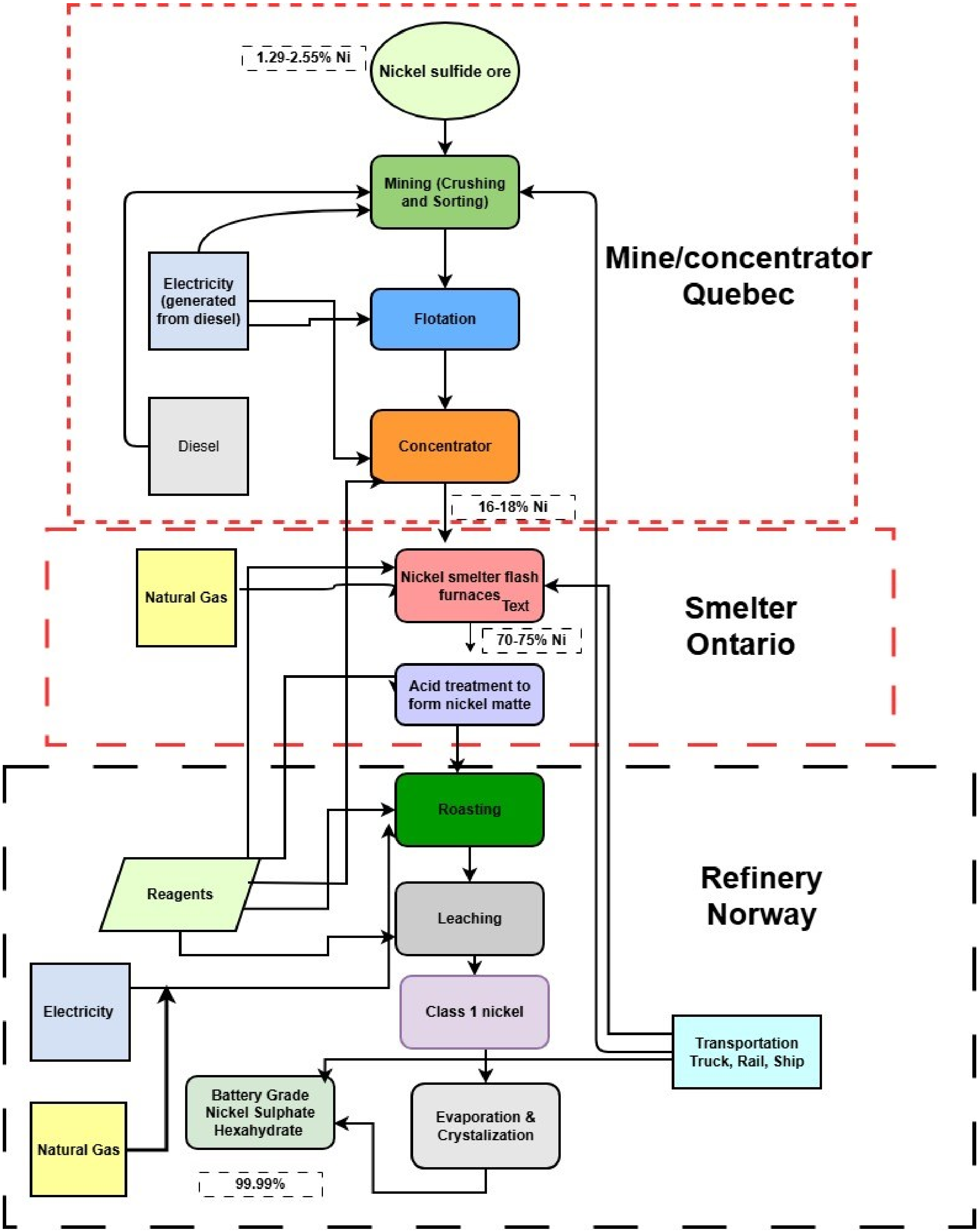


Figure 58: Disaggregated system boundaries for nickel sulfide ore extraction and processing, showing sequential mining/concentration, smelting, and refining stages leading to class 1 nickel and battery grade NHS.

5.2.3 LCA Data Sources and Modeling Methodology

To evaluate the life-cycle environmental impacts of battery-grade NSH, a LCA was conducted using *openLCA (v 2.6.1)* in combination with the *Ecoinvent database (v3.8)*, one of the most comprehensive and widely used life-cycle inventory (LCI) databases for environmental assessment. These datasets provided detailed inventories for nickel mining, smelting, refining, and chemical conversion processes, enabling a robust assessment of the environmental burdens associated with the production of Class I nickel and downstream NSH. Impact assessment was performed at the midpoint level using *Impact World+ (version 2.0.1)*, with global warming potential (GWP) selected as the primary indicator of interest.

An attributional LCA framework was applied to quantify the direct environmental burdens associated with battery-grade Class I nickel and NSH production, excluding broader market-mediated or consequential effects. This approach is well suited to evaluating the environmental performance of specific production pathways and facilitates transparent comparison of process-level contributions, with particular emphasis on energy use, greenhouse gas emissions, and material inputs.

The LCA modeling approach employed an aggregated LCA structure, in which individual unit processes including mining, smelting/ purification, refining, and conversion to NSH were assessed separately and then aggregated to quantify total cradle-to-gate impacts. This stepwise aggregation enables clear identification of dominant contributors across the supply chain while preserving consistency with standard LCA practice. Aggregated LCAs were performed for each major processing stage and subsequently combined to calculate the overall environmental footprint of Class1 Nickel and battery-grade NSH production.

Primary operational data were collected for underground nickel sulfide mining in Northern Québec, pyrometallurgical smelting and converting in Sudbury, Ontario, and hydrometallurgical refining and chemical conversion at the Kristiansand refinery in Norway. These data included energy consumption profiles, raw material inputs, process emissions, and solid and liquid waste outputs. All datasets were preprocessed and validated in spreadsheet form to ensure mass and energy balance consistency and compatibility with the openLCA modeling framework.

Following data validation, system boundaries and process linkages were modeled in openLCA, with discrete unit processes defined for each stage of the nickel sulfide extraction and refining chain. A comprehensive life-cycle inventory was constructed to capture all relevant environmental exchanges, and aggregated impact results were calculated using the selected impact assessment method. This modeling approach ensured transparent, reproducible quantification of the environmental impacts associated with the integrated Canadian European nickel supply chain.

5.2.4 Goal and Scope Definition

The LCA conducted in this study followed the ISO 14040 (ISO, 2006a) framework, encompassing the definition of system boundaries, compilation of the LCI, and selection of appropriate impact assessment methods. The functional unit was defined as the production of 1 metric ton of battery-grade NSH, with Class I nickel modeled as an intermediate or co-product where applicable. This definition enables comparison with previously published Life-cycle assessments and established industrial benchmarks. A cradle-to-gate system boundary was adopted, capturing all environmental burdens associated with raw material extraction, intermediate processing stages, and final class 1 nickel production (Table 24).

Primary (foreground) data were sourced directly from operational activities at nickel sulfide extraction and processing facilities, ensuring an accurate representation of site-specific conditions. These data were complemented by secondary (background) datasets from the *Ecoinvent v3.8* database to improve completeness and enable robust modeling of upstream processes. The LCIA addressed key environmental indicators, including atmospheric emissions, freshwater consumption, solid waste generation, transportation-related burdens, and co-product flows. Together, these categories provided a comprehensive characterization of the system's environmental performance and supported the identification of potential opportunities to enhance overall sustainability.

Co-products generated during smelting and refining, including copper, cobalt, and ammonium sulphate, were treated using a system expansion approach, consistent with ISO 14044 recommendations for multifunctional processes. System expansion was selected to reflect the avoided burdens associated with the displacement of equivalent primary production and to preserve physical transparency across the integrated nickel supply chain. While the application of co-product credits reduces absolute greenhouse gas emission values, the relative contribution of upstream processes remains unchanged, with mining and smelting consistently identified as the dominant emission hotspots regardless of allocation treatment. Although alternative allocation methods (e.g., mass-based or economic allocation) could shift absolute results, the core conclusions regarding the environmental drivers and comparative performance of the off-grid Arctic nickel production system are robust.

Table 24: Overview of methods and material for LCA research

Goal	**Cradle to gate Life-cycle assessment of the extraction and processing of nickel sulfide ore**
Scope Definition Functional Unit	1 ton of battery grade cathode active material class 1 nickel and nickel sulphate hexahydrate (NSH)
Product Technology	Class 1 nickel and NSH used in EV batteries
Background data	Nickel sulfide ore mine Québec and processing facility in Norway
Background database	Ecoinvent database (v3.8),
Cut-off criteria	No explicit cut-off criteria. All information on energy, materials, and emissions compiled from industry-specific technical documents
Impact Assessment Categories	Global Warming Potential (GWP); mainly CO_2

5.3 Results & Discussion

The results presented in this study confirm that lifecycle greenhouse gas emissions associated with sulfide based nickel production are highly sensitive to site-specific energy supply and geographic context. In particular, the use of spatially aggregated inventories and grid average electricity assumptions substantially underestimates the carbon intensity of off grid Arctic mining operations. By resolving energy use, transportation requirements, and material flows across mining, smelting, and refining stages, this analysis provides a more realistic representation of the environmental burden associated with battery-grade nickel sulfate production.

While the quantified carbon intensity of the Québec-Norway supply chain exceeds several industry-average benchmarks, these higher emissions reflect structural characteristics inherent to off grid Arctic resource systems rather than process inefficiency. Such systems contribute to supply chain resilience by enabling nickel production in geopolitically stable jurisdictions and reducing reliance on high-risk or carbon-intensive alternative sources. The results therefore highlight a fundamental trade-off between short-term emissions reduction and long-term resource security, underscoring the need for location-specific decarbonization strategies rather than uniform performance benchmarks.

The uniqueness of this research lies in the combination of factors influencing nickel sulfide extraction and the subsequent refining of material into battery-grade class 1 nickel and NSH. The operation is in the far north of Québec, within the Canadian Arctic, and functions entirely off grid, which significantly shapes its energy profile. Due to the remote location and the nature of underground mining, the site relies heavily on diesel to meet the substantial energy demands of both the off grid mine and the concentrator. This dependency makes fuel logistics and energy efficiency critical considerations throughout the production cycle.

The purpose of this research was to conduct a comprehensive LCA that fully accounts for the geographical context of the off grid mine, smelter, and refinery, as well as the associated energy consumption and transportation impacts. Significant data gaps were identified in previously published CO_2 emissions estimates (Wei et al., 2020), including those reported by Valencia et al. (2025) (Valencia et al., 2025) and the Nickel Institute (2020) (Nickel_Institute, 2020). Addressing these gaps, the objective of this study was to develop a complete LCA by incorporating all relevant parameters that contribute to CO_2 emissions across the entire nickel sulfide-to-nickel sulfate value chain (Roy et al., 2025).

5.3.1 Calculation and Aggregation of Cradle-to-Gate Impacts

A process-based (non-aggregate) LCA was conducted to quantify the cradle-to-gate greenhouse gas (GHG) emissions associated with the production of 1 ton of NSH. In accordance with ISO 14040 and ISO 14044, the product system was modeled as a sequence of linked unit processes, including mining, smelting, and refining, with each process assessed independently under its own functional unit (ISO, 2006b, 2006c). Environmental impacts were tracked through intermediate products using physical mass-based relationships, an approach recommended for process-based LCAs to ensure conservation of material and environmental flows (Guinee, 2002).

To illustrate the aggregation methodology used in this study, the following example demonstrates how process-level Life-cycle inventory results were mathematically scaled and summed to derive cradle-to-gate impacts. At the mining stage, production of nickel concentrate resulted in emissions of 1.04 ton CO_2-eq per ton of concentrate produced. Because 3.75 ton of concentrate are required to supply the downstream smelting process, mining-related emissions were scaled accordingly, yielding 3.91 ton CO_2-eq attributed to mining. The smelting stage, which converts concentrate into nickel matte, exhibited an emissions intensity of 2.1 ton CO_2-eq per ton of matte produced. When scaled to the 3.25 tons of nickel matte required for subsequent refining, cumulative emissions from the mining and smelting stages amounted to 19.37 ton CO_2-eq, or 18.73 ton CO_2-eq when co-product credits are applied. The refining stage contributed an additional 0.73 ton CO_2-eq per ton of NSH produced. Summing the scaled emissions from mining, smelting, and refining yields a total cradle-to-gate carbon footprint of 20.10 ton CO_2-eq per ton of NSH produced without co-product credits, and 18.48 ton CO_2-eq per ton of NSH when co-product credits are included. This stepwise, additive aggregation of scaled unit-process impacts is consistent with standard process-based Life-cycle assessment practice and enables transparent tracking of emissions contributions and identification of environmental hotspots across the value chain (Hauschild, 2018; Wernet et al., 2016).

5.3.2 Comprehensive Summary of NSH and Class 1 Nickel LCA Results

In this Québec case study, the LCA compares Class 1 Nickel metal and NSH across mining, smelting, and refining stages, with results reported both with and without co-product credits are shown in Figure 59. The assessment considers long-term CO_2-equivalent emissions, short-term CO_2-equivalent emissions, and water consumption per functional unit.

For Class 1 Nickel, the aggregated impacts without co-product credits total approximately 17.06 t CO_2-eq (long-term), 17.47 t CO_2-eq (short-term), and 24.18 L of water use. Mining and smelting dominate these impacts, with smelting contributing the majority of greenhouse gas emissions and water demand. When co-product credits are included, total impacts decrease significantly to 14.05 t CO_2-eq (long-term), 14.31 t CO_2-eq (short-term), and 10.46 L of water. This reduction is largely driven by refinery co-products and purification credits, which offset a substantial portion of upstream burdens.

For NSH, overall impacts are higher than Class 1 Nickel due to additional conversion and purification steps required to produce the sulphate product. Without co-product credits, NSH results in approximately 20.10 t CO_2-eq (long-term), 20.52 t CO_2-eq (short-term), and 23.18 L of water use. Mining and smelting contributions are similar in magnitude to Class 1 Nickel; however, the refining stage has a greater influence due to chemical processing and material transformation. When co-product credits are applied, NSH impacts are reduced to approximately 18.48 t CO_2-eq (long-term), 18.83 t CO_2-eq (short-term), and 15.77 L of water. Although credits significantly reduce impacts, NSH retains higher net burdens than Class 1 Nickel.

Overall, the results demonstrate that co-product allocation assumptions critically influence LCA outcomes, particularly for refinery-stage processes. Across both product systems, mining and smelting remain the dominant contributors to emissions, while co-product credits substantially improve the apparent environmental performance, especially for water consumption and long-term climate impacts.

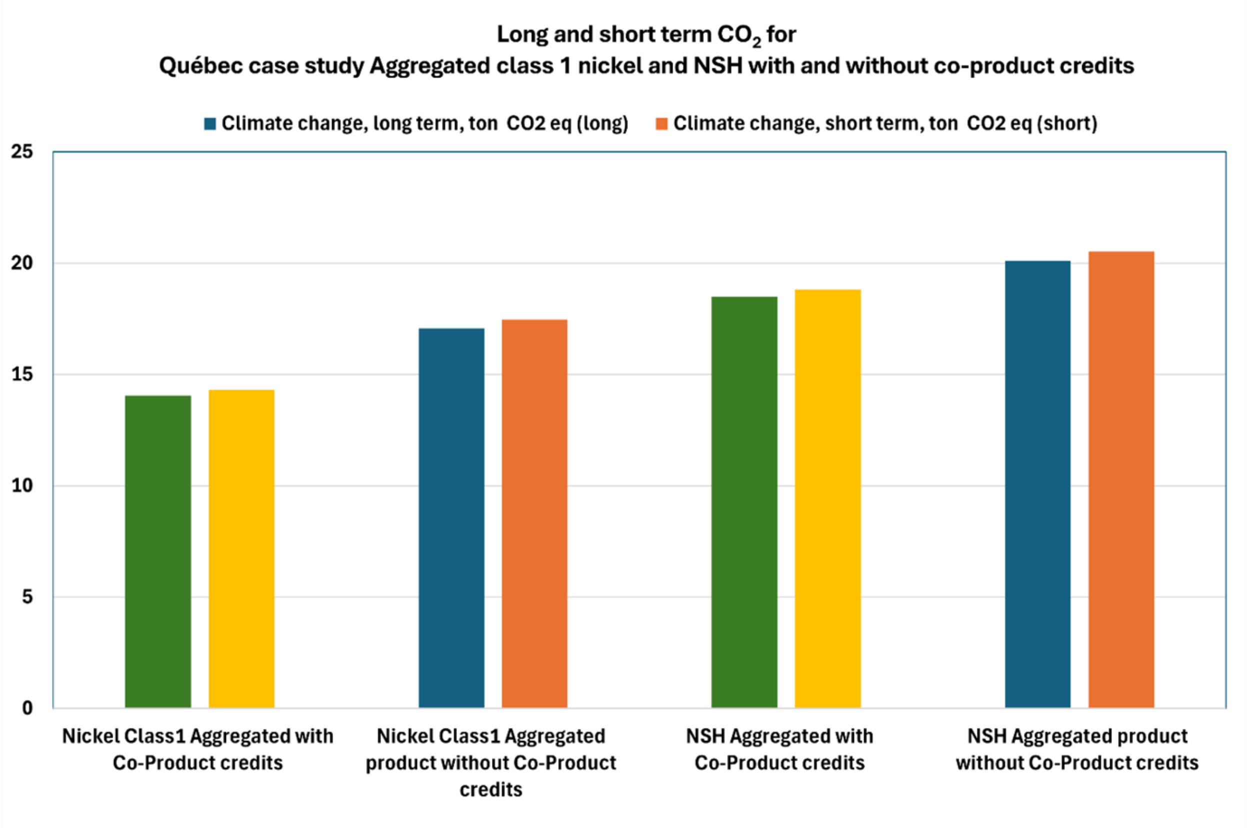


Figure 59: Aggregated Long-Term, Short-Term CO2 emissions for Québec Case Study for class 1 nickel and nickel sulfate hexahydrate; NSH (with and without co-product credits)

This outcome aligns more closely with the findings of Bartzas et al. (2024) (Bartzas & Komnitsas, 2024), who assessed mining in Indonesia combined with processing in China. However, the Québec LCA result is higher than the values reported by the German Association of the

Automotive Industry (2023), 8.9 tons NSH, Valencia et al. (2025), 6.7 NSH, and by the Nickel Institute (2020), 3.6 tons NSH; Table 25 (German-AAI, 2023; Nickel-Institute, 2024; Nickel_Institute, 2020; Valencia et al., 2025).

Table 25: NSH and class 1 nickel tons CO2eq comparison to other studies

Reference	Country	NSH tons CO_2-eq	Class 1 Nickel tons CO_2-eq
German Association of the Automotive Industry (2023)	Canadian nickel sulfide route	8.9	
Valencia et al (2025)	Canada/Norway	6.7	
Nickel Institute (2024)	Member countries (except China) not a specific mine or process plant	3.6	13.1
Bartzas et al (2024)	Indonesia/China (high pressure acid leaching and mixed hydroxide precipitate)	36.8	
Valencia et al (2025)	Indonesia/China (high pressure acid leaching and mixed hydroxide precipitate)	86.4	
This study (2026)	Canada/Norway (without co-product credits)	20.1	17.06
This study (2026)	Canada/Norway (with co-product credits)	18.48	14.05

It is hypothesized that much lower CO_2 long term emissions were based on nickel industry averages and not off grid mine and concentrator represented in this Québec case study. The Québec utilized large amounts of diesel to generate electricity and run mine excavation Equipment (NRC, 2026).

5.3.3 Water Use and Water Scarcity Considerations

Water scarcity is an increasingly critical consideration in nickel supply chains, as mining, smelting, and refining operations are often located in regions where water availability is variable or constrained. The LCA results indicate that water use is a material contributor to the overall environmental footprint of both Class 1 Nickel and NSH. For Class 1 Nickel, aggregated cradle-to-gate water consumption is approximately 24,176 m^3 per ton of product without co-product credits, reflecting the water-intensive nature of mineral processing and smelting operations. When co-product credits are applied, net water use decreases substantially to approximately 10,457 m^3, primarily due to credits associated with refinery co-products. NSH exhibits higher net water demand due to additional chemical processing and purification steps. Without co-product credits, NSH production requires approximately 23,179 m^3 of water per ton of NSH produced, while with co-product credits, water consumption is reduced to approximately 15,770 m^3. Across both product systems, mining and smelting stages dominate gross water demand, while refinery-stage co-products significantly offset net water burdens. These results underscore the importance of water-efficient process design and allocation assumptions, particularly in water-stressed regions, as co-product treatment has a pronounced influence on reported water scarcity-relevant impacts.

5.3.4 Sensitivity Analysis of Alternative Energy and Fuel Scenarios

Several challenges are faced when considering alternative energy scenarios for the northern Québec site due to extreme climate (temperature at -60 C), geography, technology, and fuel storage (Azin et al., 2025).Wind turbines are considered for Arctic regions, but have operational issues due to the extreme cold and frost build up on the turbine blades (Azin et al., 2025).

A sensitivity analysis was performed in which the diesel consumed at the off grid mine and concentrator was replaced with natural gas. As shown in Figure 60, this substitution results in a decrease in long-term CO_2 emissions from 625 kg when using diesel to just 241 kg and short-term CO_2 emissions from 631 kg when using diesel to just 260 kg when using natural gas. This change in fuel can be an additional method to help with emissions like how windmills have been incorporated into reducing diesel consumption. A recent study by Azin et al (2025) looked at decarbonizing the remote Québec mine/concentrator operations by combining wind with hydrogen (Azin et al., 2025). This study showed a reduction of up to 143,000 ton CO_2-eq annually, but the technology costs seemed to be prohibitive (Azin et al., 2025). The cost of sending natural gas by ship, storage, and arctic temperatures would also have to be considered when looking at the replacement diesel with natural gas for electricity generation.

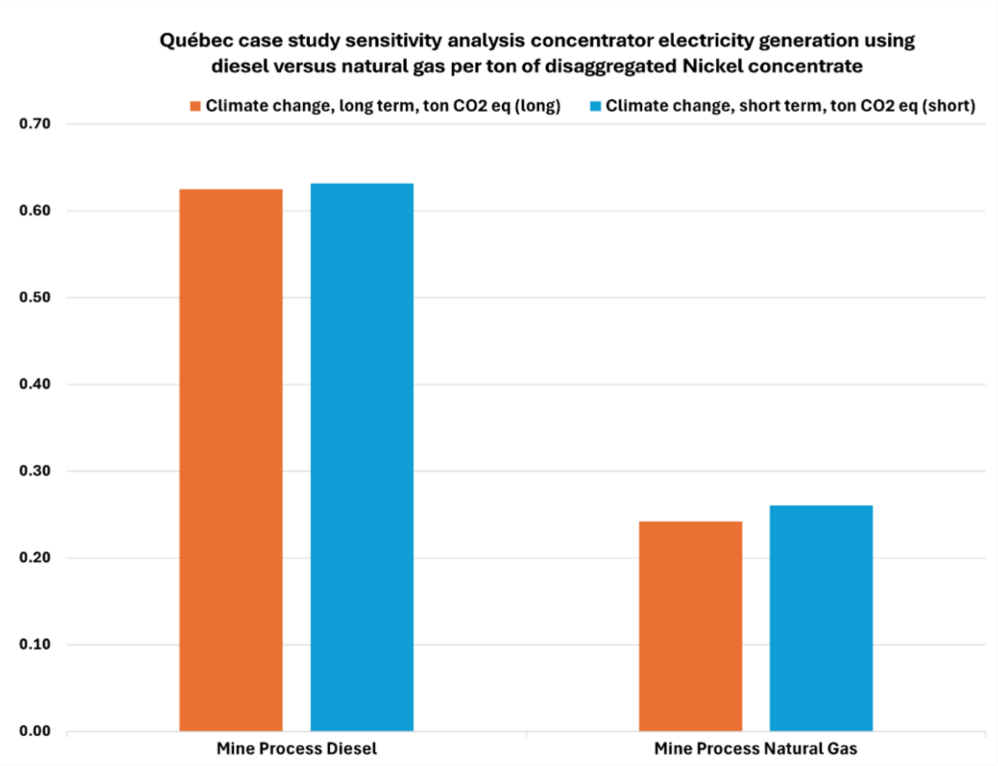


Figure 60: Sensitivity of long term and short term CO_2 emissions at the Québec concentrator to electricity generation fuel choice (diesel versus natural gas).

5.3.5 Transportation Pathways and Ton-Kilometer Contributions

Transportation plays a significant role in this LCA due to the large geographic separation between the off grid mine/concentrator, smelter, and refinery. Transportation impacts were calculated on a ton-kilometre (t·km) basis, consistent with standard LCA transport emission factors, by multiplying the mass of material transported by the distance traveled. As shown in Figure 61, the logistics pathway from the Québec mine to the final refinery in Norway includes multiple transport modes and long transit distances. One ton of material is first transported approximately 100 km by truck from the off grid mine to Deception Bay, corresponding to ~100 t·km per ton of NSH. This is followed by a 2,600 km marine shipment to Québec City (~2,600 t·km per ton), then 950 km by rail to the Sudbury, Ontario smelter (~950 t·km per ton), and a return rail shipment of similar distance back to Québec City. The final stage involves a transoceanic shipment of approximately 5,181 km to the Nikkelverk refinery in Norway, contributing ~5,181 t·km per ton of NSH. Because the off-grid mine is located in a remote Arctic region approximately 100 km from the nearest port, these long-distance trucking, rail, and marine transport stages contribute to the overall cradle-to-gate environmental burden of NSH production (Glencore, 2026).

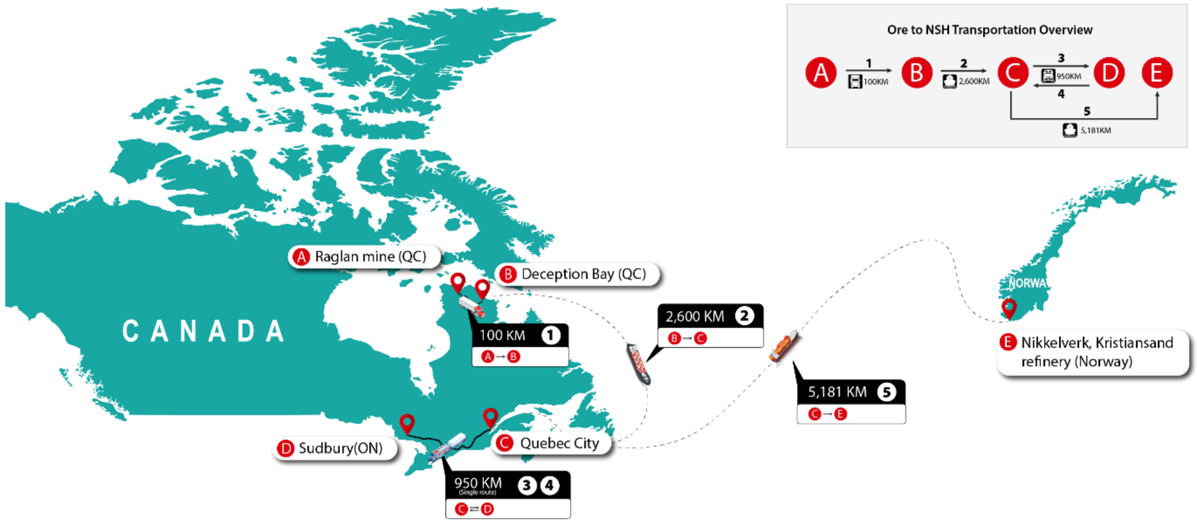


Figure 61: Transportation Network from Nickel Sulfide to Class 1 Nickel and NSH

5.3.6 On-Site Energy Supply and Diesel Consumption at the Québec Mine

The diesel data indicates that nickel sulfide production is highly dependent on on-site diesel use, with approximately 60 million liters per year consumed at the Québec mine and concentrator (NRC, 2026). This consumption is broken down by 43.8 million liters for electricity generation and 16.2 million liters for mine equipment and heating (Azin et al., 2025). This makes diesel the dominant contributor to greenhouse gas emissions in the region, as extraction and concentration activities rely heavily on mobile equipment and on-site generation. The processes nickel sulfide technical information also shows that Québec wind-diesel hybrid system provides a credit equivalent to roughly 2.1 million liters of diesel per year, partially offsetting this demand. This reduction is the result of recent investment in wind turbines developed in partnership with the Government of Canada (NRC, 2026), aimed at decreasing reliance on diesel in the Arctic environment. Overall, the data highlights that, despite renewable integration, diesel remains a major fuel input in mine operations (Glencore, 2026; Government_Canada, 2026).

5.3.7 Baseline Electricity Demand and Energy Assumptions

The Electricity data reports an estimated 157.7 GWh per year of electrical demand at the Québec concentrator, along with an indicative continuous load of approximately 18 MW (Glencore, 2026), which equates to 7,227 MJ per ton of class 1 nickel and NSH . These figures establish the baseline energy requirement used to evaluate efficiency improvements and potential renewable-energy credits within the operations. Because the mine and concentrator operate off-grid, all electricity is generated on-site through a combination of diesel-fueled generators and wind turbines, reflecting the region's hybrid power system. Downstream, electricity is also consumed at the smelter and at the refinery in Norway, where the grid is predominantly supplied by renewable energy, thereby lowering the carbon intensity of refining relative to upstream processes.

5.3.8. Natural Gas Consumption in Pyrometallurgical Nickel Production

Data published by the Nickel Institute provide the basis for modeling smelter-stage energy use, indicating that approximately 70 MJ of natural gas per kilogram of nickel produced is consumed during smelting operations. This value is consistent with multiple Nickel Institute data sources and reflects energy use associated primarily with flash furnace pyrometallurgical processing, rather than upstream mining or concentration activities. As a result, natural gas consumption is concentrated at the smelter stage, where it serves as a process fuel to support high-temperature nickel conversion. When compared to the upstream system, the overall natural gas requirement is relatively modest, particularly in contrast to the substantially higher energy demand associated with diesel-based electricity generation at the remote Québec mine and concentrator. This distinction highlights the different energy profiles of upstream and downstream processing stages and underscores the dominant role of diesel-based power in driving the overall energy intensity of primary nickel production (Nickel-Institute, 2024; Nickel_Institute, 2020).

5.3.9 BioSulphide Water Treatment for Mine Tailings and Effluent Management

The remote Québec site utilizes a specialized water treatment for mine tailings, a unique Biosulphide system developed in Canada (Adams et al., 2008). The Biosulphide system removes metal contaminants from mine tailings. This method was also used in abandoned mines in Colorado to clean up underground mine tailings with zinc and cadmium contamination(Engineering, 2009). The Québec mine in Northern Canada must adhere to strict environmental regulations that have implemented the Chemsulphide process (Engineering, 2009). Due to its location, the Québec mine can only utilize water treatment for 5 to 6 months a year. The Québec mine facility recovers nickel from the contaminated water to produce a high-grade concentrate that is transported with the Quebec production concentrate for smelting off site. The effluent from the BioteQ; Chemsulphide process plant can be discharged directly to the environment. The BioteQ treatment plant has replaced a lime treatment plant. Zinc is the main contamination recovered at the Québec facility using the tailings treatment process. The BioSulphide process is a biological sulphide-generation system used to selectively precipitate dissolved metals from mine water and tailings streams (Adams et al., 2008). It uses naturally occurring sulphate-reducing bacteria (SRB) to convert sulphate into hydrogen sulphide (H_2S) under controlled anaerobic conditions (Adams et al., 2008). This biogenic sulphide then reacts with dissolved metals such as copper, zinc, or nickel to form stable, high-grade metal sulphide precipitates (Figure 62) (Adams et al., 2008).

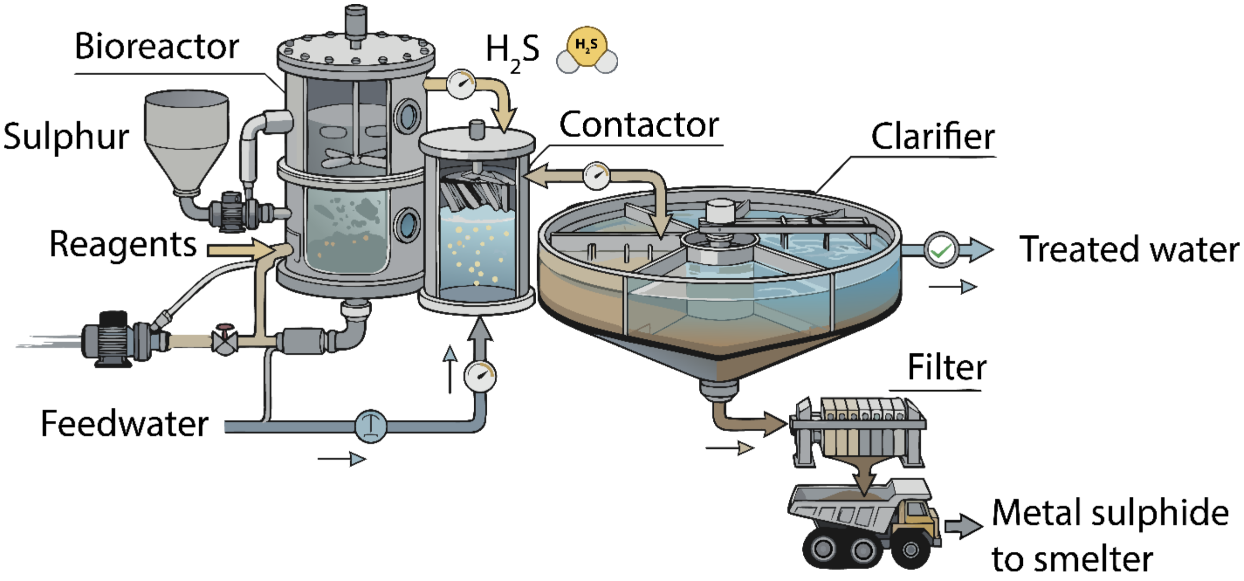


Figure 62: BioSulphide mine tailings treatment process (ref: Biogenic sulphide for cyanide recycle).

Sections 3.1-3.9 demonstrate that environmental impacts in nickel supply chains are driven primarily by site-specific operational conditions. The Québec case study shows that off-grid Arctic mining has distinct emissions profiles due to diesel-based power generation, long-distance transportation, and seasonal constraints. While downstream refining benefits from lower-carbon energy sources, upstream mining and concentration remain the dominant contributors to greenhouse gas emissions, with mitigation options constrained by climatic, technical, and economic factors.

5.4 Summary

Applying a process resolved, site specific LCA framework reveals substantial differences between off grid Arctic nickel production and previously reported industry average results. Although off grid Arctic nickel production exhibits higher greenhouse gas emissions than aggregated industry averages, it supports resource security and supply chain resilience for battery-grade materials, indicating that decarbonization strategies must be evaluated alongside geopolitical and logistical considerations. The Québec case study shows that mining and concentration operations located in remote northern regions exhibit fundamentally different energy and emissions profiles than grid-connected or aggregated systems, driven primarily by reliance on diesel-based electricity generation, long-distance transportation of intermediate products, and seasonal constraints on water management. While downstream smelting and refining benefit from comparatively low-carbon energy sources, particularly at the Norwegian refinery, the upstream mining and concentration stages remain the dominant contributors to greenhouse gas emissions and resource use for both Class 1 nickel and NSH. Sensitivity analyses further indicate that alternative fuel and energy configurations could reduce emissions; however, their implementation is constrained by technical feasibility, extreme climate conditions, and economic considerations unique to remote Arctic operations. Collectively, these findings demonstrate that LCAs based on generalized datasets may substantially underestimate the environmental burdens of battery-grade nickel produced from off-grid mining systems and underscore the importance of process-resolved, location-specific assessments to inform decarbonization strategies, supply-chain decisions, and critical-mineral policy development.

CHAPTER 6. CONTRIBUTIONS AND SIGNIFICANCE OF THESIS RESEARCH, AND SUGGESTIONS FOR FUTURE WORK

6.1 Contributions and Significance Thesis Research

This thesis makes a substantial contribution to the field of LCA and sustainable battery materials by establishing one of the first comprehensive, region-specific cradle-to-gate LCAs for multiple critical minerals lithium, natural graphite, and nickel sourced and processed in Québec, Canada. By integrating primary industrial data, validated regulatory documentation, and internationally recognized LCA tools (*OpenLCA v2.3*, *Ecoinvent v3.8*, *Impact World+*), this research addresses a critical data gap in the literature, where over 85% of publicly available LCA data for LIB materials remains focused on Asian supply chains.

A key contribution of this work lies in its process-resolved, site-specific modeling approach, which captures the unique environmental characteristics of Québec-based operations, including the province's low-carbon hydroelectric grid, stringent environmental regulations, and emerging circular-economy practices. The thesis quantifies the environmental impacts associated with producing battery-grade materials and demonstrates that Québec-based production pathways can achieve substantially lower GHG emissions compared with conventional supply chains in China and Australia. Notably, the study reports emissions of 5.46 tons CO_2-eq per ton of lithium hydroxide monohydrate, 1.44 tons CO_2-eq per ton of natural graphite anode active material, and 20.1 tons CO_2-eq per ton of nickel sulfate hexahydrate, with clear identification of dominant emission hotspots across each value chain.

Beyond quantification, this research advances methodological practice by systematically identifying upstream and facility-wide emission drivers, including natural gas-fired calcination and acid baking (lithium), purification and micronization (graphite), and diesel-intensive mining and smelting operations in off-grid Arctic contexts (nickel). The incorporation of co-product credits, such as sodium sulfate and gypsum, further demonstrates how industrial symbiosis and by-product valorization can meaningfully reduce net environmental burdens. Additionally, the cluster-based environmental impact analysis provides actionable insights into process-level interventions including electrification, renewable heating substitution, and closed-loop water systems that could reduce emissions by up to 40% in certain production stages.

The significance of this thesis extends beyond academic contribution. The results directly support policy formulation, investment decisions, and industrial strategy under frameworks such as the U.S. Inflation Reduction Act and Canada's Critical Minerals Strategy, which prioritize traceable, low-carbon, and regionally secure battery supply chains. By providing transparent, high-resolution LCA inventories, this research equips policymakers, OEMs, mining companies, and battery manufacturers with credible data needed to benchmark performance, identify decarbonization pathways, and advance the development of a localized, green battery ecosystem in North America. Collectively, this work establishes a foundational LCA baseline for Québec's critical mineral supply chain and lays essential groundwork for future full battery pack and cradle-to-cradle assessments.

6.2 Suggestions for Future Work

While this dissertation advances understanding of the environmental performance of key battery materials, it also highlights several important areas for future research. Most notably, LCAs should be extended to additional critical minerals used in lithium-ion batteries—including manganese, cobalt, aluminum, and emerging specialty materials to fully characterize the environmental implications of evolving battery chemistries. As LIB formulations continue to shift toward higher-nickel, lower-cobalt, and eventually cobalt-free or solid-state technologies, updated Life-cycle inventories will be essential to accurately assess trade-offs among energy density, supply risk, cost, and environmental impact.

Future work should also expand the system boundary from cradle-to-gate to cradle-to-cradle, integrating recycling, reuse, and end-of-life treatment of battery materials. With regulatory requirements in Europe and growing momentum in North America mandating minimum recycled content, modeling closed-loop material recovery pathways including hydrometallurgical, pyrometallurgical, and direct recycling routes will be critical for understanding long-term sustainability and resource security. Incorporating dynamic recycling rates, collection efficiencies, and recovery yields would further strengthen full battery Life-cycle analyses.

Additional research is warranted to model the environmental impacts of complete lithium-ion battery packs, integrating cathodes, anodes, electrolytes, separators, casings, and pack-level manufacturing processes. Such work would enable more accurate comparisons between battery chemistries and vehicle platforms and support harmonized environmental reporting across the EV industry. Future LCAs could also incorporate scenario-based and sensitivity analyses to evaluate the influence of alternative energy sources, fuel substitutions in remote mining operations, and emerging low-waste or electrochemical processing technologies.

Finally, continued development of transparent, standardized, and region-specific LCA datasets for North American supply chains remains a priority. Coupling LCA with digital traceability tools, such as battery passports and blockchain-based data architectures, represents a promising avenue for enhancing data reliability, regulatory compliance, and consumer trust. As Québec’s battery materials industry continues to mature, collaboration between academia, industry, and government will be essential to maintain up-to-date inventories and to guide the responsible scale-up of a resilient, low-carbon battery supply chain.

JOURNAL PUBLICATIONS

Peer-Reviewed Journal Publications

1. Vegh, G., Madikere Raghunatha Reddy, A. K., Li, X., Deng, S., Liu, T., Amine, K., & Zaghib, K. (2024). North America's Potential for an Environmentally Sustainable Nickel, Manganese, and Cobalt Battery Value Chain. *Batteries*, *10*(11), 377. https://doi.org/10.3390/batteries10110377

2. Vegh, G., Sajedi, S., Kantor, I., Amine, K., Srivastava, M., MR, A. K., & Zaghib, K. (2025). Life-cycle assessment of nickel, manganese, cobalt critical minerals: lithium hydroxide monohydrate (mine-to-material) in Québec, Canada. *Journal of Power Sources*, *657*, 238149. https://doi.org/10.1016/j.jpowsour.2025.238149

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3. Vegh, G., Sajedi, S., Kantor, I., Amine, K., Srivastava, M., Rezayi, M., Reddy, A. K. M. R., & Zaghib, K. (2026). Toward Sustainable Anode Materials: LCA of Natural Graphite Processing in Québec. *Batteries*, *12*(2), 68. https://doi.org/10.3390/batteries12020068

4. Vegh, G., Sajedi, S., Kantor, I., Amine, K., Anil Kumar, M. R., & Zaghib, K. (2026). *Life-cycle assessment of nickel sulfide ore off-grid mine in Northern Québec to battery-grade nickel sulfate hexahydrate in Norway* [Manuscript submitted to Journal].

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Conferences, Posters, and Abstracts

1. Attended the Advanced Battery for Automotive Applications ***(ABAA-13)*** conference (Morocco, October 2022)

2. Attended **Propulsion Québec** presented the latest edition of IMPULSION, the International Summit on Electric and Smart Transportation (Montreal, March 2023)

3. A poster on "Development of Characterization Methods for NMC Cathode from Mining to Recycling" was presented at the ***International Conference on the Characterization and Quantification of Lithium, from the Micro Scale to the Nano Scale, from Mining to Energy***, Paris; France June 26-27th 2023

4. Attended the; Nancy; France July 6-7th 2023. ***World Materials Forum***

5. Presented LCA on Lithium Hydroxide Monohydrate (initial case study) at Advanced Battery for Automotive Applications ***(ABAA-15)*** conference (Montreal, October 2024) Life-cycle Assessment for Battery Production

6. Poster at ***ABAA-15*** International Battery conference (Montreal; October 2024)

7. Presented my review paper (Batteries; MDPI, October 2024) to the Automotive Industry; ***Suppliers Partnership for the Environment*** (***SP)*** at Michigan State University (MSU); (Detroit, January 2025)

8. Vegh, G. P. (2025, May). Poster: Sustainable Transition: Life-cycle Assessment of North American Lithium-Ion Battery Supply Chain for Electric Vehicles: Lithium Hydroxide Monohydrate (LHM). In *247th ECS Meeting (May 18th-22nd, 2025)*. ***Electro Chemical Society (ECS)***

References/Bibliography

AAC. (2024). *Portrait of the Canadian Aluminium Industry*. Retrieved 2024/02/08 from https://aluminium.ca/en/the-industry/

Abu, S. M., Hannan, M. A., Hossain Lipu, M. S., Mannan, M., Ker, P. J., Hossain, M. J., & Mahlia, T. M. I. (2023). State of the art of lithium-ion battery material potentials: An analytical evaluations, issues and future research directions. *Journal of Cleaner Production*, *394*. https://doi.org/10.1016/j.jclepro.2023.136246

Adams, M., Lawrence, R., & Bratty, M. (2008). Biogenic sulphide for cyanide recycle and copper recovery in gold–copper ore processing. *Minerals Engineering*, *21*(6), 509-517. https://doi.org/10.1016/j.mineng.2008.02.001

Ahmed, S., Nelson, P. A., Gallagher, K. G., Susarla, N., & Dees, D. W. (2017). Cost and energy demand of producing nickel manganese cobalt cathode material for lithium ion batteries. *Journal of Power Sources*, *342*, 733-740. https://doi.org/10.1016/j.jpowsour.2016.12.069

Al-Jawad, J., Ford, J., Petavratzi, E., & Hughes, A. (2024). Understanding the spatial variation in lithium concentration of high Andean Salars using diagnostic factors. *Science of The Total Environment*, *906*, 167647. https://doi.org/10.1016/j.scitotenv.2023.167647

Alsafasfeh, A., Alagha, L., & Al-Hanaktah, A. (2024). The Effect of Methyl Isobutyl Carbinol "MIBC" on the Froth Stability and Flotation Performance of Low-Grade Phosphate Ore. *Mining, Metallurgy & Exploration*, *41*(1), 353-361. https://doi.org/https://doi.org/10.1007/s42461-024-00919-1

Amanyazova, B., Sailaukhanova, M., Kurmanbayeva, I., Kylyshbayeva, A., Tugelbay, S., Tatykayev, B., Bakenov, Z., & Umirov, N. (2026). Advances in battery-grade nickel sulfate production. *Separation and Purification Technology*, *382*. https://doi.org/10.1016/j.seppur.2025.135672

AMR. (2023). *Lithium-ion Battery Market Insight and Growth Projection, 2032*. Retrieved 2023/10/10 from https://www.alliedmarketresearch.com/lithium-ion-battery-market

ANL. (2024). *Technoeconomic Analysis of Chemical and Electrochemical Technologies*. Retrieved 2024/01/11 from https://www.anl.gov/cse/batpac-model-software

Asare, M. O., & Afriyie, J. O. (2021). Ancient Mining and Metallurgy as the Origin of Cu, Ag, Pb, Hg, and Zn Contamination in Soils: A Review. *Water, Air, & Soil Pollution*, *232*(6), 240. https://doi.org/10.1007/s11270-021-05166-4

Aslam, M. K., Niu, Y., Hussain, T., Tabassum, H., Tang, W., Xu, M., & Ahuja, R. (2021). How to avoid dendrite formation in metal batteries: Innovative strategies for dendrite suppression. *Nano Energy*, *86*, 106142. https://doi.org/10.1016/j.nanoen.2021.106142

Aubertin, A., Axsen, J., & Gunster, S. (2024). Electric vehicles for climate, a green economy, or independence? Comparing policy discourse in newspapers across three Canadian provinces. *Energy Research & Social Science*, *108*, 103353. https://doi.org/10.1016/j.erss.2023.103353

Azin, H., Mungyeko Bisulandu, B.-J. R., Ilinca, A., & Rousse, D. R. (2025). Decarbonizing Arctic Mining Operations with Wind-Hydrogen Systems: Case Study of Raglan Mine. *Processes*, *13*(10). https://doi.org/10.3390/pr13103208

B. Dunn, J., Gaines, L., C. Kelly, J., James, C., & G. Gallagher, K. (2015). The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy & Environmental Science*, *8*(1), 158-168. https://doi.org/10.1039/C4EE03029J

Baars, J. (2007). *Introduction: Chronological Time and Chronological Age: Problems of Temporal Diversity*. Routledge.

Ballinger, B., Stringer, M., Schmeda-Lopez, D. R., Kefford, B., Parkinson, B., Greig, C., & Smart, S. (2019). The vulnerability of electric vehicle deployment to critical mineral supply. *Applied Energy*, *255*, 113844. https://doi.org/10.1016/j.apenergy.2019.113844

Barma, S. D., Baskey, P. K., Rao, D. S., & Sahu, S. N. (2019). Ultrasonic-assisted flotation for enhancing the recovery of flaky graphite from low-grade graphite ore. *Ultrason Sonochem*, *56*, 386-396. https://doi.org/https://doi.org/10.1016/j.ultsonch.2019.04.033

Barman, P., Dutta, L., & Azzopardi, B. (2023). Electric Vehicle Battery Supply Chain and Critical Materials: A Brief Survey of State of the Art. *Energies*, *16*(8). https://doi.org/https://doi.org/10.3390/en16083369

Bartzas, G., & Komnitsas, K. (2024). Cradle to gate life-cycle assessment of battery grade nickel sulphate production through high-pressure acid leaching. *Sci Total Environ*, *952*, 175902. https://doi.org/10.1016/j.scitotenv.2024.175902

BASF-Canada. (2022). *BASF acquires site for North American battery materials and recycling expansion in Canada*. https://www.basf.com/ca/en/media/News-Releases/2022/basf-acquires-site-for-north-american-battery-materials-and-recy.html

Bellan, R. (2023). Tracking the EV battery factory construction boom across North America. *TechCrunch*. https://techcrunch.com/2023/08/16/tracking-the-ev-battery-factory-construction-boom-across-north-america/

Beowulf_Mining. (2024). *Graphite Anode Materials Plant Update*. https://mb.cision.com/Main/11673/4029477/2965899.pdf

Berry, C. (2023). The Paradox of Green Growth: Challenges and Opportunities in Decarbonizing the Lithium-Ion Supply Chain. In S. Kalantzakos (Ed.), *Critical Minerals, the Climate Crisis and the Tech Imperium* (pp. 107-123). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-25577-9_6

Bettenhausen, C. (2022). *BASF and a GM-Posco joint venture select sites in Canada for battery materials*. https://cen.acs.org/energy/energy-storage-/BASF-GM-Posco-joint-venture/100/i10

Bibra, E. M., Connelly, E., Gorner, M., Lowans, C., Paoli, L., Tattini, J., & Teter, J. (2021). Global EV Outlook 2021: Accelerating Ambitions Despite the Pandemic. https://trid.trb.org/View/1925380

Bloomberg_NEF. (2026). *Electric Vehicles Have a Bumpy Road Ahead in 2026*. https://www.bloomberg.com/news/newsletters/2026-01-06/electric-vehicles-have-a-bumpy-road-ahead-in-2026

Brinn, J. (2023). *BUILDING BATTERIES BETTER: DOING THE BEST WITH LESS* (NRDC, Issue. https://www.nrdc.org/resources/building-batteries-better-doing-best-less

Burkin, A. R. (2001). *Chemical Hydrometallurgy: Theory and Principles*. PUBLISHED BY IMPERIAL COLLEGE PRESS AND DISTRIBUTED BY WORLD SCIENTIFIC PUBLISHING CO. http://www.worldscientific.com/worldscibooks/10.1142/p158

Campagnol, N., Hoffman, K., Lala, A., & Ramsbottom, O. (2017). *The Future of Nickel: A Class Act*. https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-future-of-nickel-a-class-act

Canada-Service. (2022). The Canadian Critical Minerals Strategy [campaigns]. https://www.canada.ca/en/campaign/critical-minerals-in-canada/canadian-critical-minerals-strategy.html

CarbonScape. (2022). *CarbonScape Toward a Life Cycle Inventory for Graphite Production*. https://static1.squarespace.com/static/6213f06671d00e605c9eea45/t/62ce206273cd8e10b634d6bb/1657675880422/TOWARD%2BA%2BLIFE%2BCYCLE%2BINVENTORY%2BFOR%2BGRAPHITE%2BPRODUCTION_carbonscape.pdf

Carmen. (2022). The five largest nickel mines in operation in Canada. *Mining Technology*. https://www.mining-technology.com/marketdata/five-largest-nickel-mines-canada/

Celeste, A., Tuccillo, M., Menon, A. S., Brant, W., Brandell, D., Pellegrini, V., Brescia, R., Silvestri, L., & Brutti, S. On the Elusive Crystallography of Lithium-Rich Layered Oxides: Novel Structural Models. *Small Methods*, *n/a*(n/a), 2301466. https://doi.org/10.1002/smtd.202301466

Chae, C., Park, H., Kim, D., Kim, J., Oh, E.-S., & Lee, J. K. (2013). A Li-ion battery using LiMn2O4 cathode and MnOx/C anode. *Journal of Power Sources*, *244*, 214-221. https://doi.org/10.1016/j.jpowsour.2013.01.157 (16th International Meeting on Lithium Batteries (IMLB))

Chandrasekharam, D., Şener, M. F., Recepoğlu, Y. K., Isık, T., Demir, M. M., & Baba, A. (2024). Lithium: An energy transition element, its role in the future energy demand and carbon emissions mitigation strategy. *Geothermics*, *119*, 102959. https://doi.org/10.1016/j.geothermics.2024.102959

Chen, M., Zheng, Z., Wang, Q., Zhang, Y., Ma, X., Shen, C., Xu, D., Liu, J., Liu, Y., Gionet, P., O'Connor, I., Pinnell, L., Wang, J., Gratz, E., Arsenault, R., & Wang, Y. (2019). Closed Loop Recycling of Electric Vehicle Batteries to Enable Ultra-high Quality Cathode Powder. *Scientific Reports*, *9*(1), 1654. https://doi.org/10.1038/s41598-018-38238-3

Chen, S., Niu, C., Lee, H., Li, Q., Yu, L., Xu, W., Zhang, J.-G., Dufek, E. J., Whittingham, M. S., Meng, S., Xiao, J., & Liu, J. (2019). Critical Parameters for Evaluating Coin Cells and Pouch Cells of Rechargeable Li-Metal Batteries. *Joule*, *3*(4), 1094-1105. https://doi.org/10.1016/j.joule.2019.02.004

Chen, Z., Zhang, W., & Yang, Z. (2019). A review on cathode materials for advanced lithium ion batteries: microstructure designs and performance regulations. *Nanotechnology*, *31*(1), 012001. https://doi.org/10.1088/1361-6528/ab4447

Cheng, C., Tan, L., Liu, H., & Huang, X. (2011). High rate performances of the cathode material LiNi1/3Co1/3Mn1/3O2 synthesized using low temperature hydroxide precipitation. *Materials Research Bulletin*, *46*(11), 2032-2035. https://doi.org/10.1016/j.materresbull.2011.07.004

Choi, J., Choi, S., Park, S.-M., An, J.-C., Park, H. W., Jung, J. C., & Yang, I. (2025). Eco-friendly recycling of coke waste: Transforming steel manufacturing waste into high-purity graphite for lithium-ion batteries. *Carbon*, *236*. https://doi.org/10.1016/j.carbon.2025.120119

Choi, K. H., & Azimi, G. (2023). Crystallization of nickel sulfate and its purification process: towards efficient production of nickel-rich cathode materials for lithium-ion batteries. *RSC Advances*, *13*(41), 28501-28512. https://doi.org/10.1039/d3ra04280d

Chordia, M., Wickerts, S., Nordelöf, A., & Arvidsson, R. (2022). Life cycle environmental impacts of current and future battery-grade lithium supply from brine and spodumene.

Resources, Conservation and Recycling, *187*. https://doi.org/10.1016/j.resconrec.2022.106634

Chu, B., Guo, Y.-J., Shi, J.-L., Yin, Y.-X., Huang, T., Su, H., Yu, A., Guo, Y.-G., & Li, Y. (2022). Cobalt in high-energy-density layered cathode materials for lithium ion batteries. *Journal of Power Sources*, *544*, 231873. https://doi.org/10.1016/j.jpowsour.2022.231873

Church, S., Laske, N., Leschiner, D., Simmons, N., Verhalen, S., & Willis, M. (2023). *The Impact of the U.S. Inflation Reduction Act on Global Clean Energy Supply Chains* (Bureau of Energy Resources, Issue. https://media.journoportfolio.com/users/37537/uploads/4731e77b-1493-404b-9512-477240181b5a.pdf

Cimino, A., Gnoni, M. G., Longo, F., & La Rosa, A. (2023). Digital Twin (DT) based methodology to support effective design of industrial production lines. *Procedia Computer Science*, *217*, 1896-1907. https://doi.org/10.1016/j.procs.2022.12.390 (4th International Conference on Industry 4.0 and Smart Manufacturing)

Clarke, C., & Upson, S. (2017). A global portrait of the manganese industry—A socioeconomic perspective. *NeuroToxicology*, *58*, 173-179. https://doi.org/10.1016/j.neuro.2016.03.013

Club, B. D. *Diesel engine power to Fuel Consumption table - Naturally aspirated Engines*. https://barringtondieselclub.co.za/

Dai, Q., Kelly, J. C., Gaines, L., & Wang, M. (2019). Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications. *Batteries*, *5*(2). https://doi.org/10.3390/batteries5020048

Das, J., Kleiman, A., Rehman, A. U., Verma, R., & Young, M. H. (2024). The Cobalt Supply Chain and Environmental Life Cycle Impacts of Lithium-Ion Battery Energy Storage Systems. *Sustainability*, *16*(5). https://doi.org/10.3390/su16051910

Davis, K., & P. Demopoulos, G. (2023). Hydrometallurgical recycling technologies for NMC Li-ion battery cathodes: current industrial practice and new R&D trends. *RSC Sustainability*, *1*(8), 1932-1951. https://doi.org/10.1039/D3SU00142C

Deng, D. (2015). Li-ion batteries: basics, progress, and challenges. *Energy Science & Engineering*, *3*(5), 385-418. https://doi.org/10.1002/ese3.95

Ding, Y., Cano, Z. P., Yu, A., Lu, J., & Chen, Z. (2019). Automotive Li-Ion Batteries: Current Status and Future Perspectives. *Electrochemical Energy Reviews*, *2*(1), 1-28. https://doi.org/10.1007/s41918-018-0022-z

Diouf, B., & Pode, R. (2015). Potential of lithium-ion batteries in renewable energy. *Renewable Energy*, *76*, 375-380. https://doi.org/10.1016/j.renene.2014.11.058

Dixit, M., Engel, H., Eitan, R., Aurbach, D., Levi, M. D., Kosa, M., & Major, D. T. (2015). Classical and Quantum Modeling of Li and Na Diffusion in FePO4. *The Journal of Physical Chemistry C*, *119*(28), 15801-15809. https://doi.org/10.1021/acs.jpcc.5b00405

Do, M. P., Jegan Roy, J., Cao, B., & Srinivasan, M. (2022). Green Closed-Loop Cathode Regeneration from Spent NMC-Based Lithium-Ion Batteries through Bioleaching. *ACS Sustainable Chemistry & Engineering*, *10*(8), 2634-2644. https://doi.org/10.1021/acssuschemeng.1c06885

Dong, Z., Hao, H., Sun, X., Liu, B., Dou, H., Li, H., Liu, M., Zhao, F., & Liu, Z. (2026). How international trade shapes critical material demand in electric vehicle batteries. *Resources, Conservation and Recycling*, *226*. https://doi.org/10.1016/j.resconrec.2025.108648

Dou, S., Xu, D., Zhu, Y., & Keenan, R. (2023). Critical mineral sustainable supply: Challenges and governance. *Futures*, *146*. https://doi.org/10.1016/j.futures.2023.103101

E&MJ. (2023). *Anticipated Demand for Battery Minerals Creates Excitement in Québec*. https://www.e-mj.com/news/australia-and-oceania/anticipated-demand-for-battery-minerals-creates-excitement-in-quebec/

ECO-Canada. (2024). *Canada's Electric Vehicle Supply Chain Sector Profile*. https://eco.ca/wp-content/uploads/2024/04/Canadas-EV-and-Battery-Supply-Chain-Report-EN.pdf

Electric Vehicles - North America. https://www.statista.com/outlook/mmo/electric-vehicles/north-america

Ellingsen, L. A. W., Majeau-Bettez, G., Singh, B., Srivastava, A. K., Valøen, L. O., & Strømman, A. H. (2013). Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. *Journal of Industrial Ecology*, *18*(1), 113-124. https://doi.org/https://doi.org/10.1111/jiec.12072

Emilsson, E., & Dahllöf, L. (2019). *Lithium-Ion Vehicle Battery Production - Status 2019 on Energy Use, CO2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling*. IVL Svenska Miljöinstitutet. https://urn.kb.se/resolve?urn=urn:nbn:se:ivl:diva-132

Engels, P., Cerdas, F., Dettmer, T., Frey, C., Hentschel, J., Herrmann, C., Mirfabrikikar, T., & Schueler, M. (2022). Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data. *Journal of Cleaner Production*, *336*. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.130474.

Engineering, M. (2009). *Metals recovered from mine water provide new revenue stream*.

euronews. (2022, 2022/02/01/). *South America's 'lithium fields' reveal the dark side of electric cars*. https://www.euronews.com/green/2022/02/01/south-america-s-lithium-fields-reveal-the-dark-side-of-our-electric-future

Falcon Energy Materials, P. D. A. U. L. (2025). *Technical Report on the Natural Graphite Active Anode Integrated Global Strategy Preliminary Economic Assessment*.

Fallah, N., & Fitzpatrick, C. (2023). Is shifting from Li-ion NMC to LFP in EVs beneficial for second-life storages in electricity markets? *Journal of Energy Storage*, *68*, 107740. https://doi.org/10.1016/j.est.2023.107740

Fallah, N., Fitzpatrick, C., Killian, S., & Johnson, M. (2021). End-of-Life Electric Vehicle Battery Stock Estimation in Ireland through Integrated Energy and Circular Economy Modelling. *Resources, Conservation and Recycling*, *174*, 105753. https://doi.org/10.1016/j.resconrec.2021.105753

Fantke, P., Huang, L., Overcash, M., Griffing, E., & Jolliet, O. (2020). Life cycle based alternatives assessment (LCAA) for chemical substitution. *Green Chemistry*, *22*(18), 6008-6024. https://doi.org/https://doi.org/10.1039/d0gc01544j

Fastmarkets. (2022). *Rising synthetic graphite costs may push battery makers to rely on natural material - Fastmarkets*. https://www.fastmarkets.com/insights/rising-synthetic-graphite-costs-may-push-battery-makers-to-rely-on-natural-material

Fischer, S., Doose, S., Müller, J., Höfels, C., & Kwade, A. (2023). Impact of Spheroidization of Natural Graphite on Fast-Charging Capability of Anodes for LIB. *Batteries*, *9*(6). https://doi.org/https://doi.org/10.3390/batteries9060305

Flexer, V., Baspineiro, C. F., & Galli, C. I. (2018). Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. *Sci Total Environ*, *639*, 1188-1204. https://doi.org/10.1016/j.scitotenv.2018.05.223

Gaines, L. (2018). Lithium-ion battery recycling processes: Research towards a sustainable course. *Sustainable Materials and Technologies*, *17*(C). https://doi.org/10.1016/j.susmat.2018.e00068

Gaines, L., Sullivan, J., & Burnham, A. (2011). *Paper No. 11-3891 Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling* (Transportation Research Board 90th Annual Meeting, Washington, DC, Issue. https://www.researchgate.net/publication/265158823_Paper_No_11-3891_Life-Cycle_Analysis_for_Lithium-Ion_Battery_Production_and_Recycling

Gao, S. W., Gong, X. Z., Liu, Y., & Zhang, Q. Q. (2018). Energy Consumption and Carbon Emission Analysis of Natural Graphite Anode Material for Lithium Batteries. *Materials Science Forum*, *913*, 985-990. https://doi.org/https://doi.org/10.4028/www.scientific.net/MSF.913.985

Gao, T.-m., Fan, N., Chen, W., & Dai, T. (2023). Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. *China Geology*, *6*(1), 137-153. https://doi.org/10.31035/cg2022088

Garcia, J. C., Bareño, J., Yan, J., Chen, G., Hauser, A., Croy, J. R., & Iddir, H. (2017). Surface Structure, Morphology, and Stability of Li(Ni1/3Mn1/3Co1/3)O2 Cathode Material. *The Journal of Physical Chemistry C*, *121*(15), 8290-8299. https://doi.org/10.1021/acs.jpcc.7b00896

German-AAI. (2023). *Product Carbon Footprint of Nickel Sulfate Hexahydrate Production* (German Association of the Automotive Industry Issue. https://www.minviro.com/resources/guides/vda-results-nickel-sulfate-hexahydrate

Glencore. (2026). *Raglan Quebec Mining Site*. https://www.glencore.ca/en/raglan/what-we-do/our-mining-activity

Global_Battery_Alliance. (2019). *A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation* (World Economic Forum, Issue. https://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf

GM-News. (2023). *Driving Electric Vehicles for Good | General Motors*. Retrieved 2023-10-17 from https://www.gm.com/public/us/en/gm/home/stories/evs-for-good.html

GM-News. (2024). *General Motors and POSCO Future M Welcome Québec and Canada Government Support For Bécancour CAM Project to Develop the EV Battery Supply Chain in North America*. https://news.gm.ca/public/ca/en/gm/home/newsroom.detail.html/Pages/news/ca/en/2023/may/0529_posco-announcement.html

Gohlke, D., Zhou, Y., Wu, X., & Courtney, C. (2021). *Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010 – 2020* (Argonne National Labaratory, Issue. https://publications.anl.gov/anlpubs/2021/06/167626.pdf

Gong, Z., & Yang, Y. (2011). Recent advances in the research of polyanion-type cathode materials for Li-ion batteries. *Energy & Environmental Science*, *4*(9), 3223-3242. https://doi.org/10.1039/C0EE00713G

Gonzales-Calienes, G., Kannangara, M., & Bensebaa, F. (2023). Economic and Environmental Viability of Lithium-Ion Battery Recycling—Case Study in Two Canadian Regions with Different Energy Mixes. *Batteries*, *9*(7), 375. https://doi.org/10.3390/batteries9070375

Gorachinova, E., & Wolfe, D. A. (2023). New Path Development in a Semi-peripheral Auto Region: The Case of Ontario. *Economic Geography*, *0*(0), 1-22. https://doi.org/10.1080/00130095.2023.2212902

Gorman, S., Hitt, C., Kesler, S., Keoleian, G., Kim, H. C., De Kleine, R., & Anderson, J. E. (2025). US graphite sourcing for electric vehicle battery applications. *Journal of Industrial Ecology*, *29*(6), 2162-2181. https://doi.org/10.1111/jiec.70104

Government_Canada. (2025a). *The Canadian Critical Minerals Strategy*. Retrieved 2025/05/20 from https://www.canada.ca/en/campaign/critical-minerals-in-canada/canadian-critical-minerals-strategy.html

Government_Canada. (2025b). *Graphite facts - Natural Resources Canada*. Retrieved 2025/05/20 from https://natural-resources.canada.ca/minerals-mining/mining-data-statistics-analysis/minerals-metals-facts/graphite-facts

Government_Canada. (2026). *Nickel Facts*. Retrieved 2026/01/22 from https://natural-resources.canada.ca/minerals-mining/mining-data-statistics-analysis/minerals-metals-facts/nickel-facts

Greenwood, M., Wentker, M., & Leker, J. (2021). A region-specific raw material and lithium-ion battery criticality methodology with an assessment of NMC cathode technology. *Applied Energy*, *302*, 117512. https://doi.org/10.1016/j.apenergy.2021.117512

Grimm, V., Malmendier, U., Schnitzer, M., Truger, A., & Werding, M. (2023). *The Inflation Reduction Act: Is the new U.S. industrial policy a threat to europe?* (German Council of Economic Experts, Issue. https://www.sachverstaendigenrat-wirtschaft.de/fileadmin/dateiablage/PolicyBrief/Policy_Brief_2023_01_ENG.pdf

Gu, X., Bai, H., Cui, X., Zhu, J., Zhuang, W., Li, Z., Hu, X., & Song, Z. (2024). Challenges and opportunities for second-life batteries: Key technologies and economy. *Renewable and Sustainable Energy Reviews*, *192*, 114191. https://doi.org/10.1016/j.rser.2023.114191

Guinee, J. B. (2002). *Handbook_on_Life_Cycle_Assessment*. Klumer Academic Publishers. https://doi.org/10.1007/978-1-4020-0228-1

Gutsch, M., & Leker, J. (2024). Costs, carbon footprint, and environmental impacts of lithium-ion batteries – From cathode active material synthesis to cell manufacturing and recycling. *Applied Energy*, *353*. https://doi.org/10.1016/j.apenergy.2023.122132

Guzman-Anaya, L. (2023). Challenges to Mexico's Automotive Industry. The USMCA, COVID-19, and Electric Vehicle Production. In L. Guzman-Anaya (Ed.), *Japanese Cooperation and Supporting Industry in Mexico's Automotive Sector: USMCA, Covid-19 Disruptions, and Electric Vehicle Production* (pp. 1-5). Springer Nature. https://doi.org/10.1007/978-981-99-3985-5_1

Han, M., & Li, P. (2025). Harmonizing critical mineral resources with storage-integrated renewable energy transition in China. *Energy Conversion and Management*, *333*. https://doi.org/10.1016/j.enconman.2025.119785

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. . (2018). *Life cycle assessment: Theory and practice*. Springer. https://doi.org/10.1007/978-3-319-56475-3

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2012). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, *17*(1), 53-64. https://doi.org/10.1111/j.1530-9290.2012.00532.x

Hawley, W. B., Li, M., & Li, J. (2023). Room-Temperature Eutectic Synthesis for Upcycling of Cathode Materials. *Batteries*, *9*(10), 498. https://doi.org/10.3390/batteries9100498

Heenan, T. M. M., Wade, A., Tan, C., Parker, J. E., Matras, D., Leach, A. S., Robinson, J. B., Llewellyn, A., Dimitrijevic, A., Jervis, R., Quinn, P. D., Brett, D. J. L., & Shearing, P. R. (2020). Identifying the Origins of Microstructural Defects Such as Cracking within Ni-Rich NMC811 Cathode Particles for Lithium-Ion Batteries. *Advanced Energy Materials*, *10*(47), 2002655. https://doi.org/10.1002/aenm.202002655

Hu, J., Wang, H., Xiao, B., Liu, P., Huang, T., Li, Y., Ren, X., Zhang, Q., Liu, J., Ouyang, X., & Sun, X. (2023). Challenges and approaches of single-crystal Ni-rich layered cathodes in lithium batteries. *National Science Review*, *10*(12), nwad252. https://doi.org/10.1093/nsr/nwad252

Hu, J., Wang, Q., Wu, B., Tan, S., Shadike, Z., Bi, Y., Whittingham, M. S., Xiao, J., Yang, X.-Q., & Hu, E. (2021). Fundamental Linkage Between Structure, Electrochemical Properties, and Chemical Compositions of LiNi1–x–yMnxCoyO2 Cathode Materials. *ACS Applied Materials & Interfaces*, *13*(2), 2622-2629. https://doi.org/10.1021/acsami.0c18942

Hu, M., Pang, X., & Zhou, Z. (2013). Recent progress in high-voltage lithium ion batteries. *Journal of Power Sources*, *237*, 229-242. https://doi.org/10.1016/j.jpowsour.2013.03.024

Huang, T.-Y., Pérez-Cardona, J. R., Zhao, F., Sutherland, J. W., & Paranthaman, M. P. (2021). Life Cycle Assessment and Techno-Economic Assessment of Lithium Recovery from Geothermal Brine. *ACS Sustainable Chemistry & Engineering*, *9*(19), 6551-6560. https://doi.org/10.1021/acssuschemeng.0c08733

Hydro-Québec. (2023). *GHG Emission Rate Associated with Residual Electricity Supplies, 1990–2023*. https://www.hydroquebec.com/data/developpement-durable/pdf/hq-ghg-emission-rate-1990-2023.pdf

Hydro-Québec. (2025). *Québec hydropower: clean, renewable and low in GHG emissions*. https://www.hydroquebec.com/about/our-energy.html

Hydrofluoric Acid vs Hydrogen Fluoride: Detailed Comparison and Applications. (2024). https://rawsource.com/hydrofluoric-acid-vs-hydrogen-fluoride-detailed-comparison-and-applications

Hydrofluoric Acid vs. Hydrogen Fluoride – What's the Difference? (2025). https://thisvsthat.io/hydrofluoric-acid-vs-hydrogen-fluoride

Ibarra-Gutiérrez, S., Bouchard, J., Laflamme, M., & Fytas, K. (2021). Assessing the potential of quebec lithium industry: Mineral reserves, lithium-ion batteries production and greenhouse gas emissions. *Resources Policy*, *74*. https://doi.org/https://doi.org/10.1016/j.resourpol.2021.102371.

IBAT. (2024). *What Are The Sources For Lithium?* Retrieved 2023/10/03/13:03:21 from https://www.ibatterymetals.com/lithium-market

icct. (2024, 2024). *International Council on Clean Transportation,*. Retrieved 2024/01/11/21:30:24 from https://theicct.org/

IEA. (2020, 2020). *Global EV Outlook*. Retrieved 2024-10-24 from https://www.iea.org/reports/global-ev-outlook-2

IEA. (2021, 2021). *The role of critical minerals in clean energy transitions*. Retrieved 2024/06/29 from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

IEA. (2023). *Electric car sales, 2016-2023 – Charts – Data & Statistics*. Retrieved 2024/06/29 from https://www.iea.org/data-and-statistics/charts/electric-car-sales-2016-2023

IEA. (2024). *Graphite Outlook for key transition minerals*. Retrieved 2024/06/29 from https://www.iea.org/reports/graphite

Insidexploration. (2023, 2023/03/07/T16:03:03+00:00). *Zero Waste & Low Energy Lithium Processing Provisional Patent Filed & Proposed Plant Engineering Study Initiated*. https://insidexploration.com/zero-waste-low-energy-lithium-processing-provisional-patent-filed-proposed-plant-engineering-study-initiated/

Iriyama, Y., Kurita, H., Yamada, I., Abe, T., & Ogumi, Z. (2004). Effects of surface modification by MgO on interfacial reactions of lithium cobalt oxide thin film electrode. *Journal of Power Sources*, *137*(1), 111-116. https://doi.org/10.1016/j.jpowsour.2004.05.029

ISO. (2006a). *ISO 14040:2006*
Environmental management — Life cycle assessment — Principles and framework. ISO. https://www.iso.org/standard/37456.html

ISO. (2006b). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. https://www.iso.org/standard/37456.html

ISO. (2006c). *ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines*. https://www.iso.org/standard/38498.html

ISO. (2024). *Global EV Outlook 2024*. Retrieved 2024/06/29 from https://www.iea.org/reports/global-ev-outlook-2024

Issa, M., Ilinca, A., Rousse, D. R., Boulon, L., & Groleau, P. (2023). Renewable Energy and Decarbonization in the Canadian Mining Industry: Opportunities and Challenges. *Energies*, *16*(19), 6967. https://doi.org/10.3390/en16196967

Iyer, R., Dai, Q., & Kelly, J. (2023). *Nickel Life Cycle Analysis and Additions in the GREET® Model* (Argonne National Laboratory, Issue. https://www.researchgate.net/publication/377111891_Nickel_Life_Cycle_Analysis_Update_and_Additions_in_the_GREET_Model_Rev_1

Jacob, M., Wissel, K., & Clemens, O. (2024). Recycling of solid-state batteries—challenge and opportunity for a circular economy? *Materials Futures*, *3*(1), 012101. https://doi.org/10.1088/2752-5724/acfb28

Jannesar Niri, A., Poelzer, G. A., Zhang, S. E., Rosenkranz, J., Pettersson, M., & Ghorbani, Y. (2024). Sustainability challenges throughout the electric vehicle battery value chain. *Renewable and Sustainable Energy Reviews*, *191*, 114176. https://doi.org/10.1016/j.rser.2023.114176

Jin, H., Kim, C., Park, S.-M., An, J.-C., Yang, I., & Choi, D. (2025). Coal tar-coated artificial graphite anode derived from polyethylene for lithium-ion batteries. *Carbon Letters*, *35*(3), 1259-1270. https://doi.org/10.1007/s42823-024-00855-6

Jones, B., Nguyen-Tien, V., & Elliott, R. J. R. (2023). The electric vehicle revolution: Critical material supply chains, trade and development. *The World Economy*, *46*(1), 2-26. https://doi.org/https://doi.org/10.1111/twec.13345

Jones, B., Nguyen-Tien, V., & Elliott, R. J. R. (2022). The electric vehicle revolution: Critical material supply chains, trade and development. *The World Economy*, *46*(1), 2-26. https://doi.org/10.1111/twec.13345

Julien, C. M., & Mauger, A. (2024). Fabrication of Li(4)Ti(5)O(12) (LTO) as Anode Material for Li-Ion Batteries. *Micromachines (Basel)*, *15*(3). https://doi.org/10.3390/mi15030310

Julien, C. M., Mauger, A., Zaghib, K., & Groult, H. (2014). Comparative Issues of Cathode Materials for Li-Ion Batteries. *Inorganics*, *2*(1), 132-154. https://doi.org/10.3390/inorganics2010132

Jung, R., Metzger, M., Maglia, F., Stinner, C., & Gasteiger, H. A. (2017). Oxygen Release and Its Effect on the Cycling Stability of LiNixMnyCozO2 (NMC) Cathode Materials for Li-Ion Batteries. *Journal of The Electrochemical Society*, *164*(7), A1361. https://doi.org/10.1149/2.0021707jes

Kaboli, S., Demers, H., Paolella, A., Darwiche, A., Dontigny, M., Clément, D., Guerfi, A., Trudeau, M. L., Goodenough, J. B., & Zaghib, K. (2020). Behavior of Solid Electrolyte in Li-Polymer Battery with NMC Cathode via in-Situ Scanning Electron Microscopy. *Nano Letters*, *20*(3), 1607-1613. https://doi.org/10.1021/acs.nanolett.9b04452

Kadivar, S., Sharifian, S., & Vahidi, E. (2025). Natural, synthetic, or recycled? A life cycle and techno-economic analysis of battery-grade graphite production. *J Environ Manage*, *395*, 127747. https://doi.org/https://doi.org/10.1016/j.jenvman.2025.127747

Kampker, A., Heimes, H. H., Offermanns, C., Vienenkötter, J., & Robben, T. (2023). Framework and Classification of Battery System Architectures. *World Electric Vehicle Journal*, *14*(4), 88. https://doi.org/10.3390/wevj14040088

Kaur, G., & Gates, B. D. (2022). Review—Surface Coatings for Cathodes in Lithium Ion Batteries: From Crystal Structures to Electrochemical Performance. *Journal of The Electrochemical Society*, *169*(4). https://doi.org/10.1149/1945-7111/ac60f3

Kazyak, E., Chen, K. H., Chen, Y., Cho, T. H., & Dasgupta, N. P. (2021). Enabling 4C Fast Charging of Lithium-Ion Batteries by Coating Graphite with a Solid-State Electrolyte. *Advanced Energy Materials*, *12*(1). https://doi.org/https://doi.org/10.1002/aenm.202102618

Kellen. (2020). SP's 1st Quarter Meeting of 2020 Held at Honda of Alabama. *Suppliers Partnership for the Environment*. https://www.supplierspartnership.org/meetings/sps-1st-quarter-meeting-of-2020-held-at-honda-of-alabama/

Kelly, J. C., Dai, Q., & Wang, M. (2020). Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. *Mitigation and Adaptation Strategies for Global Change*, *25*(3), 371-396. https://doi.org/10.1007/s11027-019-09869-2

Kelly, J. C., Wang, M., Dai, Q., & Winjobi, O. (2021). Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. *Resources, Conservation and Recycling*, *174*. https://doi.org/10.1016/j.resconrec.2021.105762

Kendall, A., Slattery, M., & Dunn, J. (2024). End of Life EV Battery Policy Simulator: A dynamic systems, mixed-methods approach. https://doi.org/10.7922/G2BZ64DC

Khaleel, M., Nassar, Y., El-Khozondar, H. J., Elmnifi, M., Rajab, Z., Yaghoubi, E., & Yaghoubi, E. (2024). Electric Vehicles in China, Europe, and the United States: Current Trend and Market Comparison. *Int. J. Electr. Eng. and Sustain.*, 1-20. https://ijees.org/index.php/ijees/article/view/70

Kiemel, S., Glöser-Chahoud, S., Waltersmann, L., Schutzbach, M., Sauer, A., & Miehe, R. (2021). Assessing the Application-Specific Substitutability of Lithium-Ion Battery Cathode Chemistries Based on Material Criticality, Performance, and Price. *Resources*, *10*(9), 87. https://doi.org/10.3390/resources10090087

Kim, J., & Amine, K. (2002). A comparative study on the substitution of divalent, trivalent and tetravalent metal ions in LiNi1−xMxO2 (M = Cu2+, Al3+ and Ti4+). *Journal of Power Sources*, *104*(1), 33-39. https://doi.org/10.1016/S0378-7753(01)00900-4

Kim, J., Lee, H., Cha, H., Yoon, M., Park, M., & Cho, J. (2018). Prospect and Reality of Ni-Rich Cathode for Commercialization. *Advanced Energy Materials*, *8*(6), 1702028. https://doi.org/10.1002/aenm.201702028

Kinnunen, P., Riihimäki, T., Kinnunen, K., Salo, M., Heikola, T., & Mäkinen, J. (2024). Process Design for Direct Production of Battery Grade Nickel Sulfate. *Journal of Sustainable Metallurgy*, *10*(3), 1369-1379. https://doi.org/10.1007/s40831-024-00864-9

Klier, T. H., & Rubenstein, J. M. (2022). North America's rapidly growing electric vehicle market: Implications for the geography of automotive production. *Economic Perspectives*. https://doi.org/10.21033/ep-2022-5

Kolahchian Tabrizi, M., Bonalumi, D., & Lozza, G. G. (2024). Analyzing the global warming potential of the production and utilization of lithium-ion batteries with nickel-manganese-cobalt cathode chemistries in European Gigafactories. *Energy*, *288*. https://doi.org/10.1016/j.energy.2023.129622

Kraft, L., Zünd, T., Schreiner, D., Wilhelm, R., Günter, F. J., Reinhart, G., Gasteiger, H. A., & Jossen, A. (2021). Comparative Evaluation of LMR-NCM and NCA Cathode Active Materials in Multilayer Lithium-Ion Pouch Cells: Part II. Rate Capability, Long-Term Stability, and Thermal Behavior. *Journal of The Electrochemical Society*, *168*(2), 020537. https://doi.org/10.1149/1945-7111/abe5e6

Kulkarni, S., Huang, T.-Y., Thapaliya, B. P., Luo, H., Dai, S., & Zhao, F. (2022). Prospective Life Cycle Assessment of Synthetic Graphite Manufactured via Electrochemical Graphitization. *ACS Sustainable Chemistry & Engineering*, *10*(41), 13607-13618. https://doi.org/https://doi.org/10.1021/acssuschemeng.2c02937

Lähde, A., Välikangas, J., Meščeriakovas, A., Karhunen, T., Meščeriakovė, S.-M., Sippula, O., Leinonen, S., Lassi, U., & Jokiniemi, J. (2024). Effect of high temperature thermal treatment on the electrochemical performance of natural flake graphite. *Journal of Materials Research*, *39*(6), 944-954. https://doi.org/https://doi.org/10.1557/s43578-024-01282-z

Lampert, D. J., Cai, H., & Elgowainy, A. (2016). Wells to wheels: water consumption for transportation fuels in the United States. *Energy & Environmental Science*, *9*(3), 787-802. https://doi.org/10.1039/C5EE03254G

Lee, K. K., Yoon, W. S., Kim, K. B., Lee, K. Y., & Hong, S. T. (2001). Characterization of LiNi0.85Co0.10M0.05O2 (M = Al, Fe) as a cathode material for lithium secondary batteries. *Journal of Power Sources*, *97-98*, 308-312. https://doi.org/10.1016/S0378-7753(01)00516-X (Proceedings of the 10th International Meeting on Lithium Batteries)

Lewrén, A. (2019). Life cycle assessment of nickel-rich lithium-ion battery for electric vehicles A comparatative LCA between the cathode chemistries NMC 333 and NMC 622. https://hdl.handle.net/20.500.12380/300644

Li, M., & Lu, J. (2020). Cobalt in lithium-ion batteries. *Science*, *367*(6481), 979-980. https://doi.org/10.1126/science.aba9168

Li, S., Chai, Z., Wang, Z., Tai, C.-W., Zhu, J., Edström, K., & Ma, Y. (2023). A Multiscale, Dynamic Elucidation of Li Solubility in the Alloy and Metallic Plating Process. *Advanced Materials*, *35*(47), 2306826. https://doi.org/10.1002/adma.202306826

Li, T., Yuan, X.-Z., Zhang, L., Song, D., Shi, K., & Bock, C. (2020). Degradation Mechanisms and Mitigation Strategies of Nickel-Rich NMC-Based Lithium-Ion Batteries. *Electrochemical Energy Reviews*, *3*(1), 43-80. https://doi.org/10.1007/s41918-019-00053-3

Li, W., Lee, S., & Manthiram, A. (2020). High-Nickel NMA: A Cobalt-Free Alternative to NMC and NCA Cathodes for Lithium-Ion Batteries. *Adv Mater*, *32*(33), e2002718. https://doi.org/10.1002/adma.202002718

Li, X., Ren, Z., Norouzi Banis, M., Deng, S., Zhao, Y., Sun, Q., Wang, C., Yang, X., Li, W., Liang, J., Li, X., Sun, Y., Adair, K., Li, R., Hu, Y., Sham, T.-K., Huang, H., Zhang, L., Lu, S.,…Sun, X. (2019). Unravelling the Chemistry and Microstructure Evolution of a Cathodic Interface in Sulfide-Based All-Solid-State Li-Ion Batteries. *ACS Energy Letters*, *4*(10), 2480-2488. https://doi.org/10.1021/acsenergylett.9b01676

Li, Y. Z., & Mungall, J. E. (2022). Chalcophile element heterogeneity in Ni-Cu-(platinum group element) orebodies of Raglan Horizon in Cape Smith Belt; implications for ore-forming processes. *Economic Geology and the Bulletin of the Society of Economic Geologists*, *117*(5), 1131-1148. https://doi.org/10.5382/econgeo.4909

Liu, C., Li, Y., Lin, D., Hsu, P.-C., Liu, B., Yan, G., Wu, T., Cui, Y., & Chu, S. (2020). Lithium Extraction from Seawater through Pulsed Electrochemical Intercalation. *Joule*, *4*(7), 1459-1469. https://doi.org/10.1016/j.joule.2020.05.017

Liu, H., & Azimi, G. (2022). Production of Battery Grade Lithium Hydroxide Monohydrate Using Barium Hydroxide Causticizing Agent. *Resources, Conservation and Recycling*, *179*. https://doi.org/10.1016/j.resconrec.2021.106115

Liu, X., Yin, H., Zhao, J., Guo, Z., Liu, Z., & Sang, Y. (2021). Understanding the coagulation mechanism and floc properties induced by Fe(VI) and FeCl(3): population balance modeling. *Water Sci Technol*, *83*(10), 2377-2388. https://doi.org/10.2166/wst.2021.150

Liu, Y., Zhang, R., Wang, J., & Wang, Y. (2021). Current and future lithium-ion battery manufacturing. *iScience*, *24*(4), 102332. https://doi.org/10.1016/j.isci.2021.102332

Livent_Nemaska_Lithium. (2023). *Livent Sec Technical Report Summary Pre-Feasibility Study on the Whabouchi Mine Nemasaka, Quebec*. https://www.costmine.com/wp-content/uploads/2023/11/Whabouchi.pdf

LME. (2025). *LME Lithium Hydroxide Monohydrate*. https://www.lme.com/en/Metals/EV/LME-Lithium-Hydroxide-CIF-Fastmarkets-MB/Contract-specifications

Long, B. R., Rinaldo, S. G., Gallagher, K. G., Dees, D. W., Trask, S. E., Polzin, B. J., Jansen, A. N., Abraham, D. P., Bloom, I., Bareño, J., & Croy, J. R. (2016). Enabling High-Energy, High-Voltage Lithium-Ion Cells: Standardization of Coin-Cell Assembly, Electrochemical Testing, and Evaluation of Full Cells. *Journal of The Electrochemical Society*, *163*(14), A2999. https://doi.org/10.1149/2.0691614jes

Lu, L., Han, X., Li, J., Hua, J., & Ouyang, M. (2013). A review on the key issues for lithium-ion battery management in electric vehicles. *Journal of Power Sources*, *226*, 272-288. https://doi.org/10.1016/j.jpowsour.2012.10.060

Ma, F., Wu, Y., Wei, G., Qiu, S., & Qu, J. (2019). Enhanced electrochemical performance of $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ cathode via wet-chemical coating of MgO. *Journal of Solid State Electrochemistry*, *23*(7), 2213-2224. https://doi.org/10.1007/s10008-019-04308-3

Mahmoud, U. A. A. G. a. A. A. (2019). Comparison Between Different Types of Chemical Coagulants Used In Water Purification. *Engineering Research Journal*, *Vol. 1*(No. 41), 89-93. https://doi.org/10.21608/erjsh.2019.288241

Maisel, F., Neef, C., Marscheider-Weidemann, F., & Nissen, N. F. (2023). A forecast on future raw material demand and recycling potential of lithium-ion batteries in electric vehicles. *Resources, Conservation and Recycling*, *192*. https://doi.org/10.1016/j.resconrec.2023.106920

Malik, M., Chan, K. H., & Azimi, G. (2022). Review on the synthesis of LiNixMnyCo1-x-yO2 (NMC) cathodes for lithium-ion batteries. *Materials Today Energy*, *28*. https://doi.org/10.1016/j.mtener.2022.101066

Mao, Y., Wang, X., Xia, S., Zhang, K., Wei, C., Bak, S., Shadike, Z., Liu, X., Yang, Y., Xu, R., Pianetta, P., Ermon, S., Stavitski, E., Zhao, K., Xu, Z., Lin, F., Yang, X.-Q., Hu, E., & Liu, Y. (2019). High-Voltage Charging-Induced Strain, Heterogeneity, and Micro-Cracks in Secondary Particles of a Nickel-Rich Layered Cathode Material. *Advanced Functional Materials*, *29*(18), 1900247. https://doi.org/10.1002/adfm.201900247

Marchese, D., Giosuè, C., Staffolani, A., Conti, M., Orcioni, S., Soavi, F., Cavalletti, M., & Stipa, P. (2024). An Overview of the Sustainable Recycling Processes Used for Lithium-Ion Batteries. *Batteries*, *10*(1), 27. https://doi.org/10.3390/batteries10010027

Markets, R. a. (2026). *Nickel Sulfate for EV Battery Market - Global Forecast 2026-2032*. https://www.researchandmarkets.com/reports/6127670/nickel-sulfate-ev-battery-market-global

Marks, T., Trussler, S., Smith, A. J., Xiong, D., & Dahn, J. R. (2010). A Guide to Li-Ion Coin-Cell Electrode Making for Academic Researchers. *Journal of The Electrochemical Society*, *158*(1), A51. https://doi.org/10.1149/1.3515072

Mayyas, A., Moawad, K., Chadly, A., & Alhseinat, E. (2023). Can circular economy and cathode chemistry evolution stabilize the supply chain of Li-ion batteries? *The Extractive Industries and Society*, *14*. https://doi.org/10.1016/j.exis.2023.101253

McClelland, I., Booth, S. G., Anthonisamy, N. N., Middlemiss, L. A., Pérez, G. E., Cussen, E. J., Baker, P. J., & Cussen, S. A. (2023). Direct Observation of Dynamic Lithium Diffusion Behavior in Nickel-Rich, LiNi0.8Mn0.1Co0.1O2 (NMC811) Cathodes Using Operando Muon Spectroscopy. *Chemistry of Materials*, *35*(11), 4149-4158. https://doi.org/10.1021/acs.chemmater.2c03834

McGovern, M. E., Bruder, D. D., Huemiller, E. D., Rinker, T. J., Bracey, J. T., Sekol, R. C., & Abell, J. A. (2023). A review of research needs in nondestructive evaluation for quality verification in electric vehicle lithium-ion battery cell manufacturing. *Journal of Power Sources*, *561*. https://doi.org/10.1016/j.jpowsour.2023.232742

Meron, N., Blass, V., & Thoma, G. (2020). Selection of the most appropriate life cycle inventory dataset: new selection proxy methodology and case study application. *The International Journal of Life Cycle Assessment*, *25*(4), 771-783. https://doi.org/https://doi.org/10.1007/s11367-019-01721-8

Microlit. (2023). *Uses and Industrial Applications of Hydrofluoric Acid*. https://www.microlit.us/uses-and-industrial-applications-of-hydrofluoric-acid

Mining. (2024). *The five largest nickel mines in operation in Canada*. https://www.mining-technology.com/marketdata/five-largest-nickel-mines-canada/

Mining_Market_Watch. (2025). *Mining Market Watch Graphite*. https://miningmarketwatch.net/graphite.htm

Mistry, M., Gediga, J., & Boonzaier, S. (2016). Life cycle assessment of nickel products. *The International Journal of Life Cycle Assessment*, *21*(11), 1559-1572. https://doi.org/10.1007/s11367-016-1085-x

Mizushima, K., Jones, P. C., Wiseman, P. J., & Goodenough, J. B. (1981). LixCoO2 (0. *Solid State Ionics*, *3-4*, 171-174. https://doi.org/10.1016/0167-2738(81)90077-1

Mohammadi, F., & Saif, M. (2023). A comprehensive overview of electric vehicle batteries market. *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, *3*. https://doi.org/10.1016/j.prime.2023.100127

Moloughney, T. (2023). *What's The Real World Highway Range Of Today's Electric Cars? We Test To Find Out*. https://insideevs.com/reviews/443791/ev-range-test-results/

Moores, S. (2021, 2021). *THE GLOBAL BATTERY ARMS RACE: LITHIUM-ION BATTERY GIGAFACTORIES AND THEIR SUPPLY CHAIN*. Retrieved 2024/05/22 from https://www.readkong.com/page/the-global-battery-arms-race-lithium-ion-battery-6236059

Mordo_Intelligence. (2026). *Graphite Market Size & Share Analysis - Growth Trends and Forecast (2026 - 2031)*. Retrieved January 31, 2026 from https://www.mordorintelligence.com/industry-reports/graphite-market

Morris, C. (2023). Ford signs lithium and nickel deals to secure IRA-compliant supply. *Charged EVs*. https://chargedevs.com/newswire/ford-signs-lithium-and-nickel-deals-to-secure-ira-compliant-supply/

Munk, L. A., Hynek, S. A., Bradley, D. C., Boutt, D., Labay, K., & Jochens, H. (2016). Lithium Brines: A Global Perspective. In P. L. Verplanck & M. W. Hitzman (Eds.), *Rare Earth and Critical Elements in Ore Deposits* (Vol. 18, pp. 0). Society of Economic Geologists. https://doi.org/10.5382/Rev.18.14

Nagmani, Pahari, D., Tyagi, A., & Puravankara, D. S. (2022). Lithium-Ion Battery Technologies for Electric Mobility – State-of-the-Art Scenario. *ARAI Journal of Mobility Technology*, *2*(2), 233-248. https://doi.org/10.37285/ajmt.1.2.10

Natural-Resources-Canada. (2023, 2023/03/09/). *Cobalt facts*. https://natural-resources.canada.ca/our-natural-resources/minerals-mining/mining-data-statistics-and-analysis/minerals-metals-facts/cobalt-facts/24981

Naz, B. (2024). Proposal of New Solid-State Battery Denser and Safer.

Nemasaka_Lithium. (2022). *Chaptre 1 Resume executif*. https://nemaskalithium.com/wp-content/uploads/2025/05/ffead2805-nli-ees-resumeexecutif.pdf

Nemasaka_Lithium. (2023a). *Usine de production d'hydroxyde de lithium a Becancour Evaluation environnementale et sociale Volume 1, chapitres 1 a 6*. https://nemaskalithium.com/wp-content/uploads/2025/05/nli-ees-vol-1-chap-1-a-6-ed-octobre-2023.pdf

Nemasaka_Lithium. (2023b). *Usine de production d'hydroxyde de lithium a Becancour Evaluation environnementale et sociale Volume 1, chapitres 7 a 15*. https://nemaskalithium.com/wp-content/uploads/2025/05/nli-ees-vol-2-chap-7-a-15-ed-octobre-2023.pdf

Nemaska_Lithium. (2019). *NI 43-101 Technical Report Report on the Esimate to Complete for the Whabouchi Lithium Mine and Shawinigan Electrochemical Plant Nemaska Project*. https://minedocs.com/22/Whabouchi-TR-05312019.pdf

Neshat, N., Kaya, M., & Ghaboulian Zare, S. (2023). Exploratory policy analysis for electric vehicle adoption in European countries: A multi-agent-based modelling approach. *Journal of Cleaner Production*, *414*, 137401. https://doi.org/10.1016/j.jclepro.2023.137401

Nickel-Institute. (2024). *Life Cycle Data Executive Summary*. N. Institute. https://nickelinstitute.org/media/r5wn5u4j/2025-lifecycledata-executive-summary.pdf

Nickel_Institute. (2020). *Life Cycle Assessment of Nickel Products Reference year 2017 Final Report*. N. Institute. https://nickelinstitute.org/en/sustainability/nickel-life-cycle-management/nickel-life-cycle-data/

Nie, K., Hong, Y., Qiu, J., Li, Q., Yu, X., Li, H., & Chen, L. (2018). Interfaces Between Cathode and Electrolyte in Solid State Lithium Batteries: Challenges and Perspectives. *Frontiers in Chemistry*, *6*. https://www.frontiersin.org/articles/10.3389/fchem.2018.00616

NIOSH. (2017). *Hydrogen Fluoride Hydrofluoric Acid. National Institute for Occupational Safety and Health.* (National Institute for Occupational Safety and Health, Issue. https://www.cdc.gov/niosh/npg/npgd0334.html

Nisa, S. S., Rahmawati, M., Yudha, C. S., Nilasary, H., Nursukatmo, H., Oktaviano, H. S., Muzayanha, S. U., & Purwanto, A. (2022). A Fast Approach to Obtain Layered Transition-Metal Cathode Material for Rechargeable Batteries. *Batteries*, *8*(1), 4. https://doi.org/10.3390/batteries8010004

Niu, B., Xu, H., & Mu, Z. (2024). To divide or not to divide: Impact of carbon market connections on firms' resilient profitability and emission reduction. *International Journal of Production Economics*, *270*, 109167. https://doi.org/10.1016/j.ijpe.2024.109167

Notter, D. A., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., & Althaus, H.-J. (2010). Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles. *Environmental Science & Technology*, *44*(17), 6550-6556. https://doi.org/10.1021/es903729a

Nouveaux_Monde_Graphite. (2022). *NI 43-101 Technical Feasibility Study Report for The Matawinie Mine and the Becancour Battery Material Plant Integrated Graphite Projects; Quebec, Canada*. https://nmg.com/integrated-feasibility-study/

Nouveaux_Monde_Graphite. (2023a). *Graphite 101 Powering The Clean Energy Transition*. https://nmg.com/wp-content/uploads/2023/06/NMG-Graphite-101.pdf

Nouveaux_Monde_Graphite. (2023b). NI-43-101_January_2023_Technical Report.pdf. https://nmg.com/wp-content/uploads/2023/02/PEA-Uatnan-Mining-Project.pdf

Nouveaux_Monde_Graphite. (2025). *NI 43-101 Updated Technical Feasibility Study Report for The Matawinie Mine and the Becancour Battery Material Plant Integrated Graphite Projects; Quebec, Canada*. https://nmg.com/wp-content/uploads/2025/03/NMG-2025-Updated-Feasibility-Study.pdf

NRC. (2018, 2018/01/23/). *Nickel facts*. https://natural-resources.canada.ca/our-natural-resources/minerals-mining/minerals-metals-facts/nickel-facts/20519

NRC. (2024a, 2018/01/19/). *Aluminum facts*. https://natural-resources.canada.ca/our-natural-resources/minerals-mining/mining-data-statistics-and-analysis/minerals-metals-facts/aluminum-facts/20510

NRC. (2024b). *Lithium Facts*. Retrieved 2024-10-20 from https://natural-resources.canada.ca/minerals-mining/mining-data-statistics-analysis/minerals-metals-facts/lithium-facts

NRC. (2026). *Front End Engineering Design Study (FEED) of Xstrata's Raglan Renewable Electricity Micro-Grid & Smart-Grid Pilot Demonstration*. https://natural-resources.canada.ca/funding-partnerships/front-end-engineering-design-study-feed-xstrata-s-raglan-renewable-electricity-micro-grid-smart-grid-pilot-demonstration

NREL. (2025). *NAATBatt Lithium-Ion Battery Supply Chain Database*. https://www2.nrel.gov/transportation/li-ion-battery-supply-chain-database

Osaka, S. (2023, 2023/07/19/). Analysis | The obsession with EV range is all wrong. *Washington Post*. https://www.washingtonpost.com/climate-solutions/2023/07/07/ev-range-anxiety-battery-myth/

Pandey, R., Gracida-Alvarez, U. R., Iyer, R. K., & Kelly, J. C. (2025). Energy, greenhouse gas, and water life cycle analysis of synthetic graphite anode production in the United States. *Environmental Science: Advances*. https://doi.org/https://doi.org/10.1039/d5va00171d

Para, M. L., Querio, A., Amici, J., Versaci, D., Barresi, A. A., Bodoardo, S., & Marchisio, D. (2023). Electrochemical performance optimization of NMC811 through the structure design of its precursor. *Journal of Electroanalytical Chemistry*, *943*, 117630. https://doi.org/10.1016/j.jelechem.2023.117630

Patry, G., Romagny, A., Martinet, S., & Froelich, D. (2015). Cost modeling of lithium-ion battery cells for automotive applications. *Energy Science & Engineering*, *3*(1), 71-82. https://doi.org/10.1002/ese3.47

PEMC. (2009). *TECHNICAL REPORT AND RESOURCE ESTIMATE ON THE PUIMAJUQ Ni-Cu-PGE DEPOSIT NUNAVIK NICKEL PROJECT, NUNAVIK, QUEBEC For Canadian Royalties Inc.* P. E. M. C. Inc. https://www.canadianminingjournal.com/news/nickel-resources-canadian-royalties-increase-numbers-at-nunavik/

Pereira, L. G., Chagas, M. F., Dias, M. O. S., Cavalett, O., & Bonomi, A. (2015). Life cycle assessment of butanol production in sugarcane biorefineries in Brazil. *Journal of Cleaner Production*, *96*, 557-568. https://doi.org/https://www.sciencedirect.com/science/article/abs/pii/S0959652614000729?via%3Dihub

Pereira, P. M. P. (2024). *Equity research - Tesla Inc* [masterThesis, https://repositorium.sdum.uminho.pt/handle/1822/88250

Piedmont_Lithium. (2025). *Piedmont Lithium*. https://www.piedmontlithium.com/scoping-update-highlights-the-exceptional-economics-and-industry-leading-sustainability-of-piedmonts-carolina-lithium-project/?utm_source=chatgpt.com

Porzio, J., & Scown, C. D. (2021). Life-Cycle Assessment Considerations for Batteries and Battery Materials. *Advanced Energy Materials*, *11*(33). https://doi.org/10.1002/aenm.202100771

Prina Cerai, A. (2024). Geography of control: a deep dive assessment on criticality and lithium supply chain. *Mineral Economics*. https://doi.org/10.1007/s13563-023-00414-x

Purwanto, A., Ikhsanudin, M. N., Asri, P. P. P., Giasari, A. S., Hakam, M., Yudha, C. S., Widiyandari, H., Dyartanti, E. R., Jumari, A., & Nur, A. (2024). The Optimization of Nickel-Rich Cathode-Material Production on a Pilot Plant Scale. *Processes*, *12*(4). https://doi.org/10.3390/pr12040685

PWCCERC. (2025). *Battery Grade Synthetic Graphite Market*. https://pmarketresearch.com/chemi/battery-grade-synthetic-graphite-market

Qian, G., Li, Z., Wang, Y., Xie, X., He, Y., Li, J., Zhu, Y., Xie, S., Cheng, Z., Che, H., Shen, Y., Chen, L., Huang, X., Pianetta, P., Ma, Z.-F., Liu, Y., & Li, L. (2022). Value-creating upcycling of retired electric vehicle battery cathodes. *Cell Reports Physical Science*, *3*(2), 100741. https://doi.org/10.1016/j.xcrp.2022.100741

Qiao, D., Ma, Y., Bao, Y., Hong, Y., Batunacun, Narenmandula, & Dai, T. (2024). Exploring the potential impact of electric passenger vehicle battery recycling on China's cobalt supply and demand under the goals of carbon peaking and carbon neutrality during 2010–2060. *Journal of Cleaner Production*, *444*, 141139. https://doi.org/10.1016/j.jclepro.2024.141139

Quebec_Government. (2022). *Critical and Strategic Minerals in Quebec*. Retrieved from https://cdn-contenu.quebec.ca/cdn-contenu/ressources-naturelles/_critical_strategic_minerals.pdf

Rasbash, D., Dillman, K. J., Heinonen, J., & Ásgeirsson, E. I. (2023). A National and Regional Greenhouse Gas Breakeven Assessment of EVs across North America. *Sustainability*, *15*(3), 2181. https://doi.org/10.3390/su15032181

Reddy, M. V., Mauger, A., Julien, C. M., Paolella, A., & Zaghib, K. (2020). Brief History of Early Lithium-Battery Development. *Materials*, *13*(8), 1884. https://doi.org/10.3390/ma13081884

Ren, H., Mu, D., Wang, C., Yue, X., Li, Z., Du, J., Zhao, L., & Lim, M. K. (2024). Vulnerability to geopolitical disruptions of the global electric vehicle lithium-ion battery supply chain network. *Computers & Industrial Engineering*, *188*, 109919. https://doi.org/10.1016/j.cie.2024.109919

Reuters. (2021). *U.S. automakers to say they aspire to up to 50% of EV sales by 2030 -sources | Reuters*. https://www.reuters.com/business/autos-transportation/us-automakers-say-they-aspire-up-50-ev-sales-by-2030-sources-2021-08-04/

Rijo, J. R. (2024). Viability and Eco-Consequences of Synthetic and Natural Graphite for Lithium-Ion Battery Anodes in the USA. *IEEE Engineering Management Review*, *52*(3), 131-147. https://doi.org/10.1109/emr.2024.3372697

Roelich, K., Dawson, D. A., Purnell, P., Knoeri, C., Revell, R., Busch, J., & Steinberger, J. K. (2014). Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity. *Applied Energy*, *123*, 378-386. https://doi.org/10.1016/j.apenergy.2014.01.052

Roy, S., Moustafa, H., Vaidya, K., Harvey, J. P., & Fradette, L. (2025). Improving process granularity of life cycle inventories for battery grade nickel. *Npj Mater Sustain*, *3*(1), 15. https://doi.org/10.1038/s44296-025-00059-7

S. Ziegler, M., Song, J., & E. Trancik, J. (2021). Determinants of lithium-ion battery technology cost decline. *Energy & Environmental Science*, *14*(12), 6074-6098. https://doi.org/10.1039/D1EE01313K

Sadeghian, A., & Iqbal, N. (2022). A review on dissimilar laser welding of steel-copper, steel-aluminum, aluminum-copper, and steel-nickel for electric vehicle battery manufacturing. *Optics & Laser Technology*, *146*, 107595. https://doi.org/10.1016/j.optlastec.2021.107595

Sankar, T. K., Abhilash, & Meshram, P. (2024). Environmental Impact Assessment in the Entire Life Cycle of Lithium-Ion Batteries. *Reviews of Environmental Contamination and Toxicology*, *262*(1), 5. https://doi.org/10.1007/s44169-023-00054-w

Schöberl, J., Ank, M., Schreiber, M., Wassiliadis, N., & Lienkamp, M. (2024). Thermal runaway propagation in automotive lithium-ion batteries with NMC-811 and LFP cathodes: Safety requirements and impact on system integration. *eTransportation*, *19*, 100305. https://doi.org/10.1016/j.etran.2023.100305

Schulz-Mönninghoff, M., Neidhardt, M., & Niero, M. (2023). What is the contribution of different business processes to material circularity at company-level? A case study for electric vehicle batteries. *Journal of Cleaner Production*, *382*. https://doi.org/10.1016/j.jclepro.2022.135232

Schwich, L., Küpers, M., Finsterbusch, M., Schreiber, A., Fattakhova-Rohlfing, D., Guillon, O., & Friedrich, B. (2020). Recycling Strategies for Ceramic All-Solid-State Batteries—Part I: Study on Possible Treatments in Contrast to Li-Ion Battery Recycling. *Metals*, *10*(11), 1523. https://doi.org/10.3390/met10111523

SGS. (2014). *West Raglan Technical Report Northern Quebec, Canada*. https://www.newswire.ca/news-releases/royal-nickel-provides-exploration-update-for-high-grade-ni-cu-pgm-west-raglan-project-517949791.html

Shahzad, K., Helo, P., Ranta, M., & Nousiainen, E. (2024). Blockchain technology for operational excellence and supply chain resilience: a framework based on use cases and an architecture demonstration. *Technology Analysis & Strategic Management*, *0*(0), 1-18. https://doi.org/10.1080/09537325.2024.2304698

Shang, H., Sun, Y., Huang, D., & Meng, F. (2024). Life cycle assessment of atmospheric environmental impact on the large-scale promotion of electric vehicles in China. *Resources, Environment and Sustainability*, *15*, 100148. https://doi.org/10.1016/j.resenv.2024.100148

Shukla, A. K., & Kumar, T. P. (2008). Pillars of modern electrochemistry: a brief history. In *Electrochemistry Encyclopedia*.

Sika. (2014). *Sika at Work Mining The Canadian Arctic; The Glencore Raglan Mine, Quebec, Canada*. https://can.sika.com/en/construction/shotcrete-tunnelingmining/case-studies/mining-the-canadian-arctic.html

Slattery, M., Dunn, J., & Kendall, A. (2024). Charting the electric vehicle battery reuse and recycling network in North America. *Waste Manag*, *174*, 76-87. https://doi.org/10.1016/j.wasman.2023.11.018

SNC_Lavalin. (2007). *Raglan South Nickel Project Technical Report* (SNC Lavalin, Issue. https://docslib.org/doc/5248082/feasibility-study-report-the-study-prepared-for-canadian-royalties-inc

Song, Y., Zhao, T., He, L., Zhao, Z., & Liu, X. (2019). A promising approach for directly extracting lithium from α-spodumene by alkaline digestion and precipitation as phosphate. *Hydrometallurgy*, *189*. https://doi.org/10.1016/j.hydromet.2019.105141

SP_Battery_Group. (2024). SP Responsible Battery Work Group. *Suppliers Partnership for the Environment*. https://www.supplierspartnership.org/responsible-battery-work-group/

Stallard, J. C., Wheatcroft, L., Booth, S. G., Boston, R., Corr, S. A., De Volder, M. F. L., Inkson, B. J., & Fleck, N. A. (2022). Mechanical properties of cathode materials for lithium-ion batteries. *Joule*, *6*(5), 984-1007. https://doi.org/10.1016/j.joule.2022.04.001

Statista. (2022). *Canada: cobalt production by province* https://www.statista.com/statistics/434662/estimate-of-cobalt-production-in-canada-by-province/

Stephan, A. K. (2020). A Pathway to Understand NMC Cathodes. *Joule*, *4*(8), 1632-1633. https://doi.org/10.1016/j.joule.2020.08.004

Sun, Y., Li, J.-C., Zhou, H., & Guo, S. (2023). Wide-temperature-range sodium-metal batteries: from fundamentals and obstacles to optimization. *Energy & Environmental Science*, *16*(11), 4759-4811. https://doi.org/10.1039/D3EE02082G

Survey_U.S.G. (2020). *Mineral commodity summaries 2020*. https://pubs.usgs.gov/publication/mcs2020

Tahmasebi, M. H., Zheng, L., Hatchard, T. D., & Obrovac, M. N. (2023). Li[Ni0.6Mn0.2Co0.2]O2 Made From Crystalline Rock Salt Oxide Precursors. *Journal of The Electrochemical Society*, *170*(3), 030531. https://doi.org/10.1149/1945-7111/acc212

Tan, Y., Duchesne, M., Doninger, A., Meyers, M., & Barsukov, I. V. (2025). Ultrahigh Temperature Purification of Graphite for the Development of a Continuous Process. *ACS Omega*, *10*(38), 44162-44172. https://doi.org/https://doi.org/10.1021/acsomega.5c05566

Tardy, A., Rousse, D. R., Mungyeko Bisulandu, B.-J. R., & Ilinca, A. (2025). Enhancing Energy Sustainability in Remote Mining Operations Through Wind and Pumped-Hydro Storage; Application to Raglan Mine, Canada. *Energies*, *18*(9). https://doi.org/10.3390/en18092184

The Metallurgy and Materials Society of CIM; The Society for Mining, M. E. a. T. M., Metals & Materials Society. (2025). 6th International Symposium on NICKEL AND COBALT Proceedings of the Extraction 2025 Meeting & Exhibition. Ni-Co 2025, 6th International Symposium on Nickel and Cobalt,

The_Commission. (2017). *THE SIVUMUT PROJECT THE RAGLAN MINE PROPERTY AFTER 2020 PHASES II and III RAGLAN-SIVUMUT-PROJECT-DECISION-OF-THE-Kativik* (Kativik Environmental Quality Commission Issue. https://minedocs.com/19/RAGLAN-SIVUMUT-PROJECT-DECISION-OF-THE-Kativik%20Environmental%20Quality%20Commission-July-2017.pdf

Tiozzo, A., Ghaseminezhad, K., Mazzucco, A., Giuliano, M., Rocca, R., Dotoli, M., Nicol, G., Nervi, C., Baricco, M., & Sgroi, M. F. (2024). Investigating the Influence of Three Different Atmospheric Conditions during the Synthesis Process of NMC811 Cathode Material. *Crystals*, *14*(2), 137. https://doi.org/10.3390/cryst14020137

Toki, G. F. I., Hossain, M. K., Rehman, W. U., Manj, R. Z. A., Wang, L., & Yang, J. (2024). Recent progress and challenges in silicon-based anode materials for lithium-ion batteries. *Industrial Chemistry & Materials*, *2*(2), 226-269. https://doi.org/10.1039/d3im00115f

Trost, J. N., & Dunn, J. B. (2023). Assessing the feasibility of the Inflation Reduction Act's EV critical mineral targets. *Nature Sustainability*, *6*(6), 639-643. https://doi.org/10.1038/s41893-023-01079-8

U.S._DOE. (2024). *Building America's Clean Energy Future*. https://www.energy.gov/invest

U.S.DT. (2023). U.S. Department of the Treasury. *U.S. Department of the Treasury*. https://home.treasury.gov/news/press-releases

Umicore-Canada. (2024). *Umicore prepares to construct battery materials production plant in Canada*. https://www.umicore.ca/en/news/umicore-prepares-to-construct-battery-materials-production-plant-in-canada/

USGS. (2024a). *Aluminum Statistics and Information*. https://www.usgs.gov/centers/national-minerals-information-center/aluminum-statistics-and-information

USGS. (2024b). *Lithium Statistics and Information*. https://www.usgs.gov/centers/national-minerals-information-center/lithium-statistics-and-information

USGS. (2024c). *Nickel Statistics and Information | U.S. Geological Survey*. https://www.usgs.gov/centers/national-minerals-information-center/nickel-statistics-and-information

Valencia, F., Rabbani, M., Fahimi, A., & Vahidi, E. (2025). Assessing the environmental burden of nickel sulfate for batteries: A life cycle perspective. *Resources, Conservation and Recycling*, *215*. https://doi.org/10.1016/j.resconrec.2025.108130

Vegh, G. (2023, 2023/06/26/27). *International Conference on the Characterization and Quantification of Lithium, from the Micro Scale to the Nano Scale, from Mining to Energy; Paris, France (June 2023)* https://cqlmns.sciencesconf.org/

Vegh, G., Madikere Raghunatha Reddy, A., Li, X., Deng, S., Liu, T., Amine, K., & Zaghib, K. (2024). North America's Potential for an Environmentally Sustainable Nickel, Manganese, and Cobalt Battery Value Chain. *Batteries*, *10*(11). https://doi.org/10.3390/batteries10110377

Vera, M. L., Torres, W. R., Galli, C. I., Chagnes, A., & Flexer, V. (2023). Environmental impact of direct lithium extraction from brines. *Nature Reviews Earth & Environment*, *4*(3), 149-165. https://doi.org/10.1038/s43017-022-00387-5

Wang, X., Wang, L., Cui, B., Xing, J., Zhang, Y., & Ren, X. (2022). Development Trend and Countermeasures of Nickel Sulfate Industry in China. *Chinese Journal of Engineering Science*, *24*(3). https://doi.org/10.15302/j-sscae-2022.03.005

Wei, G., Wang, M., Lin, C., Xu, C., & Gao, J. (2024). Optimizing Operational Parameters for Lithium Hydroxide Production via Bipolar Membrane Electrodialysis. *Separations*, *11*(5). https://doi.org/10.3390/separations11050146

Wei, W., Samuelsson, P. B., Tilliander, A., Gyllenram, R., & Jönsson, P. G. (2020). Energy Consumption and Greenhouse Gas Emissions of Nickel Products. *Energies*, *13*(21). https://doi.org/10.3390/en13215664

Wentker, M., Greenwood, M., & Leker, J. (2019). A Bottom-Up Approach to Lithium-Ion Battery Cost Modeling with a Focus on Cathode Active Materials. *Energies*, *12*(3), 504. https://doi.org/10.3390/en12030504

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218-1230. https://doi.org/10.1007/s11367-016-1087-8

White, J. L., Gittleson, F. S., Homer, M., & El Gabaly, F. (2020). Nickel and Cobalt Oxidation State Evolution at Ni-Rich NMC Cathode Surfaces during Treatment. *The Journal of Physical Chemistry C*, *124*(30), 16508-16514. https://doi.org/10.1021/acs.jpcc.0c04794

Winjobi, O., Kelly, J. C., & Dai, Q. (2022). Life-cycle analysis, by global region, of automotive lithium-ion nickel manganese cobalt batteries of varying nickel content. *Sustainable Materials and Technologies*, *32*. https://doi.org/10.1016/j.susmat.2022.e00415

Wood, D. L., Li, J., & An, S. J. (2019). Formation Challenges of Lithium-Ion Battery Manufacturing. *Joule*, *3*(12), 2884-2888. https://doi.org/10.1016/j.joule.2019.11.002

Xiao, J., Shi, F., Glossmann, T., Burnett, C., & Liu, Z. (2023). From laboratory innovations to materials manufacturing for lithium-based batteries. *Nature Energy*, *8*(4), 329-339. https://doi.org/10.1038/s41560-023-01221-y

Xu, L., Zhou, F., Liu, B., Zhou, H., Zhang, Q., Kong, J., & Wang, Q. (2018). Progress in Preparation and Modification of LiNi_{0.6}Mn_{0.2}Co_{0.2}O₂ Cathode Material for High Energy Density Li-Ion Batteries. *International Journal of Electrochemistry*, *2018*, e6930386. https://doi.org/10.1155/2018/6930386

Xu, M., Vanderbruggen, A., Kupka, N., Zhang, H., & Rudolph, M. (2022). Influence of MIBC on the surface-air nucleation and bubble-particle loading in graphite froth flotation. *Minerals Engineering*, *185*. https://doi.org/https://doi.org/10.1016/j.mineng.2022.107714

Xue, Y., & Li, T. (2024). The Significance of Flotation Frothers Chemical Structure and Fundamental Properties: A Review. *Open Journal of Applied Sciences*, *14*(08), 2124-2132. https://doi.org/https://doi.org/10.4236/ojapps.2024.148140

Yabuuchi, N., & Ohzuku, T. (2003). Novel lithium insertion material of LiCo1/3Ni1/3Mn1/3O2 for advanced lithium-ion batteries. *Journal of Power Sources*, *119-121*, 171-174. https://doi.org/10.1016/S0378-7753(03)00173-3 (Selected papers presented at the 11th International Meeting on Lithium Batteries)

Yakub, M. (2024). *Canada leaps to top spot in Bloomberg NEF battery supply chain ranking*. https://electricautonomy.ca/news/2024-02-05/canada-top-spot-bloombergnef-battery-supply-chain-ranking/

Yang, I., Choi, S., Kim, S.-W., Ha, M. Y., Park, S.-M., & An, J.-C. (2024). Utilizing Graphite Waste from the Acheson Furnace as Anode Material in Lithium-Ion Batteries. *Applied Sciences*, *14*(23). https://doi.org/10.3390/app142311353

Yang, Z., Huang, H., & Lin, F. (2022). Sustainable Electric Vehicle Batteries for a Sustainable World: Perspectives on Battery Cathodes, Environment, Supply Chain, Manufacturing, Life Cycle, and Policy. *Advanced Energy Materials*, *12*(26), 2200383. https://doi.org/10.1002/aenm.202200383

Yee, M. S. O. O. (2023). Promoting electric vehicles as the silver bullet for tackling climate change. In R. Leal-Arcas (Ed.), *Climate and Energy Governance for a Sustainable Future* (pp. 157-170). Springer Nature. https://doi.org/10.1007/978-981-19-8346-7_12

Yu, J., Fang, D., Zhang, H., Leong, Z. Y., Zhang, J., Li, X., & Yang, H. Y. (2020). Ocean Mining: A Fluidic Electrochemical Route for Lithium Extraction from Seawater. *ACS Materials Letters*, *2*(12), 1662-1668. https://doi.org/10.1021/acsmaterialslett.0c00385

Zhang, H., Yang, Y., Ren, D., Wang, L., & He, X. (2021). Graphite as anode materials: Fundamental mechanism, recent progress and advances. *Energy Storage Materials*, *36*, 147-170. https://doi.org/https://doi.org/10.4028/www.scientific.net/MSF.913.1011

Zhang, J., Liang, C., & Dunn, J. B. (2023). Graphite Flows in the U.S.: Insights into a Key Ingredient of Energy Transition. *Environ Sci Technol*, *57*(8), 3402-3414. https://doi.org/https://doi.org/10.1021/acs.est.2c08655

Zhang, Q. Q., Gong, X. Z., & Meng, X. C. (2018). Environment Impact Analysis of Natural Graphite Anode Material Production. *Materials Science Forum*, *913*, 1011-1017. https://doi.org/10.4028/www.scientific.net/MSF.913.1011

Zhang, R., Wang, C., Zou, P., Lin, R., Ma, L., Li, T., Hwang, I.-h., Xu, W., Sun, C., Trask, S., & Xin, H. L. (2023). Long-life lithium-ion batteries realized by low-Ni, Co-free cathode chemistry. *Nature Energy*, *8*(7), 695-702. https://doi.org/10.1038/s41560-023-01267-y

Zhao, E., Fang, L., Chen, M., Chen, D., Huang, Q., Hu, Z., Yan, Q.-b., Wu, M., & Xiao, X. (2017). New insight into Li/Ni disorder in layered cathode materials for lithium ion batteries: a joint study of neutron diffraction, electrochemical kinetic analysis and first-principles calculations. *Journal of Materials Chemistry A*, *5*(4), 1679-1686. https://doi.org/10.1039/C6TA08448F

Zhu, Y., Xu, Y., Liu, Y., Luo, C., & Wang, C. (2013). Comparison of electrochemical performances of olivine NaFePO 4 in sodium-ion batteries and olivine LiFePO 4 in lithium-ion batteries. *Nanoscale*, *5*(2), 780-787. https://doi.org/10.1039/C2NR32758A

Zinnwald_Lithium. (2022). *Zinnwald Lithium PLC - PEA - Robust Economics for German Lithium Project*. https://www.research-tree.com/newsfeed/article/zinnwald-lithium-plc-pea-robust-economics-for-german-lithium-project-1473101

Zuo, D., Tian, G., Li, X., Chen, D., & Shu, K. (2017). Recent progress in surface coating of cathode materials for lithium ion secondary batteries. *Journal of Alloys and Compounds*, *706*, 24-40. https://doi.org/10.1016/j.jallcom.2017.02.230