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Review

North America's Potential for an Environmentally Sustainable Nickel, Manganese, and Cobalt Battery Value Chain

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Abstract: The Detroit Big Three General Motors (GMs), Ford, and Stellantis predict that electric vehicle (EV) sales will comprise 40–50% of the annual vehicle sales by 2030. Among the key components of LIBs, the LiNixMnyCo$_{1-x-y}$O$_2$ cathode, which comprises nickel, manganese, and cobalt (NMC) in various stoichiometric ratios, is widely used in EV batteries. This review reveals NMC cathodes from laboratory research. Furthermore, this study examines the environmental effect of NMC cathode production for EV batteries (including coating technologies), encompassing aspects such as energy consumption, water usage, and air emissions. Although gaps persist in NMC cathode environmental assessments (NMC111, NMC532, NMC622, and NMC811), limited life cycle assessments "(LCA)" have been conducted. Most available data originate from Asia (primarily China), accounting for 85% of the production of EV LIB cathode materials. The concept of battery passports for data collection on LIB components has been proposed to facilitate material traceability as a system for ensuring a sustainable supply chain for critical minerals. The automotive industry's shift to electrification necessitates a sustainable supply chain from mine to vehicle end-of-life. As the critical mineral supply moves from Asia to North America, environmentally friendly industrial methods must be studied to provide this supply chain direction.

Keywords: lithium-ion battery; mine-to-cells; NMC cathode materials; green battery; battery passport

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1. Introduction

The automotive industry is investing hundreds of billions of "dollars (USD)" in transitioning from internal combustion engine (ICE) vehicles to electric vehicle (EV) platforms [1,2]. Many countries have planned to ban the sale of ICE vehicles by 2035–2040 [3–6]. This change in vehicle drivetrains is rapid, and every original equipment manufacturer (OEM) is engaged in this market [7–9] (Figure 1). Automotive manufacturers estimate that EVs will constitute 40–50% of the annual vehicle sales volume by 2030 [7,10–12], thus increasing the need for 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 [13]. There is a long history of using batteries for energy storage, from the Alessandro Volta cell in the 1800s to the commercialization of the LIB in 1992 [14,15]. The mining industry has a long history of providing hydrometallurgical processes [16] dating back to pre-industrial times [17–19].

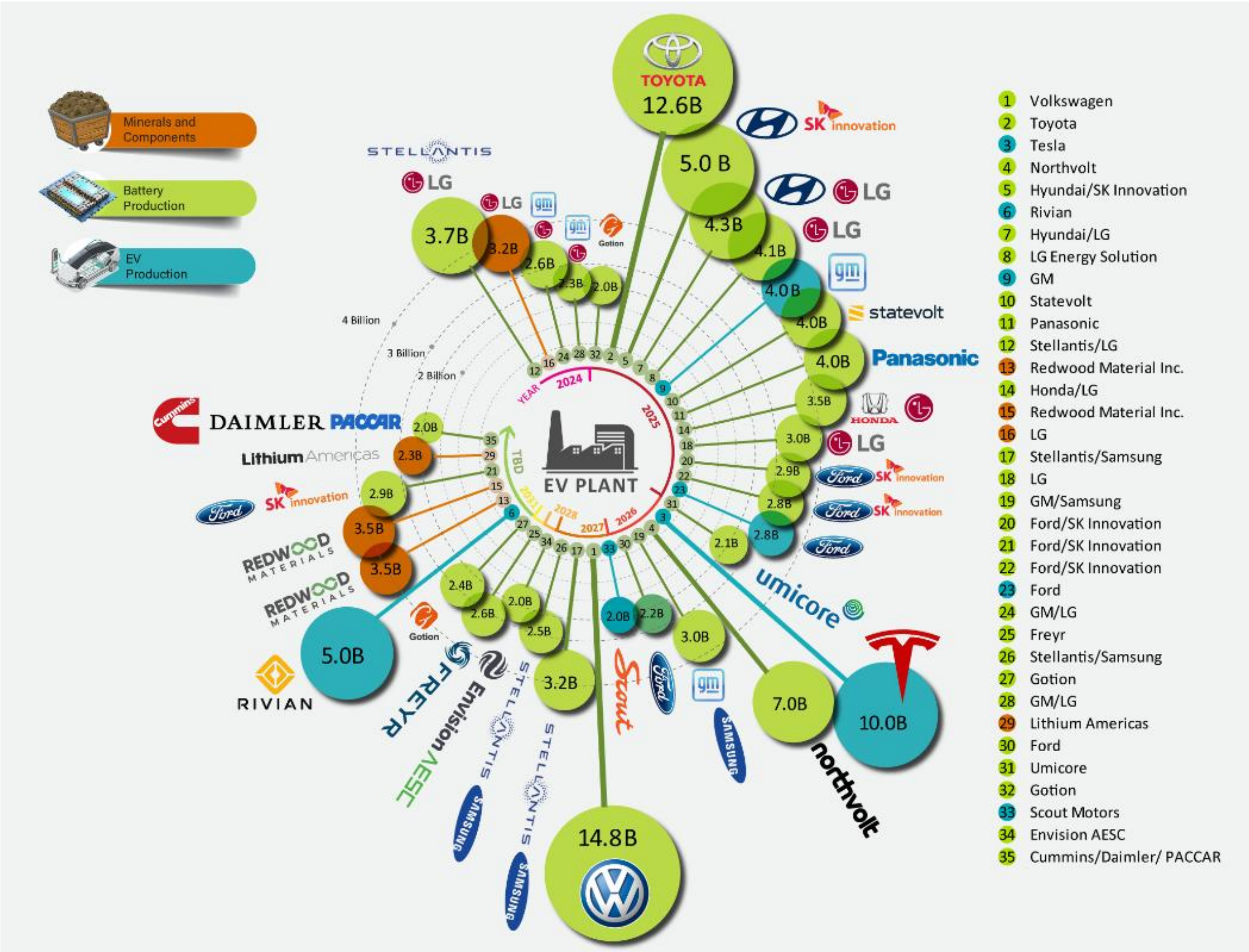


Figure 1. North American investments in the electric vehicle (EV) battery industry (January 2024) [20].

With this major change in the automotive industry, OEMs are seeking to secure a dependable and sustainable supply chain [21,22] that considers the environmental impact. The United States Inflation Reduction Act (IRA) [23–25] is a primary driving force providing strong incentives for using raw materials sourced from the US and free-trade partner countries [26]. 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 has now been referred to as the US–Mexico–Canada agreement (USMCA) since July 2020 [27]. 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 (GMs), Ford, Tesla, and Northvolt are investing in critical minerals in Quebec [28–30] to secure reliable sources for creating precursors that can be used in producing cells for LIBs in EVs [31,32]. Many companies in Canada have invested in the EV market in cathode active material (CAM) and EV battery plants [33]. Stellantis and LG Energy Solutions are investing in an LIB facility in Windsor, Ontario, Canada [33]. Figure 2 shows investments in Quebec and Ontario, and these investments come from OEMs and chemical companies dealing with important minerals. The GMs/POSCO, BASF, and Umicore facilities produce CAMs [34–36].

With the exponential growth of the EV market, more LIBs are urgently required [8,37,38]. 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 [39,40].

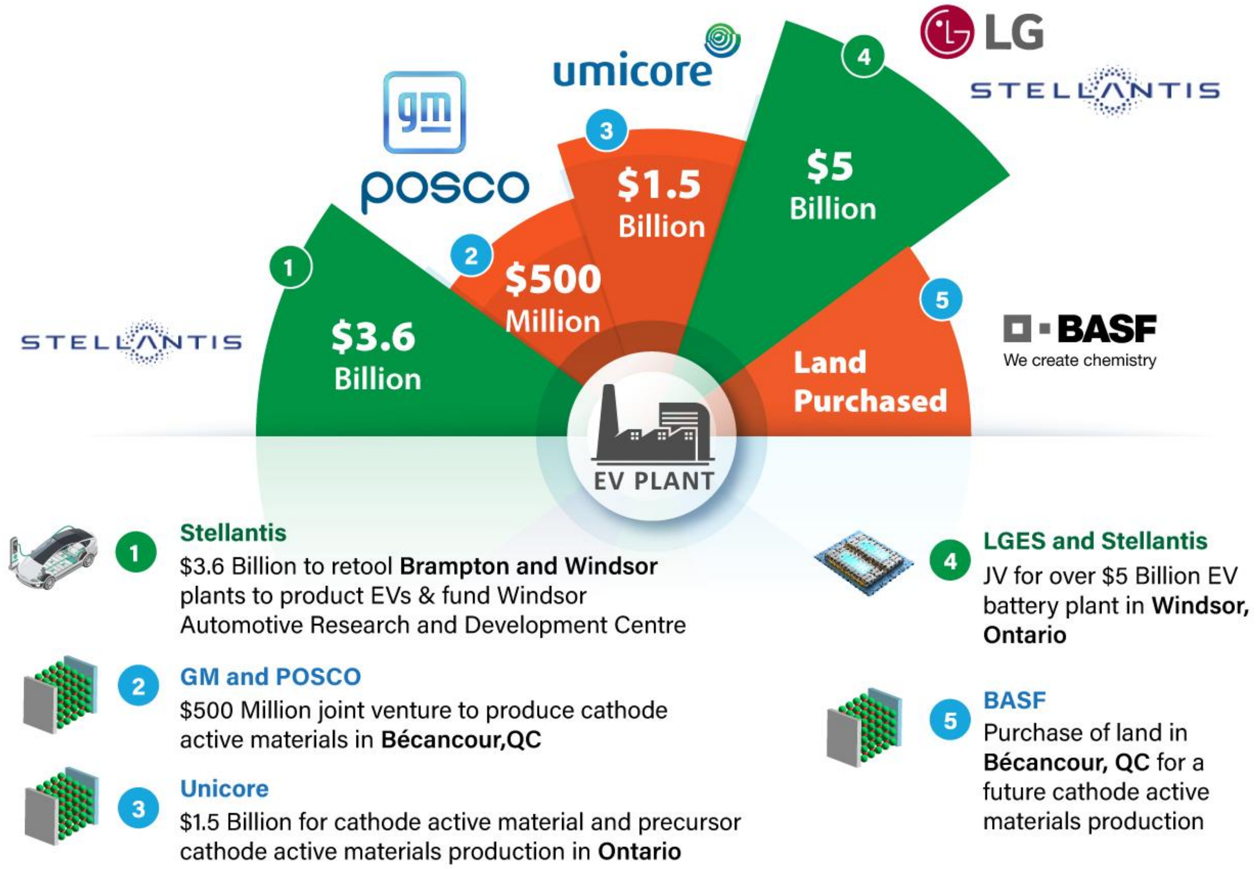


Figure 2. EV plant investments in Canada (Quebec and Ontario) (redesigned) [26].

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 [41]. With the availability of larger battery packs in the market, there has been a push to develop NMC cathodes with higher nickel content and lower cobalt (NMC111, NMC622, and NMC811) in R&D technologies [42], which play a major role; thus, the industry focuses 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 [43]".

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 [44]. Figure 4 depicts the history of the development of LIBs over time [45]. 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 (Figure 4). The Li-rich cathodes and C–Si alloy anodes were developed in the 2020s. Solid-state batteries are the next phase in battery development, with their predicted commercialization in the 2030s. The difference between a solid-state battery and 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 [46].

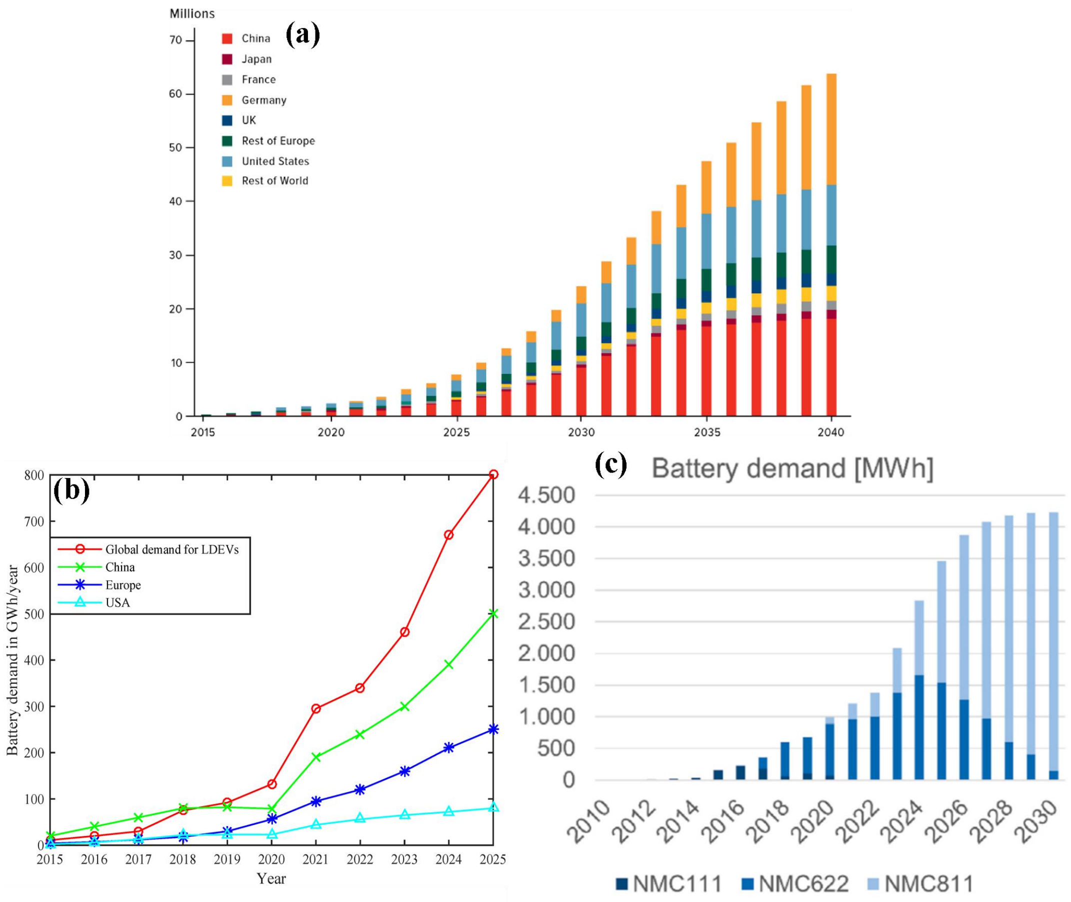


Figure 3. (**a**) Annual demand (millions) estimate for EVs worldwide [8]. (**b**) Global demand of batteries for light-duty vehicles [41]. (**c**) Increase in NMC111, NMC622, and NMC811 battery demand over time [42].

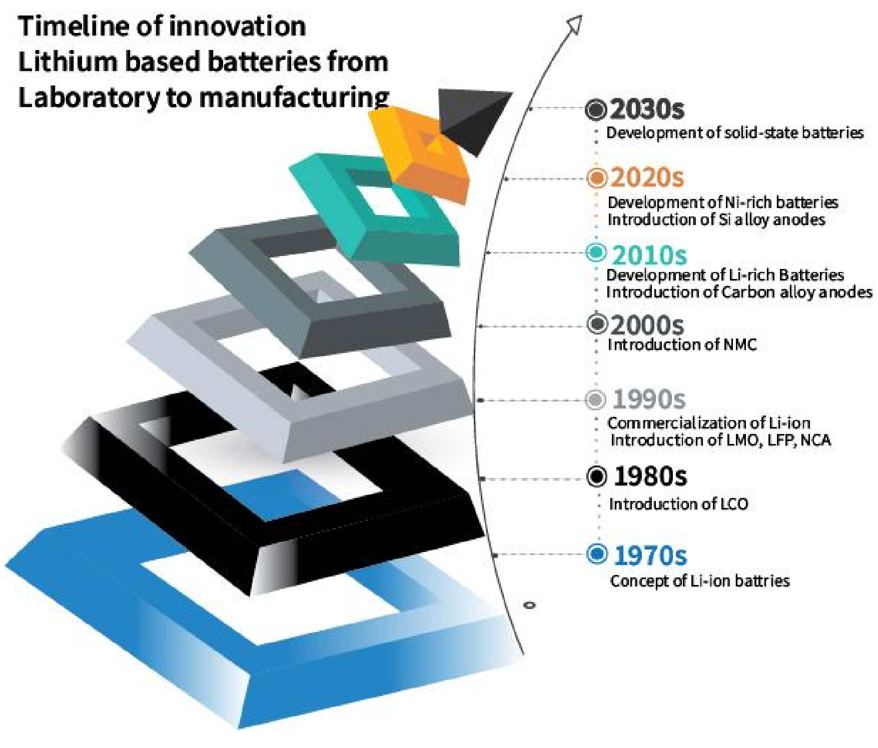
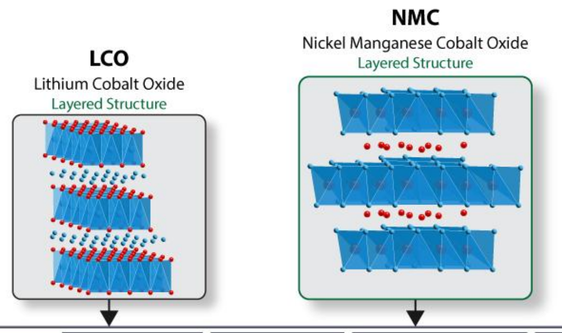


Figure 4. History of lithium-ion batteries (LIBs) (redesigned) [45].

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.

1.1. 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 [14,47]. Figure 5 shows the various cathode chemistries (namely, lithium cobalt oxide (LCO), LFP, LMO, NCA, and NMC). Variations in the "Elements" or "Chemical compositions" of the cathode material [48] (as found in LCO/NMC), olivine, and spinel phases play an important role in the performances of these cathodes, and these variations 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 [49]. The next stage in the development of LIBs is solid-state batteries due to the intrinsic safety characteristics and high theoretical energy density [50].



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]

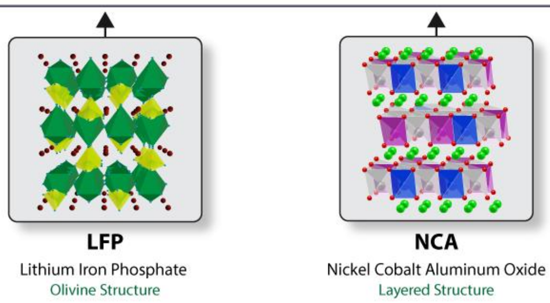


Figure 5. Cathode chemical structures (redesigned) [51,52].

1.2. Battery Properties

1.2.1. Why NMC?

Cathode is one of the main components of an LIB. In the automotive industry, NMC cathodes comprise dominant transportation since they meet the industry requirements of battery range, charging, cost, and safety [5]. The NMC cathodes consist of various stoichiometric ratios of Ni, Mn, and Co atoms [53]. In an LIB, Mn stabilizes the structure, Ni determines the capacity, and Co increases the electrical conductivity, significantly influencing battery performance [54,55] with respect to electrodes and are independent active materials.

Stoichiometric ratios of these atoms affect different properties, including structural and chemical stabilities and charging capacity, of the NMC cathode [56]. NMC compounds can vary in size and crystal orientation, thereby leading to potential issues such as structural degradation, chemical destabilization, and heterogeneity of NMC [53]. Therefore, appropriate methods for material identification are required to ensure material quality, which significantly impact LIB performance [57]. Excellent performance of NMC cathodes is 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 [2,58]. 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 performance over time [59]. 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 [8]. 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 and meet the requirement for application in higher-energy-capacity EV batteries [60].

1.2.2. 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 amounts of Co, reducing costs (since it does not have to be mined and imported from Africa). This aligns 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 [61]. 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 [62]. $LiNi_{0.5}Mn_{1.5}O_4$ exhibits a specific capacity of 200 $mA{\cdot}h{\cdot}g^{-1}$ and promising performance over a voltage range of 2.8–4.6 V [62]. Polyanionic compounds, such as $LiFePO_4$, offer stability, safety, and low-cost advantages; nevertheless, they demonstrate low electrical conductivity. $LiFePO_4$ exhibits a stable redox potential of 3.5 V (vs. Li^+/Li) and high theoretical capacity of 170 $mA{\cdot}h{\cdot}g^{-1}$ [62]. 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 favorability of Ni^{2+} [62]. NMC111, for instance, demonstrates a specific capacity of 200 $mA{\cdot}h{\cdot}g^{-1}$ within a voltage range of 2.8–4.6 V and a reversible capacity of 160 $mA{\cdot}h{\cdot}g^{-1}$ [62]. Coating NMC811 with magnesium oxide (MgO) improves the coulombic efficiency of NMC811 because of less Ni and Li mixing within the NMC lattice [63]. Additionally, MgO coatings improve the stability of NMC811 during potential cycling, reducing the resistance during Li^+ insertion and extraction [64]. 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 $LiNi_{1-x}M_xO_2$ [37,65–67]. 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 [39,55,66,68–72].

Widespread adoption of NMC in EVs and other applications is attributed to the balance between cost [73], capacity, and reduced Co content [74] of NMC as compared to that in the case of LCO [14]. 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 [47] (Figure 6a,b).

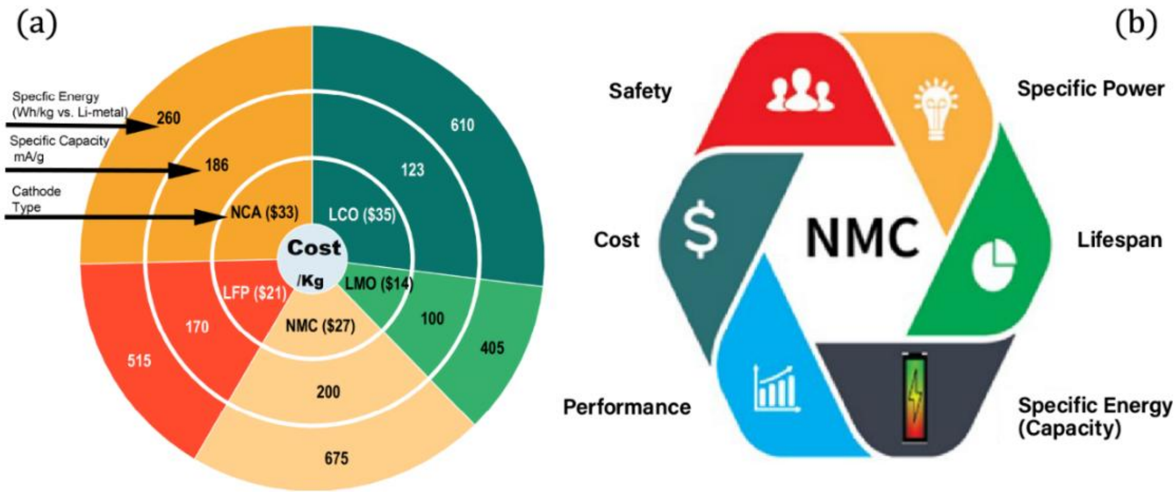


Figure 6. (**a**) Graphical representation of Table 1: Specific capacity (mA g^{-1}), specific energy (Wh kg^{-1}), and cost/kg of LCO, LMO, NMC, LFP, and NCA cathodes [75–77]. (**b**) Important NMC parameters [78].

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 [75–77].

Reference	Chemical Formula	Abbreviation	Specific Capacity (mA g^{-1})	Specific Energy (Wh kg^{-1} vs. Li Metal)	Cost kg^{-1}	Advantage(s)	Disadvantage(s)
[72]	$LiCoO_2$	LCO	123	610	35	High energy density	High cost and moderate stability
[71]	$LiMn_2O_4$	LMO	100	405	14	Low cost and high-power density	Lower energy density and accelerated capacity fade
[75,79,80]	$LiNixMnyCo_{1-x-y}O_2$	NMC	200	675	27	Performs well in all metrics	Moderate cost and moderate stability
[72]	$LiFePO_4$	LFP	170	515	21	High-power density and very stable	Lower energy density
[74]	$LiNi_xCo_yAl_{1-x-y}O_2$	NCA	186	260	33	High 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 [74–76]. 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 performances and costs of LIBs [16]. NMC and NCA ($LiNi_xCo_yAl_{1-x-y}O_2$) cathodes [81], 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 [78,82]. 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, during the syntheses of NMC cathodes [77,83]. Specific power and lifespan are optimized [84] in the NMC cathode, which make it very attractive to the automotive industry. Cathodes considerably contribute to production costs and the 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 [85,86]. Therefore, advancing LIBs using more sustainable cathode materials is essential to balance sustainability, cost, and performances of these batteries [83]. Precursor preparation conditions (for example, sintering time, temperature, and atmosphere), morphology, electrochemical performance, capacity retention, impedance, and cycle stability are also important for developing NMC cathodes [87]. Preparation techniques incorporated into the manufacturing of NMC cathodes are a significant factor that contribute to the overall costs of the materials [88]. In addition to the critical mineral costs for cathodes, the processes employed for developing the precursors can utilize large amounts of water and generate waste [89]. 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 [90].

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 [91]. NMC cathodes contribute to more than 20% of the costs of EV batteries [78]. 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 the NMC is ascribed to the costs of raw materials. Specific energy, cost, specific power, safety, performance, and lifespan are all drivers of the changing NMC cathode chemistry [78,92].

1.2.3. Performance

Understanding the relationships among the cathode performance, mechanical properties, and degradation are crucial for the appropriate functioning of LIBs [93]. With an increase in the demand for LIBs by the automotive industry, the requirement of NMC cathodes with higher performance, which are dependent on the crystallinity, morphology characterization [94], and other parameters during the syntheses of these NMC cathodes, has increased [47]. Charge/discharge cut-off voltages play an important role in the development of high-performance LIBs, as shown in Figure 7a,c,e. Although layered oxides, including $LiCoO_2$ and $LiNiO_2$, exhibit outstanding conductivities, they demonstrate structural instabilities during charge cycling [62]. $LiCoO_2$ 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 [39,95]. These cathodes are highly sensitive to the mechanical pressure exerted on the cell, which can affect their performances and cycling life [65,96,97].

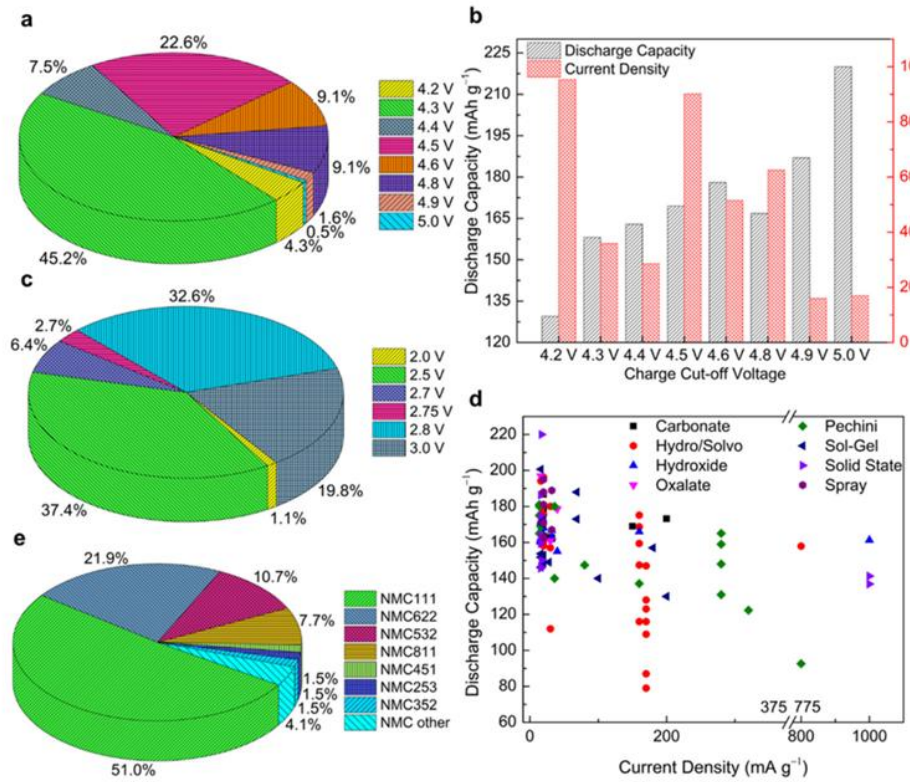


Figure 7. (**a**,**c**,**e**) Summary of the charge and discharge cut-off voltages and current densities and (**b**,**d**) their effects on the discharge capacity of the $LiNi_xMn_yCo_{1-x-y}O_2$ cathode material [47].

1.2.4. Specific Energy

NMC811 exhibits a specific energy of over 600 $Whkg^{-1}$, indicating its potential for realizing high energy density [56,98,99]. It demonstrates favorable rate capabilities with an electrical conductivity of ~2.8×10^{-5} S cm^{-1} and Li^+ diffusivity [100] of 8–9 cm^2 s^{-1}. These characteristics support the potential of NMC811 for achieving high reversible capacities (>200 mAh $gNMC^{-1}$) and desirable rate capabilities [56] (Figure 7).

Despite the challenges related to Ni-rich formulations, such as oxygen release and structural instabilities, 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 [65,98,99]. 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 achieves a balance between the strengths of Ni and Mn, thereby ensuring stable performance [101] (see Figure 7).

1.2.5. Safety

Safe operation of the cathode is a crucial characteristic of LIBs. Table 2 lists the safe operating parameters of the NMC cathode [77].

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 render them promising candidates for LIBs [14,102].

Safety issues associated with LIBs due to their physical/chemical natures support the need for suitable characterization [103] 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, (8) transition metal dissolution [77], and (9) corrosion of current collectors, as shown in Figure 8. These challenges can lead to side reactions that decrease the battery performance [104], resulting in reduced battery life and power capacity [77]. Dendrites are formations across the separator that cause short circuits and result in thermal runaway [105] (Figure 8).

Table 2. Safe operating parameters for the NMC cathode [77].

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.

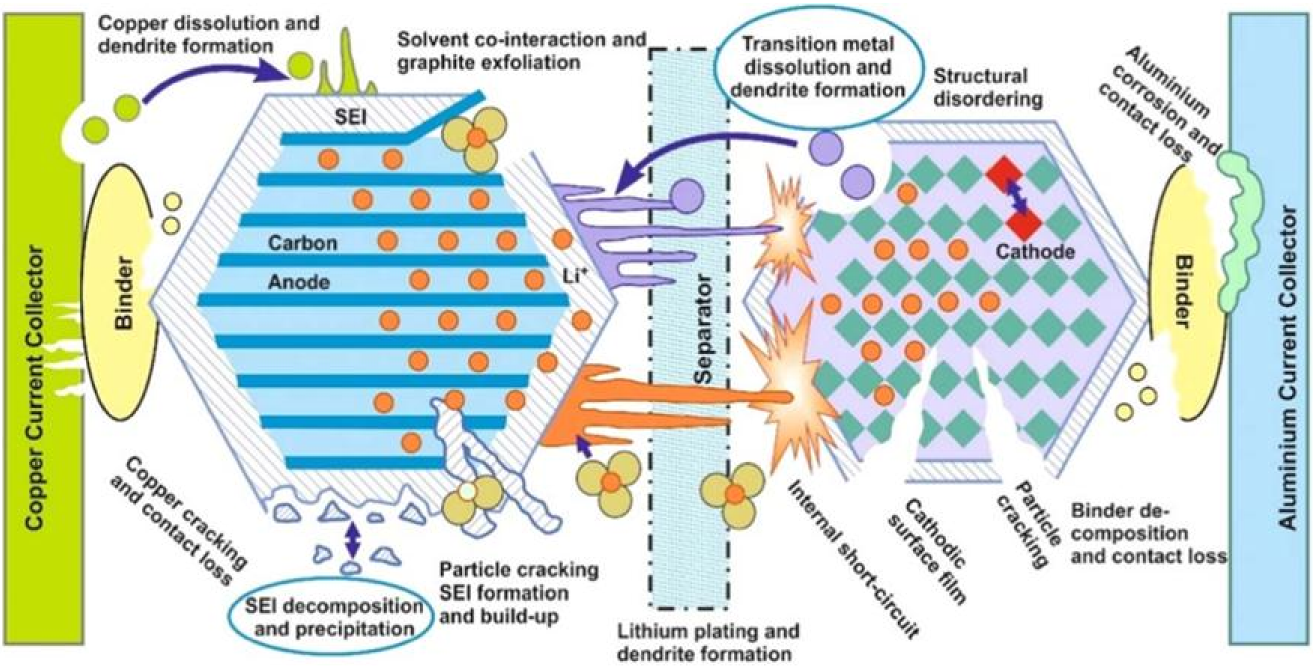


Figure 8. Dendrite formation based on material properties and different chemistries [77].

Moreover, other limiting factors such as cell performance, cost, manufacturing capabilities, supply chain, and logistics, must be considered during the production of NMC cathodes [106]. Several parameters of NMC cathodes and desired properties of the cathode are important in developing the synthesis method with respect to cathode properties [47] (Figure 9) and have been modified to realize high energy densities, multi-cycling capabilities, fast-charging rates, cost effectiveness, and safety of these cathodes in LIBs [107].

Electrochemical performance is a crucial aspect of lithium-ion EV batteries and is directly related to the crystal structures [108] of materials, for example, the NMC cathode [77,109]. 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) [77]. 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 [110]. Specific energy is a driving force in the development of LIBs, and automotive battery manufacturers are dedicating significant efforts to eliminating the use of Co [111]. 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) [45,101].

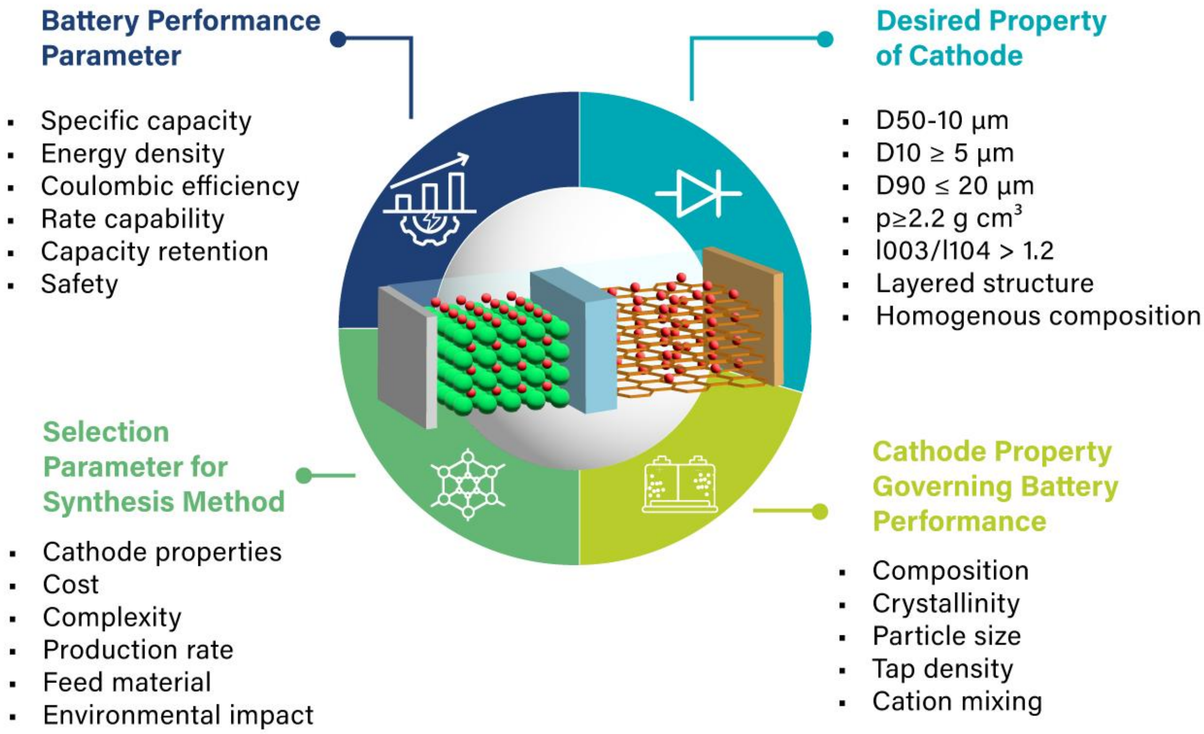


Figure 9. Review on the synthesis of $LiNi_xMn_yCo_{1-x-y}O_2$ (NMC) cathodes for LIBs (redesigned) [47].

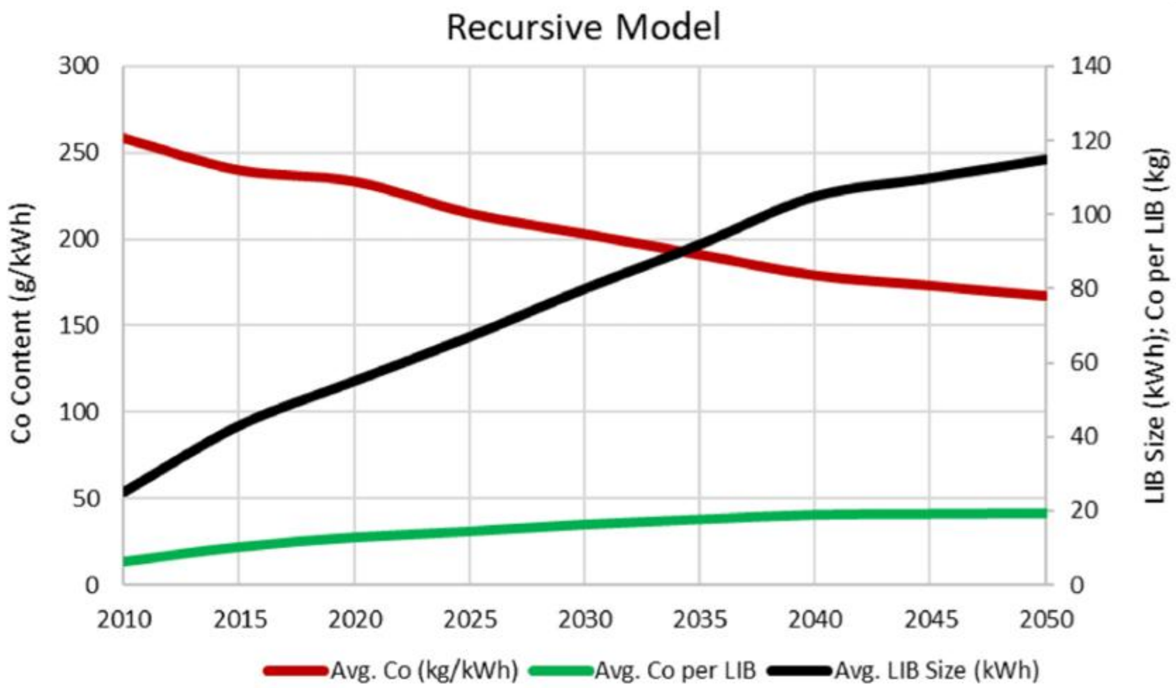


Figure 10. Evolution of battery chemistry using a recursive model of average Co content (g/kWh) and average LIB size (kWh) [101].

Assumptions of the recursive model demonstrate 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 11 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) [101]. Furthermore, Ni is becoming an issue for EV makers, and therefore, fabricating an LIB with very low Ni and Co contents that maintains a high specific energy and stable system is challenging [111]. 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.

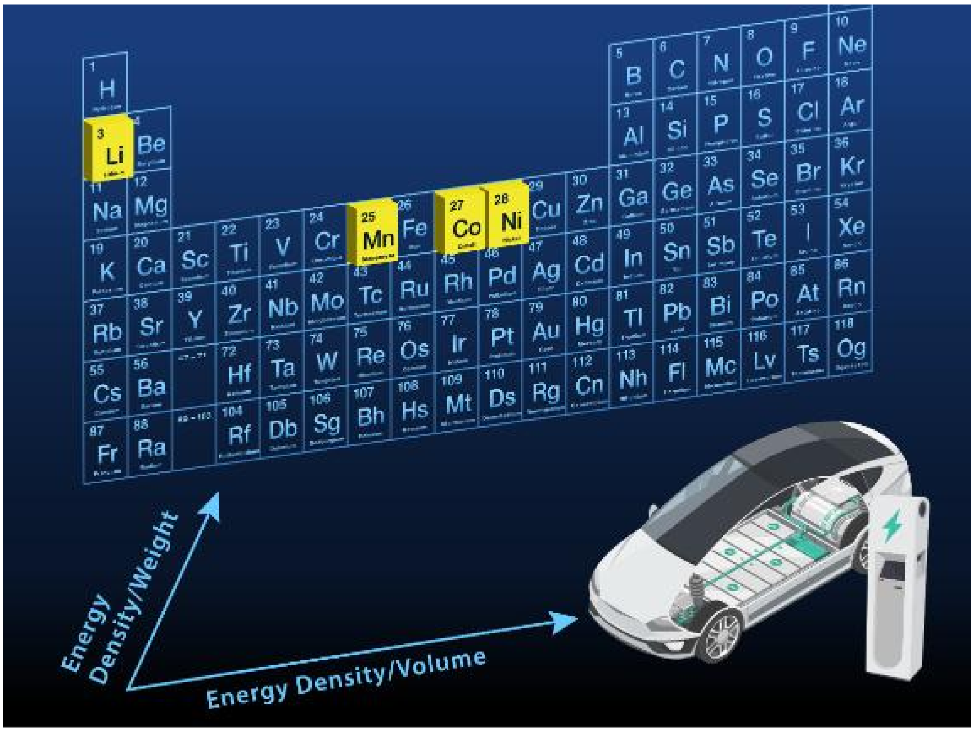


Figure 11. Critical minerals (Li, Mn, Co, and Ni) used in NMC cathodes.

Table 3. Assumptions of recursive model for the evolution of the NMC cathode [101].

Cathode	2010	2015	2020	2025	2030	2035	2040
NMC	NMC111 (45%)	NMC111 (35%)	NMC111 (40%)	NMC111 (20%)	NMC111 (10%)		
	NMC532 (55%)	NMC532 (50%)	NMC532 (30%)	NMC532 (50%)	NMC532 (35%)		
		NMC622 (205)	NMC622 (25%)	NMC622 (30%)	NMC622 (35%)		
		NMC811 (<5%)	NMC811 (<5%)	NMC811 (10%)	NMC811 (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%)		

Table 3. *Cont.*

Cathode	2010	2015	2020	2025	2030	2035	2040
			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. Mining

2.1. Availabilities of Critical Minerals

A considerable supply of critical minerals is essential to address the increasing global demand for LIBs. Currently, over 85% of LIB components are acquired from Asian countries, mainly China [112]. 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 12). The Biden administration in the US is encouraging LIB growth under IRA [113] to ensure the availability of jobs in America [114].

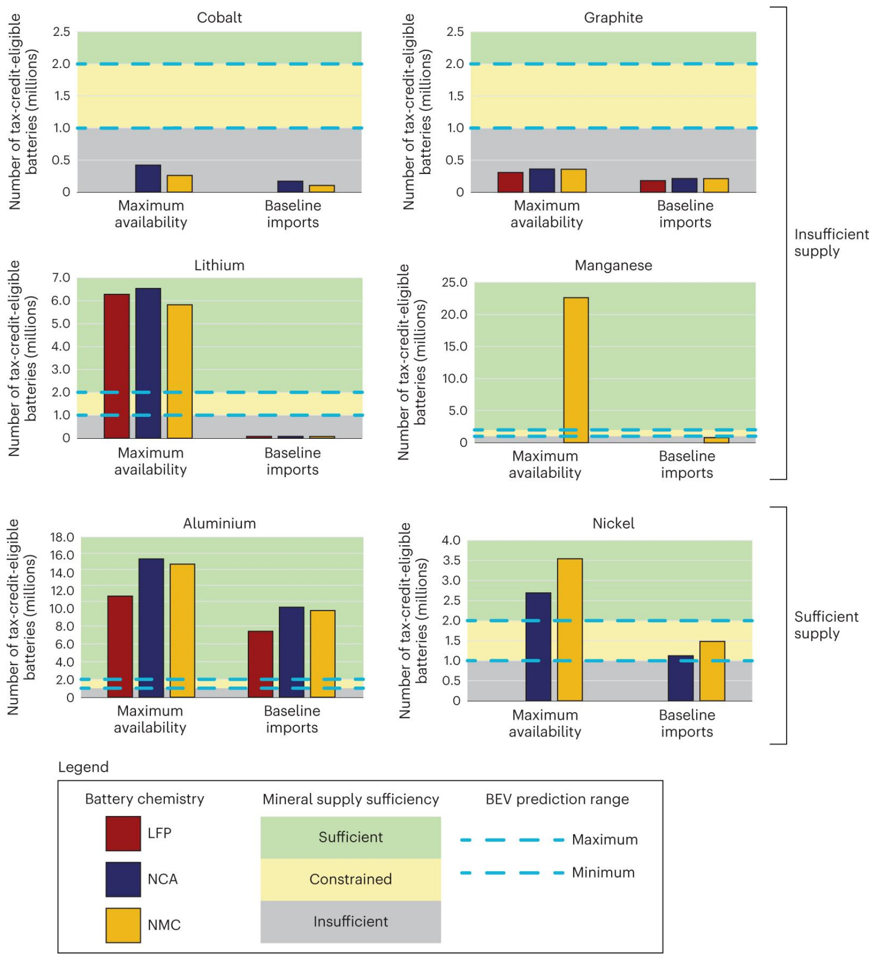


Figure 12. Critical mineral supplies based on battery chemistry [114] with NMC, NCA, and LFP chemistries are represented by blue-, yellow-, and rust-colored bars, respectively. Bars that fall within areas that are shaded in gray, yellow, or green, respectively, represent inadequate, limited, and sufficient 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 targets or market values 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 [114].

2.2. Lithium (Li) Sources

Lithium can be found in different parts of the world. Australia leads the global Li production with several mines, and brine operations have been reported in Chile, Argentina, and Bolivia (lithium triangle), with the remaining Li mining conducted in China [32]. Spodumene mines and salt brine water are the two primary global sources of Li [32]. Li projects range from traditional hard rock mining to unconventional sources, including salt brines and industrial wastewaters [32]. Extracting lithium from ores involves more resource-intensive processes like calcination, roasting, and purification, consuming 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 [115].

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) [18,116]. 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 sulfuric acid and water to transform α-spodumene to β-spodumene via roasting to obtain Li_2CO_3 [117] (Figure 13a–c).

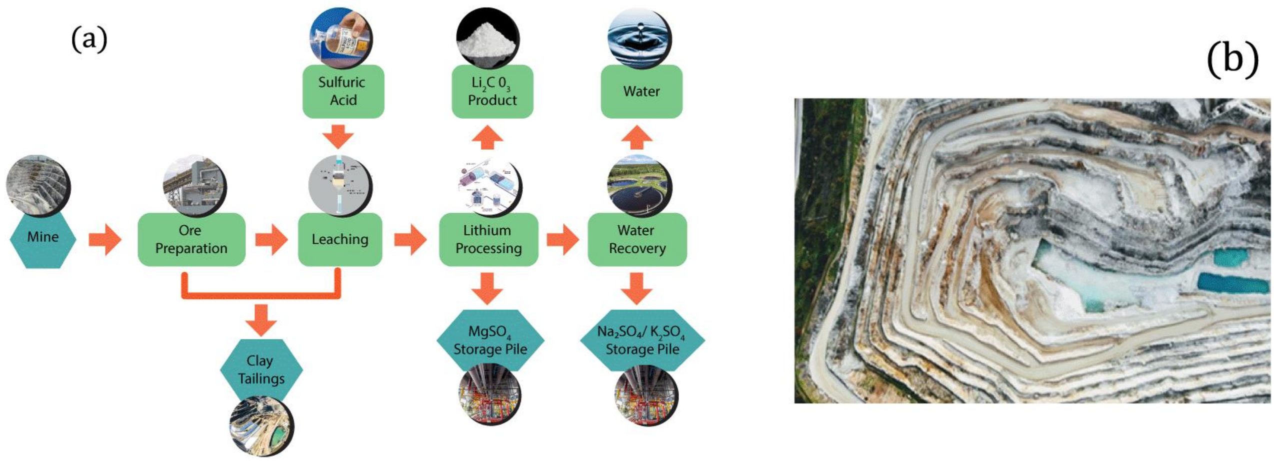


Figure 13. *Cont.*

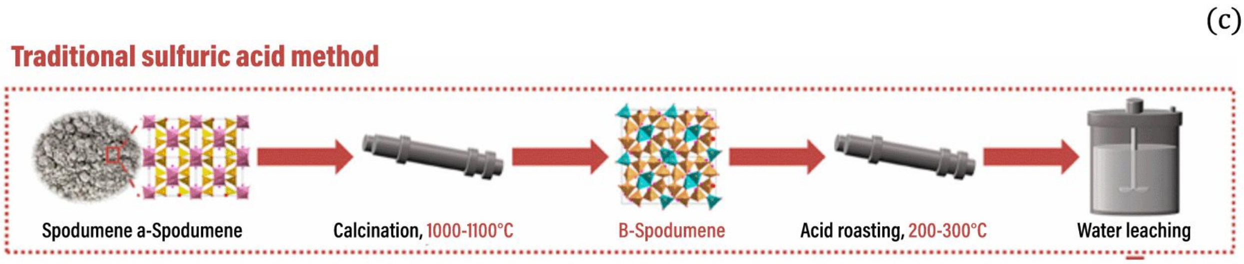


Figure 13. (**a**) Spodumene (hard rock ore mining) (redesigned) [117]. (**b**) Open-pit hard rock mining of α-spodumene [118]. (**c**) Transformation of lithium from α-spodumene to β-spodumene via roasting to achieve Li_2CO_3 [117].

Lithium is extracted from salar brine water in South American countries such as Argentina, Bolivia, and Chile [32]. 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 very low Li recovery rates. Figure 14a shows the typical extraction of Li from salar brine to produce Li_2CO_3 [119].

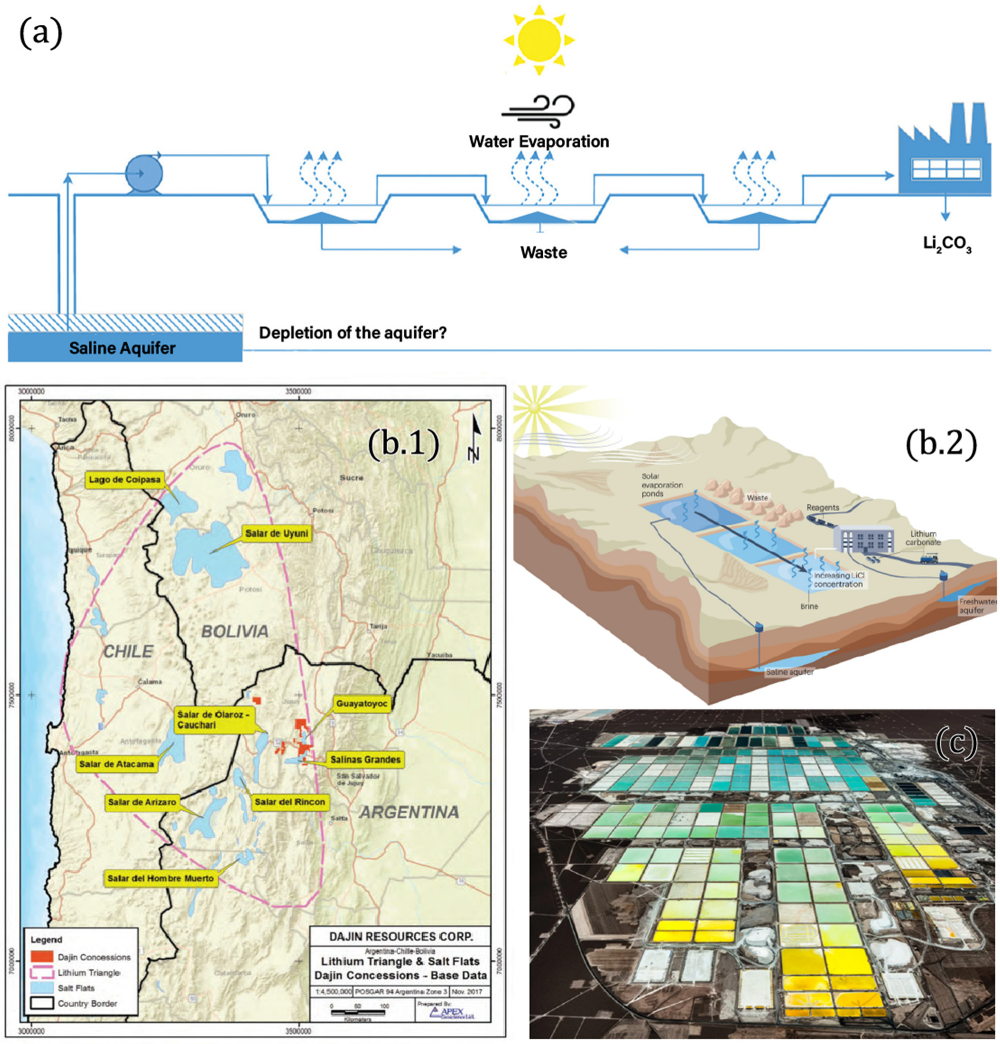


Figure 14. (**a**) Traditional Li extraction from salt brine lakes [119]. (**b.1**) "Lithium triangle" in South America (Source: ResearchGate) in a world map of lithium brine deposits. (**b.2**) Direct Li extraction from brines [120]. (**c**) Li salt brine extraction in South America [121].

Extraction of Li_2CO_3 requires large quantities of water and is a time-consuming process [122]. Salar brine deposits represent over 50% of the global Li resources [123], 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 [124]. 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 14c, suggest visual representations of various concentrations of Li as water is evaporated by the sun over time [32].

Researchers have been investigating other sources of Li because of the globally increasing demand for Li. Extracting from sea water (Figure 15) via pulsed electrochemical intercalation is another possible method of Li extraction [125], which is an interesting method to explore, as the amount of Li in sea water is 5000 times the combined amount of Li in ore- (hard rock) and brine-based resources [125]. Intercalation chemistry naturally offers high selectivity for Li owing to the higher structural activity of Li in $FePO_4$ and faster ion diffusion [126–128].

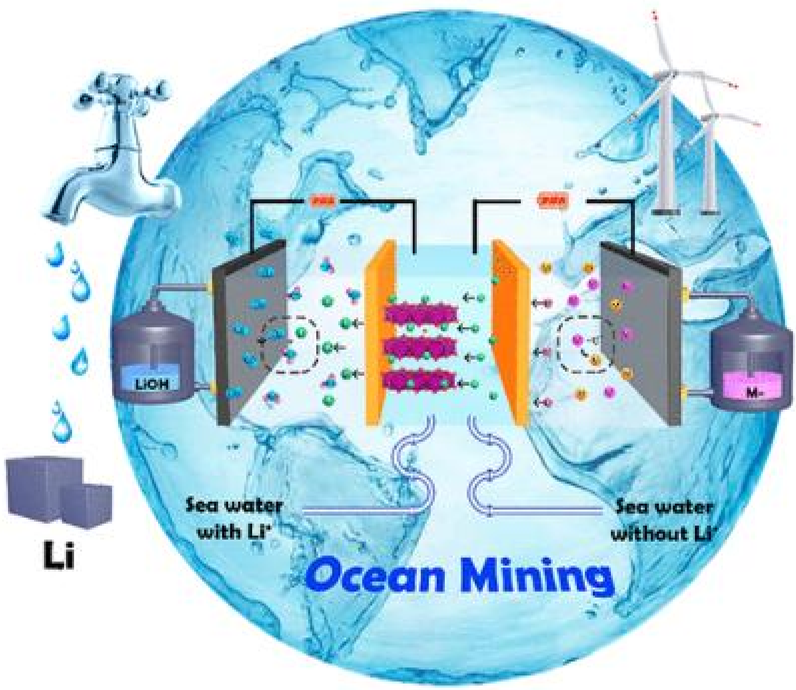


Figure 15. Extraction of lithium from sea water (purple equals sea water with Li+ and without Li+ [126].

Canada is rich in critical minerals, for instance, Li, Ni, Mn, Co, and graphite used in the syntheses of LIBs [30]. Canada is estimated to comprise 2.9 million tons of Li resources [30] (Figure 16). Advantageously, Canada is a part of the USMCA signed in July 2020 [32]. Under this agreement, the North American automobile sector can obtain critical minerals and low-cost hydroelectric power from Canada, specifically from Quebec [129,130]. 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 the extraction of lithium in comparison 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.

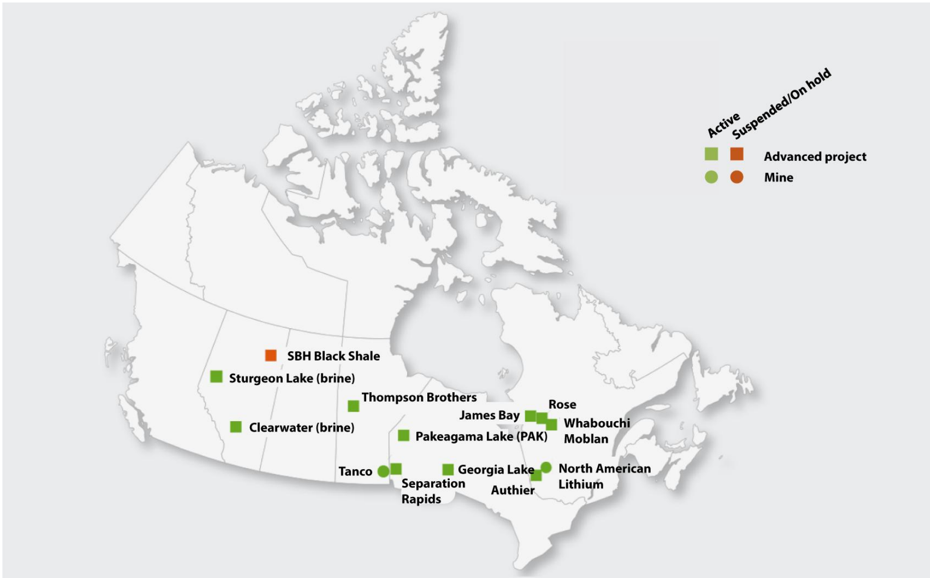


Figure 16. Canadian Li projects during 2021–2022 [32].

2.3. Nickel (Ni) Sources

Battery-grade Ni used in Ni cathode chemistries such as NMC and NCA [131] 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 [132]. Class I Ni represents 70%; whereas the other 30% comes from lower-purity Ni as matte and mixed sulfide precipitates. Lattice ore is another form of Ni and is found in countries including Indonesia, the Philippines, and New Caledonia [132]. Among 186 Ni mines operating globally [122] are located in Canada [133]. Canada produced 134,000 metric tons of Ni in 2021, ranking sixth in global Ni production [134]. In addition to Ni, Canada has other critical minerals, including Mn, Co, graphite, and Al [30] (Figure 17).

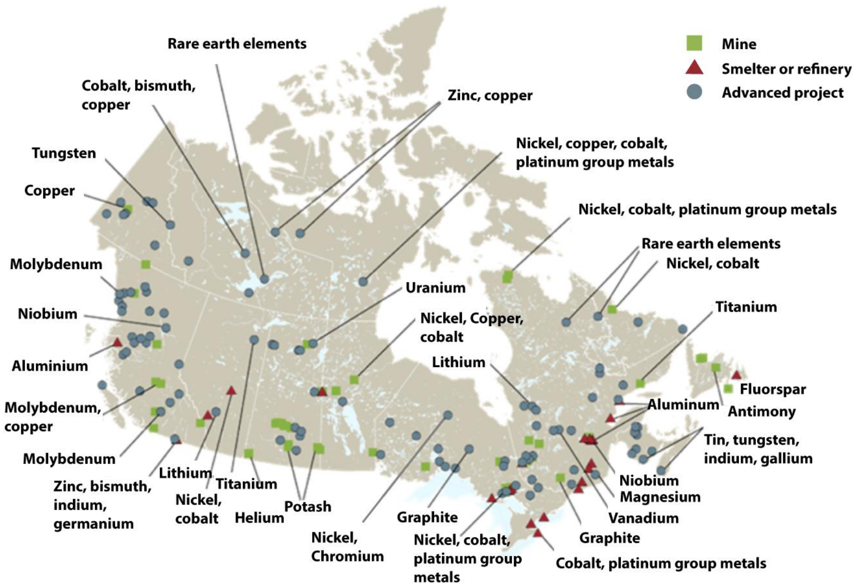


Figure 17. Critical mineral-rich regions of Canada [30].

2.4. Manganese (Mn) Sources

According to the US Geological Survey (USGS) [118], the largest Mn resources are located in South Africa [118], accounting for 74% of the global Mn resources, along with reserves in Ukraine and Brazil [135]. 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 [135]. Mn is a part of the Canadian government's critical minerals list [30] (Figure 18). The LIB cathode consists of manganese sulfate ($MnSO_4$) [136].

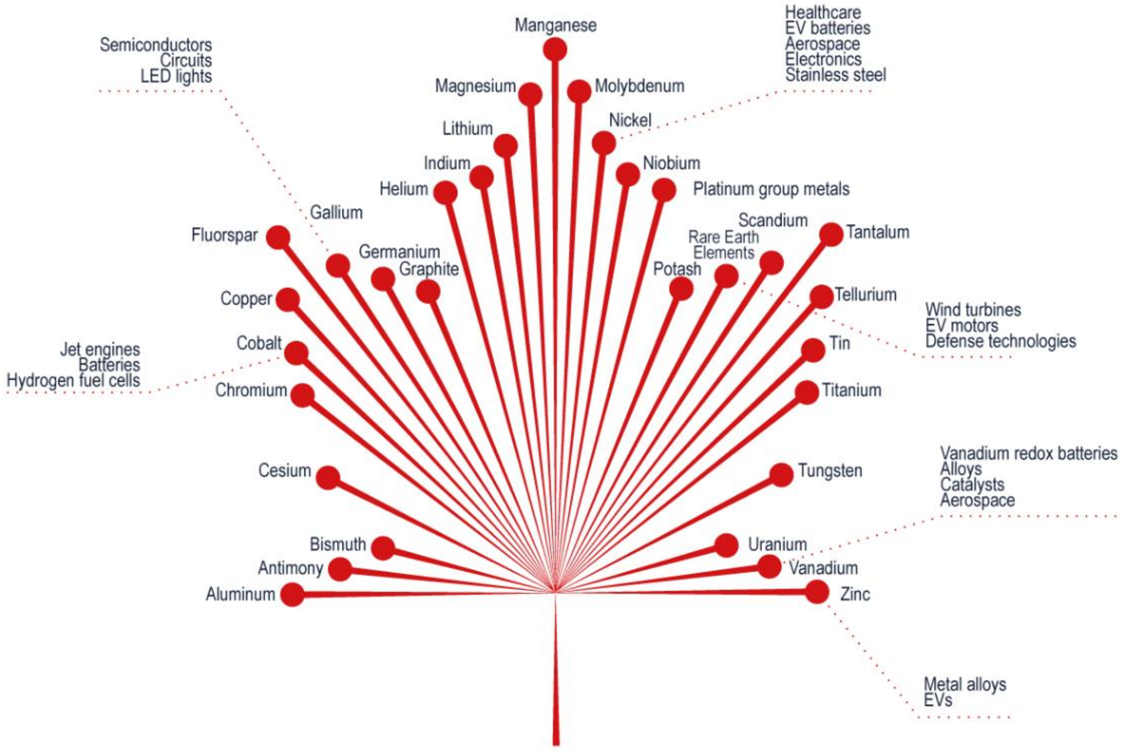


Figure 18. Canadian government critical mineral list [30].

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 EVs [137].

2.5. Cobalt (Co) Resources

Cobalt resources are mined mainly in the Democratic Republic of Congo (DRC), and according to the USGS, it represents 70% of the global production of LIBs [138], following Indonesia, Russia, Australia, and the Philippines [139]. NMC LIBs utilize cobalt sulfate ($CoSO_4$), primarily generated in China, which accounts for 80% of the global production [138]. 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 [139] (Figure 19).

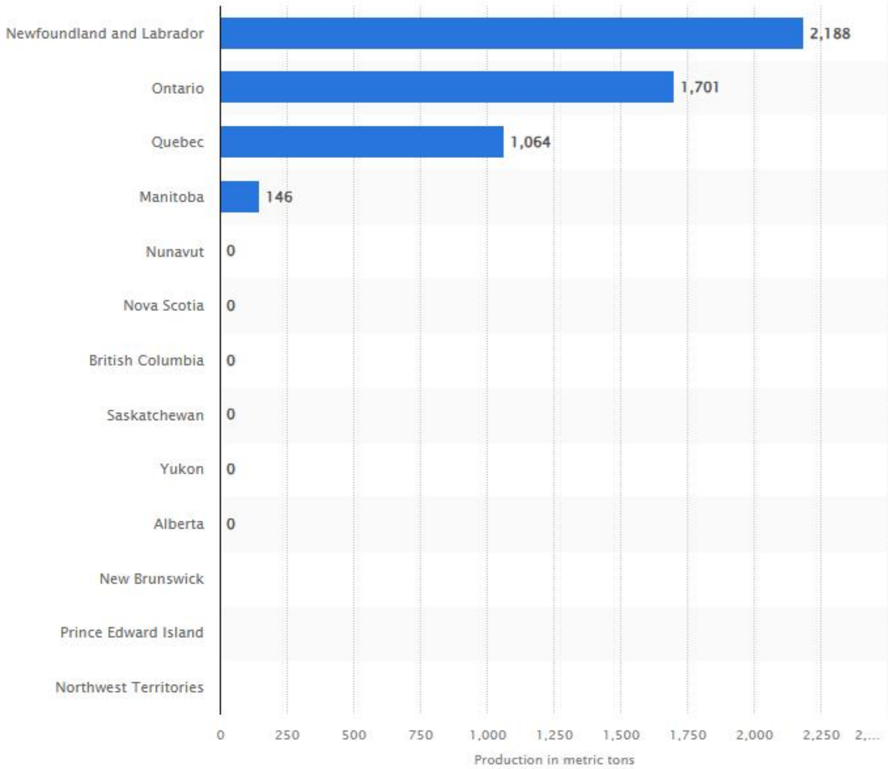


Figure 19. Cobalt production in Canada by province [140].

2.6. Aluminum (Al) Sources

NMC LIBs utilize 17–18% Al because Al represents several components [141] in the battery [138]. Al reserves are mainly present in Canada, Mexico, China, and Russia [142]. Canada produced three million metric tons of primary Al in 2022, with plants primarily situated in Quebec [143] (Figure 20). Currently, Canada is the fourth largest manufacturer of Al following China, India, and Russia [144].

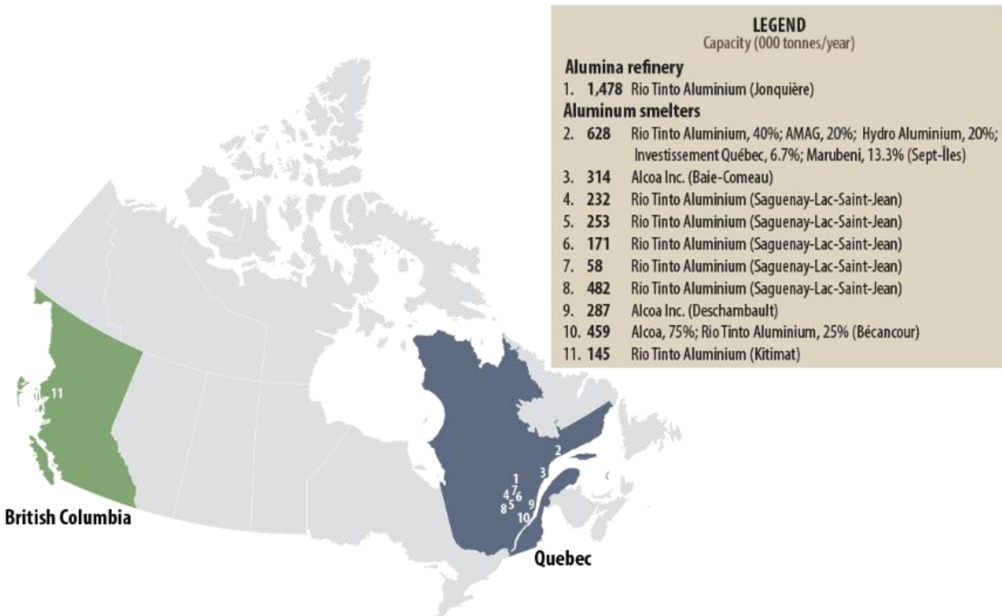


Figure 20. Alumina refinery and smelters located in Canada [144].

2.7. Manufacturing of 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 [39].

Figure 21 reveals that 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 indicates electric energy storage; (5) during discharging, Li ions move from the anode to the cathode; and (6) separator is a microporous membrane that enables Li^+ migration and prevents short circuiting.

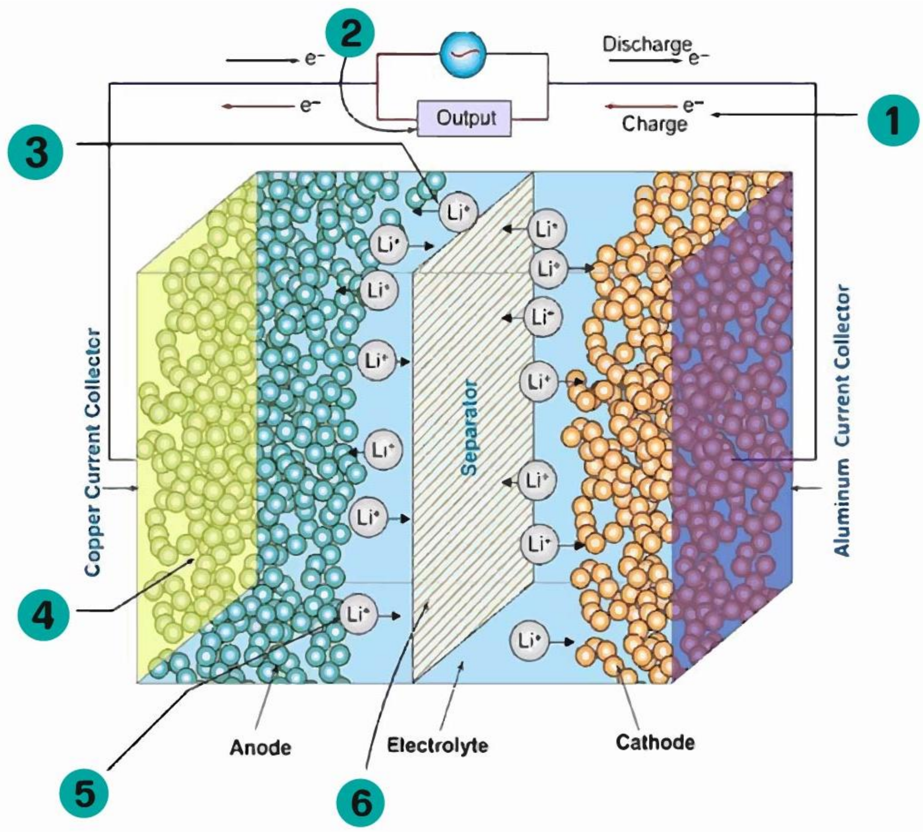


Figure 21. Basic functionality and mechanism of an LIB (redesigned) [73].

Construction of NMC cathodes requires material acquisition, transportation, distribution, and final battery assembly [145]. 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 lives can be developed by reducing the electrolyte wetting, formation, and aging times associated with LIBs [59]. 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 two 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 the standard manufacturing process of an NMC cathode [75]. 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. The drying process utilizes NH_4OH and heat.

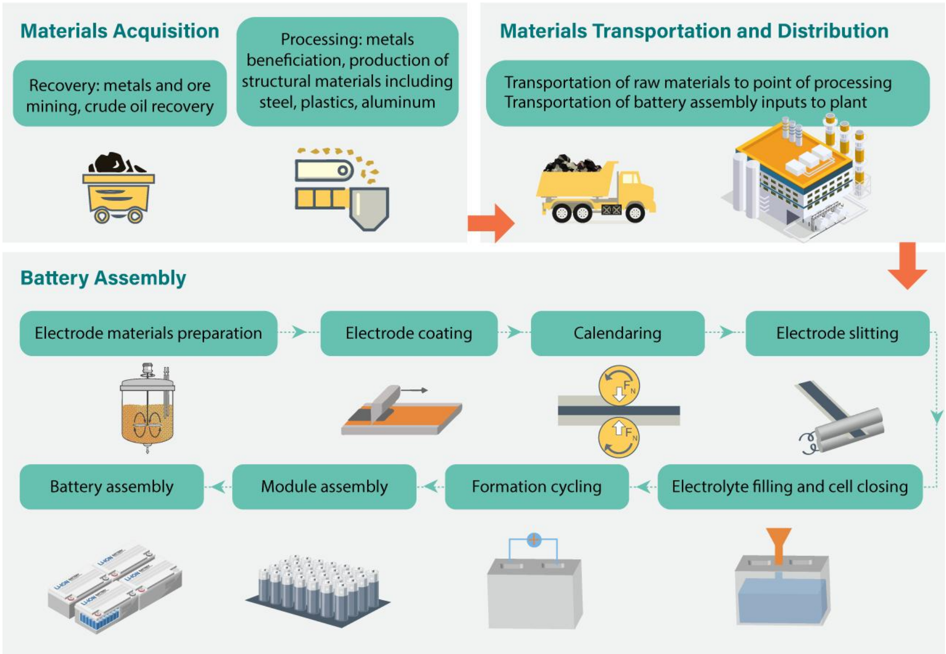


Figure 22. Battery cradle-to-gate schematic (redesigned) [145].

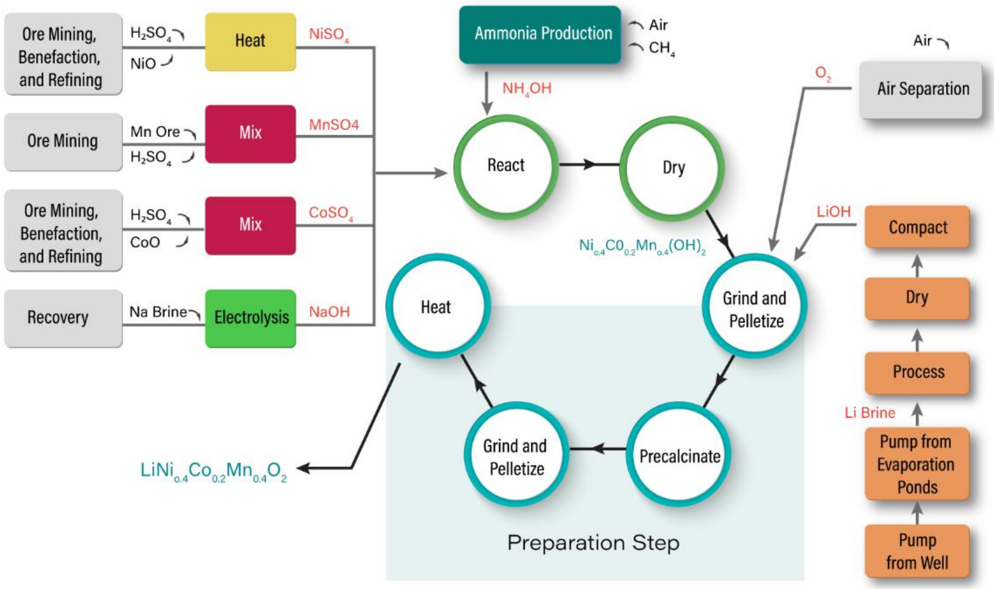


Figure 23. NMC cathode manufacturing (redesigned) [75].

2.8. 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 23). A single crystal structure and high truncation (planes) lend to higher ion transfer in NMC cathodes [49]. Storage of Li ions and adsorption of the electrolyte solution are the main functions of CAMs [146,147] (Figure 24).

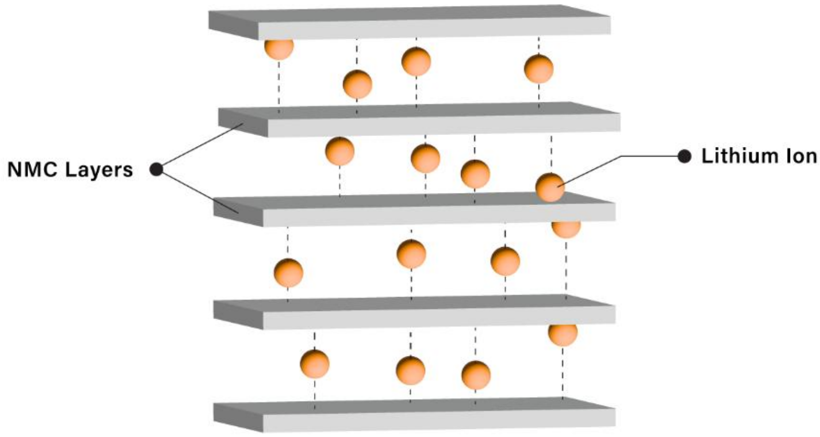


Figure 24. Li-ion transfer on NMC cathode layers.

2.9. Cell Production Mechanism

Synthesis of the Ni–Mn–Co cathode material is the first step in the preparation of NMC cathode materials [147]. NMC cathodes are fabricated by creating a homogeneous low-viscosity black slurry [87]. Production of NMC cathodes requires Ni, Co, and Mn salts and a Li source [47] (Figure 25).

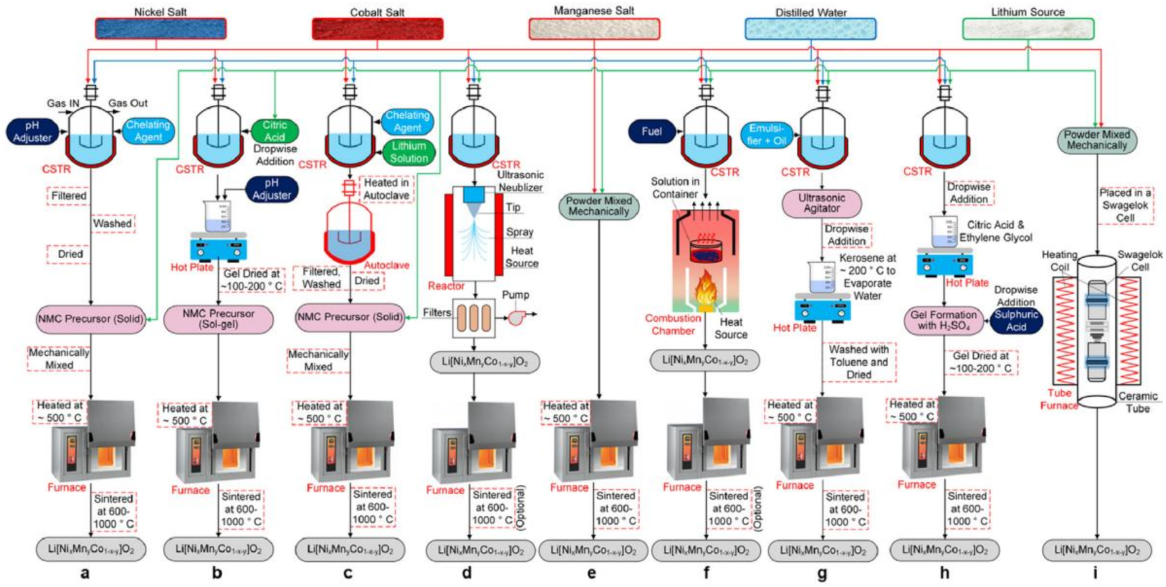


Figure 25. Synthesis of NMC cathode precursors from Ni, Co, and Mn salts [47].

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 26) to minimize material usage at the bench stage. After the coin cells are produced, their performance must be evaluated [57]. Voltage profiles, specific capacities, and electrochemical stabilities are the standard parameters that need to be analyzed [148,149].

Pouch cell production has been reported in a recent study by GMs regarding quality verification during EV LIB manufacturing [7]. 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 [7] (Figure 27).

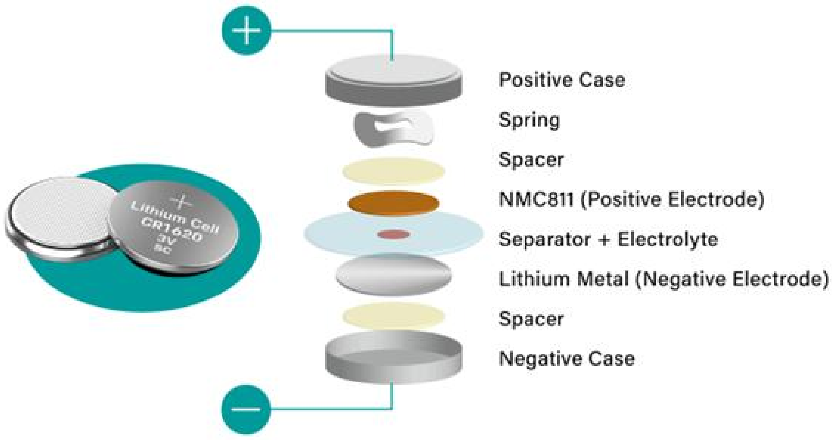


Figure 26. Schematic of a typical coin cell assembly.

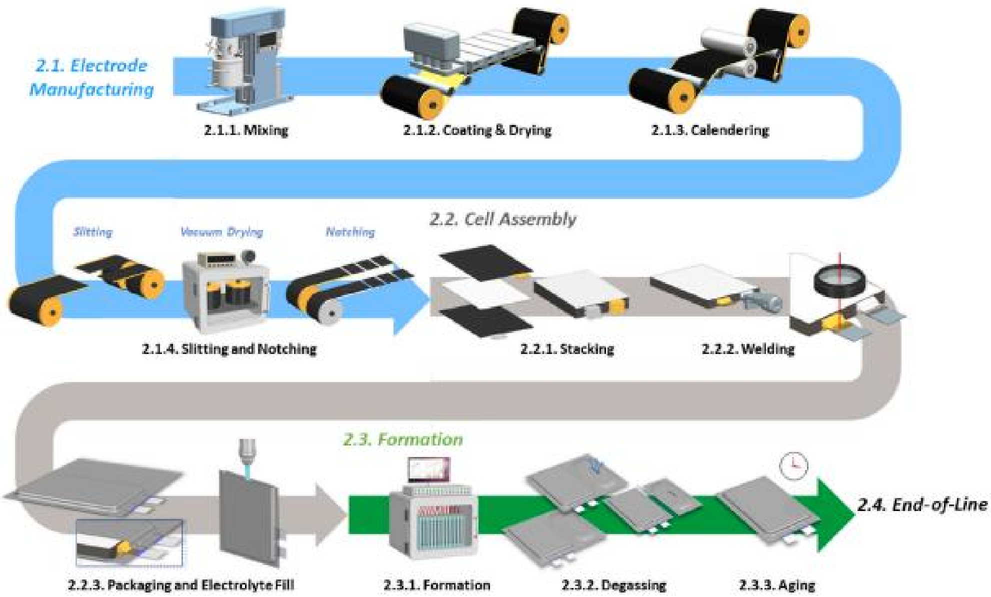


Figure 27. Typical Li-ion pouch cell manufacturing process [7].

2.10. Zero Waste

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 [150]. Zero-waste [151] processes must be incorporated into the extraction and processing of critical minerals [86].

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 is 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 [57] (Figure 28).

In Quebec, there has been a movement towards extracting and processing critical minerals with zero waste. 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 [151]. 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 [151]. 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.

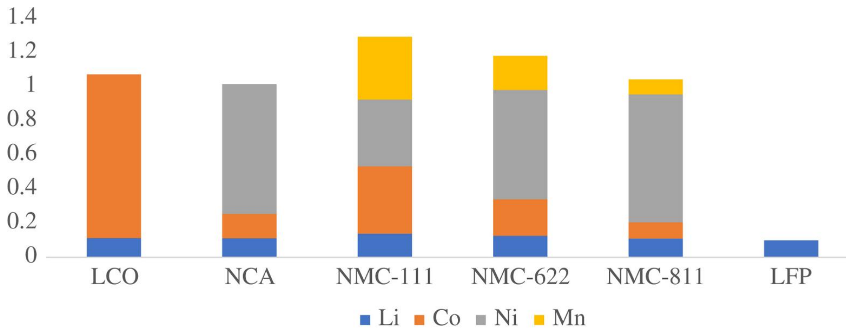
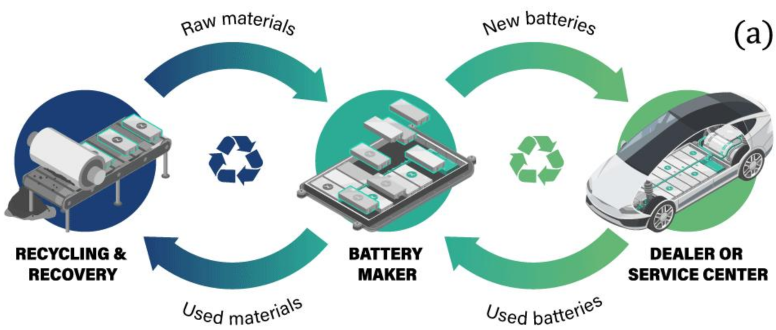


Figure 28. Amounts (kg kWh^{-1}) of Li, Co, Ni, and Mn required by various cathode chemistries [57].

2.11. Reusing/Recycling

A circular economy is essential for developing a critical mineral supply chain. Reusing and recycling [152] NMC cathodes play important roles in the supply of LIBs [153]. The automotive lead-acid battery closed-loop recycling [154] program has been very successful in North America and can serve as a model for emerging LIBs [135]. Figure 29 depicts the recycling of LIBs from EVs for creating a circular economy.



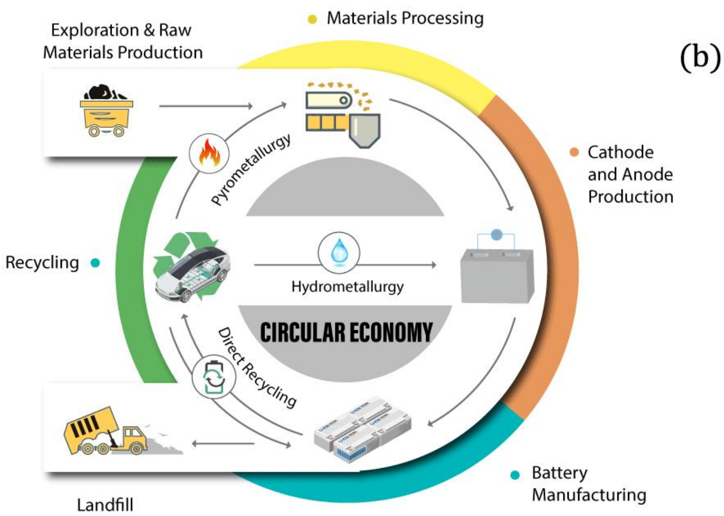


Figure 29. *Cont.*

Figure 29. (**a**) Model for closed-loop recycling (redesigned) [135] and (**b**) 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 LIB recycling that can help achieve a circular economy [155,156].

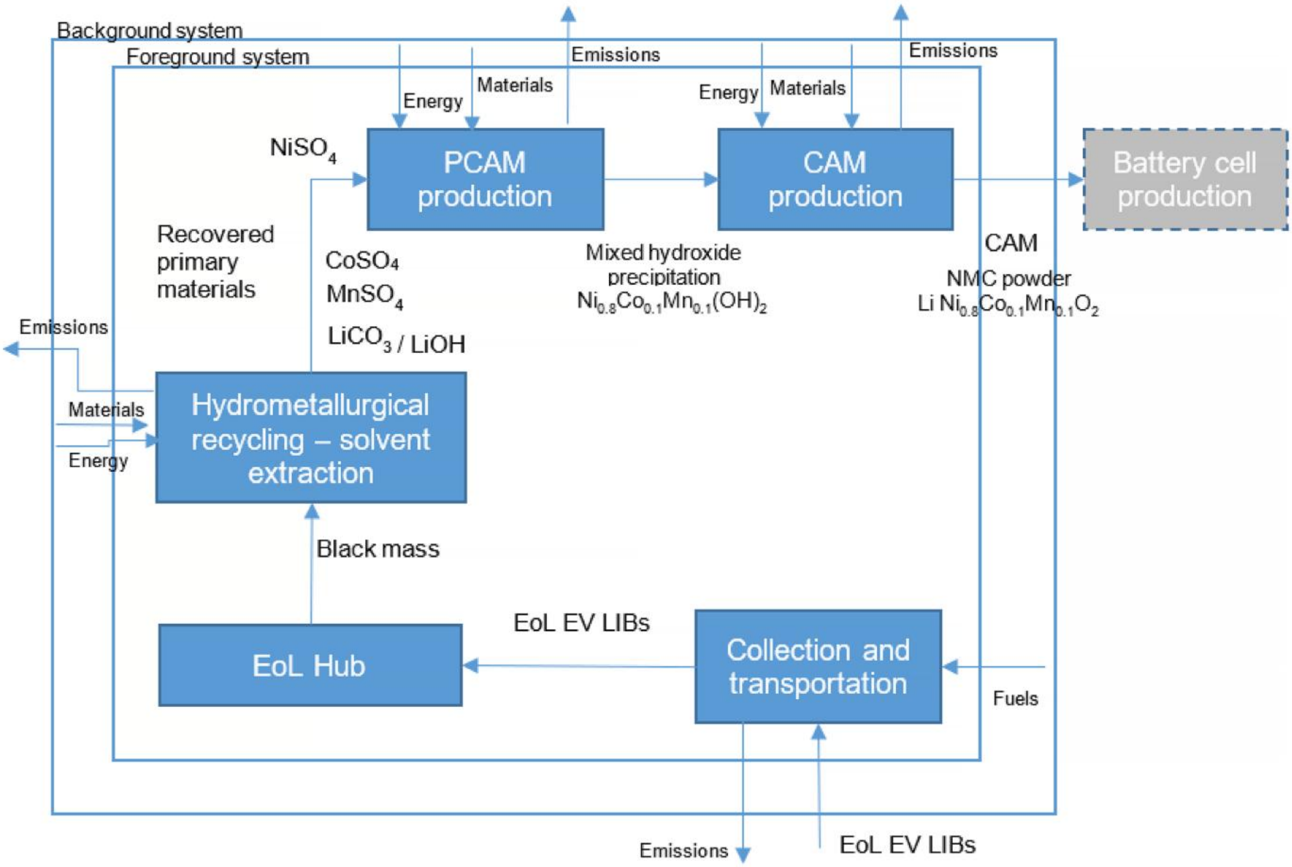


Figure 30. Standard process of NMC cathode material recycling [157].

Recycling of LIBs requires energy and produces emissions [158] 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.

2.12. Creation of New Production Facilities

With the construction of numerous battery plants in the US, Canada, and Europe, a supply of precursors, including those entering the NMC cathode, is needed. Several investments have been made in North America, setting its path to becoming the fastest-growing battery manufacturing hub [159]. Figure 31a,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 [158].

The Argonne National Laboratory (ANL) and the US Department of Energy (DOE) compiled a map of battery plant capacity (GWh year^{-1}) in North America until the year 2030 [159]. Since November 2022, many automotive companies have announced various battery pack plants in North America [160]. These plants are presented according to the battery company, location, automotive company, and production start date in Table 4.

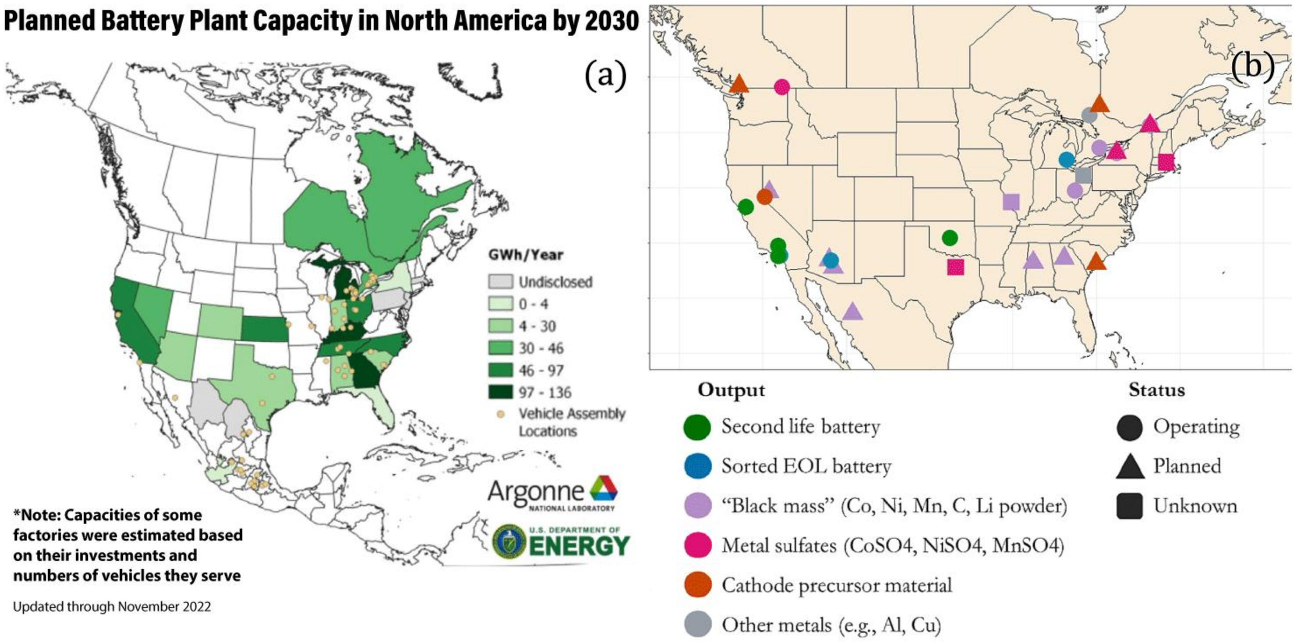


Figure 31. (**a**) Planned battery plant capacity based on state/province in 2030 GWh year^{-1}, as of November 2022 [159]. (**b**) North American LIB recycling facilities [161].

Table 4. North America's rapidly growing electric vehicle market: implications for the geography of automotive production [160].

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	GMs	TBD
LG Chem	Lansing, Michigan	GMs	2024
LG Chem	Holland, Michigan	GMs	2011
LG Chem	Lordstown, Ohio	GMs	2022
LG Chem	Jeffersonville, Ohio	Honda	2025
LG Chem	Windsor, Ontario, Canada	Stellantis	2024
LG Chem	Spring Hill, Tennessee	GMs	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

Table 4. *Cont.*

Battery Pack Plants in North America Operating and Announced Since November 2022			
Battery Company	**Location**	**Automaker Customer**	**Production Start Year**
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

Notes: TBD means to be determined. Unless indicated otherwise, the locations are within the US. BMW refers to Bavarian Motor Works; CATL, Contemporary Amperex Technology Co., Limited; Envision AESC, Envision Automotive Energy Supply Corporation; GMs, General Motors; ONE, Our Next Energy; SKI, SK Innovation; TBMNC Toyota Battery Manufacturing, North Carolina; and VW, Volkswagen. Sources: Battery company websites and Plante and Rindels (2022).

3. 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) reusing/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 LIB supply chain [135] (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 [135]. 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 [125]. In the US, the Federal Land Policy and Management Act of 1976 and the US Forest Service have been provided authority over hard rock mining.

The EV industry is a multi-stakeholder industry with agencies working on the definitions of waste, reuse, and manufacturing [135]. Accessing critical minerals such as nickel (Ni), cobalt (Co), manganese (Mn), and lithium (Li) in an environmentally sustainable manner [161] 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 [101]. 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 oxide (SO_x), nitrogen oxide (NO_x), and particulate matter (PM).

NMC cathode production accounts for 50% of the GHG emissions of NMC LIBs [138]. Synthesis of the active material for an NMC cathode (NMC111 LIB) constitutes 40% of the water consumption [138]. During the evaluation of the environmental effects of NMC cathode production, the focus should be on CAMs (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 [138]. 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 [138]. 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 LIBs [138]. 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 manufacturing in a few countries, mainly DRC [162]. 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 [86,163]. 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 [163,164]. Increased cost may be associated with higher nickel content due to the addition of clean room, infrastructure, and energy [165].

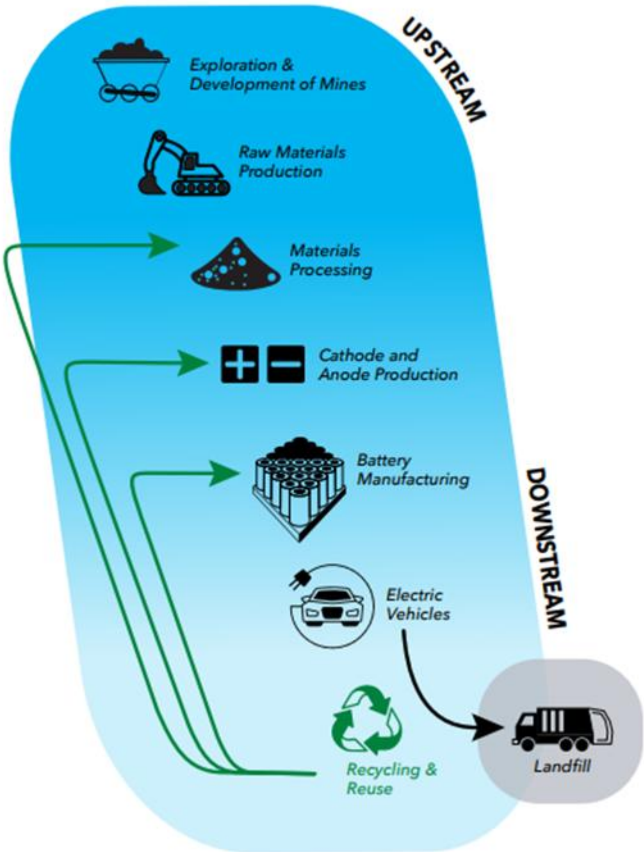


Figure 32. Mine (upstream) to electric vehicle (downstream) material flow [135].

Table 5. Sample CO_2 emissions from different processes [101,130,138].

Reference	Process Parameter	CO_2 Emissions (kg CO_2 Eq/kg)
[94]	NMC emissions (virgin raw material)	8.9
[129]	$CoSO_4$ (cathode active material; (pCAM))	6.73
[129]	$NiSO_4$ (pCAM)	8.61
[120]	Electricity power (concrentration plant) to produce LiOH monohydrate (raw material) from spodumene	0.00254
[120]	Electricity power (electrochemical plant) to produce LiOH monohydrate (raw material) from spodumene	0.01095
[120]	Natural gas (electrochemical plant) to produce LiOH monohydrate (raw material) from spodumene	1.861

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 [138,166–168]. 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 [136,138,167,169,170]. 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 [136,138,166]. 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 lowering SO_x emissions [138,167,169,170]. With an increase in the Ni content of batteries (for instance, NMC532, NMC622, and NMC811 batteries), water consumption consistently decreases during battery production as compared to those in the cases of lower-Ni batteries (NMC111 LIBs) [138,166,171]. Limited data are available on the environmental effects related to air emissions and water use for NMC (virgin raw material and CAMs), which are provided in Table 5.

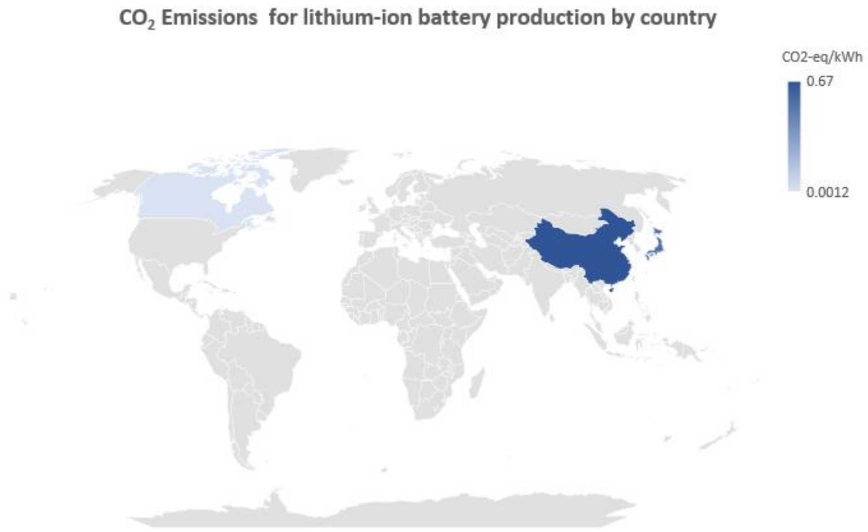
Table 6 presents the data for CO_2, SO_x emissions, and water consumption for various types of NMC cathodes (NMC111, NMC532, NMC622, and NMC811) [94,120,129]. The water consumption of LIB production using NMC111 is 43% higher than that using LFP.

Table 6. CO_2, SO_x, and water consumption [101,130,138].

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
[120,129]	NMC811 Assembly of single lithium-ion battery	55.1	141.5	142%	12%	
[129]	NMC111	59.1			44%	
[129]	NMC532			130%	28%	
[129]	NMC622			130%	27%	
[120]	(LIB)		141.5			
[94]	NMC cathode (recycling; hydrometallurgy)					>23%
[94]	NMC cathode (recycling; pyrometallurgy)					0%

Comparison of CO_2 emissions generated from LIB production in China, Japan, Korea [138], and Canada (Quebec) [130] 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 [130]. 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 [130] results summarized in Table 7.



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 the country [131,139].

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 [130].

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)	7610 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	1861.14 kg CO_2
Total	69.21 GJ	1874.63 CO_2

3.1. 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 [172]. The US and Canadian governments are seeking to establish new regulations governing the transportation, storage, and fabrication of LIBs in the automotive industry [173]. With the introduction of more EVs into the market, the US government is working to set stricter standards for the quality, safety, and performance of LIBs [135].

3.2. Consumer Demand

Consumers are starting to adopt EVs over traditional ICE vehicles because of the low costs, high driving ranges, and lower 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 [174].

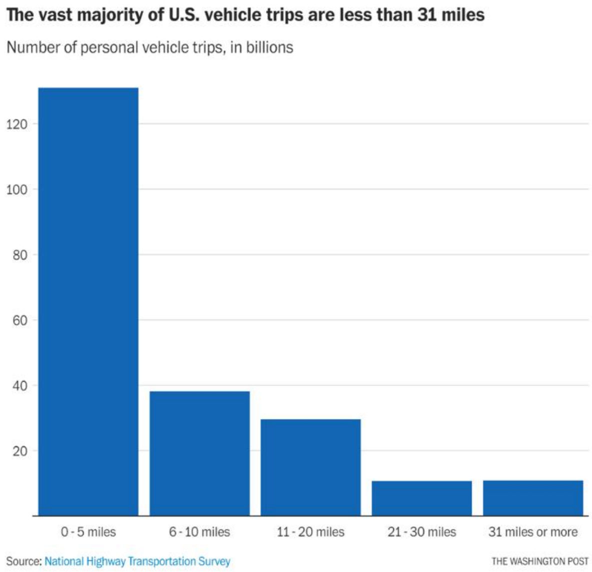


Figure 34. Average vehicle trips in the US [174].

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

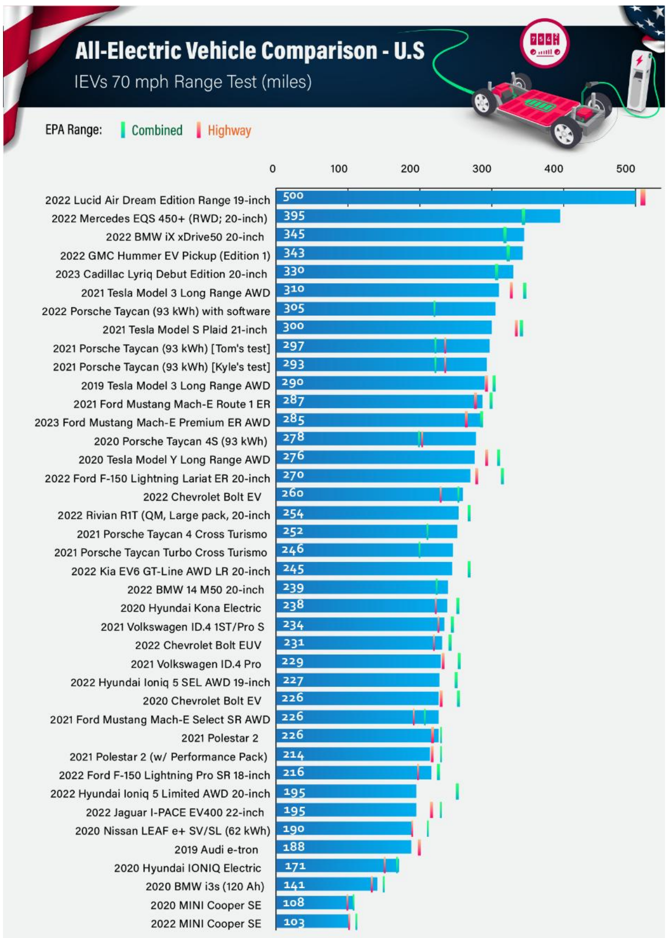


Figure 35. Driving range of electric vehicles currently being sold in the US (redesigned) [175].

3.3. 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 [176]. Many parts of the world have set climate change targets to reduce GHG emissions via EV adoption [177]. The shift from ICE vehicles to EVs is a means of decarbonizing the transport sector [178]. 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 [179]. Table 8 provides the initiatives undertaken in Canadian mines via the adoption of fully electrified vehicles.

Table 8. Canadian mines that have adopted fully electrified vehicles [179].

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	Entire fleet of Epiroc battery–electric mining equipment (scoop tram loader, Minestruck 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	Twelve 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

3.4. 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 [180] (Figure 35. Presently, the materials employed in LIBs are obtained from outside North America, with 74% of these materials originating from China, Africa, and Latin America [101]. 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 [181].

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 [182]. In Canada, considerable emphasis is being placed on the acquisition of a "green battery" constructed in Quebec [183]. To establish a sustainable LIB supply chain, various environmental parameters must be considered [184]. The following table presents the historical data of these environmental parameters for China, Japan, and Korea [138]. NMC cathode preparation accounts for 50% of the GHG emissions of an NMC LIB [138]. Production of the active material for an NMC cathode (NMC111) constitutes 40% of the total water consumption [138].

Ni, Co, and Li precursors as CAMs should be considered during the evaluation of the environmental effects of NMC cathode production [83]. Reduced water consumption was detected for a higher-Ni cathode because Co processed in DRC is treated using hydroelectric power [138]. 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 a new battery plant "Giga factory" [185] in Quebec.

4. Battery Passport (Future Perspectives)

With the global increase in demand for critical minerals, the development of a system that recovers EV LIB materials is crucial [182]. Many recommendations have been made to develop a circular economy [186] by the recovery of LIB critical minerals and other materials and creation of a battery passport [187] (Figure 36). The idea of a battery passport is to facilitate the tracking of several components of LIBs and LIB packs (Figure 36).

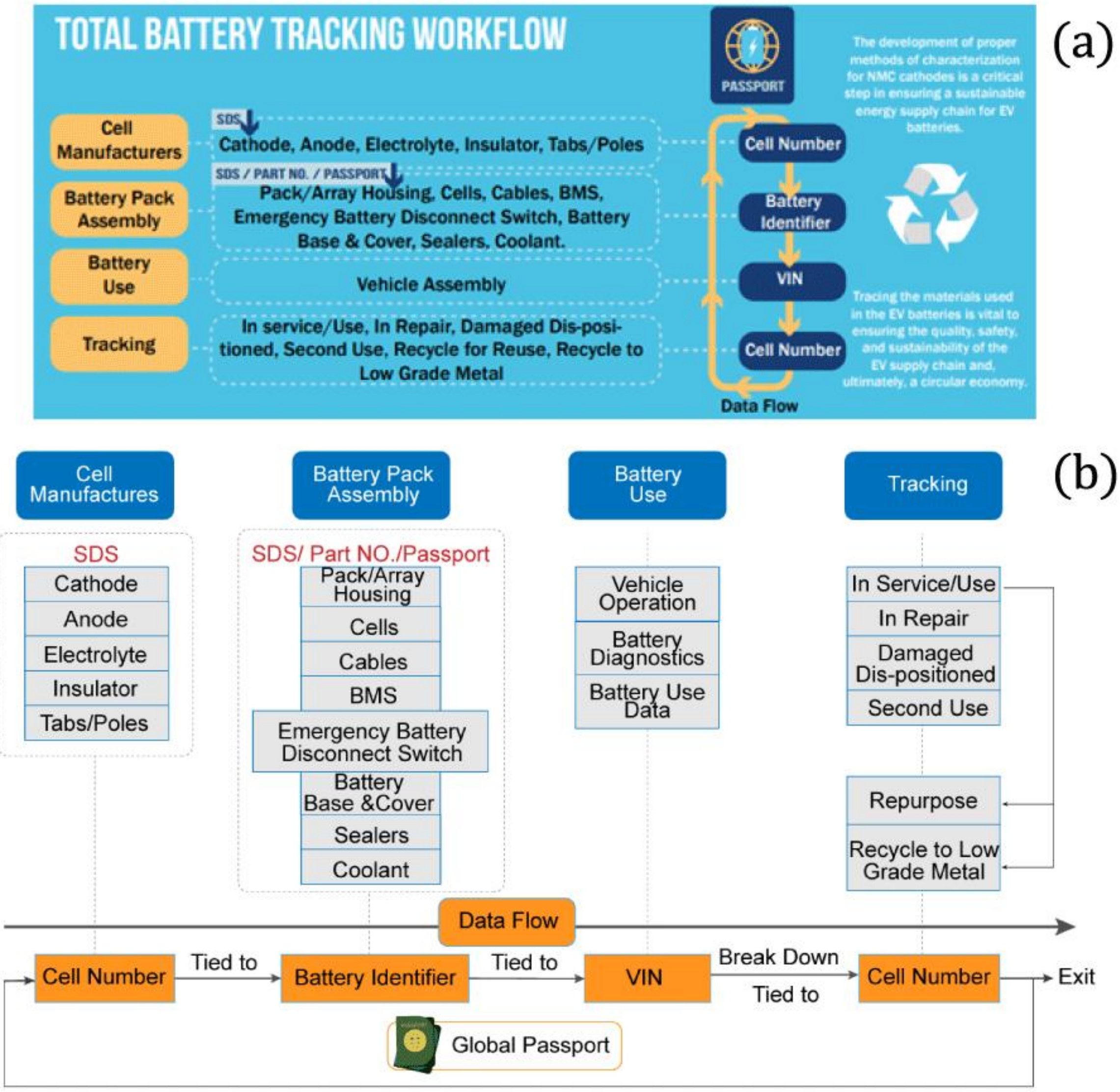


Figure 36. Battery traceability "passport" portion of the poster presented (**a**) overview and (**b**) detail view (Vegh et al., 2023; Concordia University; Chemical and Materials Engineering Department) at International Workshop on the Characterization and Quantification of Lithium, from Mirco- to Nano-Scale, from Mining to Energy; Paris, June 2023 [1]. Proposed "battery passport" from cell to pack to vehicle to end-of-life.

Suggested flows (cell to pack to vehicle to end-of-life) have been presented to the North American automotive industry [188] (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.

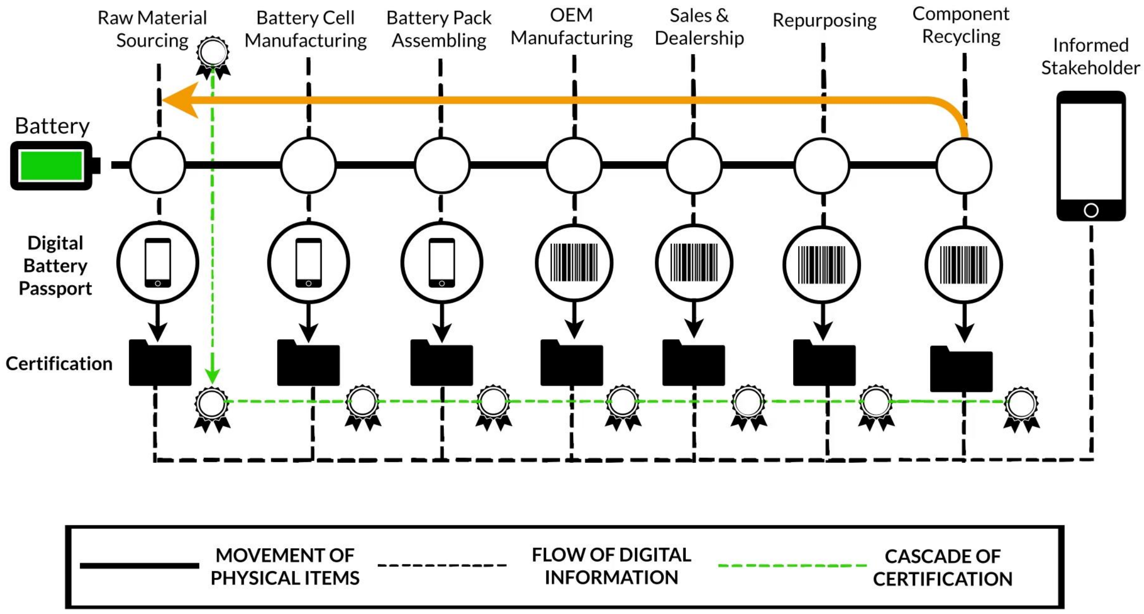


Figure 37. Proposed method for digitizing the LIB cell data "Big data" via blockchain.

Considering the volume of information (big data of individual cells/pack), digitization of data via blockchain [189] has been recommended as a format to track LIB materials [190] (Figure 37).

5. Conclusions and Perspectives

Presently, hundreds of billions of dollars (USD) are being globally invested by the automotive industry [2]. 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 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 [78]. 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 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 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 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.

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