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POLICY IMPLICATIONS OF EV BATTERY UNCERTAINTY UNDER CANADA'S EV AVAILABILITY STANDARD

A Material Flow Modelling Approach

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Policy Implications of EV battery uncertainty under Canada's EV Availability Standard: A material flow modelling approach

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Abstract**:** It is generally assumed that Electric vehicles (EVs) will play a critical role in decarbonizing the light-duty vehicle sector globally. Government policies are helping to drive this transition. At the same time, there is growing awareness of the critical mineral and broader material demand implications of scaling EV and other low-carbon technology adoption as global decarbonization efforts ramp up in the coming years. In this study, we aim to address how different assumptions around the future chemistry, size, and lifespan of competing EV battery technologies influence the magnitude, composition, and timing of EV battery material demand and waste if Canada is to meet its target of no new internal combustion engine vehicle sales by 2035 (as per Canada's new EV Availability Standard). To do so, we develop a novel material flow model to assess EV battery material requirements for the fleet of light-duty EVs in Canada under the Electric Vehicle Availability Standard and explore different future EV battery technology adoption pathways and different consumer choices over types of EVs and vehicle size classes. We then discuss policy linkages that stem from this modelling analysis and provide preliminary insights to inform policymaking related to the broader critical mineral demands and environmental impacts of decarbonizing the light duty vehicle segment in Canada.

Introduction

Electric vehicles (EVs) are assumed to play a critical role in decarbonizing the light-duty vehicle sector globally, with battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) expected to dominate the light-duty zero-emission vehicle (ZEV) market in the coming decades. Government policies are helping to drive this transition. For example, the Canadian government has committed to the Electric Vehicle Availability Standard, a regulation mandating a rising share of ZEVs in the sales of new light-duty vehicles. Current sales requirements include 20% ZEVs by 2026, 60% by 2030, and 100% by 2035 (Transport Canada, 2024).

While this rapid shift to EVs (BEVs and PHEVs) is crucial for achieving decarbonization goals, it is important to recognize and understand the environmental impact of the lifecycle of these technologies to inform ongoing policymaking. Compared to internal combustion engine vehicles, EVs require more materials per unit of service provision, and they also include many globally important metals and minerals in their battery construction, including critical minerals (CMs)

(Zhang et al., 2023; Shaffer et al., 2021). Given the anticipated surge in EV demand globally, there are concerns about the environmental impacts of battery material demand and waste, as well as the current limited availability of CMs used in EVs and other low-carbon technologies (Zeng, et al., 2022; Hund et al., 2020).

A growing number of studies in both academic and grey literature assess the material footprint of the low-carbon transition (Wang et al., 2023; Deetman et al., 2021; Hossaini et al., 2021), and more specifically, quantify the stock and material flows of EV batteries (Tarabay et al., 2023; Xu, et al., 2023; Xu et al., 2020). However, there is currently limited research on the potential future material flows of EV batteries in a Canadian context. Consequently, the likely battery material demand and waste outcomes of key EV adoption policies such as Canada's Electric Vehicle Availability Standard are unknown.

This lack of understanding makes it difficult for planning and policymaking at both the material demand and waste sides of the EV lifecycle. Governments looking to reduce battery material demand need to understand how different policy levers can influence this metric. Similarly, governments looking to tackle EV battery waste through recycling need to be able to predict future waste volumes in order to gauge when recycling operations will become feasible, planning investments and policymaking accordingly.

One way that governments can impact EV battery demand and waste is by influencing the chemistry, size, and lifespan of the EV batteries used within their borders. Different battery sub-chemistries require different relative and total levels of CMs, resulting in variable demand and waste profiles (Quan et al., 2022). Battery size, which can be influenced by vehicle size or the type of EV (e.g. BEV vs. PHEV), has a direct influence on total material requirements (Richa et al., 2014). Battery lifespan in the context of secondary use periods extends the use-period of a battery, delaying the timing of waste (Haram et al., 2021). Understanding how these EV characteristics shape the magnitude, composition, and timing of demand and waste is essential to inform government policy in the near-term, as they impact future demand and waste outcomes and, therefore, the overall sustainability of Canada's electromobility transition.

In this study, we aim to address the research question: In meeting Canada's Electric Vehicle Availability Standard, how do assumptions around the future chemistry, size, and lifespan of EV batteries influence the magnitude, composition, and timing of EV battery material demand and waste? We use an EV battery material flow model to assess battery material demand and waste for the fleet of light-duty EVs in Canada to 2050 under the Electric Vehicle Availability Standard. We next project total EV battery demand and waste under standard conditions and then assess how these outcomes change under different EV characteristic assumptions. We then discuss the relevant policy linkages that stem from this modelling analysis and provide preliminary insights to inform policymaking related to EV battery value chain in Canada.

We focus on three primary metrics in our assessment—the magnitude, composition, and timing of mineral demand and EV battery end-of-life (EoL) flows—because they each hold unique influence over the management of EV battery EoL flows and are, therefore, essential to informing policy development. We also assess the potential for recycled material to offset primary demand for key CMs in Canada in the light-duty transportation sector, which again are critical for understanding the potential impact of the Canadian EV Availability standard and its potential ties to other complementary climate policy measures for decarbonizing light-duty vehicle transportation.

Background

While there is an urgent need to meet decarbonization objectives and address climate change, zero-emission technologies, such as EVs, create material demands that pose sustainability concerns both up and downstream. Thus, policymakers must balance sometimes competing objectives in order to successfully implement policies that move sectors such as personal transport rapidly towards decarbonization while also addressing material demand and waste issues, particularly for CMs (Niri et al., 2024). Quantitative modelling, such as the material flow modelling used in this study, is an essential tool for aiding policymakers in better understanding the complexities of policies aimed at addressing climate change and broader sustainability concerns.

Upstream, the expansion of extraction and production activities for in-demand EV battery CMs poses significant sustainability challenges. Lead times for new mines can span decades, and the procurement of specific supplies entails geopolitical risks (Wang et al., 2022; Umbach, 2018). Ethical and human rights issues also surround the current value chains of low-carbon technologies and CMs (Wang, 2023a). Recent findings further underscore that over half of the global resource base for minerals and metals essential to the energy transition is situated on or near the lands of Indigenous and peasant communities—two groups historically marginalized and subject to discrimination (Owen et al., 2022; Parlee, 2015).

On the opposite side of the value chain, EoL EV batteries generate significant waste streams that require sustainable management. Presently, there is minimal focus in climate and decarbonization policy discussions on encouraging material recovery or minimizing waste produced by low-carbon technologies at their EoL (Niri et al., 2024; Duran et al., 2022). This represents a considerable policy gap and missed opportunity as recovered materials can function as inputs for manufacturing, offering a supplementary domestic source of important minerals, including CMs. This process has the potential to address the uneven distribution of mineral reserves and enhance energy and materials security by reducing dependence on imports (Heath et al., 2020).

The development of cost-effective recycling technologies could establish recycled materials, also known as secondary materials, as a stable, low-cost resource, contributing to the stabilization of material prices and potentially reducing technology costs (Bai et al., 2020). Recent research has suggested that recovering cobalt from EoL EV batteries, for example, is more cost-effective than primary extraction (Mansur et al., 2022).

However, while the recycling of minerals is anticipated to increase in upcoming decades, research suggests that it will only partially offset the rising demand for CMs (Tarabay et al., 2023; Hossaini et al., 2021). Several barriers limit the potential of secondary CMs to satisfy growing material demand. The recycling of EoL EV batteries is still in its infancy and increased recovery rates are low due to several impediments such as economic barriers, science and technology gaps, regulatory barriers, and logistics and sorting issues (Bai, et al., 2020). Fluctuations in the price of raw materials and significant uncertainty regarding innovations in new battery chemistries both pose a risk to the economics of recycling (Bai et al., 2020; Mitch, 2019). Moreover, a lack of established collection infrastructure, high costs of transportation—particularly prevalent in nations like Canada with large geographical distances between urban centres—and stringent regulatory constraints surrounding the storage and transport of EV batteries act as major barriers to increased recycling (Hossaini et al., 2021; Slattery et al., 2021).

Because secondary materials will only partially offset demand, primary material extraction by the metals and mining sector will persist as a necessity (McCarney et al., 2021). Just as government policy is needed to streamline battery waste management, so too is policy needed for reducing battery material demand and thereby primary material extraction. Demand-side measures that reduce total travel demand or shift people toward active and public forms of transport will reduce the demand for personal vehicles, lowering demand for EV battery CMs. Other demand-side measures could also influence key EV characteristics such as battery chemistry, size, and lifespan, and in doing so, they could directly influence the magnitude, composition, and/or timing of EV battery demand and waste. We describe these key EV characteristics, as well as how they can be impacted by policy, in more detail below.

Battery Chemistry

While the future market penetration of different EV battery technologies is highly uncertain, Lithium Nickel Cobalt (NCX), Lithium Iron Phosphate (LFP), Lithium Sulphur and Lithium Air (Li-S/Air) are three classes of battery chemistries that experts believe could dominate the market in the coming decades (Reuters, 2020; Cano et al., 2018). Understanding the outcomes of different battery chemistry market share scenarios is vital as each technology has its unique total quantity and mix of CMs, thereby resulting in distinct recycling requirements and potentials. Research, for example, shows that the amount of cobalt in EoL batteries significantly affects the economics of recycling (Dunn et al., 2022).

Battery chemistry market shares can influence both the magnitude and composition of demand and waste. These market shares influence magnitude because different battery chemistries vary in their total material requirements. Li-Air batteries for example have approximately 10% the material requirements of LFP or some NCX chemistries (Zackrisson et al., 2016). Understanding magnitude is important as it directly impacts the amount of primary mineral extraction and scale of recycling operations required to manage EoL EV battery waste.

The composition of EoL battery flows pertains to changes in the relative quantities of CMs present in discarded EV batteries. Analyzing composition is essential as different CMs require distinct recycling processes (e.g., pyrometallurgical, hydrometallurgical, direct recycling). Understanding the CM composition enables the identification of required recycling infrastructure and informs the quantity of different secondary materials that may become available to offset primary demand of different CMs over time. LFP, Li-Air, and Li-S batteries for example contain no nickel or manganese, whereas in the NCX family of batteries, these elements are key components. These differences lead to different mineral extraction and recycling needs.

Battery Size

There are two important EV characteristics that influence the size of the battery, and both influence the magnitude of CM demand and waste. The first is the market share of BEVs versus PHEVs. BEVs contain larger batteries than PHEVs, and with all other things being held equal, will therefore result in a greater magnitude of material demand and waste. Recycling complexities exist with PHEVs as well due to their smaller battery size and interaction with internal combustion engine components.

The second characteristic is the market share of different vehicle size classes. Quite simply, larger vehicles require larger batteries to power them. Vehicle size, therefore, directly impacts the magnitude of demand and CM waste flows, and an understanding of this relationship is crucial for assessing the scale of recycling needs and guiding investments in waste management infrastructure.

Battery Lifespan

There are two primary characteristics that influence the usage timeline of battery, and both directly influence the timing of EoL waste. The first characteristic is the in-vehicle lifespan of a battery. While the average lifespan of internal combustion engines is well understood, the lifespan of EVs is more uncertain, especially with ongoing chemistry innovations (Haram et al., 2021). Longer in-vehicle battery lifespans defer EoL flows, potentially reducing the immediate need for recycling infrastructure, whereas shorter lifespans may accelerate waste generation, while also potentially increasing near-future volumes of secondary materials to offset primary demand.

The second battery lifespan metric is the length of a second-life period. When an EV is retired, there is potential for the battery to enter a second-life period where the battery is reused or repurposed for other uses, such as for stand-alone energy storage. Repurposing batteries for secondary uses extends their useful life, delaying waste flows and the availability of recycled materials to offset primary demand.

While second-life periods can be influenced by government policy through instruments like regulation and infrastructure investments, it is more difficult to directly influence in-vehicle lifespan. This characteristic is largely a function of technological development and innovation, which can potentially be influenced in the long-term through R&D, although it is difficult to quantify direct impacts. For these reasons, we only evaluate second-life period assumptions in this study and do not assess in-vehicle battery lifespan assumptions.

Methodology

In this study, we use the Battery Performance and Cost (BatPac) model developed by the Argonne National Laboratory to assess EV battery material demand and waste for the fleet of EVs in Canada to 2050 (Argonne National Laboratory, 2023).

After structuring and parameterizing the model for a Canada-level case study, we assess the magnitude, composition, and timing of EV battery demand and waste for a base scenario containing business-as-usual assumptions. We then compare this base scenario with sub-scenarios that alter key battery characteristic assumptions, including the market shares of battery chemistries, the market share of BEVs versus PHEVs, the market share of EV size classes, and the duration of potential second-life use periods. We also assess how different recycling assumptions influence secondary material volumes and the offset of CM primary demand.

In the sections below, we overview our 2050 EV fleet projection, the BatPac model, and our modelling scenario assumptions, including the differences between our base scenario and individual sub-scenarios on battery chemistry, BEV/PHEV market share, vehicle size, and secondary life assumptions. We also discuss how we model recycling rates.

EV Fleet Deployment

The first step in the modelling exercise was to estimate the number of new vehicles sold annually in Canada by 2050. To build this projection, we first performed linear regression analysis on Statistics Canada's historical new vehicle registration data (Statistics Canada, 2022) and assumed the observed growth trend would continue until 2050. To account for EVs in this projection, we constrained the percentage of EVs in new car sales to meet the requirements of Canada's Electric Vehicle Availability Standard, reaching mandated targets in 2026 (20%), 2030 (60%), and 2035 (100%) (Transport Canada, 2022).

This results in particularly rapid growth in EV adoption between the 2026 and 2035 model timesteps, with annual EV sales growing from under 500,000 to over 2 million. Growth tapers post-2035, as all new vehicle sales are EVs from this date onward. By 2050, nearly 2.3 million EVs are sold per year, with a total EV stock of over 30 million, representing nearly the entirety of the total light-duty vehicle stock, as the majority of non-EVs retire by 2050.

It is important to note that our modelling does not account for demand-side measures that could reduce future new vehicle sales below the historical business-as-usual trend. The total light-duty vehicle stock in Canada in 2022 was 26.3 million vehicles (Satistics Canada, 2022). In our modelling, this value increases gradually from 2022 to 2050 in line with historical growth in new vehicle registrations. If ambitious investments or polices to support transit or mobility programs are made between now and 2050, these policies could reduce new vehicle sales and lower stock over time compared to our projections. On the other hand, if metrics such as population growth and new vehicle adoption rates are significantly greater than in the recent past, future new vehicle sales could be higher than the ones used in this study.

BatPac Model

Developed by the Argonne National Laboratory, the Battery Performance and Cost (BatPaC) model is a tool that can be used to quantify the performance and cost of lithium-ion battery production (Argonne National Laboratory, 2023). We used the model for two electric vehicle categories, BEVs and PHEVs, across several distinct battery chemistry (i.e. cathode) types, each with its own unique set of factors such as range and material composition.

The BatPaC model adopts a battery cell design featuring rectangular pouches, reflecting a more compact cell design compared to cylindrical cells, and the cathodes share a common structure, comprised of two electrodes and an electrolyte. BatPac model cathode technologies included in our study are Lithium Iron Phosphate (LFP), Lithium Nickel Cobalt Aluminum Oxide (NCA), and Lithium Nickel Cobalt Manganese Oxide (NCM), three currently prominent battery chemistries. We include several important variations of NCM chemistries, each differing in the proportion of nickel, cobalt and manganese in the cathodes. Given the variety of NCA and NCM chemistries, we use the shorthand NCX to refer to the family of lithium nickel cobalt batteries modelled, with the X representing either aluminum or manganese.

To consider the potential implications of innovation in newer battery technologies still under development, we also explore lithium metal (Li-metal) batteries, both lithium sulfur (Li-S) and lithium air (Li-Air) varieties. Unlike NCX or LFP chemistries, Li-metal batteries typically do not use graphite in their electrodes and overall contain a reduced volume of CMs (Bruce et al., 2011). Because Li-metal batteries are emerging technologies and have not yet reached significant market share, BatPaC does not include data on their material composition. To include both Li-S and Li-Air chemistries in this study, we incorporate data from Xu et al. (2020) in the BatPaC modelling framework.

In our modelling, we input the sales-weighted average rated peak power of the battery pack (kW) and total battery pack energy (kWh) into the BatPaC model to quantify critical material composition, weight, and energy density for each cathode type, EV type (BEV vs. PHEV), and vehicle range considered in this analysis. We follow the methodology developed by Xu et al. (2020) who classified EV types into three market segments by size—small, mid-size, and large—and use estimates from the Marklines database to approximate the sales-weighted average battery capacity required (kWh) and motor power (kW) across each vehicle segment (Marklines, 2020). See Appendix 1 for more information about these model parameters.

Battery Chemistry Scenarios

The EV battery market is constantly changing and while there are ever-evolving battery chemistries, the North American EV market is currently dominated by nickel-rich cathodes (Xu, et al., 2020). Recent battery trends have seen cobalt being substituted in favour of nickel-rich batteries (MIT, 2024). Nickel-rich cathodes such as NCM and NCA are transitioning towards low cobalt and high nickel content, and these represent the likely dominant sub-technology of lithium-ion batteries over the coming years (Mallick et al., 2023).

In our modelling, we assume the trend of NCX batteries moving towards low cobalt and high nickel composition will continue. In addition to NCX batteries, LFP batteries are also currently gaining market share as they have a cobalt- and nickel-free cathode (Weslosky, 2023). We model Li-metal batteries as a backstop technology as they are expected to potentially gain battery market share due to their advantages over LFP and NCX chemistries (Cano et al., 2018).

In our study, we therefore assess three battery technology scenarios, each defined by the market shares of the different battery chemistries defined above. The scenarios are labelled by which technology achieves a relatively more significant market share by 2050: *NCX*, *LFP*, and *Li-S/Air.* Our *Base* scenario, the scenario to which all other sub-scenarios are compared, assumes NCX technologies remain relatively dominant, as this is the current case for the North American EV battery market. The *LFP* and *Li-S/Air* scenarios serve as comparative scenarios where we analyze changes to critical mineral demand if the North American EV market were to shift away from NCX chemistries.

We draw our battery material compositions from the BatPaC model (Argonne National Laboratory, 2019) for NCX and LFP chemistries and Xu, et al. (2020) for Li-metal chemistries. Figure 1 summarizes the pack-level material composition for different battery chemistries used in this study. Figure 2 illustrates our projected battery sales market shares for the *Base* (NCX), *LFP*, and *Li-S/Air* scenarios.

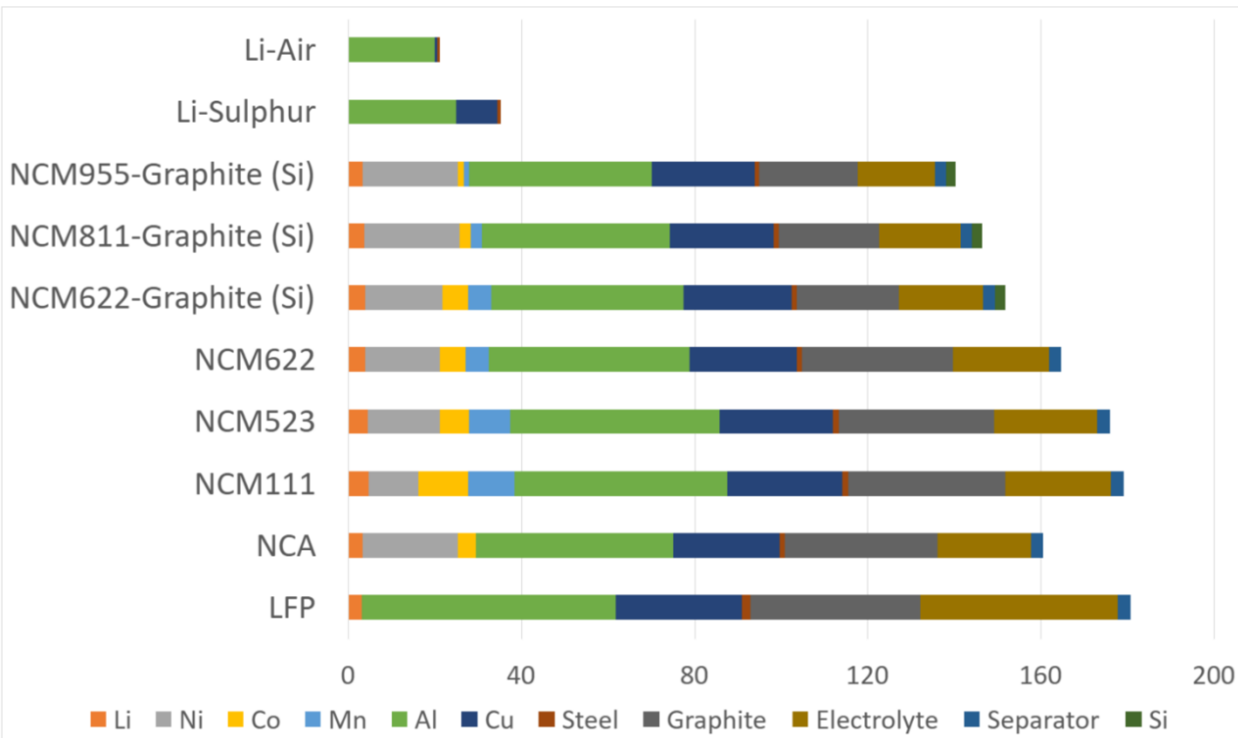

Figure 1. Battery material composition for battery technologies used in this study (NCM=Lithium nickel cobalt manganese oxide; NCA= Lithium nickel cobalt aluminum oxide; LFP=Lithium iron phosphate). NCM523, for example, means five parts of nickel are used with two parts of cobalt and three parts of manganese.

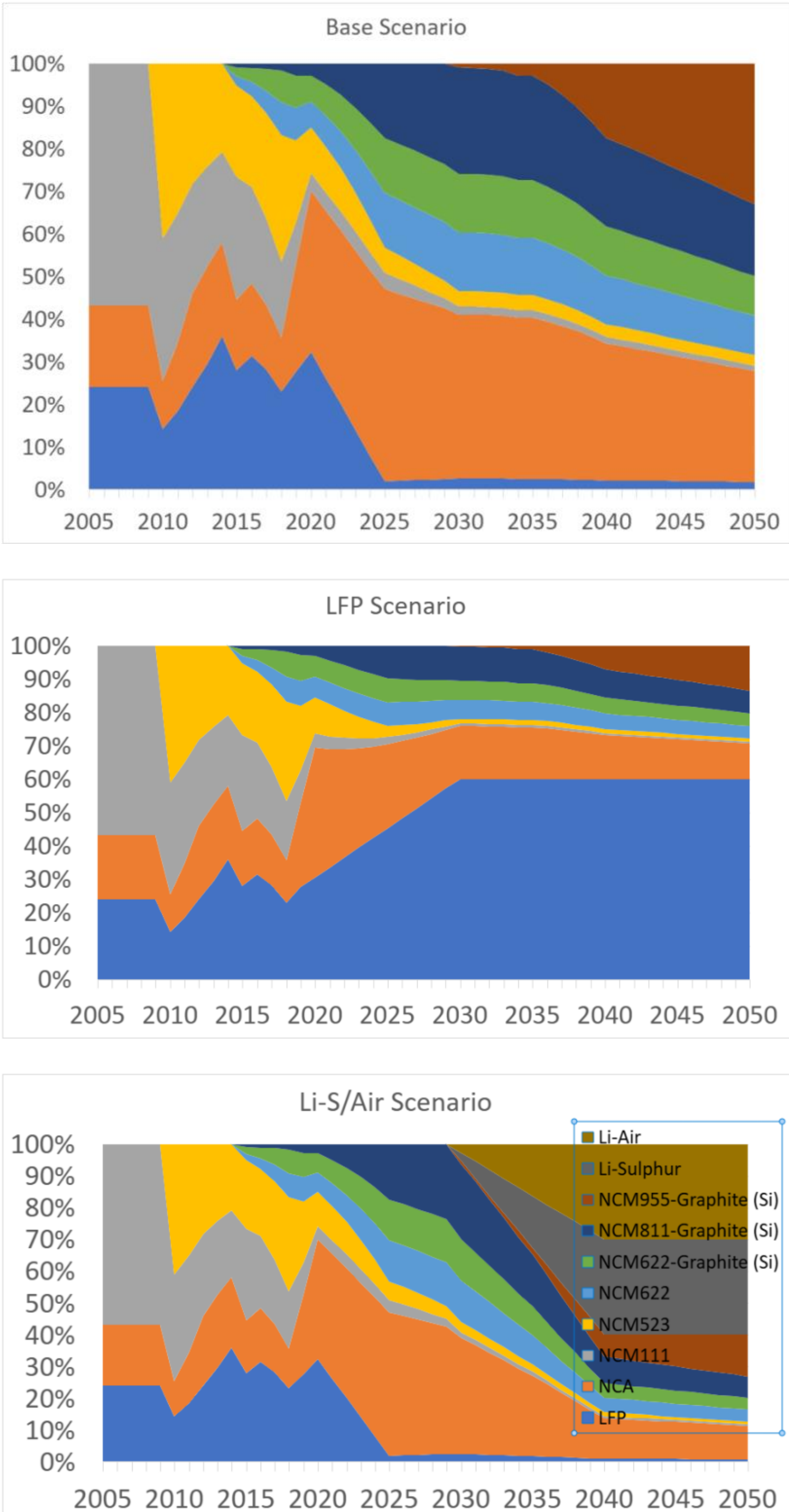

Figure 2. EV battery chemistry technology market shares to 2050 for *Base* (NCX), *LFP*, and *Li-S/Air* scenarios.

Battery Size Scenarios

To estimate market shares of BEV and PHEV in total vehicle stock, we assume that in our *Base* scenario, the Canadian share of BEVs increases similarly to the US BEV share projected by the US EIA, from 66% in 2030 to 71% in 2050, with PHEVs making up the remainder (U.S. Energy Information Administration, 2020). We also run a comparative *BEV+* scenario where the BEV share of the market grows to 90% by 2050 to represent an upper bound for material demand in a scenario with larger BEV deployment.

Similarly, for vehicle size segments, we adopt the approach of Xu et al. (2020) and classify EV models into three segments based on US sales data—small, mid-size, and large for both BEVs and PHEVs. Our *Base* scenario therefore assumes market shares of 19%, 48%, and 34% for small, mid-size, and large size classes respectively for BEVs and 23%, 45%, and 32% for PHEVs respectively.

We model two additional sub-scenarios, *SmallShift* and *LargeShift*, to evaluate the effects of large vehicles gaining relatively more market share in the future. In the *SmallShift* scenario, 5% of market share from small vehicles and 10% of market share from mid-size vehicles shifts to large vehicles. In the *LargeShift* scenario, 10% of market share from small vehicles and 20% of market share from mid-size vehicles shifts to large vehicles. See Appendix 2 for a summary table of these size-class market share assumptions for each scenario.

Lifespan Scenarios

Second-life applications of EV batteries vary in scale and can result in a second-use lifespan of six to 30 years (Casals et al., 2019). Due to large uncertainty in the potential applications of second-life uses, in this research, we take a technology-agnostic view of second-life use and simply assume an average 10-year second-use lifespan in the *Base* scenario, which matches assumptions used by National Renewable Energy Lab (2015). All scenarios in this study assume a median in-vehicle battery lifespan of 15 years (with a maximum of 19 years) as parameterized based on data from Xu et al. (2020).

We model two alternative second-life lifespan scenarios. The first is *NoSecondLife*, where we assume no second-life period. In this scenario, once an EV is retired, the battery immediately enters the waste strem. The second is *SecondLife+*, where we model a 15-year second-life period to explore the impacts of an extended second life. Our three second life scenarios impact the timelines to when EV batteries finally enter EoL waste streams and recycling, and subsequently when their components are available as secondary CMs.

While we assume uniform 10- and 15-year second-life use durations for our EoL batteries, we distinguish second-use rates for LFP batteries versus other chemistries. LFP batteries tend to have longer cycle life and reduced risk of cascading failure, and therefore, we assume a 100% second-use rate for EoL LFP batteries versus a 75% second-use rate for other chemistries following similar assumptions by previous studies (Xu et al., 2020; Said et al., 2020; Nitta et al., 2015).

Waste Recycling Scenarios

There are currently several battery recycling techniques that are at a commercial or near-commercial stage of technological development: direct, pyrometallurgical, and hydrometallurgical. Each recycling technique has unique characteristics and EoL recycling rates for constituent materials across NCX, LFP, and Li-S/Air batteries.

Due to large uncertainties in future recycling rates and which recycling technique will come to dominate, in this research, we instead assess the maximum potential for CM recovery from EoL battery recycling to help bound the potential for EoL material recovery to offset future primary material demand. We therefore focus on the hydrometallurgical approach because this methodology results in the highest yields of material recovery compared to other recycling techniques. We assume that hydrometallurgical recycling results in 90% recovery for lithium, aluminum, copper, graphite, and silicon and 98% recovery for nickel, cobalt, and manganese, which are the maximum rates based on data from Xu et al. (2020).

In this approach, we also assume 100% recovery of EoL EV batteries for handling through the recycling system. While this assumption almost certainly over-estimates the potential quantities of secondary materials that can be generated through EoL recycling of EV batteries, we view it as a useful outer envelope from which to gauge the overall potential for secondary material to potentially offset primary CM demand.

It is important to clarify that our choice of assuming closed-loop recycling in our analysis is a modeling attribute and not a prescription that secondary supply streams must remain within the same sector. While there are compelling reasons to advocate for closed-loop recycling of EoL batteries—such as comparative cross-sector demand growth rates—for the purposes of this study, we employ closed-loop recycling to illustrate the maximum potential for primary mineral demand reductions within the sector (Ziemann et al., 2018).

Summary of Scenarios

In the sections above, we described our modelling approach and key parameters of interest for scenario development including battery chemistry, BEV versus PHEV market share, vehicle size market shares, and secondary life lengths.

In our presentation of results below, we compare a *Base* scenario with standard business-as-usual assumptions to seven sub-scenarios where at least one key parameter is adjusted. The comparison of the *Base* scenario to sub-scenarios allows for the assessment of the influence of key parameters on our estimates of maximum primary mineral demand, EoL battery flows, and potential for closed-loop recycling. The key parameter assumptions of our Base scenario and sub-scenarios are outlined in Table 1.

Table 1. Key parameter assumptions for Base scenario and sub-scenarios.

		Influence magnitude and composition of material demand and waste	Influence magnitude of material demand and waste	Influence timing of material demand and waste

	Base (NCX)	LFP	Li-S/Air	BEV+	SmallShift	LargeShift	NoSecondLife	SecondLife+
Battery chemistry	NCX	LFP	Li-S/Air	NCX	NCX	NCX	NCX	NCX
BEV/PHEV market share	71% BEV 29% PHEV	71% BEV 29% PHEV	71% BEV 29% PHEV	90% BEV 10% PHEV	71% BEV 29% PHEV	71% BEV 29% PHEV	71% BEV 29% PHEV	71% BEV 29% PHEV
Vehicle size classes	BAU	BAU	BAU	BAU	15% shift to large size class	30% shift to large size class	BAU	BAU
Second life length	10 years	10 years	10 years	10 years	10 years	10 years	0 years	15 years

<u>Results</u>

Base Scenario

We find that in meeting Canada's Electric Vehicle Availability Standard, annual battery material demand grows from approximately 50,000 tonnes/year in 2024 to nearly 500,000 tonnes/year in 2050 in our *Base* scenario where NCX chemistry dominates the market. Demand grows particularly rapidly in the period from 2027 to 2035 as EVs gain market share to meet 2030 and 2035 EV sales targets.

The material demand outcomes lead to annual EoL battery waste volumes growing rapidly year over year to 2050, with particularly fast growth in the 2040-2050 period, which follows from the sharp increase in new EV sales prior to 2035. Waste volumes reach nearly 300,000 tonnes/year in 2045 and approximately 450,000 tonnes/year by 2050.

Chemistry Scenarios

Comparing our *Base* scenario to our scenarios with relatively larger shares of LFP and Li-S/Air chemistries, we observe that battery chemistry assumptions impact both the relative demand for different CMs, as well as the total aggregate material demand, particularly for the *Li-S/Air* scenario (Figure 3a). While *Base* and *LFP* scenarios experience essentially the same total material demand by 2050, the material composition is different between the two technology trajectories. Compared to the *Base* scenario, by 2050, the *LFP* scenario uses relatively more graphite and aluminum and less nickel and manganese.

The *Li-S/Air* scenario leads to significantly less material demand compared to the other two chemistry scenarios. In 2050, the total demand is approximately 250,000 tonnes, nearly half that of *Base* or *LFP*. Li-S/Air batteries are considerably lighter than the other two technologies, reducing overall material demand.

It is important to remember that in the *Li-S/Air* scenario, by 2050, only around half of the new market share will be from Li-S and Li-Air technologies. If these battery types were to continue to gain market share post-2050, material demand would continue to decline, highlighting the potential demand and waste reduction opportunities of these technologies compared to NCX and LFP chemistries.

As observed for material demand, different technology scenarios lead to different outcomes for total waste volume, as well as waste composition (Figure 3b). *Base* and *LFP* scenarios result in near-identical waste volumes in 2040 and 2050, although *LFP* sees relatively more graphite and aluminum, and relatively less nickel and manganese. The *Li-S/Air* scenario results in considerably less waste, compared to the other two scenarios, although this difference isn't as extreme as the trend observed for material demand. While waste volumes reach 450,000 tonnes/year in 2050 for *Base* and *LFP*, *Li-S/Air* results in approximately 325,000 tonnes/year.

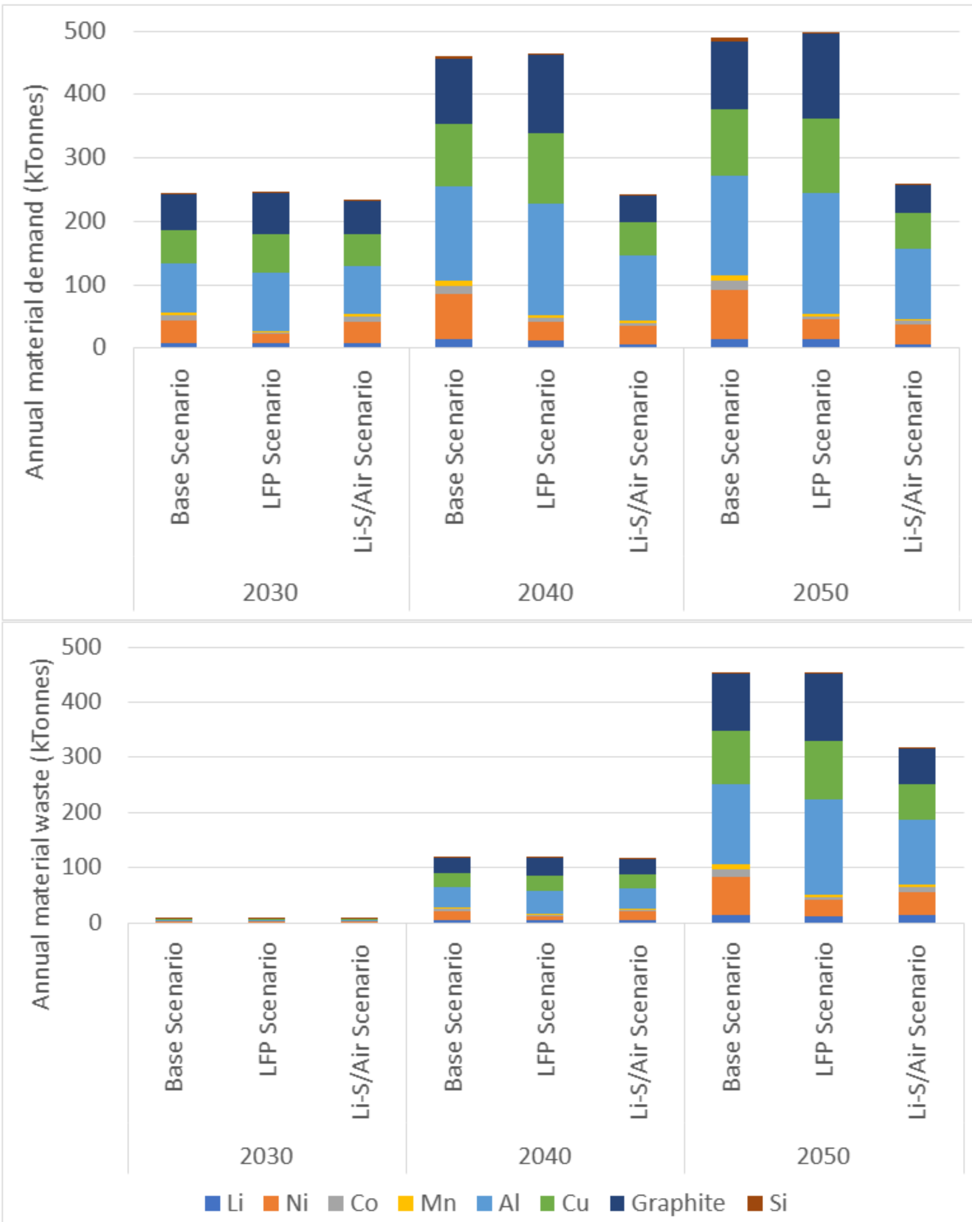

Figure 3. Annual material demand (a) and waste (b) in 2030, 2040, and 2050 across *Base* (NCX), *LFP*, and *Li-S/Air* scenarios.

Because NCX, LFP, and Li-S/Air batteries each have their own unique critical mineral composition, the dynamics in our assumed rates of adoption of different battery chemistry choices in the coming decades influence the demand trajectories for different CMs. To give a sense of how these dynamics evolve, Figure 4 shows how the annual demand for lithium, nickel, cobalt, graphite, copper, and manganese in our *Base*, *LFP*, and *Li-S/Air* scenarios emerges over time.

For lithium, demand rises rapidly for all battery chemistries, although *Li-S/Air* demands significantly more than *Base* and *LFP*. This is because in Li-S/Air technologies lithium is used in both the anode and cathode of the battery.

After first seeing an increase in demand, post-2035, cobalt demand declines in each scenario. Even in the *Base* scenario, this pattern is observed—although relatively less so and at much higher aggregate levels—as nickel-rich cathodes (NCM523, NCM622, NCM811, and NCM955) gain market share over conventional NCM111 cathodes. A similar, slow decline over time is seen for manganese as nickel-rich cathodes gain market share over NCM111 cathodes.

Nickel sees steady growth in *Base* and *LFP* scenarios, although demand is over two times higher in *Base* than in *LFP*. As with cobalt, nickel demand declines in the Li-S/Air scenario post-2035 as the market shifts away from NCX constructions.

Graphite sees the largest growth in the *LFP* scenario with annual demand reaching 130,000 tonnes/year by 2050. The *Base* scenario sees a smaller growth in graphite demand versus the *LFP* scenario since NCX batteries require less graphite per battery pack compared to LFP batteries. Moreover, nickel-rich NCX batteries such as NCM622-Graphite (Si), NCM811-Graphite (Si), and NCM955-Graphite (Si) that incorporate a hybrid anode composed of graphite and silicon, gain market share in the *Base* scenario driving down graphite demand.

The Li-S/Air scenario has the smallest growth in graphite demand as these batteries typically do not use graphite in their electrodes. The anode is made of lithium metal or a lithium-containing material and therefore, graphite demand in the *L-S/Air* scenario is driven exclusively by LFP and NCX batteries with smaller market shares.

A similar pattern for copper is seen as for graphite. The *LFP* scenario experiences the largest demand growth in the metal, reaching nearly 120,000 tonnes/year by 2050. The *Base* scenario sees slightly less copper demand than the *LFP* scenario because all battery chemistry types in the NCX family use less copper in their construction. The *Li-S/Air* scenario has the lowest amount of copper demand by 2050. While copper is a key component in Li-S batteries, these types of batteries use less than half the amount of copper found in LFP or NCX chemistries.

Manganese is present in the NCX family of batteries but not in LFP or Li-S/Air. In the *LFP* and *Li-S/Air* scenarios, manganese demand falls dramatically as the market transitions to predominantly LFP and Li-S/Air chemistries respectively. In the *Base* scenario, manganese demand falls slightly post-2035 due to gaining market share of nickel-rich (i.e. manganese-poor) NCX chemistries.

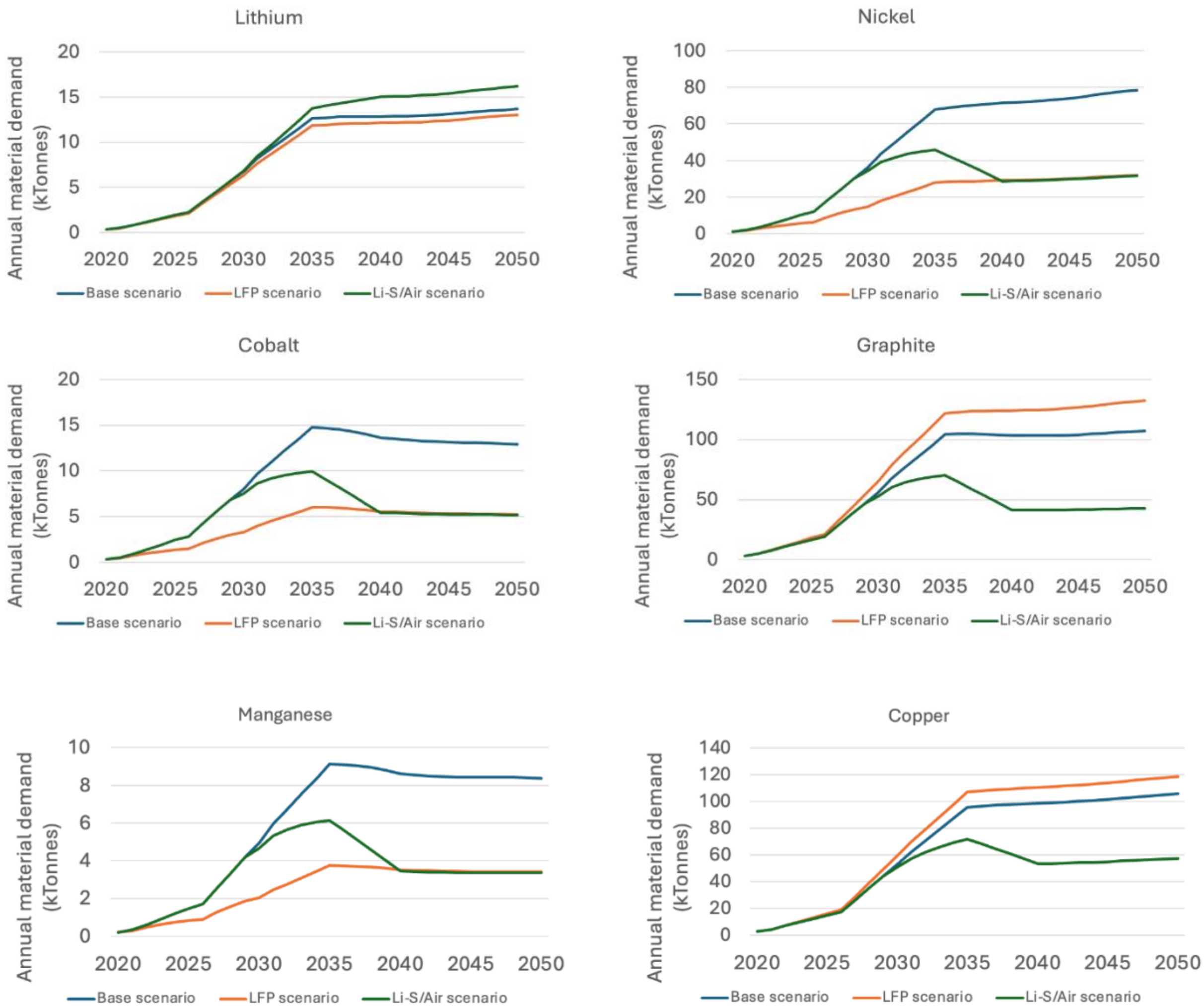

Figure 4. Annual battery mineral demand for select battery minerals across *Base* (NCX), *LFP*, and *Li-S/Air* scenarios.

Size Scenarios

By 2050, annual battery material demand is nearly 600,000 tonnes in the *BEV+* scenario, which is approximately 100,000 tonnes/year higher than the *Base* scenario (Figure 5a). This additional demand results in greater waste volumes: the *BEV+* scenario experiences 20% higher annual waste levels by 2050 compared to the *Base* scenario (Figure 5b).

Just as BEV/PHEV market shares influence CM demand and waste volumes, so do assumptions around vehicle size. We find that annual material demand and waste increase by 9% for every 15% shift toward larger vehicle size classes.

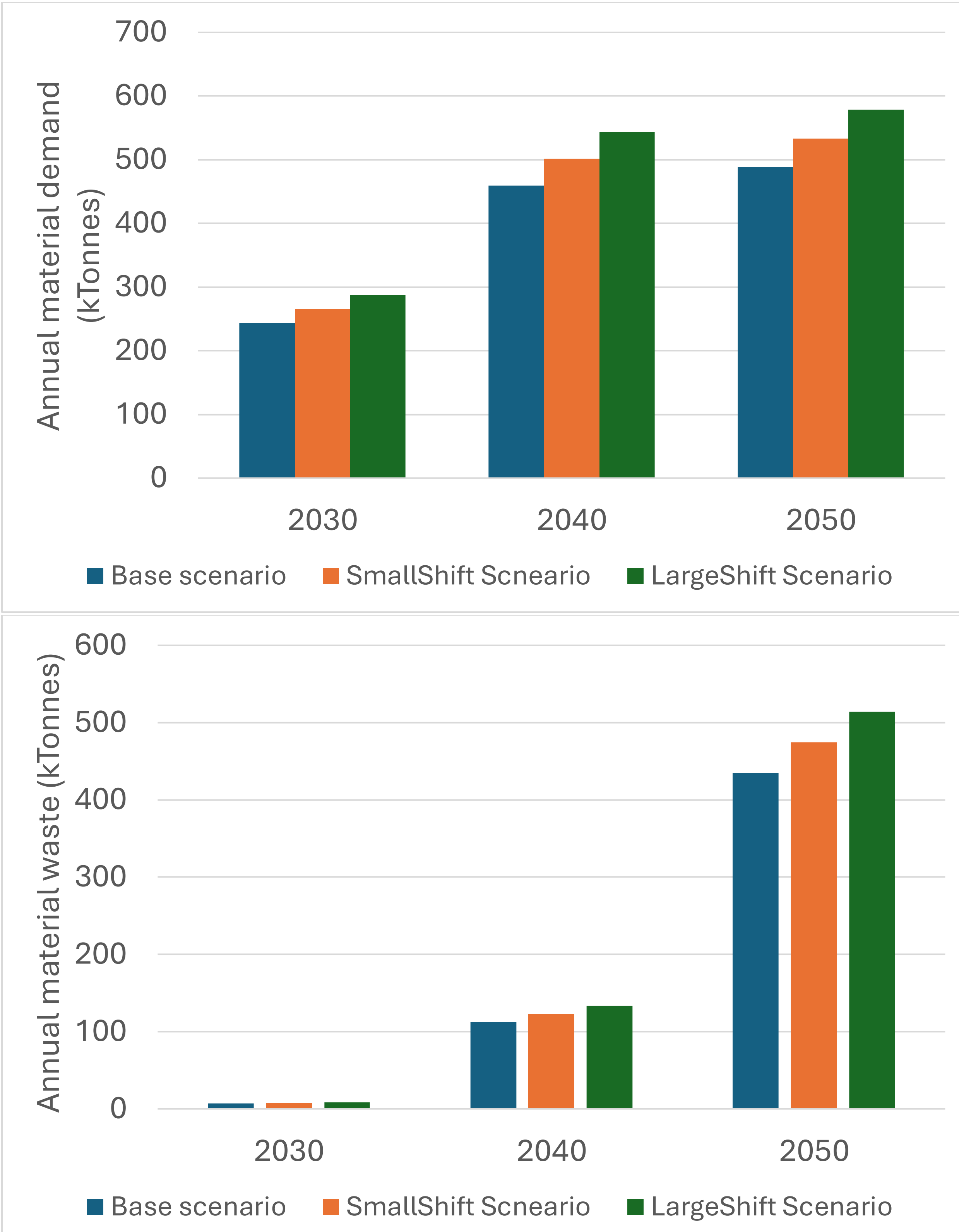

Figure 5. Annual demand (a) and waste (b) in 2030, 2040, and 2050 in *Base* (blue), *BEV+* (green), *SmallShift* (orange), and *LargeShift* (grey) scenarios.

Lifespan Scenarios

The length of a battery's second-life period determines when its material enters the waste stream. As we move from the *NoSecondLife* scenario, to the *Base* scenario with a 10-year second-life period, and finally to the *SecondLife+* scenario which uses a 15-year second-life period, total waste material produced by 2050 continues to decline proportionately.

This pattern is also seen when focusing on specific elements. For lithium, for example, in the *NoSecondLife* scenario, waste is 12 kTonnes in 2050. In the *Base* scenario, the 10-year second-life period delays waste production, reducing lithium waste to nearly three kTonnes. In the SecondLife+ scenario, the extra five years of a second-life period drops lithium waste to approximately two kTonnes in 2050.

It is important to note that the length of second-life periods do not reduce total waste volumes; rather, they delay the accumulation of waste. It's only the timing of this material into the waste stream that differs between the scenarios.

Recycling Analysis

Recycling of battery CM waste can be used to offset primary demand for CMs. Figure 6 compares demand for lithium, nickel, cobalt, and copper under different recycling assumptions where waste is used as secondary supply to offset demand. The solid green line shows demand over time in the *Base* scenario with no EoL recycling, which we refer to as 'maximum primary demand'.

The dashed green line illustrates leftover primary CM demand in the *Base* scenario after potential secondary CM supply is subtracted. The dashed and dotted green line shows leftover primary CM demand in the *NoSecondLife* scenario, where CMs enter the waste stream immediately after the battery is retired from in-vehicle use.

A second-life period delays when battery minerals are available for recycling and therefore, in our modelling results, we observe a smaller reduction in maximum primary demand in the *Base* scenario relative to the *NoSecondLife* scenario, where batteries are recycled immediately at the end of their in-vehicle use phase. For example, by 2050, 15% of lithium demand can be satisfied by secondary supply in the *Base* scenario, whereas in the *NoSecondLife* scenario, this recycling potential reaches 73%. It is important to note that we assume recycled material from EoL EV batteries is recycled directly back into the EV battery chain (i.e. closed-loop recycling), and that there is no cross-sector sourcing of secondary material from or to electronics or other sectors that demand these critical.

Figure 6 also compares CM demand in the three recycling scenarios to current annual Canadian production (included in the figures as the solid black line). In performing this comparison, we are not suggesting that Canada source all of its CM supply domestically. Instead, this comparison helps ground future magnitudes of CM flows against current extraction activity in Canada.

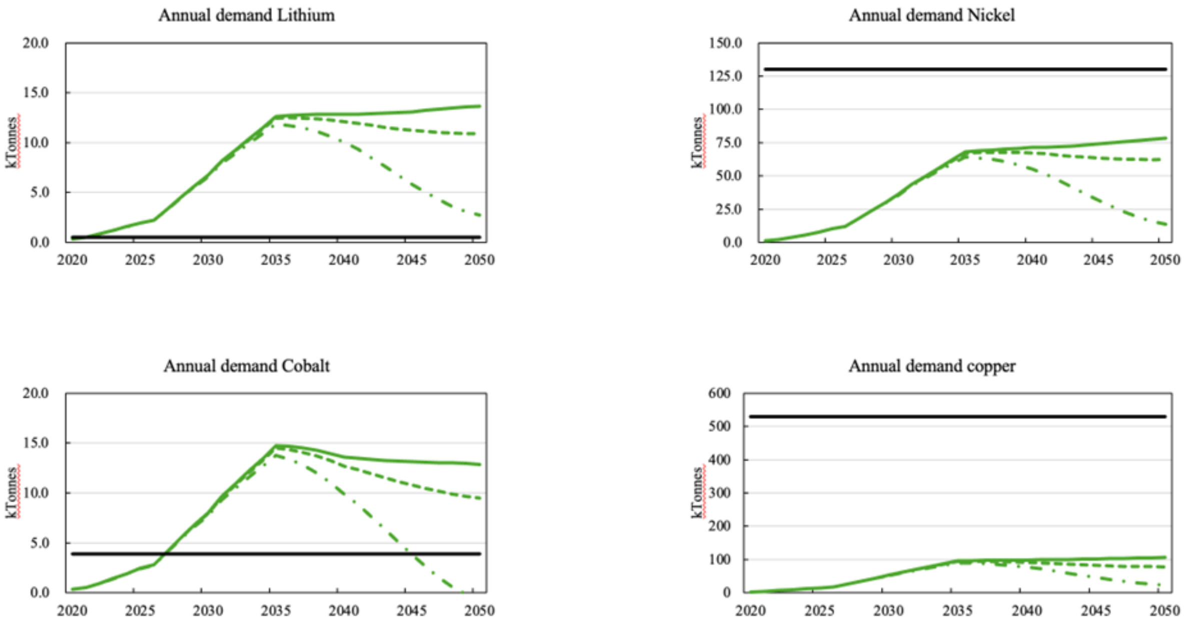

Figure 6. Annual demand for lithium, nickel, cobalt, and copper under different recycling assumptions. Solid green line = *Base* scenario demand with no recycling (i.e. maximum primary demand). Dashed green line = *Base* scenario demand minus secondary supply offset. Dashed and dotted green line = *NoSecondLife* scenario demand minus secondary supply offset. Solid black line = current (2020) Canadian production.

Policy Discussion

Important policy insights and linkages stem from our analysis of how assumptions about the evolution of key EV battery characteristics—chemistry, size, and lifespan—influence the magnitude, composition, and timing of CM flows. The analysis below highlights these interlinkages to inform ongoing policymaking related to the EV battery value chain in Canada.

As governments develop policies that (directly or indirectly) impact EV battery CM extraction and waste accumulation, they should consider these policy implications and linkages in their planning and policymaking, accounting for variability in material flow quantities, heterogeneity in flow composition, and uncertainty in flow timing.

Policy Implications - Battery Chemistry

Battery chemistry market shares dictate which CMs experience rapid demand growth in the coming years and, subsequently, the type of materials present in EoL battery waste. Therefore, government policy must consider potential changes in battery chemistry market shares when directly or indirectly investing in and designing collection, storage, and recycling infrastructure.

For example, in market conditions where NCX batteries dominate, as they do today in Canada, the economic value of cobalt is the primary influencer of battery recycling profitability. While research suggests that it can be more cost-effective to recover cobalt from EoL waste compared to primary extraction, it is important to account for the potential future substitution away from cobalt in lithium-ion batteries (Mansur et al., 2022). For example, if LFP, Li-S, or Li-Air batteries gain significant market share in the near future, cobalt and nickel recovery rates will decline, potentially negatively impacting the feasibility of recycling infrastructure investments.

While battery chemistry technological substitution adds to the complication of policymaking by potentially disrupting recycling pathways, it also has the promise of greatly reducing total CM demand, and thereby waste. As the modelling in this study shows, Li-Air/S batteries have the potential to substantially reduce the material footprint of the EV lifecycle due to their lower material requirements per unit of energy density.

From a governance perspective, battery chemistry arguably presents the most complex and uncertain evolution of the three characteristics analyzed in this study, not only due to rapid technological innovation but also political economy dynamics involving trade relations and supply chain security. Here, policymaking may be complicated by sometimes competing objectives, for example between reduced demand for specific EV battery CMs and supply chain security. This uncertainty further underscores the need to understand the implications for EoL CM circularity flowing from different policy options.

Policy Implications - Battery Size

The relative market shares of BEVs and PHEVs and different vehicle size classes are important parameters to consider when evaluating investments in battery recycling infrastructure as they dictate the magnitude of demand and waste. As our modelling results highlight, a future in which the EV market is dominated by large-size class BEVs will have considerably more battery material demand and waste than an EV market comprised primarily of small-size class PHEVs, although the relative emissions intensity will be determined by lower direct scope 1 tailpipe emissions versus the balance of scope 2 and 3 emissions from producing larger amounts of CMs for bigger batteries. The evolution of battery size in the fleet of EVs impacts the economics of battery recycling as each recycling process becomes viable at a particular material throughput. To inform policy development, Canadian equivalent assessments of these material throughput levels are currently unknown and need to be estimated.

Governments can influence battery size through incentives, regulations, and pricing mechanisms that favour smaller vehicles. For example, sales requirements or subsidies could be introduced to promote smaller vehicles over larger models. Another important policy consideration is the inclusion of PHEVs in ZEV policy definitions. Incentivizing PHEVs via their inclusion in ZEV policies will impact their relative market share, and thus reduce the average battery size of the EV fleet. However, due to the current fossil fuel-based liquid fuel supply, incentivizing PHEVs will decrease the total rate of GHG reductions from transitioning the vehicle fleet to EVs.

Policy Implications - Battery Lifespan

Government policy impacting the presence and length of second-life periods for EV batteries will impact the timing of material availability for recycling, and therefore the economic feasibility of recycling. If second-life periods are uncommon, there will be faster stock turnover, increasing the potential for closed-loop recycling in the near-term. However, these shorter lifespan scenarios will also require investment of EoL management infrastructure sooner to ensure operational reverse supply chains for EV batteries.

In particular, the relative uncertainty regarding the second-life potential of EV batteries as a short-duration storage option requires further study to better inform assumptions regarding how current EV adoption rates and the mandated increases under Canada's EV Availability Standard will translate into EoL management requirements over the coming decades. It will be important to account for heterogeneity in second-life use when designing regulations, such as secondary content requirements, and there is a need to coordinate these policies with recycling infrastructure policy and investment.

However, there is general agreement that policy prolonging second-life use via reuse, refurbishment or remanufacturing before eventually recycling—in that hierarchical order—is essential to maximizing the utility of extracted minerals and reducing costs and environmental burdens associated with the production of new batteries (Automotive Recyclers Association, 2024; Erickson, 2020; Niri et al. 2024).

This delay in material flows caused by second life may also be advantageous from a governance perspective when considering the uncertain and rapid evolution of battery chemistry technologies. Essentially, delay in reaching the threshold level of waste volumes needed to economically recycle particular batteries means governments have more time before deciding what type of recycling infrastructure to invest in or incentivize. This additional time can be used by governments to track and understand trends in dominant battery chemistries, presenting an important opportunity to refine investment and policy approaches based on ongoing learning. Ideally, this additional time and evidence-base would help avoid suboptimal investments.

Conclusion - Laying the foundations for Policymaking Under Uncertainty

Current Policy Considerations

Our results highlight uncertainties around the magnitude, composition and timing of demand for and quantities of EoL battery materials. To manage some of this uncertainty, and to strategically craft policy objectives as it relates to EoL management for batteries, the government should focus on policy tools that increase information flows and build regulatory alignment in the short term. This approach facilitates learning and enables governments to anticipate and adapt in the face of evolving technologies and market dynamics.

In the short term, such approaches could include the standardization and implementation of information tools like state of health (SoH) assessments for batteries and battery ID and tracking mechanisms. The data provided by these tools can serve as an evidence base to make more informed subsequent policy interventions and investments. Coordination between jurisdictions around the standardization of these tools will also be essential to improve market building in Canada.

Determining the EoL pathway for batteries is another particularly impactful policy consideration. Secondary content requirements and liability rules are especially relevant targeted policy tools in this regard that should be considered in advance of when thresholds for material battery volumes are expected to be reached in Canada. They should also be designed to ensure they don't hinder innovation or induce adverse competition effects, especially for small and medium enterprises.

Priority consideration should also be given to the alignment of regulations between sub-national jurisdictions governing the safe transportation and warehousing of batteries. For example, each province classifies used lithium-ion batteries as hazardous waste, making them subject to provincial hazardous waste requirements. However, these regulations are different in each province. Regulatory alignment in this context is important to address the significant costs associated with transporting and warehousing batteries in Canada, which stem partly from this patchwork of regulations. Currently, substantial transportation costs in Canada decrease the economic viability of battery recycling and hinder market growth as transporters often ship through the U.S. where transport regulations are less stringent.

Canada's Regulatory Cooperation and Reconciliation Table is well-placed to assess, identify and facilitate cross-jurisdictional regulatory alignment required to reduce transaction costs for battery transportation and warehousing within Canada. The integrated nature of the North American auto market will also require some level of regulatory alignment with the United States, to further facilitate market building and capitalize on economies of scale to advance circularity. Importantly, stringent protections for worker health and safety should not be compromised under any efforts to align regulations across borders.

Additionally, given the risks associated with handling and transporting batteries, immediate attention should be given to supporting appropriate training and skills development to prepare for future labour demands, even though the magnitude of the throughput of batteries is relatively low at this time.

A final priority for consideration pertains to the necessary alignment among key stakeholders required to build an integrated energy system and reverse value chain for EoL batteries. There is a clear role for the federal government to facilitate alignment not only between provinces and territories that are primarily responsible for waste management but also to facilitate 'buy-in' from EV OEMs, regulators, utilities, power authorities, car dealerships, recyclers and other EoL players. This inter-sectoral and inter-governmental dialogue and alignment will be critical for building the industrial symbiosis needed to realize a coherent and efficient integrated circular energy system for batteries in Canada.

Future looking considerations

As policy objectives become more clearly defined over time via the continued evolution of EV markets, new innovations in battery chemistries, and the further development of recycling technologies, governments should consider how existing policy instruments are incentivizing different outcomes, as well as how they can be used to further shape trajectories versus where novel policy tools and regulations might be needed.

A number of policies either in place or under development in Canada are likely already incentivizing EV battery innovation and EV adoption decisions, as well as EoL management capacity and technology development that will impact the relative magnitude, composition and timing of CM demand and Canada's ability to manage, recover, and recycle the resulting EoL material flows going forward.

As highlighted in our policy discussion, while the EV Availability Standard has set Canada on a trajectory towards increased EV adoption over the coming decade, future-oriented policy considerations could focus on upstream interventions related to incentivizing lighter vehicles with smaller batteries, the relative share of BEVs vs. PHEVs in the overall vehicle stock, and/or shift incentives and support for the innovation and development of different battery chemistries or EoL recycling technologies, to align system-level outcomes. Similarly, transit, transportation and mobility policies will determine the overall magnitude of the EV stock required to meet new vehicle demand, and therefore the size of the gap between primary CM demand for near-term supply and future potential secondary CM supply from closed-loop recycling.

Considering these kinds of system-level strategies will help reduce critical mineral demand in the near term while aligning efforts to meet CM demand with investments in the needed infrastructure to enable future circularity for EV batteries. They can also help reduce overall environmental impacts and improve social and reconciliation outcomes across the value chain.

However, more research is required to understand how and when governments should intervene in a way that identifies and assesses trade-offs between options. Importantly, these different scenarios and the substitutions between materials that they imply have unique costs, upstream impacts on mineral requirements, emissions and environmental impacts and social/community challenges related to different technologies and supply chains. More research is needed in the short term to understand these trade-offs and inform targeted subsequent policy interventions that promote safe, clean and affordable solutions.

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<u>Appendix 1</u>

Table 1. Sales-weighted average BEV and PHEV range, fuel economy, motor power, and required capacity across vehicle size classes (small, medium, and large).

BEV	**Range (miles)**	**Fuel economy (Wh/mile)**	**Electric motor power (kW)**	**Required capacity (kWh)**
Small	96	291	101	33
Medium	194	291	169	66
Large	241	353	295	100
PHEV	**Range (miles)**	**Fuel economy (Wh/mile)**	**Electric motor power (kW)**	**Required capacity (kWh)**
Small	44	336	123	17
Medium	22	303	55	8
Large	22	470	61	12

Appendix 2

Table 1. Market shares of small, mid-size, and large BEVs and PHEVs in Base, SmallShift, and LargeShift scenarios

BEVs	Sales market share		
	Base scenario	SmallShift Scenario	LargeShift Scenario
Small BEV	18.5%	13.5%	8.5%
Mid-size BEV	47.9%	37.9%	27.9%
Large BEV	33.6%	48.6%	63.6%
PHEVs	Sales market share		
	Base scenario	SmallShift Scenario	LargeShift Scenario
Small PHEV	22.6%	17.6%	12.6%
Mid-size PHEV	45.4%	35.4%	25.4%
Large PHEV	32.0%	47%	62%