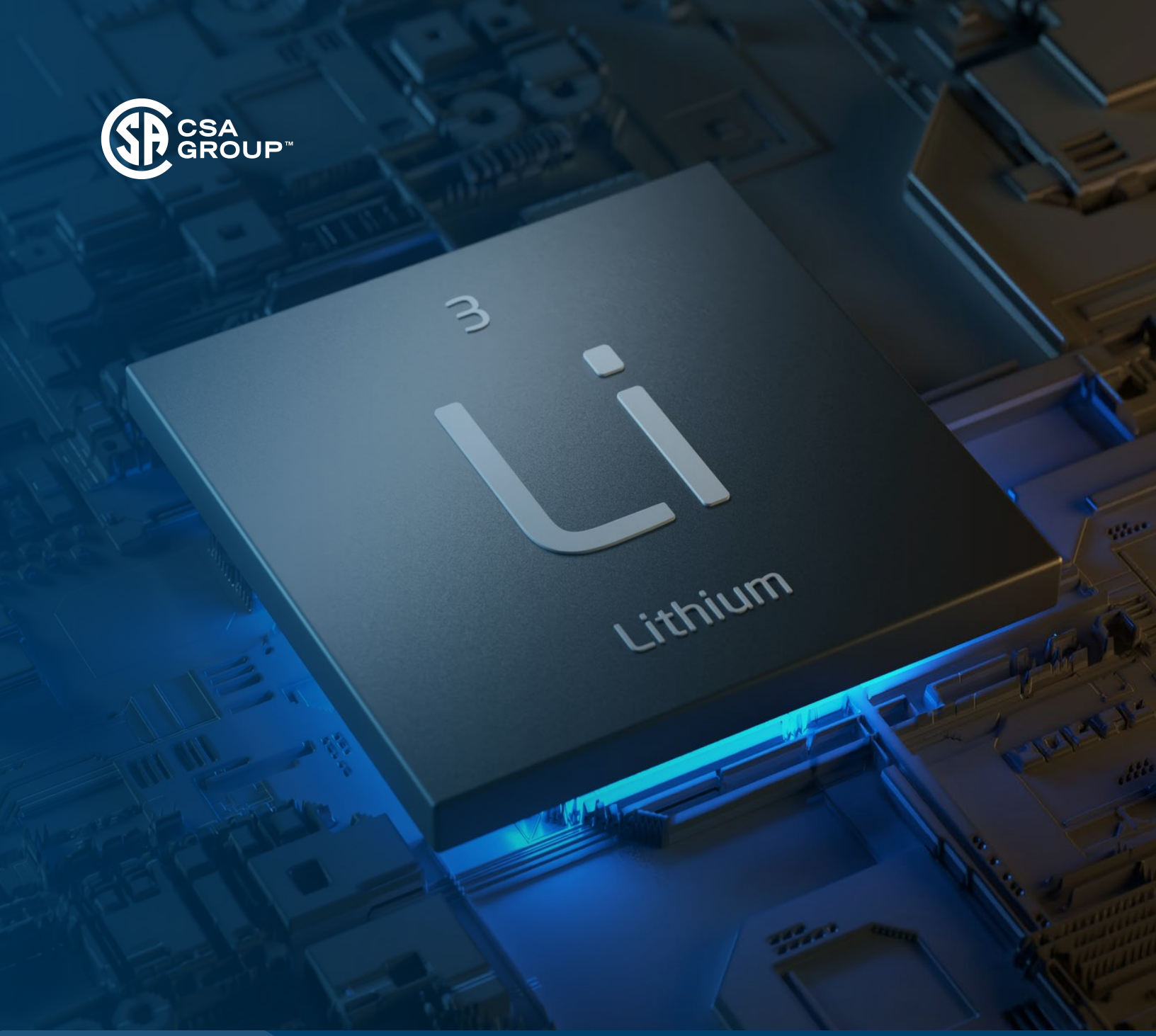


STANDARDS RESEARCH

Recovering and Recycling Lithium and Rare Earth Elements from Waste

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Executive Summary

The transition to new energy sources has repercussions throughout the lifecycles of lithium (Li), rare earth elements (REE), and other minerals that are important inputs into the technologies supporting this transition, such as electric vehicles (EVs), wind turbines, and electronic equipment. Growing demand for Li and REE puts pressure on supply chains and environmental performance, which is exacerbated by geopolitical realties and the traditional adoption of linear economic systems (from extraction to disposal). Importantly, there are finite natural reserves of these minerals, and they are concentrated in only a few countries. However, it is estimated that less than 1% of Li and REE were recycled in 2021 [1].

Sourcing Li and REE from any waste (be it from mining, manufacturing, or end-of-life products) should be carefully evaluated as an option to sustain and geographically diversify material supplies into the future. Because waste recovery and recycling options also impact sustainability and supply chain issues, other possible actions should also be considered, such as reducing consumption and reusing materials. Applying a circularity approach can address economic, sustainability, and supply chain considerations and can also facilitate decision-making. This systems approach can be applied to Li and REE lifecycles when developing standards that govern recovery and recycling from waste.

Through a lens of circularity, this research report investigates how standardization can facilitate the recovery and recycling of Li and REE from waste without obstructing overall sustainability or supply chain security and resilience. The research included a review of the current landscape and literature, supplemented by engagement with interested parties in the Li and REE lifecycles. The findings highlight that high capital and operating costs of systems for recovery and recycling are a key barrier. There are also logistical, environmental, health, safety, social, and governance barriers. Advances in data management, technology, and knowledge sharing will help bridge knowledge gaps regarding recycling and recovery. Additional policy considerations could include supporting a market system that accounts for sustainability and supply chain impacts and enables the circular flow of materials with process and product designs.

Key standardization gaps to consider are:

- **Cross-sector collaboration:** The Li and REE value chains are lengthy and have geopolitical divisions. Standards development must consider the needs of many participants.
- **Systems approach:** Economic, sustainability, and supply chain considerations throughout the lifecycles of Li, REE, and other materials are complex. A systems approach would benefit standards development pertaining to recovery and recycling of waste.
- **Canadian leadership in standards development:** Canada's involvement in the Li and REE value chains, from extraction to recycling, is increasing rapidly. These value chains are global, and therefore active participation in global standards development is crucial.
- **Health and safety risks of lithium-ion battery and magnet recycling:** Based on interviews with interested parties, significant attention is needed to remove barriers to the growth of the EV battery recycling sector and to improve the regulatory framework in Canada. Canadian standards could address health and safety risks of battery and magnet recycling.

A roadmap of standards development for recovery and recycling of Li and REE from waste should consider:

- Analytical testing methodologies for industry sectors within material lifecycles;
- Traceability throughout Li and REE lifecycles;
- Cohesive material and industry sustainability standards, from extraction to recycling;
- Standardized nomenclature, material composition specifications, and product labelling; and
- Metrics/methodologies to quantify sustainability and supply chain impacts and support of processes and products with circular flow of materials.



"A circular economic system involves recovering, retaining, or adding to the material value, while contributing to sustainable development."

1 Introduction

1.1 Background and Context

With global efforts focused on decarbonization, and with the rapid adoption of electric vehicles (EVs) and other technologies that are part of the energy transition effort, critical minerals have become increasingly important areas of interest for governments, industry, and the public at large. Consequently, lithium (Li) and rare earth elements (REE), which are key inputs for EVs, other decarbonization technologies, various consumer products, as well as some defense applications, are listed as critical minerals by most governments.

However, there are significant challenges with the security, sustainability, and sufficiency of the supply of both Li and REE, which are pressing concerns for governments and the public alike. Li and REE supply chains (including extraction and processing) are concentrated in a few jurisdictions, which poses risks to the security of the supply of these critical products to domestic markets [1], [2], [3]. Geopolitical events and other stresses on geographically dispersed supply chains (e.g., the COVID pandemic) have further increased government and public focus on strategic minerals and on securing supply chains. For example, China (the world's largest supplier of REE), halted REE exports for several weeks in 2010, possibly to mitigate environmental concerns with mine tailings [4]. In 2020, China introduced a new export law that could support future REE restrictions [5].

Limited reserves (known and recoverable amounts) of Li and REE compound the supply chain issues. Sources are not always economically feasible to produce. As such, the forecasted demand for these minerals is expected to greatly surpass the available supply in coming years and decades, furthering concerns about resource availability and security [1]. Few countries are self-reliant in terms of Li and REE, that is, where their domestic reserves, extraction, processing, and manufacturing can match their present and projected consumption.

There are also important sustainability impacts throughout the lifecycles of Li and REE, from mining to manufacturing to product recycling, which will intensify as demand rises. These include depletion of valuable resources and freshwater, increased energy demands and generation of greenhouse gases (GHG) and other air emissions, disposal of liquid and solid wastes, and degradation of ecosystems. In addition, there is an expectation that each industrial sector involved in the Li and REE lifecycles should take steps to mitigate environmental, health, and safety (EHS) risks in day-to-day operations, and take a long-term perspective on environment, social, and governance (ESG) impacts. Furthermore, manufacturers, as well as consumers, increasingly want to understand and trace the source and location of all the raw materials that go into their end products.

Waste, including waste from mining, processing, and manufacturing, as well as from consumer products that are no longer needed, offers a potential alternative

source of Li and REE and will likely become a greater focus in coming years given the supply and demand constraints noted above. This will be particularly important for domestic markets with limited primary supply or with limited processing capabilities. However, while there is some recycling of other critical minerals, Li and REE typically follow a linear economic path of extraction, use, and disposal [6]. Consequently, their rates of recycling and reuse are very low. For example, in 2021, it was estimated that less than 1% of Li and REE were recycled globally. This is dramatically short of the recycling rates for other metals, such as copper, which has a recycling rate of over 45% [1].

Even though recovering and recycling Li and REE from waste seems like an intuitive solution to sustainability and supply chain impacts, it is important to evaluate the complete supply chain. For example, artisanal battery recycling might contribute more environmental damage than a small solution mining operation in a stable jurisdiction. The concept of circularity (a circular economy) provides an overarching approach that considers the economic, sustainability, and supply chain impacts throughout a material's lifecycle.

There are several initiatives that consider Li and REE recovery and recycling as a means of achieving various objectives, including initiatives promoting critical mineral supply chains, decarbonization, product recycling, waste valorization (assigning value to waste streams), and extended producer responsibility (EPR), where producers are responsible for managing end-of-life (EoL) products instead of governments or consumers (see Appendix A for glossary of terms). Although their objectives are related, these initiatives sometimes have a narrowed emphasis or tackle symptoms rather than root causes. A circular economy approach integrates these often-isolated strategies to achieve a circular flow of materials. A circular economic system involves recovering, retaining, or adding to the material value, while contributing to sustainable development [7]. A circular strategy may consider a range of options such as recycling, repairing products, or reducing consumption. Critical to the concept of circularity is to take a systems approach to material value chains when developing projects, product designs, policies, and standards. In other words, the impacts and cumulative effects of the supply chain need to be considered in part and as a whole system.

1.2 Research Objectives

Given the importance of waste as a potential source for Li and REE, numerous global endeavours are underway to develop technologies, policies, and standards in this area. This report provides an overview of the opportunities for extracting value from waste and investigates how standardization could help with the recovery and recycling of Li and REE from waste, particularly with respect to Canadian interests and priorities. Accordingly, the research conducted for this report had the following three broad and intertwined objectives:

1. To assess the current situation, both in Canada and internationally, with respect to waste Li and REE sources and their recovery, including technologies;
2. To review policy, best practices, and standards related to the recovery of Li and REE from waste and identify gaps in standards and other barriers to Li and REE recovery and recycling from waste; and
3. To provide recommendations to inform a roadmap of standards development for recovery and recycling of Li and REE from waste.

It should be noted that the research specifically included two source categories of Li and REE waste:

1. Waste streams from industry sectors of the Li and REE value chains (mining, processing, manufacturing) that are normally disposed of (e.g., Li from petroleum brines or REE from the waste of uranium operations); and
2. EoL products (e.g., REE motor magnets or EV Li batteries).

2 Methods

To meet the research objectives, a review of the current state of Li and REE recovery and recycling was undertaken, including waste streams, market trends, and technologies in Canada and around the world. Current and developing policy and best practices from mining, processing, manufacturing, and recycling industries in the Li and REE supply chains, along with governments, research and innovation centres, and industry associations were also examined. This

information was supplemented by consultations with interested parties via interviews and a webinar. Insights from the review and consultations with interested parties were used to analyze the gaps and barriers to Li and REE recovery and recycling, and to identify opportunities to support these processes via standardization.

2.1 Landscape and Literature Scan

The landscape and literature scan included searching Google scholar, news articles, governmental websites, and websites of non-profit, industry, and standards organizations. Publication years between 2009 and 2023 were included, and the following topic areas were examined as part of the scan:

- Li and REE lifecycles and value chains;
- Sources of Li and REE in waste;
- Commercial and emerging recovery and recycling technologies; and
- Drivers, policies, best practices, and standards related to Li and REE waste.

Key search words included, but were not limited to: "lithium," "rare earth elements," "strategy," "supply chain," "recycling," "recovery," "policy," "hydrometallurgy," "pyrometallurgy," "critical minerals," "standards," "sustainability," "mining," "lithium-ion batteries," "electric vehicles," "end-of-life product management," "e-waste," "circular economy,"

Table 1: Interviewees by sector and area of expertise

Sector of Interviewee	Number of Interviewees	Area of Expertise and Information Shared
Li and REE industry	2	Mining, milling, and mineral processing industrial sectors, investigation of Li and REE recovery from waste streams
Industry of other minerals	2	Mining, milling, and mineral processing industrial sectors; investigation of Li and REE recovery from waste streams
EoL product management industry	1	EoL product collection and management industry; policy
Li and REE recycling from EoL products (industry)	3	Recycling processes to obtain Li and REE from EoL products (pre-commercial or under construction); policy
Li and REE recovery from other waste streams (industry)	1	Recovery processes to obtain Li and REE from other waste streams (pre-commercial or under construction); standards development
Consulting in the Li and REE supply chains	3	REE and Li mining, milling, and mineral processing industries; recovery of REE and Li from waste streams; circularity in mineral lifecycles; lifecycle analysis; development of standards and sustainability metrics
Services for Li and REE lifecycles	1	Analytical testing and analytical standards development related to Li and REE mining, milling, mineral processing, and waste streams
Government	2	Policy; standards development
Academia, research, and development institutions	2	REE and Li mining, milling, and mineral processing; recovery of REE and Li from waste streams; circularity in mineral lifecycles

"circularity," "extended producer responsibility," "product stewardship," "batteries," "magnets," "tailings," "brine," "waste valorization," "waste," and "midstream processing."

2.2 Engagement with Interested Parties

Individuals involved in the Li and REE material lifecycles were engaged to supplement the information gathered during the landscape and literature scan. The engagement process involved identifying individuals for interviews, carrying out interviews, presenting preliminary findings to a wider audience in a webinar, and incorporating results into the research report. Responses were anonymized so that neither the individuals nor their organizations could be identified. As shown in Table 1, a total of 17 interested parties agreed to be interviewed.

Engagement with interested parties supported critical analysis of the gaps, barriers, and opportunities to promote recovery and recycling of Li and REE. Along with the literature and landscape scans, the engagement process highlighted the critical needs that may inform a standards roadmap. The engagement process also echoed the findings of other similar studies [6], [8], [9], [10]. Because only a small portion of Li and REE are recovered from waste, there is limited analysis of this topic in the academic literature and other public sources. Also, the lack of well-established industries to recover Li and REE from waste emphasized that expertise on this topic is incipient.

3 Material Lifecycles and Waste Streams

To identify opportunities where waste could be recovered, it is important to understand the lifecycle of a resource as well as its processing methods and uses. The Li and REE value chains are lengthy, affecting many interested parties from mining through product manufacturing and recycling. There are also numerous waste streams containing Li and REE along each of the supply chain segments.

3.1 Production and Use of Lithium and Rare Earth Elements

Li is the lightest metal in the periodic table. Its unique properties make it ideal for use in lightweight, long-life batteries. It is increasingly used in lithium-ion batteries (LIBs) for EVs and for stationary energy storage systems for large solar and wind power installations [11]. Li is also used in cell phone and household batteries, glass and ceramics, and other end products [1]. Li is extracted from salt water (brines), mineral clays, or hard rock [1].

REE consist of the 15 lanthanide elements along with scandium and yttrium [12]. REE are used in permanent magnets (found in computer hard drives, electric motors, and generators), military equipment, lasers, lighting, batteries, oil refining catalysts, ceramics, and polishing powders. There is growing use of REE in the magnets of EV motors and wind turbine generators. REE are typically mined from mineral sands, hard rock (ore), and ionic clays [1], [3].

As shown in Figure 1 and Figure 2, several countries dominate the mining and extraction of Li (Australia, Chile, and China) and REE (China, the United States, and Australia).

3.2 Lifecycle Overview

Li and REE can be extracted from a natural resource on their own or co-extracted with other natural resources. Figure 3 shows a conceptual lifecycle of Li and REE. After extraction, the materials are reduced in size, if necessary, and concentrated. The material is then processed (i.e., chemically converted to another mineral, separated, purified, refined, and formed into metals, alloys, or precursors/battery active material). In the case of REE, these processing steps are executed by multiple entities. Finally, alloys and precursor/battery active material are used to manufacture products. The final manufactured product typically contains many material inputs, including Li, REE, other metals and minerals, and plastic.

Figure 1: Annual mining and extraction of Li. United States Li production is withheld due to confidentiality concerns. Data sourced from United States Geological Survey [2]

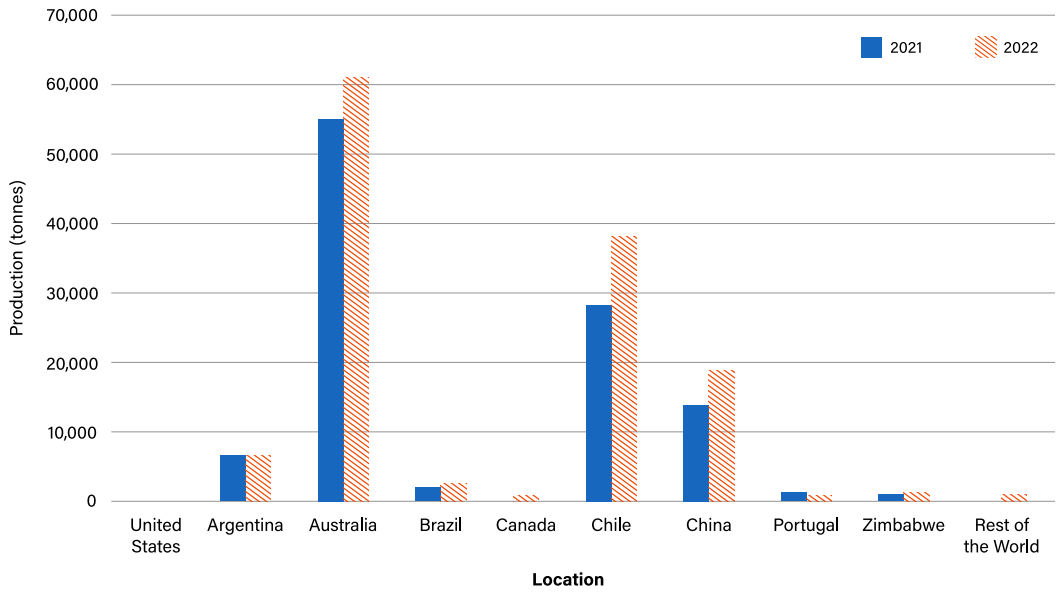
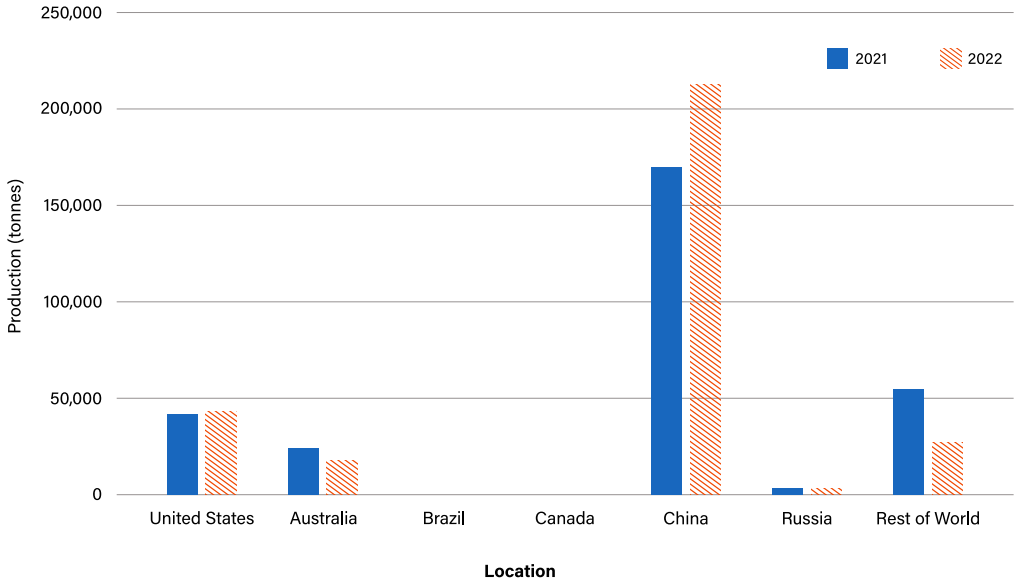


Figure 2: Annual mining and extraction of REE. Excludes yttrium and scandium. Data sourced from United States Geological Survey [3]



Solid and liquid waste material, which may contain residual Li and REE, is generated throughout the material lifecycles. Li and REE do not get destroyed, and products and waste streams can be recirculated via reuse, repurpose, repair, remanufacture, and waste recovery and recycling, with circular flow of materials.

Throughout the material lifecycles, there are several potential waste streams of Li and REE:

- Extraction waste (e.g., mine tailings from a solid rock Li mining operation that contain residual Li);
- Waste from mineral processing (e.g., slags);
- Waste from production of metals and alloys;
- Waste from production of precursor/ battery active material;
- Product manufacturing waste (e.g., scrap magnet material from a motor manufacturer); and
- Waste collection of EoL products from consumers and industries (e.g., e-waste and batteries).

The Li and REE lifecycles are also linked with the lifecycles of other resources. For example, in the production of energy and materials such as petroleum, phosphate, and uranium, Li and REE may naturally occur with the material but remain in various waste streams. Li and REE can be recovered from those streams, then processed and manufactured into products. As a result, the material streams change from wastes to resources. For example, if REE are recovered from a uranium mining operation, the REE become a co-product along with the uranium.

3.3 Industry Sectors within Material Lifecycles

There are multiple business entities in the material lifecycles that convert sources of Li and REE into inputs for industrial and consumer products. Metal and mineral extraction, mineral processing, and manufacturing companies are often categorized as upstream, midstream, and downstream, as shown in Figure 4 [13]. In the production of EVs, upstream mining organizations extract Li or REE from a natural source. These are processed to intermediate mineral products, metals, alloys, or precursors/battery active material by midstream processing companies. Downstream companies manufacture battery cells, modules and assemblies, magnets, motors, and EVs. There is potential to recover or recycle Li or REE from the waste streams of any of these industry sectors, as shown in Figure 3.

Figure 3: Conceptual lifecycle of Li and REE

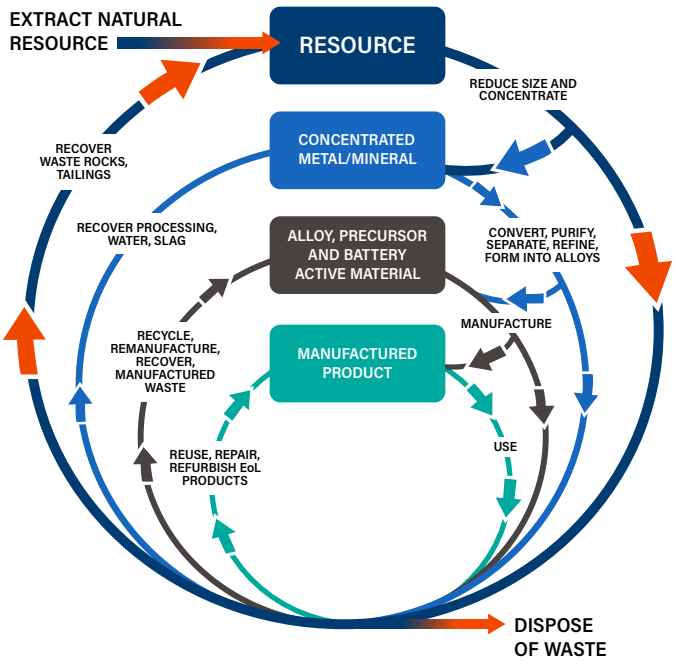
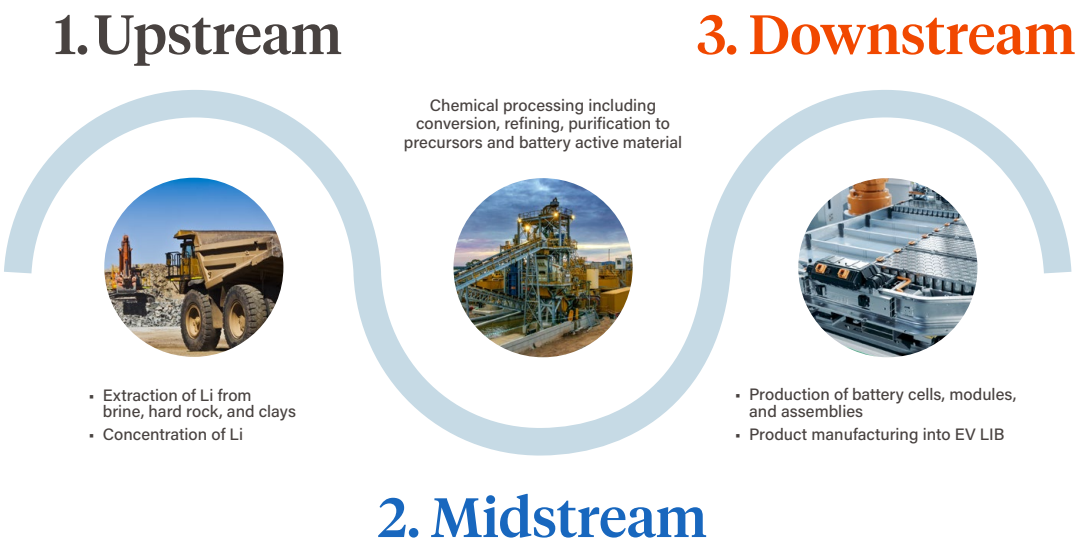


Figure 4: Upstream, midstream, and downstream industry sectors for Li to LIBs (top), and REE to EV (bottom) magnets



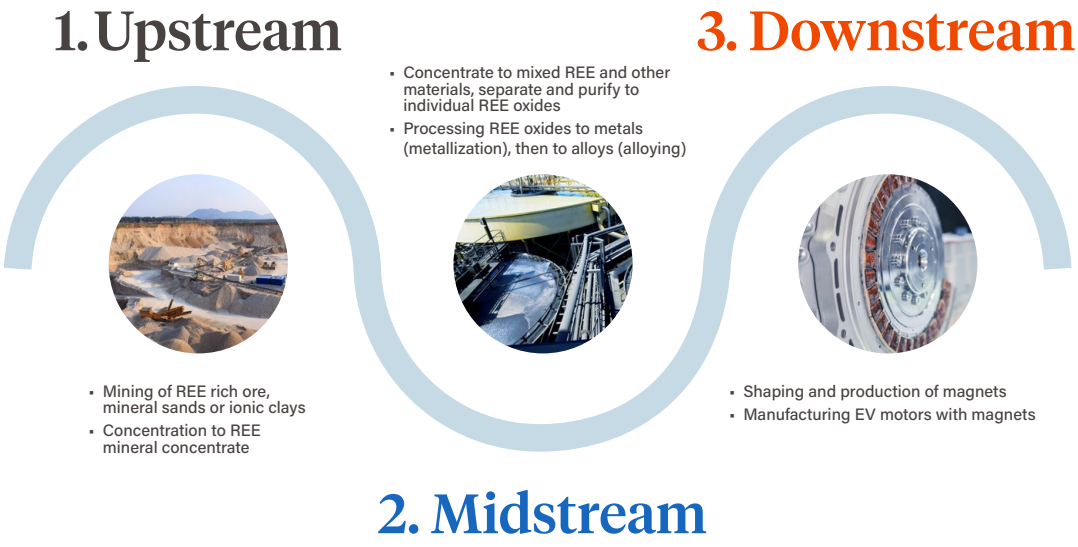


Figure 5: Overview of Li and REE waste streams



At the time of writing, most of the midstream and downstream industrial sectors of the Li and REE value chains are in China [1]. Chinese export law could be enforced to restrict the sharing of knowledge on rare earth processing [5]. Some of the technologies for recovering and recycling Li and REE from waste are similar to other existing technologies of the midstream sector. However, midstream REE processing technologies are complex, so there are potential logistical barriers and knowledge gaps when implementing recovery and recycling processes in other parts of the world.

3.4 Waste Streams of Lithium and Rare Earth Elements

There are several waste streams within the lifecycles of Li, REE, and other materials that are known to contain concentrations of Li and REE, as shown in Figure 5. Many of these wastes have been studied and continue to be studied as alternatives to natural sources of Li and REE. Based on projections from multiple sources, it has been estimated that waste REE could supply a significant proportion of global REE demand [14].This section provides an overview of the waste streams containing Li and REE.

3.4.1 Extraction and Milling Waste Streams

Extraction operations produce both liquid and solid waste [15]. There are numerous investigations of Li and REE recovery from mine tailings and wastes, including red mud from alumina production [16], oilsands tailings [17], and tailings from titanium production [18], [19]. In addition to the potential economic and sustainability benefits in recovering Li and REE from waste, it can also complement methods to remediate existing mining operations or to reduce waste disposal. In May 2023, mining companies Rio Tinto and BHP issued an open call for innovation in tailings management [20], and E3 Lithium Ltd. is investigating the recovery of Li from brines in Alberta and Saskatchewan [21].

Extraction waste streams are often high in volume and low in concentrations of Li and REE. This impacts the economics of recovery because it requires specialized technology, additional capital expenses, and high energy use.

Figure 6: Summary of waste streams discussed in Section 4



3.4.2 Mineral Processing, Manufacturing, and Other Waste Streams

Li and REE can be found in the midstream processing and downstream manufacturing waste of various industrial sectors. This includes material from processing (e.g., metallurgical slag) and product manufacturing (e.g., cuttings and scrap alloy). Li and REE are also found in the waste streams from the processing or manufacturing of other materials (e.g., fly ash from coal-based power generation or wastewater from a geothermal power plant).

An assessment of the potential recovery of REE from Alberta and Saskatchewan coal combustion by-products found that elemental concentrations of various REE were similar among samples from different coal power plants and were fractions of a percent (0.026 to 0.032 wt.%) [22].

Although Li can be found in geothermal brines [23], there are no operating geothermal power facilities in Canada at the time of writing. However, Saskatchewan's DEEP Earth Energy Production Corporation has plans to construct a geothermal power generation facility, using

brine from over 3,000 m below the surface [24]. The company has also secured subsurface mineral rights, which include Li from the brine.

3.4.3 End-of-Life Products and Landfill Waste Streams

Li and REE can be recycled from EoL products that cannot be reused or remanufactured. This waste includes electronic products, fluorescent lamps, EV motors, LIBs, and other batteries (nickel-metal hydride). Li and REE concentrations are particularly high in EV LIBs and magnets, respectively. It is anticipated that these will be available in increasingly high volumes in the coming decades as a significant number of vehicles containing these products will reach their EoL [13], [25]. Li and REE are also found in ceramics and spent catalyst material that is often used in oil refining. Some EoL products have been landfilled or incinerated, and these are potential sources of Li and REE. While landfills may have low concentrations of Li and REE, REE are often concentrated in the ash of incinerated garbage [26]. Federal funding in the United States is supporting research into the recovery of REE and other metals from incineration ash [26].

4 Recovery and Recycling of Lithium and Rare Earth Elements from Waste

In Canada and elsewhere, regular evaluation of all waste streams as sources of Li and REE would determine the total economic and sustainability advantages of traditional and alternative sources. This section presents the characteristics and recovery technologies applicable to a selected list of waste streams, as shown in Figure 6, that are either produced in Canada at multiple sites, contain relatively high concentrations of Li and REE, produced in high volumes, or require research and development.

4.1 Characteristics of Selected Waste Streams

The selected waste streams are characterized in sections 4.1.1 through 4.1.5, including available volumes and their compositions, where public data is available.

4.1.1 Uranium Mining, Milling, and Refining

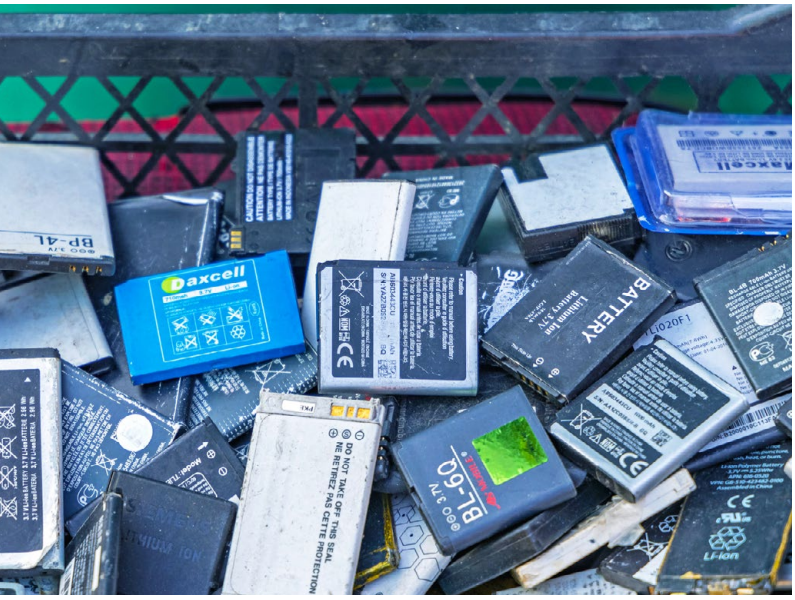
In 2019, Canada produced nearly 7,000 tonnes of uranium, but there is no available data on the volumes of waste streams for this industry [27]. At the time of writing, all of Canada's operating uranium mines and mills are in Saskatchewan. Uranium mining, milling, and refining waste containing REE includes liquid tailings from leaching processes (leaching tails), raffinate from solvent extraction, and wastewater treatment sludge [28]. The volume of these waste streams is proprietary information of the uranium milling and refining industry. REE are difficult to remove from leaching tails using current technology. Typical concentrations of REE (reported as rare earth oxides) are approximately 0.008 to 0.018 wt.% in raffinate, and 0.05 to 0.14 wt.% in dry water treatment sludge [28]. Waste streams of uranium operations can also contain other valuable metal and minerals (including Li), depending on the technologies used to extract and refine the uranium.

4.1.2 Petroleum Brines

In Alberta, British Columbia, Manitoba, and Saskatchewan, subsurface brine exists in oil and gas reservoirs as well as in other reservoirs. There are 6.7 million tonnes of reported Li resources in Canadian brine [29]. Typical western Canadian brines contain Li concentrations of 0.005 to 0.01 wt.%. Potential sources of petroleum brines include waste brine from an oil and gas production facility or brine pumped from an inactive oil and gas production well. Brine can also be produced from a standalone operation by drilling a new well into a subsurface brine reservoir.

4.1.3 Phosphogypsum

Phosphogypsum is a by-product from processing minerals such as phosphate. It is often stockpiled as a waste product and many of these waste piles contain REE. Globally, 180 to 270 million tonnes of waste phosphogypsum are stacked per year [30]. No public information could be found on Canadian phosphate fertilizer production or stockpiling of phosphogypsum waste in Canada. Around the world, REE concentrations in waste phosphogypsum are as high as 0.02 to 0.9 wt.% [30]. Phosphogypsum sometimes contains radioactive compounds, including uranium and toxic metals (e.g.,



"In Canada and elsewhere, regular evaluation of all waste streams as sources of Li and REE would determine the total economic and sustainability advantages of traditional and alternative sources."

cadmium), which adds to the complexity of recovering REE but also presents an opportunity for reducing EHS/ESG impacts of phosphogypsum waste.

4.1.4 E-Waste

Large volumes of e-waste containing varying concentrations of Li and REE are generated throughout Canada. Canada produced 954,000 tonnes of e-waste in 2020 and is projected to produce 1.2 million tonnes in 2030 [31]. Characterization of e-waste is difficult, and its composition fluctuates rapidly. The phosphor powder of a fluorescent lamp contains 2.6 to 7.2 wt.% REE, a mobile phone contains 0.29 wt.% of REE, and a nickel-metal hydride battery contains over 5 wt.% REE [32], [33]. The higher concentrations in certain products suggests that there may be economical benefits to collecting certain categories of EoL products separately, such as lighting, batteries, mobile phones, and computers.

An advantage of sourcing REE from e-waste is that EoL products contain the particular REE that are consumed [34], whereas in developing a new mineral resource, there will likely be an imbalance in naturally occurring REE ore deposits. The 17 REE often occur together in ore, and sometimes the least valuable REE (those with few product applications) comprise the majority of the REE content [34]. Furthermore, e-waste does not contain the radioactive elements (uranium, thorium, and radium) that often co-occur with natural REE deposits, and e-waste also contains other valuable minerals and metals.

4.1.5 Electric Vehicle Lithium-Ion Batteries and Magnets at End-of-Life

The magnets of most EV motors contain between 19 to 37% of REE by weight and there are 2 to 5 kg of magnet material per vehicle [33], [8], which is equivalent to 0.4 to 2 kg of REE per vehicle. In addition, each EV LIB contains approximately 6 kg of Li [8]. In the battery, the Li exists as part of salt and inorganic compounds and as dissolved ions [35].

There is an absence of market projections for EVs reaching EoL in Canada over the next several decades [8]. The Government of Canada has set targets that will increase the number of EVs in the country. By 2030, EVs are targeted to account for 40% of new light-duty vehicle sales, with the target reaching 100% by 2035 [36]. In 2021, EVs accounted for only 5.6% of new vehicle sales [36], and approximately 1.6 to 1.8 million vehicles reach EoL each year [8]. The life of an EV LIB battery is estimated to be 12 years [13], but this estimate does not account for second life prospects [35].

Based on these figures, and assuming that vehicle magnets and LIBs are not reused or repurposed, by 2047, EVs will be a source of about 3,200 tonnes of REE and 9,600 tonnes of Li per year. Consequently, EVs are a potential major source of Li and REE in Canada.

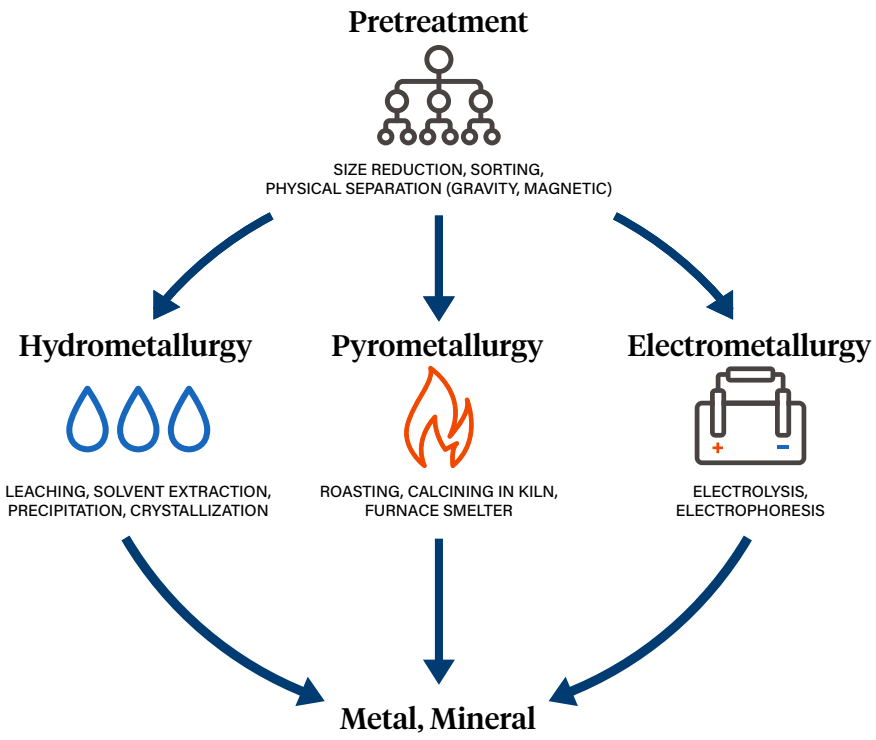
Unlike other consumer products, EV batteries and magnets are part of a consumer product with an extensive EoL management economy. There is already a profitable and established auto recycling industry in Canada where 94% of vehicles are collected for recycling, with 83% of the vehicle by weight recycled as scrap metal [8].

4.2 Technologies for Recovering and Recycling

The process technologies for recovering and recycling Li and REE from waste are similar to production from natural resources (hard rock, minerals), as shown in Figure 7. While some technologies do not fit these categories, the majority of these processes can be broadly categorized as follows:

- **Pretreatment:** Material is treated to make it easier to recover metals/minerals; products are dismantled, solids (ore, EoL products) are reduced in size by crushing and grinding; material is concentrated by sorting and physical separation (gravity, flotation, magnetic) to remove other materials such as plastic.
- **Hydrometallurgy:** Material is combined with liquids (solvents, acids, bases) to separate metals/minerals; physical and chemical processes involving reactions, dissolving materials, crystallization, and precipitation are sometimes used.
- **Pyrometallurgy:** Heat is applied to material in a furnace, smelter, or kiln.
- **Electrometallurgy:** Electrical energy is used to separate metals and minerals from other components.

Figure 7: Flow diagram for recovering and recycling metals/minerals from waste or natural resources



In the midstream sectors of the value chain (see Figure 4), many technologies are used to process Li and REE or to recycle other metals and minerals. These same technologies are often considered for recycling Li and REE from waste, which makes it difficult to differentiate between current and forthcoming technologies. Furthermore, a very small portion of Li and REE are recycled in large-scale commercial operations. In this report, *forthcoming technologies* refers to technologies requiring bench, pilot, and demonstration scale research and development on specific waste streams. Forthcoming technologies possess a technology readiness level lower than 8, while current technologies are commercial and have a technology readiness level of 8 or more [37].

4.2.1 Current Technologies

4.2.1.1 Lithium and Rare Earth Elements from E-Waste

At the time of writing, there is a lack of full-scale Li and REE recycling from e-waste. While many countries have some level of recycling to obtain mixed metals and other products from e-waste, most do not recover Li and REE as separate materials.

Recycling of Li and REE is feasible using existing hydrometallurgical and pyrometallurgical processes. In 2010, Solvay began recycling REE in France from processing and manufacturing wastes, as well as from nickel-metal hydride batteries and light bulbs [38]. Their process involves a hydrometallurgical method using solvent extraction. Nickel-metal hydride batteries are first processed by another company (Umicore) to remove nickel, and the remaining material is then shipped to Solvay for REE recycling. Solvay also recovers REE-rich powders from EoL light bulbs.

4.2.1.2 Lithium from Subsurface Brines via Evaporation

A large portion of global Li production comes from surface brine lakes or subsurface brine reservoirs in South America and China. In these locations, Li exists naturally as a component of the salt that is dissolved in the brine, and hydrometallurgical processes are used to separate the Li from water. Li is generally produced from these brines via evaporation and precipitation [29]. The brines are pumped into large, constructed ponds where a portion of the water evaporates, concentrating Li salts. This technology is suitable for high concentrations of Li in brines (0.04 to 6 wt.% Li in brine) and warm, sunny, dry climates. However, this process is a poor option for petroleum brines in western Canada due to the colder climate, high relative concentration of magnesium, and low concentration of Li (typically 0.005 to 0.01 wt.% Li in brine).

4.2.1.3 Lithium from End-of-Life Lithium-Ion Batteries

There are several established and planned commercial LIB recycling facilities in North America, Europe, Australia, and East Asia [39]. Technologies for recycling Li from EoL EV batteries are reasonably effective, with recovery rates over 90% [40].

Existing facilities separate steel casings, plastic, and other components from LIBs, leaving black mass [35], [41], which contains most of the Li of the batteries along with other metals (e.g., cobalt, nickel). Some facilities recover the cobalt and nickel but do not recover Li as a product [35], [41]. Pyrometallurgy is one method to recover cobalt and nickel where the Li remains in a waste stream called slag.

At the time of writing, Li can be recovered from black mass via two routes. The first involves hydrometallurgy, where the black mass material is treated with an acid or base solution (leaching) to dissolve Li and other components. Then Li and other components are precipitated out of the solution [42]. The second route involves a combined pyrometallurgical and hydrometallurgical method, where the black mass is treated at high temperature resulting in a residue that contains Li and other metals. Li can then be removed from the residue via hydrometallurgy [42].

4.2.2 Forthcoming Technologies

4.2.2.1 Rare Earth Elements from Uranium Production Wastes

With further testing and piloting, it is technically feasible to recover REE from uranium mining, milling, and refining wastes (e.g., raffinate from solvent extraction and wastewater treatment sludge) using

hydrometallurgical techniques [43]. These technologies include selective precipitation, sulfide precipitation, ion exchange, and solvent extraction. Of these, solvent extraction is the most established option [28].

4.2.2.2 Rare Earth Elements from End-of-Life Magnets

Several companies in Canada, the United States, and elsewhere have plans for commercial recycling of REE from magnets using either existing hydrometallurgical and pyrometallurgical processes or proprietary methods. A few examples, selected to showcase the diversity in technologies and strategies, are provided below:

- Cyclic Materials, based in Kingston, Ontario, is working with BMW Group to recycle REE from permanent magnets [44]. Their technology was successfully demonstrated at the pilot scale. This is an example of different sectors collaborating on research and development.
- Canadian company Geomega Resources and their subsidiary Innord Inc. have developed Innord's Separation of Rare Earths technology, a proprietary method that does not use organic solvents [16], [45], but is instead based on electrophoresis (the migration of charged particles in solution in the presence of an electric field). This process can recover individual REE from the waste material produced by manufacturers of magnets and magnet alloys. There is potential that this technique could also be used on other sources of REE, including red mud from alumina production.
- REE4EU, a collaboration of several European groups, have piloted direct high temperature electrolysis combined with ionic liquid extraction and hydrometallurgical processes to recover REE from magnets [46]. The technology is suitable for REE-rich waste from the manufacturing of magnets, nickel-metal hydride batteries, as well as EV magnets and batteries.
- Noveon Magnetics Inc. have implemented commercial-scale recycling of magnetic scrap and EoL computer hard disks (rich in REE) at their facility in Texas [47]. They combine recycled magnet materials with new materials to produce their own magnet products. They use a specialized treatment process that does not involve solvent extraction, hydrometallurgical, or pyrometallurgical techniques. Consequently, Noveon's process may result in less energy and material consumption compared to other processes.

4.2.2.3 Lithium and Rare Earth Elements from E-Waste

Some of the newly developed processes for extracting Li and REE from alternative natural sources or from recycling EV magnets are applicable to REE in other e-waste [46]. Due to the poor economics from low concentrations of Li and REE in e-waste, as well as sustainability and safety concerns with conventional recycling technologies, significant research and development into new pathways is ongoing, including the following examples:

- Apple Inc. has developed a robot called Daisy, which dismantles Apple cell phones at an operation in Austin, Texas [48]. Its purpose is to recycle 14 metals and minerals, including Li, and it can process 200 phones per hour.
- Bioleaching may be suitable for the economic challenges of recovering low concentrations of REE (and other metals) from e-waste. Bioleaching is a hydrometallurgical process where, instead of chemical acids, bacteria is used to leach REE from an EoL product, hard rock, or mineral sand [49]. The bacteria produce acids that break down materials.
- The flash Joule process recovers REE from multiple waste streams, including e-waste, red mud from alumina production, and coal fly ash [50]. The material is treated at very high temperatures (~3000°C) for approximately one second. This degrades the material so the REE can be more easily leached with acids, which requires smaller concentrations of acids and smaller volumes of acid and solvents.

4.2.2.4 Rare Earth Elements from Phosphogypsum Waste

There are ongoing investigations into the recovery of REE from waste phosphogypsum using hydrometallurgical processes. While there are no established commercial operations at the time of writing,

Rainbow Rare Earths Ltd. has announced plans to recover REE from phosphogypsum in South Africa [51].

Recent research and development findings into the recovery of REE from phosphogypsum waste indicate that [30]:

- Indirect leaching of REE along with co-production of other products from phosphogypsum may improve the overall economics of REE recovery; and
- Bioleaching shows promise as an economical process for recovering REE from phosphogypsum.

4.2.2.5 Direct Lithium Extraction from Petroleum Subsurface Brines

While production of Li from western Canadian petroleum and subsurface brines is not yet commercial, several companies are carrying out research and development, including pilot testing. Most are testing some form of direct Li extraction (DLE) technology, which is applicable to waste brine produced from operating oil and gas sites, old oil and gas wells, or new standalone wells. DLE technologies are also being considered as a sustainable alternative to evaporation technologies for brine sources in South America and elsewhere.

DLE produces a purified Li solution, which is then processed further. DLE technologies under investigation include one or a combination of the following [29]:

- **Selective ion exchange adsorbent:** Li-containing brine is passed through ion exchange adsorbent particles. Li attaches to the adsorbent while other metals and contaminants remain in the liquid brine.
- **Solvent based:** Li-rich brine is mixed with an organic solvent. Li, along with other components, moves from the brine solution to the organic solvent.
- **Selective membrane and nanofiltration:** Li-rich brine is pumped to sets of reverse osmosis or nanofiltration membranes. The systems are designed such that smaller components (i.e., Li ions) and some of the water pass through the membranes, while the remaining water containing larger components is rejected.
- **Electrometallurgy:** An electric current is applied to a cell containing Li-rich brine. The Li travels with the current to one side of the cell. Research indicates that selective membranes can divide the cells and reduce problems with other contaminants in the brine.

4.2.2.6 Lithium from End-of-Life Lithium-Ion Batteries

Research and development is underway to reduce the economic and sustainability costs of recycling Li from LIBs. Recent advances include:

- **Direct recycling:** Involves removing the cathode and anode from the battery and reconditioning them [39]. In theory, this process uses less energy and fewer materials because it does not involve pyrometallurgy or hydrometallurgy.
- **New hydrometallurgical and electrometallurgical processes:** New hydrometallurgical processes under development include solvent extraction, bioleaching, and selective ion exchange adsorption, which is similar to DLE. Electrochemical extraction is also under investigation [35], [39], [41].

5 Policy and Standards Landscape

This section describes current policies, best practices, and standards that address Li and REE recovery and recycling and help frame a standards roadmap in this field. Several global examples are highlighted, with an emphasis on Canada. Li and REE are sourced from waste for economic benefit and as part of initiatives to address sustainability, EHS, and supply chain impacts. A summary of the policies, best practices, and standards is provided in Appendix B.

5.1 Addressing Sustainability Impacts

There are some existing and many new and emerging policies, best practices, and standards pertaining to the recovery and recycling of Li and REE from waste that consider sustainability and long-term ESG impacts. Several include a circular economy approach, some of which were prompted by recent attention on critical mineral supply chains. Other policies, best practices,



"CSA Group is developing a battery circularity standard that will govern the material lifecycle of batteries from EVs and energy storage systems, including mining, processing, manufacturing, product design, transportation, material handling, and recycling."

and standards discussed in this section focus on EPR, waste valorization, and sustainable mining approaches. The summary report from the World Circular Economy Forum 2021 emphasized that policies and best practices around circularity are not new, and are a part of the traditions and worldviews of many Indigenous peoples throughout the world [52].

5.1.1 Canada

In Canada, a circular economy approach is mentioned in the federal Critical Minerals Strategy [53] and in the Canadian Minerals and Metals Plan [54]. Natural Resources Canada's (NRCan) Green Mining Initiative researched valorization of mining waste [15] and NRCan launched the Critical Minerals Centre of Excellence [55], which will provide grants to commercial-stage pilot projects involving traceability projects for critical mineral supply chains. Furthermore, as part of the Canadian Minerals and Metals Plan, NRCan funded research on opportunities to extract further value from mine waste streams [9].

Canada's CSA Group is developing a battery circularity standard that will govern the material lifecycle of batteries from EVs and energy storage systems, including mining, processing, manufacturing, product design, transportation, material handling, and recycling [56].

Studies that have reviewed circularity policy in Canada note that it falls under multiple government jurisdictions (federal, provincial, and municipal), with a large share at the provincial level [9], [57]. Provincial governments have collaborated on EPR policy to improve product recycling, including e-waste and batteries [58]. Several provinces have also introduced EPR legislation for different product categories, with third-party organizations overseeing EPR programs. For example, legislation in British Columbia requires EPR for various products [59], and Ontario and Quebec have implemented specific circular economy policies and legislation [57], [60].

The Battery Metals Association of Canada, which represents members of the Canadian battery supply chain industries (e.g., Li extraction, battery recyclers, and critical mineral mining companies), co-published a roadmap for the Canadian battery value chain that specifically includes Li and REE [13]. One of the roadmap's four goals is to foster a closed-loop, battery material recycling industry in Canada that can recycle at least 95% of battery materials. Other goals focus on responsibly managing and minimizing waste streams from mining, processing, and manufacturing. The roadmap stresses the importance of collaboration between Indigenous peoples, communities, governments, and industry sectors throughout material lifecycles.

5.1.2 Global

For over ten years, the International E-Waste Management Network has promoted best practices related to the circularity of e-waste [61]. It is jointly coordinated by the United States Environmental Protection Agency and the Taiwan Environmental Production Administration.

UL 3600, *Measuring and Reporting Circular Economy Aspects of Products, Sites and Organizations,* helps to evaluate circularity in products, and includes metrics and methodologies for measuring material flows and lifecycle impacts [62]. ULE 110, *Standard for Sustainability for Mobile Phones,* aims to reduce the sustainability impacts of cell phones throughout their product lifecycles [63].

5.1.2.1 Global Mining Industry

The Mining Association of Canada has created an internationally recognized standard, *Towards Sustainable Mining* (TSM) [64]. A TSM supplement on responsible sourcing helps companies evaluate circularity throughout a mining project's design, operation, and decommissioning as it promotes recovery, reuse, and recycling of materials [65]. The World Bank's Climate-Smart Mining Initiative encourages a circular economy and the valorization of mine waste [66]. Many Canadian mining companies are part of the Canadian Mining Innovation Council, which collaborates on various sustainable mining projects, including the promotion of a circular economy in mining [67].

Aspects of other sustainable mining best practices complement a circular economy strategy and promote waste valorization [9]. For example, the Initiative for Responsible Mining Assurance has developed the *Standard for Responsible Mining,* IRMA-STD-001 [68], and the International Council on Mining and Metals represents global mining companies that have committed to a set of principles that prioritize sustainable development and responsible production of metals and minerals, and has plans to incorporate circular economy principles into their framework [69].

5.1.2.2 ISO Standards

In addition to other international mining initiatives, the International Organization for Standardization (ISO) has a technical committee on Mining (ISO/TC 82) [70]. Its subcommittee on Sustainable Mining and Mine Closure (ISO TC 82/SC 7) is developing standards to reduce the environmental impact of EoL mining operations. The Standards Council of Canada has established mirror committees, which are administered by CSA Group. Canada also holds the ISO secretariat for the subcommittee on Advanced Automated Mining Systems (ISO TC 82/SC 8).

The ISO technical committee on the Circular Economy (ISO/TC 323) is developing standards related to circularity terminology and measurement [71]. In addition, the sustainability working groups on the technical committees for Lithium (ISO/TC 333) and Rare Earth (ISO/TC 298) have been developing standards applicable to the Li and REE lifecycles [72], [73]. These working groups were recently merged into one group looking at both commodities, with plans to standardize the measurement of Li and REE flows and sustainability metrics, providing a sustainability framework that will support the circular flow of materials. The Standards Council of Canada has established mirror committees to ISO/TC 298 and 333, which are administered by CSA Group.

The Association Française de Normalisation proposed a new technical area of work on specialty metals and minerals, which was approved by ISO and a new technical committee (ISO/TC 345) was launched in 2023. Its scope includes metals and minerals that are not covered by other ISO technical committees, but it explicitly excludes sustainability issues [74].

The German Institute of Standardization proposed a new ISO project committee focused on generating standards for sustainable raw materials, with the reasoning that the overarching sustainability issues and requirements are similar across the resources sector. The proposal was passed through ISO, and the new ISO project committee launched in 2023. The proposal noted that sustainable materials criteria

should apply to the full material supply chains. The criteria would also be harmonized for multiple materials, rather than creating separate criteria for different metals or industry sectors. In addition, Standards Australia has initiated an ISO International Workshop Agreement on Sustainable Critical Minerals Supply Chains [75]. The workshop will draw stakeholders from all sectors (government, industry, and civil society) to address the need for global collaboration on effective and efficient tools for achieving sustainability in critical mineral industries.

5.1.3 European Union, United Kingdom, and Chile

The European Union has an explicit circular economy policy related to Li and REE lifecycles. The European Green Deal is a plan for investing in sustainability that furthers key action plans, as well as current and proposed legislation on circularity, batteries, and critical raw materials [76], [77], [78], [79], [80]. The legislation includes EPR, recycling, recycled material targets, and promotion of critical mineral supply chains.

The British Standards Institution has published two standards related to LIBs that involve a circular economy approach [81], [82]. The standards provide guidance to reduce EHS impacts throughout material lifecycles and to facilitate reuse, remanufacture, and recycling of batteries and cells. They also promote improvements to product and manufacturing process design to reduce the consumption of new sources of Li and metals. The British Standards Institution also developed a roadmap to guide further LIB manufacturing standards development.

Chile has a large mining industry and is a major producer of Li. Chile's National Mining Policy and legislation has led to circular economy and EPR regulations [83], [84].

5.1.4 China

China has invested in circularity policies at the local, provincial, and national levels to reduce consumption of natural sources of materials [85]. Policies include taxation, incentives, recycling targets and quotas, and funding for circular industrial parks. For certain materials, consolidating most of the lifecycle steps (from processing to recycling) in the same industrial park is a benefit [85]. China is also promoting innovative data solutions to trace materials and products in order to improve circularity [86].

5.1.5 United States

The United States has initiated legislation and policies to promote local critical mineral supply chains and a circular economy of critical minerals, including the *Infrastructure Investment and Jobs Act*, America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition, and the Critical Minerals and Materials strategy [87], [88], [89]. These policies and legislation include support for EPR for EV batteries, and mining waste valorization as a source of critical materials [90].

The United States is home to many corporations and businesses that have implemented voluntary circular economy policies to achieve sustainability goals and market competitiveness. The United States Chamber of Commerce provides best practices and tools for businesses considering circular economy strategies [91].

In the field of best practices and standards, the National Institute of Standards and Technology (NIST) is developing a Circular Economy Resource Registry and is researching circularity standards along with ASTM International [92], [10]. ASTM committee E60 on Sustainability is investigating circularity standards, while supporting ISO/TC 323 [10]. In addition, ASTM committee F40 on Declarable Substances in Materials is examining standards for evaluating REE in materials and products [93].

NSF/ANSI 426, *Environmental Leadership and Corporate Social Responsibility Assessment of Servers*, encourages the recycling of REE from computer hard disk drives and the incorporation of recycled REE in new computers [94]. The purpose of this voluntary standard is to improve sustainability and REE supply chain resiliency.

The Electronic Product Environmental Assessment Tool (EPEAT) supports a circular economy strategy by providing an ecolabel for registered electronic products, including computers, monitors, imaging equipment, and cell phones, that informs purchasers how a product meets environmental performance criteria, such as reducing supply chain GHG emissions, design for circularity and product longevity, and energy conservation [95].

5.2 Addressing Environmental, Health, and Safety Risks

The recovery of Li and REE may involve EHS hazards during material handling, transportation, and processing. For example, REE often occur naturally in ore along with radioactive elements, and mining waste streams that are rich in REE are frequently radioactive. In Canada, there are federal regulations for packaging and transporting nuclear substances [96], which require the classification of material according to International Atomic Energy Agency regulations [97].

Environmental and health risks from toxic metals must be considered when recycling batteries and e-waste. LIBs can be hazardous because they can spontaneously ignite during handling, storage, transportation, and processing. A recent report on the circularity and recycling of LIBs summarizes existing standards and best practices pertaining to fire and accident risks, as well as EHS risks pertaining to labelling, shipping, handling, transportation, collection, and storage [35].

The United States Energy Storage Association (which is now part of the American Clean Power Association) issued guidelines for recycling and EoL management of stationary energy storage batteries [11]. These guidelines consider EHS impacts, and the principles are pertinent to EV LIBs and other e-waste.

As part of national and voluntary efforts in the United States, hundreds of recyclers are certified, by accredited third-party auditors, to safely recycle and manage e-waste to either the *e-Stewards*® [98] or the R2 [99] standard. Both standards promote e-waste recycling best practices to reduce EHS and data security risks. A number of Canadian companies have also obtained these certifications.

5.3 Addressing Supply Chain Impacts

In addition to critical mineral policies that address both sustainability and supply chain objectives, there are a number of policies that focus on the development of critical mineral supply chains.

Canada has partnered with the United States on a Joint Action Plan on Critical Minerals Collaboration to develop critical minerals supply chains [100]. In 2020, trade between the United States and Canada in the mineral sector was valued at over $95 billion. The Canada-EU Strategic Partnership on Raw Materials also advances critical mineral supply chains and includes collaboration on standards [101]. Canada and multiple provinces have also developed critical mineral lists that include Li and REE.

Australia, which has large Li and REE reserves, introduced its Modern Manufacturing Strategy in 2020, which included policy roadmaps for promoting local supply chains of critical minerals [102].

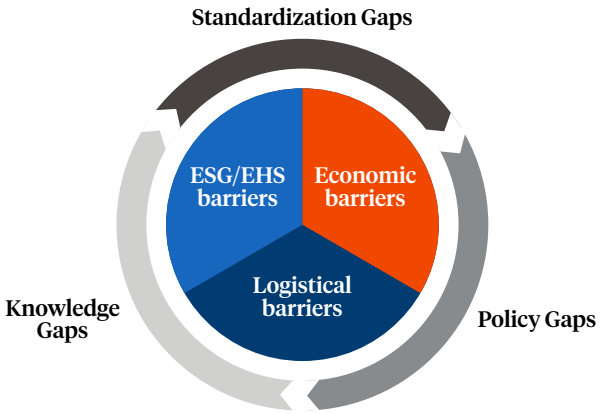
Because Li can be extracted from brines in western Canada, from new, operating, or inactive oil and gas wells, the provincial governments of Alberta and Saskatchewan have updated their legislation and regulations to include Li production from subsurface brines. Both provinces enacted regulations that are overseen by the same authorities responsible for oil and gas production (i.e., Alberta Energy Regulator and Saskatchewan Ministry of Energy and Resources) in order to streamline the process [21].

6 Barriers, Gaps, and Critical Needs

It is important to understand why less than 1% of Li and REE are recycled globally, compared to more than 45% of copper, and to find ways to improve the current situation. Barriers and gaps to recovering and recycling Li and REE from waste were highlighted by the literature and landscape scans, and through consultations with interested parties. This critical analysis indicated that there are economic, logistical, and ESG/EHS barriers, along with knowledge, policy, and standardization gaps that must be overcome to facilitate the recovery and recycling of Li and REE at a

greater scale. As illustrated in Figure 8, although these barriers and gaps are subjective, they help to focus the key issues for consideration in planning standards development related to the recovery and recycling of Li and REE.

Figure 8: Gaps and barriers affecting the recovery and recycling of Li and REE



6.1 Economic Barriers

Economics are a major barrier to the recovery and recycling of Li and REE from waste. Recovery and recycling processes often have high operating costs (labour, chemicals, water, and energy), and processing facilities require substantial capital investment (facilities can cost hundreds of millions to billions of dollars). In a market system that does not account for sustainability costs, recovery and recycling processes are sometimes unprofitable on their own and it is cheaper to dispose of waste via tailings ponds, landfills, and incinerators. As a result, less than 1% of Li and REE are recycled globally.

Factors that influence the economics of sourcing Li and REE from potential waste streams include:

- Concentrations of Li and REE, and their yield when recovered, are low, along with any variability in these values.
- Poor economies of scale because the volumes of waste are low. For example, it is less expensive to process tailings from multiple mines in the same area rather than the waste from a single mine. It may be possible to improve economies of scale by building modular recovery and recycling systems that can be moved from site to site.
- Operating and capital costs of processing Li and REE waste may be high in the jurisdiction where the waste is generated.
- Design of the mining, chemical process, manufacturing process, or consumer product does not consider recovery and recycling from waste streams. Process and product design often focuses on functionality and performance rather than circular flow of materials. There is a lower cost to recycle REE from a product if they can be easily removed and processed in a separate stream containing a high concentration of REE [103].
- There is economic risk and uncertainty caused by fluctuating prices and rapid changes in the Li and REE value chains and markets. For example, in the LIB recycling industry, because technologies are changing rapidly, it is difficult to know which business models make the most sense [25]. Furthermore, in North America, markets for EoL magnets and batteries from EVs are limited. Uncertainty discourages investment and drives up the cost of capital [35].
- Product manufacturers may avoid using recycled raw materials due to quality concerns unless there are policies to encourage the use of recycled content [104].
- Canada is geographically large with low population density, making it more expensive to collect consumer products at their EoL.
- The amount of Li and REE in consumer product designs tends to decrease as product designs are improved, thereby reducing the amount of material that can be recycled.
- Some recovery and recycling processes have negative impacts that must be mitigated (e.g., treating wastewater), resulting in additional expense.

6.2 Logistical Barriers

The main logistical barrier to the recovery and recycling of Li and REE is that existing markets, processes, and products were not established or designed with circular flow in mind. It is difficult to disrupt the current Li and REE economic system, which is largely linear, and shift to a circular economic system. It would be easier to reprocess mining or industrial waste if the waste was considered a potential future resource (e.g., dry stacking mine tailings). In addition, it is easier to recycle products that are designed for recycling, but the REE in the magnets of computer hard disk drives, for example, are often inaccessible within metal housings.

The following factors also affect logistics:

- Coordinating Li and REE recovery and recycling is complicated because there are many steps in the material lifecycles (see Figure 2) and a lack of collaboration between industry sectors (see Figure 4). Each lifecycle step often occurs in different, siloed industry sectors and government departments, which means a wide range of different parties need to work together to create systems to facilitate recovery and recycling without impeding existing waste industries. For example, there is already a profitable auto recycling sector. With the advent of EVs, recovery of Li and REE from batteries and motors may involve several different waste recyclers [8], [35].
- Li and REE recovery and recycling processes often involve technologies in the midstream processing industries of the value chains (see Figure 4). The lack of midstream Li and REE industry in North America results in less recovery and recycling experience and knowledge [14], limits collaboration throughout material lifecycles, and limits the development of markets for recycled material in Canada.
- Although in the future it may be feasible to meet domestic Li and REE demand with recycled material, there is a "chicken-and-egg" problem in using recycled material. In Canada, there is a lack of EV motors and batteries that have reached EoL, as well as a lack of recycling infrastructure and markets. Thus, manufacturers rely on current sources of Li and REE, without motivation to develop circular material flows.
- There is limited evidence that demonstrates how recycled materials will perform compared to new materials in different products, and whether they will contain impurities that impact performance or safety [105].
- Some product features cause recycling challenges that are difficult to address. For example, rust-prevention coatings on permanent magnets may contaminate recycled REE material [39], and some recycling shredding machinery is ferromagnetic, so recycled motor magnets stick to it, interfering with the machinery function. Furthermore, manufacturing aids or other inputs to consumer products can contaminate recycled materials. For example, the oil used in cutting magnets can differ between manufacturers and can interfere with recycling processes.
- There are many types of electronic products and batteries, but no standard design. In fact, there are many different designs for the same types of product and many different products containing Li and REE. New types of products now contain electronic technology (e.g., clothing) and products are changing rapidly [105]. Furthermore, packaging different types of energy storage batteries for transport is logistically complicated [11]. Recycling technologies need to be robust so they can accommodate multiple feedstocks, but in some cases, recyclers do not have a process for certain products [105].
- Labour market constraints affect whether there is skilled labour to work in the recycling industry [105]. Labour costs and availability in North America could motivate the shipment of recovered metal from consumer products overseas for further recycling.

6.3 Environmental, Social, Governance, Health, and Safety Barriers

As with other industrial ventures, there are broad ESG and EHS considerations that must be addressed when implementing waste recovery and recycling. There are also impacts specific to the Li and REE material lifecycles. Industry may be reluctant to source Li and REE from waste, even when economical, to reduce EHS and ESG risks. Three key topic areas are discussed in this section.



"Recovered metals and EoL products are often shipped overseas to areas where labour costs are cheaper but may lack regulations that protect workers, surrounding communities, and the environment."

6.3.1 Complex Environmental, Social, Governance, Health, and Safety Impacts

Interviewees and webinar participants noted that recovered metals and EoL products are often shipped overseas to areas where labour costs are cheaper but may lack regulations that protect workers, surrounding communities, and the environment. The Roundtable on the Responsible Recycling of Metals includes representatives from the metal recycling industry, the voluntary standards systems, civil society, the metals industry, and academia [106]. It is developing a roadmap, with a circularity approach, to responsibly recycle metals. Their scope includes global recycling, e-waste, and labour and human rights.

In general, technologies that recover and recycle Li and REE involve significant material (e.g., acids and solvents) and energy consumption. Recovery and recycling processes, if not adequately designed, may create additional waste streams (air, water, or land), which could impact ecosystems, communities, and other industries. It is difficult to evaluate the ESG and EHS impacts of new recovery and recycling initiatives and weigh them against alternatives. The data, metrics, and monitoring of these impacts are significant knowledge gaps.

Furthermore, certain waste streams (e.g., phosphogypsum) may involve radioactive materials, toxic metals, and organic substances [32]. E-waste may also contain toxic metals. There are risks for workers being exposed to these hazards.

6.3.2 Fire and Explosion Risk of Lithium-Ion Batteries

There are fire and explosion risks associated with LIBs during waste collection, material storage, transportation, handling, and recycling [35]. These barriers could benefit from knowledge sharing, standardized product labels, and standardized training programs [35], [50].

6.3.3 Fire and Explosion Risk of Rare Earth Elements Material

There are also safety risks to handling and processing recycled products that are high in REE. The dust of certain REE can combust or explode in the air from static electricity sparks, and dysprosium can react with water, producing flammable and explosive gas [107].

6.4 Knowledge Gaps

In conjunction with standardization and policy development, recovery and recycling of Li and REE can be supported by bridging gaps pertaining to data management, technology, and knowledge sharing. Further details with respect to these areas is provided in sections 6.4.1 through 6.4.3.

6.4.1 Data Management

Data management involves collecting, organizing, storing, and using data. Data on Li and REE quantities and ESG/EHS impacts would facilitate research, policy, long-term planning, and investment decisions related to the recovery and recycling of these materials from waste. Market supply and demand projections and data on critical minerals currently stored in mining and industrial waste would support recovery and recycling projects [9]. It is important to note that in some cases, it is not just that there is an absence of data collection, but that there is a lack of standardization of the parameters that need to be monitored and a lack of monitoring tools. Data quality improves when it is reported publicly and is transparent and verifiable [9].

6.4.1.1 Monitoring Materials Streams

The monitoring of material flows and concentrations in all waste and product streams and reservoirs (e.g., municipal landfills), from extraction to recycling, would provide valuable data. Additional monitoring may reduce ESG impacts by reducing illegal and irresponsible extraction [108]. There are knowledge gaps in monitoring the characteristics (e.g., flows, concentrations, volumes, and recovery) of streams throughout Li, REE, and other mineral lifecycles. Data monitoring of REE is particularly challenging because there are 17 elements in this group of minerals, which are used in a wide variety of products.

A research report on the provenance and traceability of REE products presents several practices to consider as part of a global traceability standard, such as officially sanctioning all participants in the material supply chain and creating a computerized record-keeping ledger [108]. Several initiatives to improve critical mineral supply chain traceability have also been implemented. For example, NRCan's Critical Minerals Centre of Excellence is accepting grant applications for critical materials traceability projects [55], and the ISO has issued ISO 23664, *Traceability of Rare Earths in the Supply Chain from Mine to Separated Products*, for tracing REE in the supply chain from mine to separated products, and is also developing traceability standards further along the value chain [109].

The Rare Earth Industry Association has partnered with industry and technology providers on the Circular System for Assessing Rare Earth Sustainability project, which will use blockchain to create a tracking and traceability tool for REE data throughout the material lifecycle, and will also integrate sustainability metrics [110].

6.4.1.2 Quantifying Sustainability Impacts

In addition to monitoring, there is a need for global collaboration on quantitative metrics that evaluate lifecycle sustainability and degree of circularity [9]. These types of metrics would allow comparison of the total economic, supply chain, social, and environmental costs of different products or processes. Although these metrics are emerging, some may favour one industry sector over another. There is likely a need for further standardization of existing lifecycle analysis and product category tools [9], [111]. Other standardization needs include methodologies, formulas, models, and technologies for monitoring these metrics. Some financial groups have developed best practices for accounting for sustainability [112] and a battery passport, which will provide full lifecycle information on batteries, is also in development [13].

A notable complication with measuring sustainability performance is that sustainability impacts are typically location and case specific, so it is difficult to develop one methodology that addresses all cases [29].

6.4.1.3 Data Specific to End-of-Life Product Management

At the EoL stage, consumers and recyclers would benefit from improved product information. For example, it would be helpful to provide product composition on a label, along with information regarding how it was manufactured, its contents, its value in secondary markets, and how to recycle it [105]. For LIBs, there is a need for information on a product's usage history and condition; this data would facilitate decisions on whether to repurpose, refurbish, or recycle the battery. New battery indicator technologies that provide information on whether the battery needs to be refurbished or recycled are emerging.

6.4.2 Technology

New technology solutions can lead to recovery and recycling processes that are more economical and more sustainable [14]. However, in many cases, there is a lack of commercial-ready technologies to recover and recycle Li and REE from certain wastes, particularly e-waste, brines with low concentrations of Li, coal fly ash, landfill incineration ash, and mining and mineral processing wastes (e.g., phosphogypsum). Further investment in research and development and access to capital for new projects would help enterprises bridge these technology gaps.

6.4.3 Knowledge Sharing

Lengthy Li and REE material lifecycles contribute to gaps in knowledge sharing. At the process and product development stage, designers lack knowledge about the material lifecycle [105]. Access to this information may facilitate more efficient designs, where products can be reused, repaired, and recycled; it could also spark improvements in processes (from extraction to manufacturing). These gaps are exacerbated by rapid changes to policy, technology, and products, and further complicated in North America by the lack of midstream industries in the Li and REE value chains [105].

Additional knowledge sharing gaps include:

- The dissemination of knowledge related to recycling often lags behind the introduction of new products. Although there are standards and best practices dealing with transportation and material handling of LIB batteries, there are also knowledge, training, and coordination gaps [35]. For example, in Canada, many EoL vehicles go to one of the country's 300-plus auto recyclers, who find secondary markets for auto part assemblies, including LIBs. There is a lack of awareness among auto recyclers of best practices or regulations about how to remove, store, and ship LIBs.
- EoL product management is also hampered because consumers are often confused about where and how each product can be reused, repaired, or recycled [105]. In addition, consumers may not understand the data security protocols that protect data on products like computers, and may therefore direct these devices to landfill.
- There is a lack of communication between companies (from mining to product manufacturing) that produce waste streams containing Li and REE, companies that are looking for alternate sources of materials, and innovators who have the best technologies to recover these elements.

6.5 Policy Gaps and Opportunities

Policy, in its broadest sense, has the potential to facilitate the recovery and recycling of Li and REE. Policy can be thought of as a systems approach (that encourages holistic solutions) to any gaps that exist among those affected by the system. Indigenous groups, governments, corporations, industry associations, nonprofit organizations, academia, and consumer organizations are all instrumental in the development and implementation of policy. Two policy opportunities that were mentioned by multiple interviewees were to: (a) support an economic system that accounts for sustainability and supply chain needs, and (b) support the circular flow of materials.

One opportunity for policy is to encourage a cost structure that integrates financial, sustainability, and supply chain costs throughout material lifecycles. As mentioned, some financial groups are developing best practices for accounting for sustainability [112]. New cost structures could increase recovery and recycling from waste when its overall cost is more attractive than other options, and could encourage other alternatives when practical. It is important to note that overall costs are specific to waste and material sources, technologies, location, and so on.

Circular flow of Li and REE could be supported by collaboration between groups, jurisdictions, and industries. Linking different objectives could lead to overarching strategies throughout the material lifecycles. A circular approach addresses the root causes of issues, using both wide and narrow perspectives. Although both perspectives are essential, it can be difficult to bring them together. For example, not all sectors in the supply chain (e.g., downstream, midstream, upstream) of the Li and REE lifecycles have the same approaches to sustainability or circularity.

A wide range of policy tools have been suggested to facilitate further recovery and recycling of Li and REE, including targets (e.g., recycled Li content in a battery

or procurement of products designed for recycling), programs (e.g., training and knowledge sharing programs), mandates (e.g., disposal bans), and incentives (e.g., tax savings for minimizing waste streams or funding research and development). However, it is not always possible to predict the unintended consequences of systemic actions, so ongoing reflection and review of the overall effects of these tools should be encouraged. For example, the concept of EPR means that manufacturers or importers are legally responsible for managing products at EoL, but in certain circumstances, EPR could worsen overall sustainability and supply chain impacts by promoting a particular method of product recycling (resulting in high material and energy use) instead of repurposing (with low material and energy use). Furthermore, a product designed for recycling might be less reliable, resulting in a shorter product lifespan and more material consumption. Policy effectiveness may depend on timing, jurisdiction, and existing markets, so a successful policy for a product in one area may not work in another.

Different types of waste may also require tailored strategies. At the time of writing, e-waste recycling is seldom economical and is often the responsibility of municipalities in Canada, but there are well-established, profitable auto recycling and scrap metal industries. As such, unique strategies might be required for these sectors to increase the recycling of Li and REE from EVs.

6.6 Standardization Gaps

Standards can support data gathering, technology development, and knowledge sharing in the Li and REE lifecycles. They can also support policies to account for sustainability costs and to encourage a circular economy. In addition to these, the following critical needs were identified for standards development during the engagement process:

- **Cross-sector collaboration:** There is a need for extensive collaboration between multiple industry sectors, governments, and many others in the Li and REE lifecycles to develop standards. It is a complex, multi-system challenge to reduce sustainability and supply chain impacts in these lifecycles, similar to the global challenge to decarbonize. It is important that one group is not favoured at the expense of another.
- **Systems approach:** There is a need to link multiple objectives related to sourcing Li and REE from waste with a systems approach to facilitate these initiatives where and when it makes sense. A systems approach considers the overall interactions between different subsystems while understanding sufficient detail in each area. Li and REE can be sourced from waste for direct economic benefit, to improve sustainability impacts, or to improve supply chain issues. There is a need to understand these different objectives, which are sometimes complementary and sometimes conflicting. Alternatively, recycling and recovery from waste can be weighed along with many other possibilities in an overarching circular economy approach, which involves promoting environmental and economic sustainability, creating resilient communities, and reducing waste. Nonetheless, there must be a capacity to focus on the detailed standards that are important in each part of the Li and REE lifecycles. CSA Group has published circularity research to support standards development in Canada [113], [114], [115].
- **Canadian leadership in standards development:** There is a need for Canada to take a timely, ongoing leadership role in developing standards related to Li and REE recovery and recycling. The Li and REE lifecycles are global, so it is important to participate in the development of global standards that impact these lifecycles. With increasing demand for EVs, there is rapid change in these value chains. Many of the industry sectors involved in recovery and recycling are in their infancy in North America. As a result, there must be ongoing assessment of standards needs and gaps. Canada must actively participate in current and future global standards development. Standards development is often voluntary but there may be a need for more full-time staff devoted to this topic in government and industry.
- **Health and safety risks of LIB and magnet recycling:** There is a need for standards that cover transportation, storage, and handling of LIBs and REE-rich products at EoL. These would support research and commercial enterprises involved with EoL management and recycling, as well as emergency personnel. Ideally, standards specific to EV LIBs could address EHS risks and would align with other countries (e.g., the United States). According to consultations with interested parties, the existing



"Canada's ongoing efforts to decarbonize, along with its political stability, can also attract investment."

regulatory framework in Canada regarding LIB recycling is seen as unnecessarily complex. There is a lack of unification of LIB storage and transportation regulations across provinces and between Canada and the United States. As result, there are lengthy delays for both pilot-scale projects and commercial operations. Separately, the regulatory frameworks were developed to reduce the EHS risks of particular industries along the supply chain but together, they can constrict recycling initiatives. Enterprises should be able to comply with standards while transporting, storing, and handling materials without facing delays. There is also a need to develop standards that address the specific safety risks of recycling magnets and consumer products that are rich in REE.

7 Opportunities and Standardization Roadmap

There are opportunities for Canada to enjoy the economic benefits of participating in the Li and REE value chains, from extraction to recycling. Canada's existing automotive and recycling sectors (e.g., automobiles and consumer products) and its close proximity to the United States are beneficial [40]. Canada also has unexploited, natural deposits of Li and REE in hard rock and brine, and current extraction industries of other materials that contain Li and REE in their waste streams (e.g., titanium and uranium production). Canada's ongoing efforts to decarbonize, along with its political stability, can also attract investment. At the same time, there is a need in Canada to minimize sustainability impacts and foster a secure, robust domestic supply chain throughout the Li and REE lifecycles. Recovery and recycling are part of a holistic approach.

The discussion of barriers and gaps in Section 6 identified several areas where standardization could potentially provide benefit. The development of standards would also benefit from work already completed for other metal products around the world. This significant endeavour could begin by developing the standards that are listed in Table 2 in order of urgency. Table 2 also lists any related initiatives that have already started to address these issues.

Engagement with interested parties highlighted that the governance of standards is not just the responsibility of governments but also the private sector. The ability to use a systems approach and integrate multiple objectives is an advantage of the public sector. Public standards can also be referenced in regulation. However, one disadvantage is that recommendations may not be adopted by industry. The private sector is likely to move faster, with less bureaucracy, but may focus on narrow objectives that lack a systems approach. In addition, private standards are voluntary and developed when there is a need in the market. Private standards may also be more readily adopted by industry and can draw on successful industrial best practices. Industries with extensive recycling experience, such as metal recycling from auto recyclers and established aluminum and copper recycling, may be able to assist with the development of standards for recovering Li and REE from waste.

Table 2: Topics for a standardization roadmap for recovery and recycling of Li and REE from waste

Category	Opportunities	Existing Standardization Efforts
Transporting, storing, and handling EV and energy storage batteries and REE-rich products	▪ Develop a Canadian standard addressing EHS risks during EoL management and recycling, including transporting, storing, and handling materials. Such a standard would facilitate cross-border and inter-provincial shipping of EoL products, and reduce complicated, time-consuming regulatory burdens.	▪ A CSA standard on LIB batteries (EVs and energy storage) is under development and will help to address this need [56].
Monitoring material flows, traceability	▪ Standardize methodologies for monitoring and tracing material flows throughout Li and REE lifecycles, possibly with composition, digital signatures, and self-certifying blockchain systems [105].	▪ Traceability is being considered from extraction to midstream processing by the merged ISO/TC 298 and ISO/TC 333 sustainability working groups.
Sustainable materials throughout Li, REE, and other material lifecycles	▪ Demonstrate the sustainability of materials throughout Li and REE lifecycles (with specificity of location, technology, and materials). It is important such standards are consistent with those of other metals and minerals. ▪ Support a sustainable material standard with traceability of Li and REE throughout their supply chains. Battery passports and similar mechanisms for other consumer products may support sustainable material standards.	▪ A sustainable materials standard is a potential outcome of the ISO International Workshop Agreement on Sustainable Critical Minerals Supply Chains [75] and ISO standards development (including the merged ISO/TC 298 and ISO/TC 333 sustainability working groups).
Sustainable best practices throughout all industry sectors of Li, REE, and other material lifecycles	▪ Develop best practices and guidelines (similar to the Mining Association of Canada's TSM and the IRMA-STD-001 standards) for other sectors (midstream processing, manufacturing, and recycling industry) in the Li, REE, and other material lifecycles. ▪ There is also a need for further global collaboration and agreement on areas where there are conflicting best practices.	▪ This is another potential outcome of the ISO International Workshop Agreement on Sustainable Critical Minerals Supply Chains [75].
Analytical testing methods and certification	▪ Develop standard analytical methodologies for measuring and analyzing composition and impurities of upstream, midstream, and recycling industry sector input and output streams. ▪ Establish certification or assurance schemes for providing reliable, transparent, and verified analytical data.	▪ Analytical testing methods of intermediate products in the Li and REE value chains are being considered by the merged ISO/TC 298 and ISO/TC 333 sustainability working groups to complement existing standards.
Standard material composition specifications	▪ Investigate whether there is a need for standard specifications for commodities and intermediate commodities throughout the material lifecycles of Li and REE, including waste streams. Impurities in recycled materials are a particular concern for EV batteries and magnets. ▪ Consider material composition specifications for manufacturing aids or other inputs (e.g., magnet cutting oil) to EV LIBs and magnets that can contaminate recycled materials.	▪ ISO 22450, *Recycling of Rare Earth Elements* partially addresses REE products at EoL [116].

Category	Opportunities	Existing Standardization Efforts
Nomenclature, terminology, and definitions	▪ Standardize nomenclature, terminology, and definitions relevant to the recovery and recycling of materials (e.g., recycle, circularity).	▪ This is a potential outcome of current ISO standards development (merged ISO/TC 298 and ISO/TC 333 sustainability working groups, and ISO/TC 323).
Consumer/industrial product labelling	▪ Consider standards for labelling EV LIBs with their chemistry and composition, while considering existing standards [35]. ▪ Investigate labelling of material composition for EV motor magnets. ▪ Investigate standards for labelling electronics with information on how to repair or where to take when product has reached its EoL. Labelling can also inform recyclers of the product composition and how to recycle the product.	
Quantifying sustainability impacts, along with supply chain and economic costs	▪ Improve standard metrics and methodologies (e.g. tests, monitoring, lifecycle analysis) for fairly evaluating and quantifying sustainability performance, including circular flow of materials. Various methodologies and metrics exist, such as different lifecycle analysis approaches, but there is a need for further global consistency. ▪ Support this standardization with detailed data and research from throughout the Li and REE lifecycles for specific technologies and jurisdictions.	▪ This is another potential outcome of the ISO International Workshop Agreement on Sustainable Critical Minerals Supply Chains [75]. ▪ Some financial groups are developing standards for quantifying sustainability [112].
Design for circular flow of materials and design for environment	▪ Investigate how standard designs can encourage circular flow of materials. For example, standardized packaging, chemistries, shapes, and sizes of LIBs may improve economics and logistics of recycling. ▪ Consider standardized designs of household battery and electronic products to facilitate recycling, such as easy to locate and remove hard drive circuit boards. ▪ Consider standardized designs of EV motor and wind turbine generator magnets to facilitate recycling. ▪ Consider guidelines for preventing impurities in recycled battery, e-waste, and magnet streams.	

8 Conclusions

As Canada and the world transition to new energy sources, there is likely to be an exponential rise in demand for Li, REE, and other metals. Sourcing Li and REE from waste is one of many actions that can reduce the sustainability and supply chain impacts of the rising demand. While other metals have more successful recycling industries [1], the main barriers to sourcing Li and REE from waste are:

- **Economic:** It is often uneconomical to source Li and REE from waste streams because the yield of these materials is low and facilities to recover/recycle these materials from waste often have high capital and operating costs.
- **Logistical:** It is logistically difficult to source Li and REE from waste because markets, facilities (mining, mineral processing, manufacturing), and products were not designed for circular flow of materials.

- **EHS/ESG:** There are environmental, health, safety, social, and governance impacts of input streams, products, or wastes in Li and REE recovery and recycling processes, such as metal contaminants or radioactive compounds, which add complexity, risk, and cost to operations.

Analysis of these barriers emphasized that the recovery and recycling of Li and REE is insufficient when conducted as part of a narrow strategy. Because of the rising demand, there is a need for comprehensive solutions to the strains on sustainability and supply chains. The concept of circularity provides an overarching perspective that helps to bridge gaps in knowledge, policy, and standardization pertaining to recovery and recycling from waste. A circular approach links the wants and needs of different entities throughout material lifecycles. A circular approach also considers other solutions, such as reduction of consumption (e.g., design for repair) or elimination of a product (e.g., walk instead of purchasing a vehicle). This allows an evaluation of the overall benefits and costs of different products, technologies, policies, and standards.

Advances in data management, technology (e.g., inexpensive recycling processes), and knowledge sharing (e.g., labelling and education) will address knowledge gaps regarding recycling and recovery. Potential policy gaps to address include supporting a market system that accounts for sustainability and supply chain impacts, and that enables the circular flow of materials with process and product designs.

Key standardization gaps to consider are:

- **Cross-sector collaboration:** The Li and REE value chains are lengthy, with geopolitical divisions. They also include many different parties who must coordinate efforts to improve the circular flow of materials, such as building batteries that are easy to recycle. Standards development must consider the needs of many participants.
- **Systems approach:** Sustainability and supply chain issues throughout the lifecycles of Li, REE, and other materials are complex. The systems approach of circularity would benefit standards development around recovery and recycling of waste in a holistic way, helping to address economic benefits along with sustainability and supply chain considerations.
- **Canadian leadership in standards development:** Canada's involvement in the Li and REE value chains is increasing rapidly. These value chains are global, and therefore active participation in global standards development is crucial. Standards development must also be dynamic and respond to change as industrial projects and new products come online.
- **Health and safety risks of LIB and magnet recycling:** Based on interviews with interested parties, significant attention is needed to remove barriers to the growth of the EV battery recycling sector and to improve the regulatory framework in Canada A Canadian standard could address these risks and support revisions to the regulatory framework, which in turn would meet the needs of recycling enterprises. There is also a need to develop standards addressing the specific safety risks of recycling REE-rich products.

A roadmap of standards development for recovery and recycling Li and REE from waste should consider:

- Analytical testing methodologies and traceability of material throughout Li and REE value chains;
- Cohesive material and industry sustainability standards for all industries and products, from extraction to recycling;
- Standardized nomenclature, material composition specifications, and product labelling; and
- Metrics/methodologies for a cost structure that accounts for sustainability and supply chain impacts, and design of industry processes and products that support circular flow of materials.

Above all, participants in standards development require thorough and detailed understanding of the root causes of various issues affecting the Li and REE supply chains and their interactions. Standards development also requires focused efforts for each waste stream, industry sector, technology type, and jurisdiction.

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Appendix A – Glossary

Term	Definition
Circularity, circular economy	An economic system that achieves circular flow of materials with a systems approach. It involves recovering, retaining, or adding to the material value, while contributing to sustainable development [7].
Electric vehicles (EVs)	In this report, the term is used broadly to refer to hybrid electric, plug-in hybrid electric, and 100% electric vehicles.
E-waste	Electrical or electronic equipment that is waste, including all components, subassemblies, and consumables that are part of the product at the time of discarding [117].
Extended producer responsibility (EPR)	Importers or producers of a product have physical or financial responsibility for a product beyond the point of purchase, through to its end-of life stage. EPR shifts collection and recycling burdens away from consumers and municipalities [58]. EPR is more expansive than product stewardship programs, which encourage the collection of products via publicly funded programs or through fees charged at point of sale, such as deposit–return programs.
Policy	An officially accepted set of rules or ideas about what could be done, or an idea that guides consistent decision-making. Policy may be developed by an individual, group of people, business, industry association, consumer association, institution, or government.
Recycling	Reprocessing a material or component that has previously been processed for inclusion in a product [118].
Recovery	A process in which waste material is treated to release materials in a form where they can be used again [118].
Waste	A resource that is no longer considered to be an asset, because at the time, it provides no value to the holder (it can become a resource if value is assigned to it) [7].
Waste valorization	A strategy to reduce both the consumption of natural sources and the disposal of materials. Waste streams are generated throughout the lifecycles of raw materials. The waste can originate from different industry sectors (mining operations, mineral refineries, manufacturing). A waste valorization approach recognizes that waste streams contain useful materials and energy that can be recovered. Waste valorization involves assigning value to waste streams and shifts it from a burden to a resource.

Appendix B – Policies, Best Practices, and Standards

Table B-1: Summary of Policies Related to Recovery and Recycling of Li and REE from Waste

Country/Organization	Policy	Waste Streams	Objective/Scope	Reference
Indigenous peoples	Indigenous and traditional knowledge	All waste streams	Includes policies and best practices to improve sustainability and circularity, and reduce waste streams.	[52]
Canada	The Canadian Critical Minerals Strategy	All waste streams in Li and REE lifecycles	Promote economic growth, energy transition, reconciliation with Indigenous peoples, ESG goals, and global security via funding of technologies and infrastructure.	[53]
Multiple parties (Indigenous, governments, industry)	Canadian Minerals and Metals Plan	All waste streams in Li and REE lifecycles	Visions, principles, and strategic directions to promote Canada's mineral and metal industry, including environmental goals.	[54]
Natural Resources Canada	Green Mining Initiative	Extraction and milling waste streams	Research program to improve mining sustainability, energy efficiency, and productivity; to reduce ESG impacts in Canada; and to develop technologies.	[15]
Natural Resources Canada	Critical Minerals Centre of Excellence	Potentially all waste streams	Leadership, development, and coordination of policy on critical minerals.	[55]
Battery Metals Association of Canada and other interested parties	A Roadmap for Canada's Battery Value Chain	All waste streams in Li and REE lifecycles	Foster world-leading, closed-loop, battery value chain in Canada (including recycling 95% of battery materials).	[92] [13]
Canadian Council of Ministers of the Environment	Canada-Wide Action Plan for Extended Producer Responsibility	EoL product waste	Reduce landfilled waste, and shift EoL product responsibilities from consumers to producers via provincial action plans and legislation.	[58]
Province of Ontario	Resource Recovery and Circular Economy Act Waste Diversion Transition Act	All waste streams, especially EoL product waste	Legislation to promote a circular economy, increase resource recovery, promote sustainability throughout product/material lifecycles.	[59]
Province of Quebec	Stratégie gouvernementale de développement durable Plan for the Development of Critical and Strategic Minerals	All waste streams	Promote a green economy and implement circular economy practices.	[57]
Province of British Columbia	Recycling Regulation	All waste streams, especially EoL product waste	Reduce waste to disposal and recover valuable resources.	[59]
International E-Waste Management Network	E-waste management (e.g., Taiwan's 4-in-1 Recycling Program)	E-waste	Share best practices, promote circular economy approach, promote recycling of e-waste, and reduce ESG impacts.	[61]

Country/Organization	Policy	Waste Streams	Objective/Scope	Reference
The World Bank	Climate-Smart Mining Initiative	Extraction and milling waste streams	To implement low GHG emission, sustainable mining and mineral strategies and practices across the mineral value chain.	[66]
Canadian Mining Innovation Council	ReThinking Mining initiative	Extraction and milling waste streams	Align industry, innovators, and other interested parties to a goal of a zero-waste mining industry.	[67]
International Council on Mining and Metals	Mining Principles and 2022–2024 Strategy and Action Plan	Extraction and milling waste	To promote responsible mining, through sustainable development and ESG objectives.	[69]
European Union	European Green Deal	All waste streams	Invest in sustainability and decarbonization goals, promote technologies, and improve standards.	[76]
European Union	Circular Economy Action Plan	All waste streams	Promote sustainable production, recovery of valuable materials, market transparency, and standardization.	[77]
European Union	Strategic Action Plan on Batteries and Sustainable Batteries Regulation	EoL batteries	Promote sustainable production, circularity, critical material supply chains, and data management.	[78]
European Union	Action Plan on Critical Raw Materials Critical Raw Materials Act	All waste streams in Li and REE lifecycles	Promote resilience and autonomy of critical material supply chains, sustainability, circular use, and facilitate climate-neutral economy.	[79], [80]
Chile	*Política Nacional Minera* 2050 (National Mining Policy 2050)	Extraction and milling waste streams	Roadmap to promote safe, diverse, and inclusive mining, meeting ESG and institutional goals.	[83]
Chile	*Ley 20.920* (Law 20920)	EoL batteries, all waste streams	Establish framework for waste management, EPR, and recycling.	[84]
China	2005 China State Council Policy Paper China's 11th Five-Year Plan 2008 Circular Economy Promotion Law	All waste streams	Reduce economic and environmental risks of raw material extraction via circularity.	[85]
United States	Infrastructure Investment and Jobs Act	All waste streams in Li and REE lifecycles	Includes direction and funding to develop domestic critical mineral supply chains, including best practices, extended producer responsibility, and design for recycling.	[87]
United States	Memorandum on Presidential Determination Pursuant to Section 303 of the Defense Production Act of 1950, as amended	All waste streams in Li and REE lifecycles	Secure a supply chain of critical materials by supporting feasibility studies and projects, including valorization of mine waste.	[90]
United States Department of Energy	America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition	All waste streams in Li and REE lifecycles	Promote strong critical mineral supply chains to facilitate an energy transition.	[88]

Country/Organization	Policy	Waste Streams	Objective/Scope	Reference
United States Department of Energy	Critical Minerals and Materials	All waste streams in Li and REE lifecycles	Promote critical mineral supply chains.	[89]
United States Chamber of Commerce	Achieving a Circular Economy: How the Private Sector is Reimagining the Future of Business	All waste streams	Provide best practices to businesses implementing circular economy strategies.	[91]
Canada	Packaging and Transport of Nuclear Substances Regulations	Radioactive waste material	Reduce ESG/EHS risks associated with radioactive material.	[96]
International Atomic Energy Agency	Regulations for the Safe Transport of Radioactive Material	Radioactive waste material	Reduce ESG/EHS risks associated with radioactive material.	[97]
Canada and United States	Joint Action Plan on Critical Minerals Collaboration	Li and REE waste streams	To secure supply chains of critical minerals in communication, aerospace and defense, and clean technology.	[100]
Canada and European Union	Canada-EU Strategic Partnership on Raw Materials	Li and REE waste streams	Advance value, security, and sustainability of trade and investment in critical minerals.	[101]
Australia	Modern Manufacturing Strategy	Waste streams in Li and REE lifecycles	Promotes domestic supply chains, recycling, and clean energy.	[102]

Table B-2: Summary of best practices and standards related to Li and REE from waste

Country/Organization	Policy	Waste Streams	Objective/Scope	Reference
CSA Group	Under development: Standard on battery circularity	Waste streams from LIB manufacturing and EoL LIBs	Develop a standard addressing material lifecycle of battery materials, including circularity, recycling, and EHS risks.	[56]
The Mining Association of Canada	*Towards Sustainable Mining* (TSM) TSM Responsible Sourcing Alignment Supplement	Waste streams from extraction, mining, and milling operations	Promote following circular economy aspects: cost-effective recovery, reuse, or recycling of energy, natural resources, and materials.	[65], [64]
UL	UL 3600, *Measuring and Reporting Circular Economy Aspects of Products, Sites and Organizations*	Waste products (e-waste, LIBs, magnets)	Standardize measurement of circularity and provide a certification program.	[62]
UL	UL 110, *Standard for Sustainability for Mobile Phones*	Waste cell phones	Improve sustainability and reduce ESG and EHS impacts throughout product lifecycle.	[63]
Initiative for Responsible Mining Assurance	IRMA-STD-001, *Standard for Responsible Mining*	Waste streams from extraction, mining, and milling operations	Improve sustainability of mining.	[68]
ISO	Under development: Standards to reduce environmental impact of EoL mining operations (ISO/TC 82 Mining, subcommittees 7 and 8)	Waste streams from extraction, mining, milling operations	Develop standards related to mine closure and reclamation to reduce ESG impacts.	

Organization	Best Practice/Standard	Waste Streams	Objective/Scope	Reference
ISO	Under development: Standards on circular economy (ISO/TC 323)	Any waste stream	Develop standards to facilitate circular economy strategies, including monitoring and measurement.	[12]
ISO	Under development: Standards on rare earth and lithium (ISO/TC 298 and ISO/TC 333)	Any waste stream in REE and Li lifecycles	Standards helpful throughout material lifecycles (including transparent and traceable monitoring of data).	[12]
British Standards Institution	PAS 7060, *Electric Vehicles. Safe and Environmentally-Conscious Design and Use of Batteries. Guide* PAS 7061, *Batteries for Vehicle Propulsion Electrification. Safe and Environmentally-Conscious Handling of Battery Packs and Modules. Code of Practice*	Waste streams from LIB manufacturing, and EoL LIBs	To reduce EHS risks and impacts throughout the lifecycle of EV batteries.	[81], [82]
National Institute of Standards and Technology (NIST) and ASTM International	Under development: Best practices and standards to support circularity and extended producer responsibility (ASTM committees E60 Sustainability and F40 Declarable Substances in Materials)	Any waste stream	Provide best practices through a NIST Circular Economy Resource Registry, develop standards to support circularity and extended producer responsibility.	[10], [93]
NSF/ANSI	NSF/ANSI 426, *Environmental Leadership and Corporate Social Responsibility Assessment of Servers*	Manufacturing waste and EoL products containing REE	Reduce ESG impacts of REE lifecycle, increase recycling of REE from products, and promote design for recycling.	[94]
Global Electronics Council	Electronic Product Environmental Assessment Tool (EPEAT) Assessment and Registration	Waste streams from EoL products, including e-waste	Meet ISO 14024, promote circularity and design for recycling and longevity, and reduce ESG impacts throughout lifecycle of electronic products.	[95]
Various	Various	Waste batteries (LIBs)	Safety impacts of batteries, including handling, EHS risks, storage, design, recycling, and transportation.	[35]
Energy Storage Association (ESA)	ESA Corporate Responsibility Initiative: Guidelines for End-of-Life and Recycling of Lithium Ion Battery Energy Storage Systems	EoL energy storage batteries	Assist industry and others to reduce ESG impacts, improve EoL management and facilitate recycling; consider design for recycling and extended producer responsibility.	[11]
SERI/ANSI	*Sustainable Electronics Reuse and Recycling (R2) Standard, version 3*	E-waste	Promote ethical and responsible reuse, reduce ESG/EHS impacts, and promote recycling of electronic equipment.	[99]
e-Stewards	*e-Stewards® Standard for Ethical and Responsible Reuse, Recycling, and Disposition of Electronic Equipment and Information Technology, Version 4.1*	E-waste	Promote ethical and responsible reuse, reduce ESG/EHS impacts, and promote recycling of electronic equipment.	[98]

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

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