GreenLIB Lithium-Ion Battery Recycling LCA Report

Alyn Sun, Elaine Zhou, Hannah Gill, Andrea Vo, Oak Kang

BEST 402 101

Dr. Qingshi Tu

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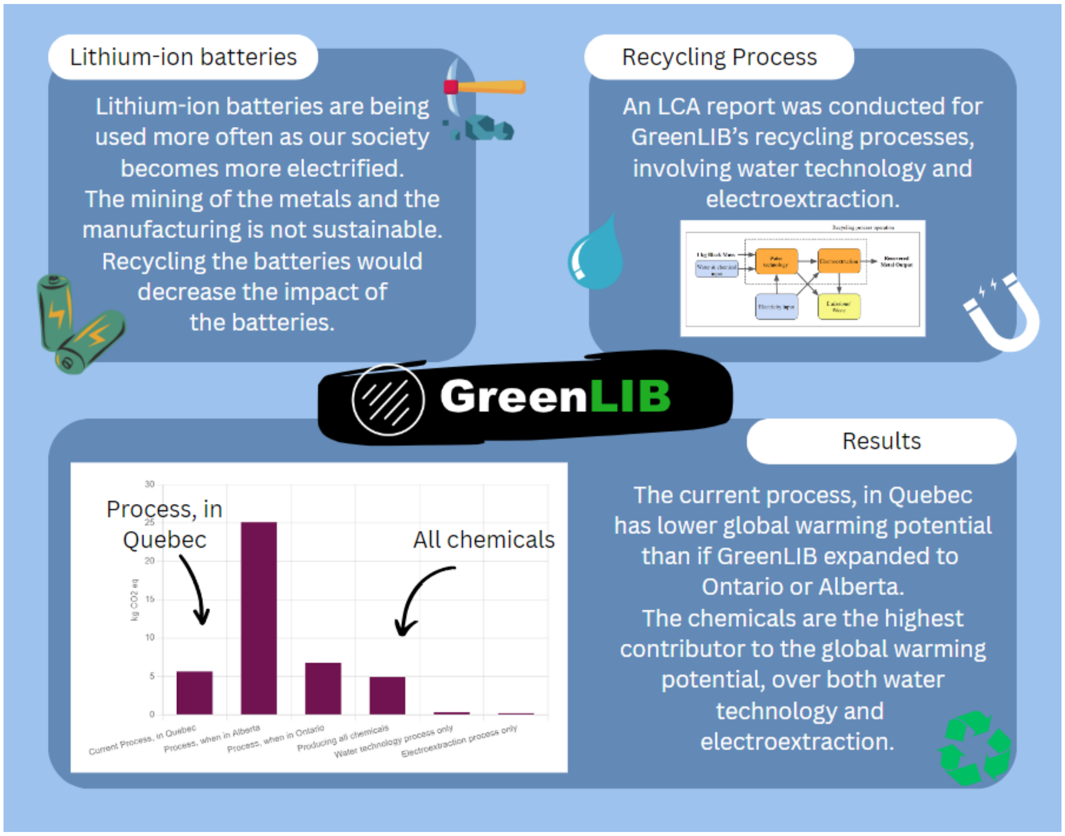


Abstract

As the world electrifies, the need for batteries is drastically increasing. Finding ways to make batteries more sustainable is imperative to helping counteract climate change and supply inefficiencies. Since the mining of metals can be very harmful to the environment, recycling components of batteries would help decrease those negative environmental impacts, and contribute to the circular economy. GreenLIB is a company located in Quebec, Canada that recycles lithium-ion batteries. With the use of renewable energy, and few other inputs, their eco-friendly recycling process helps lithium-ion batteries become a more sustainable option for our increasingly electrified globe.

Keywords: spent lithium-ion batteries; minerals; recycling; life cycle analysis; water leaching; electroextraction; energy consumption; greenhouse gas emission

Introduction

The rapidly growing trend of electrifying energy usage to minimize emissions and mitigate factors that amplify the climate change crisis inevitably leads to a tremendous demand for batteries, particularly lithium-ion (Li-ion) batteries, and it is expected to continue increasing worldwide (Precedence Research, 2023). To address the sustainability issues that arise from the amplified demand, companies like GreenLIB are providing a renewable alternative for the battery market where components of used Li-ion batteries are recycled and reused. It is important to clarify the impacts of these companies and be transparent to consuming individuals, manufacturers, and climate change-advocating organizations by providing accountability and measurable metrics.

This paper is a life-cycle assessment (LCA) report that quantifies GreenLIB's mitigation efforts by analyzing their recycling processes. By doing so, we confront the inefficiencies and negative impacts that come from the Li-ion battery market, specifically, resource exploitation, dependence on overseas procurement of critical metals, and unreasonable end-of-life waste collection. In this paper, we aim to explore the following research questions:

1. How eco-friendly are GreenLIB's recycling processes compared to current, non-recycled standards in terms of CO_2eq emissions?
2. How will a location change affect GreenLIB's recycling processes and the results of our first research question?

The Company - GreenLIB

Founded in 2022, GreenLIB was established in the city of Montreal, Quebec. They prioritize reducing environmental impacts and encourage sustainable innovation through revolutionizing the recycling of Li-ion batteries, which strengthens the global shift towards clean energy and a circular economy (GreenLIB, 2023). To address the complexities of supply chain disruption and traditional centralized end-of-life management for Li-ion batteries, GreenLIB's decentralized modular approach is pioneering in modern battery recycling (GreenLIB, 2023). The company's initial target customers are primarily manufacturers of electric vehicles (EVs), consumer electronics, and energy storage systems (GreenLIB, 2023). GreenLIB is unique from comparative recyclers because of their 95% high-efficiency recovery achieved with a high production capacity process that utilizes water technologies and electroextraction from renewable electricity, producing 57% less greenhouse gas emissions (GreenLIB, 2023).

GreenLIB can recycle both nickel manganese cobalt (NMC) and lithium iron phosphate (LFP) batteries. According to GreenLIB's internal data, the output from recycling NMC batteries is made up of aluminum, copper, nickel, phosphorus, carbon, and lithium, as well as waste materials. GreenLIB internal data also states that the output from recycling LFP batteries consists of aluminum, copper, phosphorus, carbon, lithium, iron, and waste. The two batteries also have different amounts of each metal in the output, the efficiency also differs, and the chemical makeup of the starting materials is different. However for this report, since they use the same recycling process, the models were not separated.

The Problem

Environmental Impacts from Obtaining Minerals - Lithium, Cobalt and Nickel

Li-ion batteries are made from non-renewable natural resources, primarily lithium, cobalt, and nickel, and the extraction and refining process is severely detrimental to the environment (Beales et al., 2021). The increased demand for batteries from electrification to reduce fossil fuel use will subsequently increase the extraction of these metals and minerals. Although the extraction source of each mineral varies (for example, open-pit mines for cobalt and brine lakes for lithium), the environmental impacts typically share similarities and fall under a common umbrella, differing primarily in their magnitude or quantity (Beales et al., 2021). Recycling used batteries and preventing the waste of minerals prove to benefit the environment greatly.

A great deal of the impacts come from fossil fuel usage because of transportation and refining needs (Beales et al., 2021). The significant impacts of mineral extraction and refining exist as ecosystem disruptions, habitat loss, water removal (and the resulting spread of contaminated water) dust pollution, water shortage, and water pollution (Beales et al., 2021). Directly resulting in the unintentional death of local fish and animal populations (Beales et al., 2021). Additionally, these consequences also inherently lead to social disparities and disadvantages, namely, human health detriments, damage to local populations and farmers, and work safety concerns (Beales et al., 2021).

The Dependence on Overseas Procurement of Critical Metals

As aforementioned, a large portion of environmental impacts from minerals for Li-ion batteries come from the transportation and refining processes. The detriments are especially heightened because of the fragile supply chain, where differing countries dominate separate steps for each mineral as well as the manufacturing of Li-ion batteries (Beales et al., 2021; Precedence Research, 2023). Lithium is mainly sourced from Australia, with Chile, Bolivia, and Argentina also being large contributors (Beales et al., 2021). For cobalt, 70% comes from the Democratic Republic of the Congo while 60% is refined in China (Beales et al., 2021). Finally, Nickel is predominantly procured from Russia, Australia, Canada, Indonesia, the Philippines, and New Caledonia (Beales et al., 2021). Meanwhile, as of 2022, approximately 44% of the demand for Li-ion batteries is located in China, about 22% in the European Union, and 19% in North America (Statista Research Department, 2023). Li-ion battery recycling will keep production close to where the demand and use lie, significantly reducing the emissions and damage tied to overseas procurement and transportation.

End-of-Life waste collection

Based on 2020 data, only 5-7% of Li-ion batteries globally are recycled (Beales et al., 2021). The low percentage is most likely from small-scale recycling factories as upscaling has not been developed yet, technological holdbacks, safety concerns and cost implications (Beales et al., 2021). Due to the low cost of many minerals, like lithium, there is little encouragement for manufacturers to recycle (Beales et al., 2021).

High Market Demands

The surge in demand for batteries is substantially driven by the need to replace fossil fuel energy with electricity, especially with electric vehicles, which has ultimately created an unprecedented market demand for critical minerals, with lithium experiencing the most significant growth in recent years (Beales et al., 2021). Electrification is especially crucial in the context of global climate targets and efforts to reduce emissions, such as those outlined in the Paris Agreement and Kyoto Protocol (Beales et al., 2021). It is noteworthy that the use of many battery minerals is unavoidable. With current technology, lithium and nickel, key components, are irreplaceable and although innovation could reduce the use of cobalt, it is often substituted with more nickel (Beales et al., 2021). Thus, the relationship of these factors highlights the pressing need to address alternative solutions like recycling and reusing limited natural resources.

Literature Review

Li-ion Battery Recycling Techniques

The main techniques utilized to recycle Li-ion batteries include direct recycling, pyrometallurgy, hydrometallurgy, and hybrid, which are illustrated in Figure 1 (Baum et al., 2022). The methods used differ across different countries, depending on the resources available and the market (Baum et al., 2022). Direct recycling only requires disassembling and separating reusable metals without going through high-temperature and chemical processes (Baum et al., 2022). Pyrometallurgy, which separates metals using high heat and pressure, incurs significant energy costs associated with the combustion and calcination processes (Baum et al., 2022). Hydrometallurgy requires less energy as it uses chemical solutions to dissolve and extract metals from spent Li-ion batteries (Baum et al., 2022). However, this method still has cost issues associated with reagents and water purification (Baum et al., 2022). The most commonly used method among all is the hybrid technique, which involves a combination of techniques such as pyro-hydrometallurgy (Baum et al., 2022). Except for direct recycling, all other methods, including pyrometallurgy, hydrometallurgy, and hybrid, require the pretreatment of spent Li-ion batteries to obtain a powdery mixture ready to be further processed (Zhou et al., 2021).

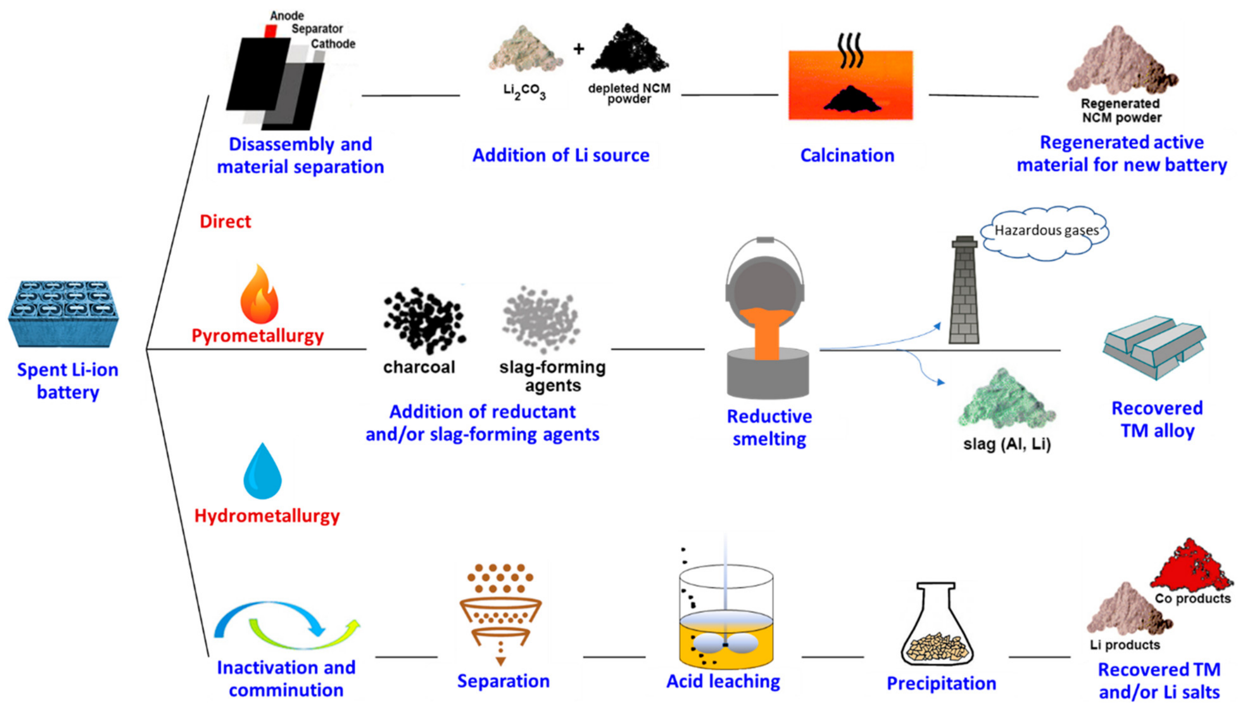


Figure 1. Diagram of common recycling techniques used for Li-ion batteries (Baum et al., 2022)

<u>LIB recycling barriers, limitations, and public awareness</u>

In terms of further considerations for recycling LIB, there are several barriers, limitations and public awareness aspects to consider. Barriers include the tendency for facilities to prioritize certain component recovery such as cathode instead of the whole battery, which can be wasteful and suboptimal (Baum et al., 2022). The incompatibility of recycled batteries in new batteries are also barriers to consider that are experienced during pyrometallurgy and hydrometallurgy processes. The direct recycling method as limitations of requiring manual battery disassembly and classification procedures, which increase costs and labour. There are also limitations associated with material purification costs, unsafe battery discharge and wastewater treatment safety. Furthermore, the lack of common battery design and labelling hinders battery collection efficiency, however, systematic social change, such as public awareness, public education programs, policies and regulation rules, may aid in overcoming these barriers and limitations. Additionally, the implementation of public education programs for battery recycling, handling, and disposal such as the US EPA may be beneficial (Neumann et al., 2022). Policies, standards, regulation rules, and monitoring systems may raise awareness for LIB recycling and collection. The effectiveness of policies and standards can be observed from the results of the 2016 Policy on Pollution Prevention Techniques of Waste Batteries in China, and the US Battery Act.

Methodology

Goal and Scope Definition:

In order to answer the research questions about GreenLIB's recycling processes, it was crucial to quantify the carbon emissions emitted and the associated environmental impacts of the company's recycling processes. This study used openLCA - an open-source software tool developed by GreenDelta to model and assess a product's or process's environmental performance throughout its life cycle. The obtained results were compared with data from existing LCA studies of emerging battery recycling procedures. Furthermore, assessing GreenLIB's recycling processes with a different energy provider from a different location was equally necessary if GreenLIB were to expand its operating schemes.

The system boundary of this study was identified and shown in Figure 2. To focus entirely on assessing GreenLIB's innovation, the selected system boundary only covered the technical recycling processes of specific pretreated battery types at a GreenLIB recycling facility. This life cycle assessment excluded the upstream processes related to the production of the original battery materials, and the collection and pretreatment of spent end-of-life batteries at the company's entrance. The downstream processes, such as regenerated battery components distribution and use, were also excluded. In this system, we identified two main recycling phases: water technology and electroextraction. After safely breaking down the spent end-of-life batteries into their basic components during pretreatment, water technology, also understood as water leaching, is a process that rinses off the valuable materials from the unwanted residues. This step is done under regular pressure conditions, saving energy and cost compared to traditional high-pressure and chemical methods. The following process is GreenLIB's patented electroextraction, also known as an electrowinning process. Similar to a highly specialized magnet, this process pulls out the valuable metals from the leaching solution obtained earlier.

The functional unit (FU) was 1 kg of the material output from GreenLIB's NMC or LFP battery recycling processes, which included recovered usable metals and waste. The recycling methods for both NMC and LFP batteries were the same, differing only in the quantity of chemical composition present in the recovered metal output. The generation of the LCA model utilized data obtained from both primary and secondary sources. The pretreated spent Li-ion batteries (Black Mass), water and chemical input, recovered metal output, and electricity used in recycling were sourced from GreenLIB's internal primary data. Emission factors and other reference data were acquired from secondary sources, including industry reports and scientific literature.

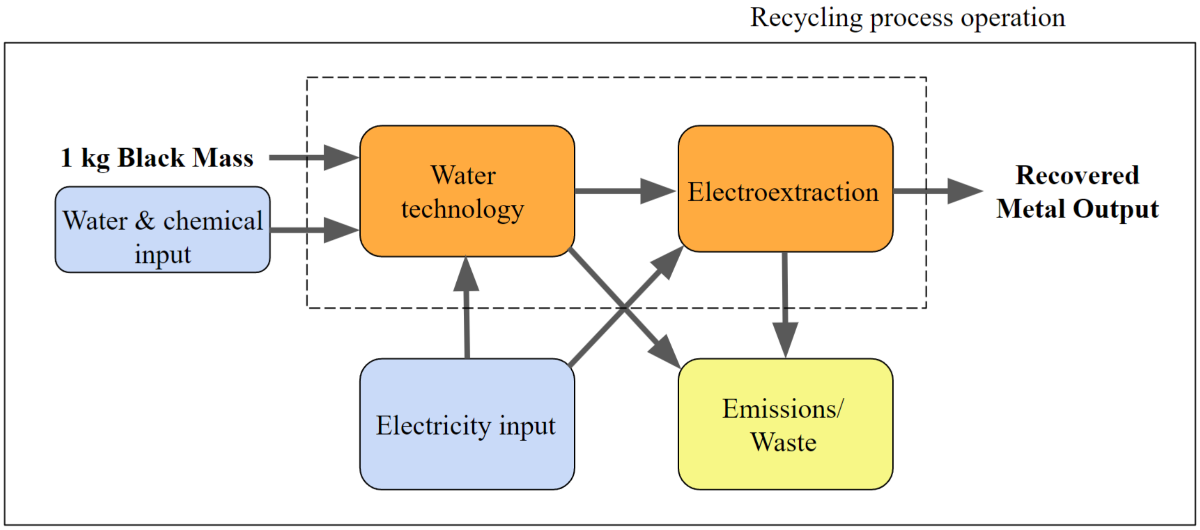


Figure 2. System boundary of pretreated spent Li-ion battery recycling used in this study.

Assumptions and Sensitivity Analysis:

There were certain uncertainty levels in the generation of this study LCA model. Firstly considering data on the type of energy source, the geographical location is crucial in determining the types of energy choices made by the producers, thus directly impacting their carbon footprint. Since GreenLIB is based in Montreal, Quebec, it was assumed that their first few recycling facilities would be in Quebec. According to Canada Energy Regulator (CER), the dominant energy source in Quebec is hydroelectricity, with 94% of the province's electricity generated from hydropower (Government of Canada - Canada Energy Regulator, 2023c). Therefore, high- to medium-voltage hydroelectricity was chosen as the type of energy used for a GreenLIB recycling facility.

As mentioned above, to focus only on assessing GreenLIB's innovative recycling processes, specific assumptions regarding transportation and pretreatment of the spent batteries from different collecting facilities to the company's entrance were made. As outlined in

GreenLIB's internal data and a 2023 Medium article written by GreenLIB, the company showed their commitment to their decentralized, modular model (GreenLIB, 2023). This model is designed to co-locate with key Li-ion battery producers, as well as waste treatment facilities, thereby minimizing the transportation required for the collection and even the pretreatment of spent end-of-life batteries (GreenLIB, 2023). For those reasons, there was no related data to be included in the LCA model, and the environmental impacts of transportation and pretreatment would not be accounted for in this study.

As a new start-up, GreenLIB possesses substantial developmental potential. In the future, GreenLIB may explore opportunities to expand its operation outside of its current headquarters in Quebec. However, the energy consumption type and resulting greenhouse gas (GHG) emissions associated with such expansions remain uncertain. Therefore, a sensitivity analysis was also included in this study to further evaluate the elasticity of the company's GHG emissions with changes in locations and energy providers. For our third assumption, two appropriate scenarios were identified for the sensitivity analysis of our LCA model: Ontario and Alberta. Realistically, Ontario was considered the nearest potential province to be operated outside of Quebec, utilizing a mix of energy sources, primarily nuclear energy (59%) and hydropower (24%) (Government of Canada - Canada Energy Regulator, 2023b). Alberta was the next viable option to be considered. With the growing electrification industry, lithium extraction and Li-ion battery manufacture can significantly benefit from Alberta's existing oil sands and minerals exploitation infrastructure. Opposite to Quebec's firm reliance on renewable energy, Alberta predominantly utilizes natural gas (54%) and coal (36%) to generate its electricity, making our sensitivity analysis more comprehensive with multiple energy sources considered (Government of Canada - Canada Energy Regulator, 2023a). Through sensitivity analysis, the changes in GHG emissions between two different scenarios with the base location in Quebec were compared, and the evaluation of the environmental impacts resulting from the changes in energy providers was discussed. It is noteworthy that GreenLIB's future sustainability plan is to be consistent with renewable energy, thus some of the assumptions made in this study might be overestimated.

Building and Explaining the Model:

Once all of the data was compiled, the model was made. The model started with a process for each of the different 15 units that were given by GreenLIB. Each unit had an energy usage, so that was added into the model, and the assumption, as mentioned previously, was made that they are using grid energy from Quebec. The company mentioned that they are planning to use renewable energy, and since the Quebec grid is mainly renewables, this was the energy chosen for the model. GreenLIB also mentioned that they would try to use residual energy from batteries as part of their energy input, but since there were no concrete numbers on how much energy comes from the batteries versus the grid, that was left out of the model. It was left out so the emissions and impacts are not underestimated, though the results of this report are now slightly overestimating the emissions and impacts. Once the energy was added to the model, the chemicals were added next. The chemicals used in the process were re-used, but the assumption was made that the numbers given are the consumption of chemicals, not the usage of chemicals. Therefore, in the model, the chemicals were reused for each unit in the process but cannot be used again. In order to show this in the model, all of the chemicals were put as inputs into unit 1, and then they were not counted for the rest of the units, so their total impact was put onto the single unit as the information of how much was used in each unit was not given. The production of all of the chemicals, except for sodium carbonate, was found in the database used (ecoinvent 38), so the process for producing sodium carbonate was created in the model. This section of the model used numbers found from literature review. The other chemicals were in the database, but no explicit concentrations were stated, so the assumption was made that the concentrations in the database were within, or at least fairly close, to the range of numbers given by GreenLIB. Black mass is the input into the system, and it consists of old used batteries, or batteries that were manufactured but did not work, but there was no black mass flow in the database used, so it was not included. Along with this, if the input of batteries was included, then emissions based on the production and usage of those batteries would have been included in the study, which is not correct and does not fall within our scope, which is gate-to-gate.

Once the chemicals and energy inputs were created, all of the linkages between units were made. Each unit's exact inputs and outputs were not given, so all of the units were combined into one process, instead of being all separated, which has the electricity and chemical inputs, and the output mix of materials. Some of the units had their outputs branching off into two different units, and there were no numbers on how much of the output went to each of them, so that problem was also mitigated by combining them into one process. Figure 3 showcases this model setup and the inputs. This main model, as well as the rest, which will be explained subsequently, do not include any waste streams. Since no data on waste management was given, no assumptions were made about the processes or the amounts. Along with this, the functional unit of 1kg of output does not include the amount of each component extracted, so the output is just total material output, which is inclusive of all of the usable extracted metals, waste, and anything else that comes out of the input of black mass. This also means that since the process for recycling both types of batteries is the same, the two batteries did not need separate models.

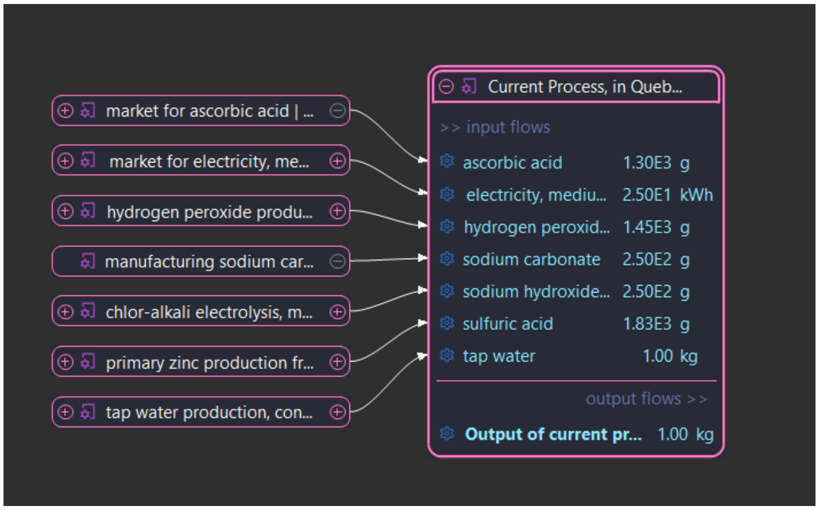
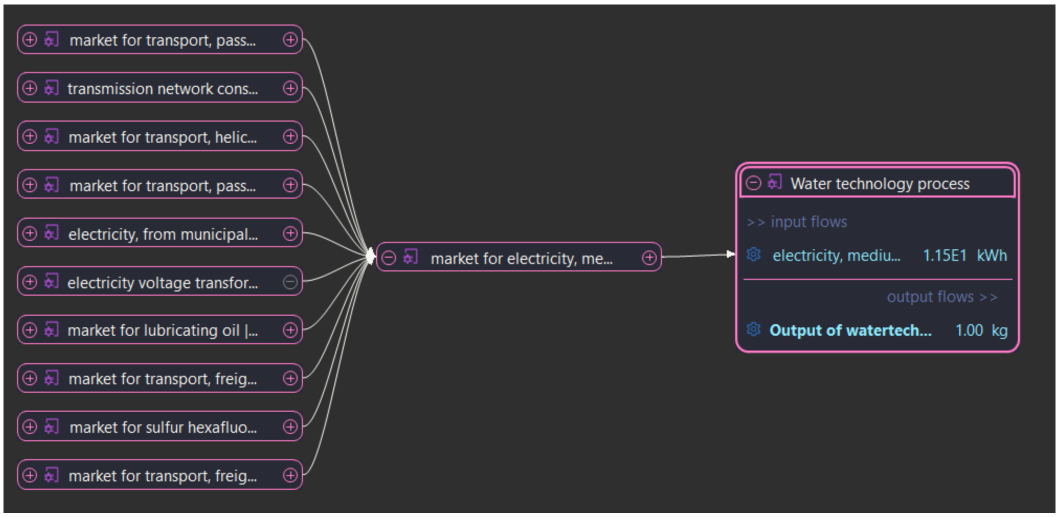


Figure 3. OpenLCA model of the entire process, when all units are combined.

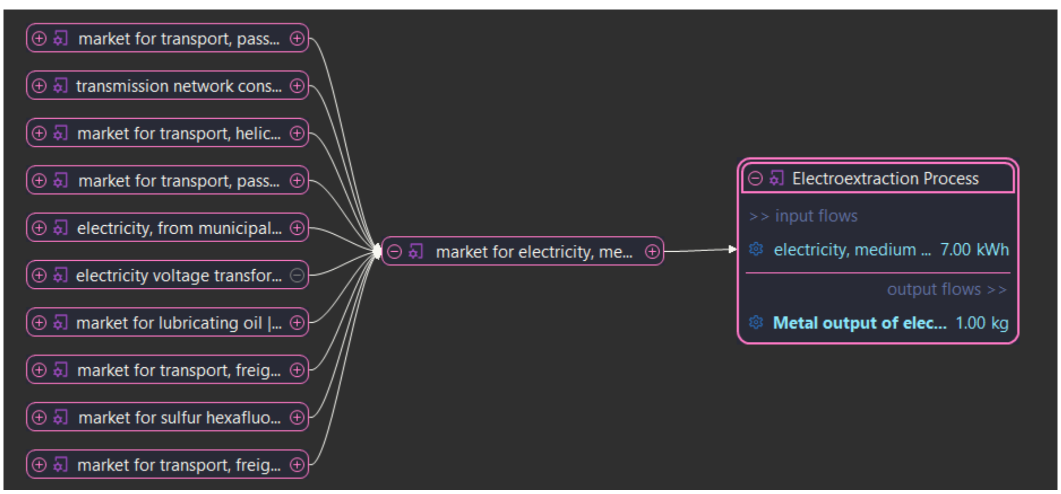
After the main model was made, two more were made that were the same, except they used electricity inputs from Alberta and Ontario. This model is testing to see how the impacts and emissions would change if GreenLIB built a plant in those provinces and used the energy from the grid. Again, assuming no energy is coming from the batteries themselves.

The next two models that were made, were each a section of the whole process. This is to find which section has the biggest associated emissions, so a model was made for electroextraction, and another was made for water technology. The model for water technology includes the electricity input for units 1 through 6, as those are what was assumed to make up the water technology process. The chemical inputs going into unit 1 were not counted as the impacts from the chemicals should be attributed to the whole process, not specific parts. For electroextraction, the model included the electricity from units 8 through 10, as well as 12 and 13. These units were chosen as they were assumed to be the processes included in electroextraction. Again, the production of the chemicals were not included in this model. Both of these models are shown in Figure 4, where the difference in electricity inputs can be seen.

Water technology uses a total of 15kWh per 1kg of output, and electroextraction only uses 7kWh.



(a)



(b)

Figure 4. Models for both water technology only (a), and electroextraction only (b).

The final model that was made, was just the production of the chemicals used, to see what percentage of impacts from the entire process can be attributed to the chemicals used. After all of the product system models were made, they were combined into a project. The project included the model of the current process in Quebec, the models using energy from Alberta and Ontario, and the models of chemical production, water technology, and electroextraction. Once the project was made, the data was exported, and the graphs were made. The graphs taken for this report are for acidification, total global warming potential, global warming potential from land transformation, eutrophication of freshwater, marine water, and terrestrial water, as well as ozone depletion, amount of hazardous waste, and net use of freshwater. All of the numbers for each of these graphs are per 1 kg of output.

Results

Some of the most commonly used LCA impact categories include acidification, climate change, depletion of abiotic sources, ecotoxicity, eutrophication, human toxicity, and land use (Acero et. al, 2015). For this study, we focused on climate change, energy resource use, and relevant environmental impacts. Climate change can be defined as the change in global temperature caused by the greenhouse effect that the release of "greenhouse gasses" by human activity creates. This rise of global temperatures is expected to cause climatic disturbance, desertification, rising sea levels and spread of disease amongst other negative effects. When comparing the two processes of GreenLIB's recycling procedures, water technology possessed a higher GWP total than electroextraction, which was highly due to the greater overall net use of water and chemicals.

Referencing a study by Zhou et al. (2021), we used the following equation to investigate the sensitivity of climate change impacts to changing operating locations for GreenLIB:

$$\Delta G = \frac{G° - Gi}{G°},$$

where $G°$ is the initial GHG emissions in the case of Quebec (kg CO2eq/FU), and *Gi* is the altered GHG emissions in either the case of Ontario or Alberta. We found that initial GHG emissions for Quebec were 5.64 kg CO2eq/FU, and the altered GHG emissions were 25.11 for Alberta, and 6.76 for Ontario. A sensitivity analysis was then conducted and the results are shown below in Figure 5.

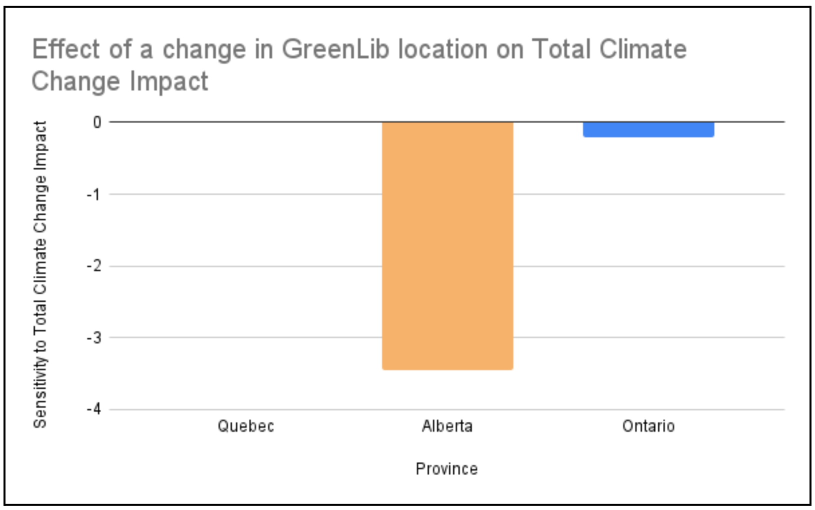


Figure 5. Effect of a Change in GreenLIB location on Total Climate Change Impact

The negative sensitivity analysis results show that changing locations, and therefore energy providers, result in increased climate change impact for our alternate scenarios. Our results shed light on a crucial factor - local supply mix for electricity generation - influencing the environmental impact of GreenLIB's scalable and modular approach, particularly in the context of its potential expansion to Ontario and Alberta. GreenLIB also claims to harness minimal electricity for their electroextraction and water technology process to curb GHG emissions by 82% relative to traditional mining methods. Back calculated, for GreenLIB's claim to be substantiated traditional mining methods should have an impact of at least 29.6 kg CO2eq. In

China, which dominates the global battery mining market and therefore makes a suitable comparison, GWP for 1 kg of NMC CAM (metal component) synthesized has been reported as 32 kg CO2eq (Lai et. al, 2022). If GreenLIB were to expand to Ontario and Alberta, the GWP emissions equivalent curbed would be relatively lower. Another aspect of the openLCA results that emphasizes the importance of local energy composition is the differences in primary energy use amongst the three provinces. The provinces in order of highest to lowest total renewable energy use (sum of renewable primary energy as energy carrier, and renewable primary energy resources as material utilization) were Quebec, Ontario, and Alberta. This order was inverted for total non-renewable primary energy use (sum of non-renewable primary energy as energy carrier, and non-renewable primary energy resources as material utilization), as can be seen in Figure 6.

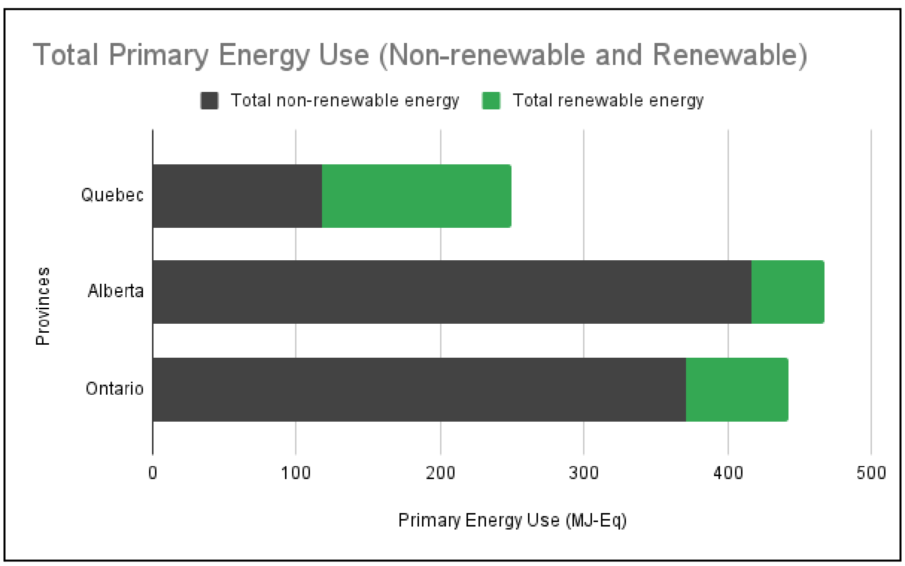


Figure 6. Total primary energy use (non-renewable and renewable).

When looking at results, we isolated three relevant environmental impacts: GWP from land transfer, net fresh water use, and hazardous waste disposal. For lithium battery production from virgin raw materials as opposed to recycled materials, the major environmental damages from mining - air and water pollution, land degradation, high water consumption and groundwater contamination - are most relevant to these three LCIA categories. Results shown in Table 1 reveal that the impact from land transformation is much higher for Quebec than for Alberta or Ontario. Alberta's hazardous waste disposal is much higher than both Quebec and Ontario, and Ontario's net use of fresh water surpasses that of the other two provinces. These results are difficult to conclusively account for within the scope of our project; the factors driving differences between the impacts of these energy mixes are complex and multi-faceted. For example, hydroelectric projects alter freshwater habitat, degrade water quality, and change land use through flooding land for reservoirs, and constructing dams, power lines, and access roads the project needs. One reason why Alberta's hazardous waste disposed far surpasses the other provinces is that Alberta today continues to use coal to generate electricity, and coal ash is the toxic byproduct with wide-ranging effects on human health and environmental pollution.Tar sands also leak toxic wastewater and generate giant ponds of waste.

Province	**GWP land transformation (kg CO2-Eq.)**	**Hazardous Waste Disposed (kg)**	**Net use of Freshwater (m^3)**
Quebec	0.32	15.17	0.70
Alberta	0.021	156.74	0.28
Ontario	0.24	15.93	0.95

Table 1. Comparison of Three Relevant Environmental Impact Metrics

For other impact categories, such as eutrophication (marine, freshwater, and terrestrial), acidification, radioactive waste and photochemical ozone formation, the impacts were negligible. We compared our results to that of a competitor's publicly available LCIA results, in Table 2 below. In two categories (GWP and fossil fuel depletion), GreenLIB outperformed the competitor. These results will be further discussed below.

Impact Category	GreenLIB Process	RecycLiCo Process	Unit
Global Warming Potential	5.6	7.1	kg CO2eq.
Acidification Potential	0.06	0.03	Mol H+ eq.
Minerals + Metal Depletion	2.8E-04	6.3E-05	kg Sb eq.
Fossil Fuel Depletion	46	102	MJ

Table 2. Comparison of GreenLIB's Current Process against a Competitor (adapted from RecycLiCo, 2022)

Overall, our key finding was that understanding and optimizing for the local energy landscape is crucial to maintaining GreenLIB's sustainability goals, and that electricity obtained from varying energy sources, even renewables, have a nuanced impact across the various categories. These results align with those in literature that the electricity mix has a significant influence on the lithium battery assembly process; GHG emissions from battery production decrease with the decrease of the carbon intensity of electricity (Lai et. al, 2022). In China, which has ambitious plans to green their grid, GHG emission from battery production in 2030 is predicted to be 70% of that in 2020. Under the low-carbon electricity mix in 2060 in China, the GHG emission of battery production will be reduced by 90% compared to 2020 (Lai et. al, 2022). This synthesis of our project findings and existing literature shows the importance of analyzing the regional energy mix to achieve a well-rounded approach to environmental considerations within GreenLIB's decentralized operating model.

Discussion

Research question 1

To interpret LCA and literature review results, two research questions were raised and will be answered in this discussion. The first question is looking at the quantitative benefits of GreenLIB's recycling processes compared to current standards in terms of emissions. The performance of GreenLIB's recycling process was compared with recycling facility processes in LCA studies, traditional competitors, and local facilities.

In terms of emissions, GreenLIB's recycling process emissions were compared to current standards. GreenLIB's recycling process results were compared against 76 other LCA studies in the same field, and found that their recycling process is relatively more eco-friendly by 73% (Zhao et al., 2021). As shown above in Table 3, GreenLIB's total global warming potential (GWP) was found to be 5.64 kg CO2eq/FU compared to 19.78 kg CO2eq/FU for others in the studies. In addition, we compared GreenLIB to RecycLiCo, which is a local recycling facility based in Surrey that uses the hydrometallurgical method, and found them less eco-friendly with higher GWP at 7.1 kg CO2eq/FU battery recycled (RecycLiCo, 2022).

	GWP Total
GreenLIB	**5.4** kg CO2eq/FU
Other 76 LCA studies	**19.78** kg CO2eq/FU
RecycLiCo	**7.1** kg CO2eq/FU

Table 3. Environmental impact and GWP total between GreenLIB, 76 LCA studies, and RecycLiCo (Surrey).

The difference in emissions between GreenLIB and RecycLiCo also resulted in varying effects on other impact categories, which contribute to the eco-friendliness of the facilities. The impact categories compared were associated with acidification and resource depletion summarized in Table 2. GreenLIB was found to have a higher negative impact on acidification and mineral, metal depletion. However, RecycLiCo depletes fossil fuels by more than double compared to GreenLIB, which may be attributed to mining and/or energy sources (RecycLiCo, 2022).

Globally, traditional competitors of GreenLIB include Redwood Materials, Ascend Elements, and Li-Cycle (GreenLIB, 2023). When compared to the average LIB recycling facilities, GreenLIB can reduce recycling GHG emissions by 57% using the efficient hybrid hydrometallurgy technique (GreenLIB, n.d.-b). According to LCA back calculations, the minimum of GreenLIB's emissions impact was estimated to be 29.6 kg CO2eq. The reduction in emissions may be due to GreenLIB having higher resource efficiency than average facilities. Although the statistics for GreenLIB's electricity and water consumption are not available, these statistics can be inferred from the difference in total GHG emissions. GreenLIB mentioned that average facilities consume a substantial amount of electricity up to 10,000 MWh of electricity every year (GreenLIB, 2023). This electricity consumption per facility results in 4,000MtCO2 emissions per year (GreenLIB, 2023). Water consumption of average facilities is also high at approximately 1.9 ML of water per day (GreenLIB, 2023). Since GreenLIB has over 50% reduced recycling emissions, it can be inferred that GreenLIB's electricity and water consumption may be significantly lower, and contribute less to total emissions.

GreenLIB's other benefits

Moreover, other benefits observed for GreenLIB include eco-friendliness, scalability, recovery efficiency, technology capability, and profitability. GreenLIB's recycling processes are more eco-friendly than other metal production because they reduce the need for mining. The usage of water technology and electroextraction enables GreenLIB to reduce GHG emissions associated with traditional mining by 82% (GreenLIB, n.d.-b). GreenLIB has scalability benefits and is prepared to scale up. GreenLIB has been experiencing a yearly increase in production capacity (GreenLIB, n.d.-a), and has set an annual production target of 60,000 metric tons of recycling capacity by 2034 (GreenLIB, n.d.-a). GreenLIB also possesses excellent recovery efficiency that can reach 95% recovery of essential elements in batteries (GreenLIB, n.d.-a). GreenLIB can further profit through recovery efficiency by supplying an increasing amount of resources to manufacturers (GreenLIB, n.d.-a). The hydro hybrid technology utilized is also incredibly versatile, being able to process five different battery chemistries, including LFP, LCO, NCA, etc. (GreenLIB, n.d.-a).

Lastly, GreenLIB benefits by being cost-effective. GreenLIB facilities only require 50% of the operation cost that competitors require. Competitor facilities require between 30,000 to 100,000Mt of recycling capacity to sustain the facilities (GreenLIB, 2023). On the other hand, GreenLIB facilities are not large-scale, instead, these facilities are streamlined and decentralized, so a recycling capacity of 5,000Mt is enough to sustain the facilities (GreenLIB, 2023). The business model that GreenLIB operates on, allows for its recycling facilities to be co-located near battery cell, cathode, and anode production facilities, to optimize resource collection (GreenLIB, 2023). The small co-location facility strategy also enables GreenLIB to reduce costs and emissions associated with long-distance transportation and capital costs, since the recycling facilities will be close to the upstream resource collection sites (GreenLIB, 2023).

Research question 2

As for the second research question, the LCA and literature review results are interpreted to answer how a change in the location of facilities across provinces will affect GreenLIB's recycling processes. In this report, the situations looked at are if GreenLIB co-located from Quebec to Ontario or Alberta. The change may affect energy consumption, GHG emissions, and environmental impact/indicator categories.

Following the location change, energy emissions are expected to increase. This increase will be caused by the change in energy providers as GreenLIB co-locates from Quebec to Alberta and Quebec, and Ontario from majority hydro to non-renewable power including fossil fuels and nuclear energy which is illustrated in Figure 7. As mentioned previously in the assumptions and sensitivity analysis, Quebec uses more renewable energy sources such as hydro for up to 94%, while Alberta is a large producer of fossil fuels such as natural gas, and is natural gas-dependent for up to 54% (Canada Energy Regulator, 2022a; Canada Energy Regulator, 2022c). Therefore, the hydro energy source used in the LCA to model GreenLIB's energy in Quebec is medium voltage power, while the energy in Alberta is assumed to be medium voltage power generated from fossil fuels. To maintain low GHG emissions comparable to Quebec, GreenLIB would have to select renewable energy providers, which may pose a challenge. Otherwise, the energy source change to non-renewables will lead to increased GHG emissions as fossil fuels are more carbon intensive than renewable hydropower. The electricity emission factor will change from 1.5 gCO2eq/kWh (Canada Energy Regulator, 2022c) for hydro energy to a significantly higher 590 gCO2eq/kWh for fossil fuel energy (Canada Energy Regulator, 2022a).

For similar reasons as co-locating to Alberta, GHG emissions are expected to increase in Ontario with the use of uranium for non-renewable nuclear energy. The electricity emissions factor for energy in Ontario is 25 gCO2e/kWh (Canada Energy Regulator, 2022b). The difference in carbon intensity of energy between Quebec, Ontario, and Alberta suggests that a move to Ontario may be slightly less eco-friendly, but still significantly less emissions heavy than switching to Alberta.

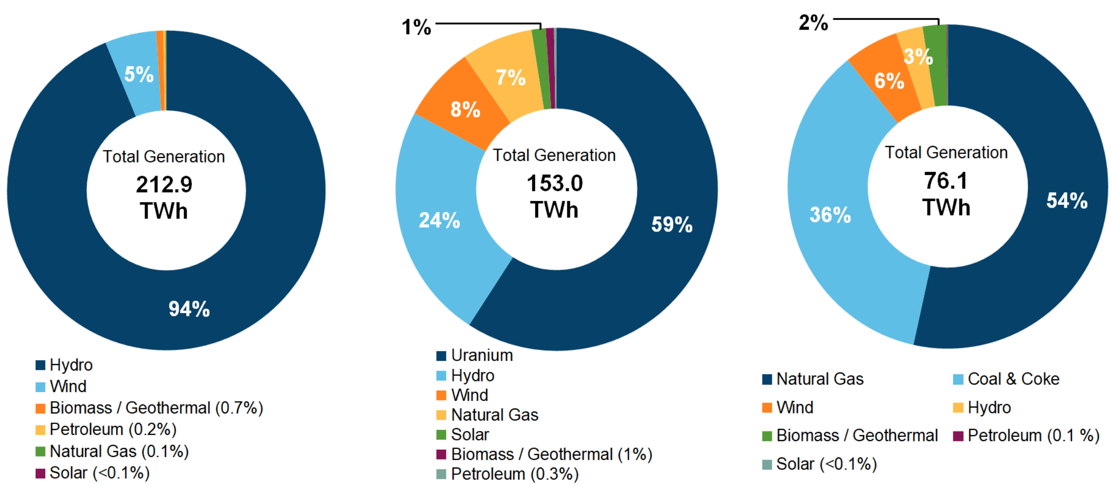


Figure 7. Left: Total power generation in Quebec, and composition in percentage of energy generation source (Canada Energy Regulator, 2022c). Middle: Graph of energy generation source composition in Ontario (Canada Energy Regulator, 2022b). Right: Graph of energy generation source composition in Alberta (Canada Energy Regulator, 2022a)

Impact categories comparison

Furthermore, the shift in processes from Quebec to Alberta and Ontario may lead to adverse changes across 15 impact categories from environmental impacts to resource usage and waste. The LCA models constructed for GreenLIB estimate that the Quebec to Alberta location change will lead to a high negative impact increase mainly in the environmental impact (EI) categories by 50% or more as illustrated in Figure 8 below. As for Ontario, the impact on EI categories seems relatively similar to Quebec.

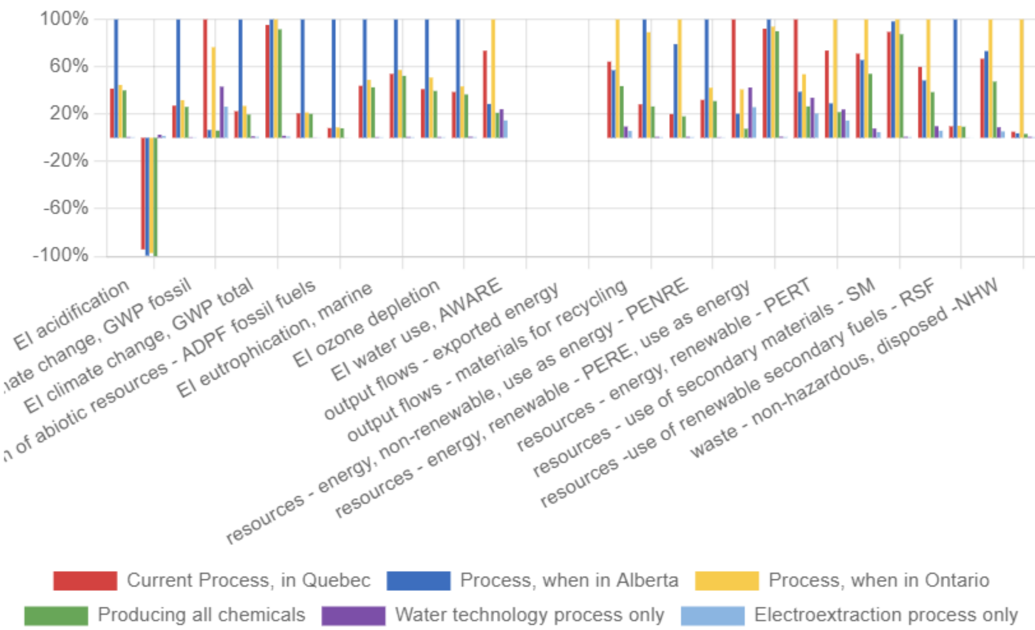


Figure 8. The bar graph compares GreenLIB's recycling processes in Quebec, Alberta, and Ontario across 15 impact categories from environmental impacts to resource usage and waste. As well as comparing impacts from three selective process scenarios for chemicals, water technology, and electroextraction.

The main impact category results focused on and compared in this report were outlined in Table 1 previously which are GWP of land transformation, hazardous waste disposal, and net freshwater usage. The results associated with location change demonstrated that all three categories would be changed and that each province has downsides. As mentioned earlier in the results, Quebec will have more issues with land transformation, Alberta will perform worse for waste disposal, and Ontario will require higher water consumption. The differences in change suggest that GreenLIB will have different areas of impact and challenges to consider when operating in different locations. On the other hand, categories such as the hazardous waste disposal impact were found to be similar for Quebec (15.17 kg) and Ontario (15.93 kg). The minimal change in impact implies that GreenLIB may share disposal processes as is between the two provinces, and focus more on compensating the large freshwater requirement.

As modelled for GreenLIB, the negative effects associated with climate change GWP from Quebec to Ontario are expected to increase by around 20% from 5.64 kg CO2 eq/FU to 6.76 kg CO2eq/FU as shown previously in Figure 5. The expected increase is significantly higher for Alberta to 25.11 kg CO2eq/FU, which is more than 400% from 5.64 kg CO2eq/FU. This drastic increase may be one of the major sources of difference from changing locations and should be considered and compensated for.

Limitations

The findings presented in this LCA study are subject to the following limitations that should be considered when interpreting and generalizing the results. These limitations encompass data reliability, process information gaps, and challenges in substantiating certain claims made by GreenLIB. Our study acknowledges the challenge of relying on self-reported data, introducing potential deficiencies in measurement accuracy. The accuracy of LCA assessment results heavily depends on the quality of the data inputs, and uncertainties may arise due to variations in data collection methodologies. The self-reported nature of the primary data raises concerns about the completeness and reliability of the information, as it may be influenced by factors such as reporting biases or incomplete data sets. Stemming from the above, limitations encompass missing data regarding waste processes and inputs. In our LCA mode, the recycling process starts from 1kg of black mass, after batteries have undergone disassembly, washing, and parts separation. GreenLIB has self-reported a recovery rate of 95% for its essential battery elements, a claim our study is unable to test. The absence of details regarding the waste processes and black mass composition complicates the comprehensive understanding of the entire life cycle of GreenLIB's battery production and recycling. Without a clear understanding of these processes, it becomes challenging to assess the overall sustainability and environmental performance of GreenLIB's operations. For further results, having data on the amount of chemicals used in each process would allow these models to include their share of chemicals and therefore be more accurate. As well as the data on chemicals used in each process, having data on the amounts of black mass going into each unit in the process and its composition would allow for even more accurate results. Additionally, while our study references a competitor's LCIA results for comparison, due to data access issues, we lack information on the methodologies used by the competitor, making it challenging to draw robust conclusions about the comparative environmental performance.

Conclusion

Our LCA on Greenlib's Li-ion battery recycling revealed results that, compared to non-recycling practices, Greenlib reduces the GWP of batteries by 73% and also derived a lower GWP compared to other battery recycling facilities. GreenLIB can be considered exceptionally eco-friendly in terms of CO2eq however, considering other impact categories, GreenLIB exhibits higher negative impacts on acidification and mineral, metal depletion. Moreover, the current Quebec location of GreenLIB produced the least amount of environmental impacts and climate change contribution in terms of energy consumption as Quebec's is primarily renewable. The LCA on a relocation to Alberta and Ontario, where fossil fuel energy use is more dominant, revealed that the GWP would significantly increase due to the change in energy providers. Thus, choosing specific energy sources when upscaling to different provinces would benefit GreenLIB to reduce its contribution to climate change. GreenLIB's unique commitment to eco-friendliness is supported by its use of water technology and electroextraction, reducing GHG emissions associated with traditional mining and refining by 82%. The company's cost-effectiveness is evident in streamlined and decentralized facilities, requiring only 50% of the operational cost compared to its competitors.

For work in the future, we suggest an investigation on whether recycling would take away from national revenue, as material mining and battery production is a large source of income for many countries. Furthermore, technological advancement methods to increase mineral recovery, lithium in particular, would be a breakthrough for the recycling industry, Finally, repurposing residual energy at facilities before recycling may prove to be advantageous for both the environment and social concerns.

Contribution statement of all group members

Everyone in the group contributed to the project. Every member communicated a lot and was very involved in the process from the very beginning. Everyone also did their parts on time, and followed internal deadlines that were made. Hannah did all of the LCA modelling, and focused on the methodology, and abstract sections of the report. Andrea did a lot of data collection, literature review, and focused on the methodology and abstract sections of the paper as well. Oak did lots of literature review and focused on the intro, conclusion, and literature review sections of the report. Alyn did literature review and focused on the discussion and literature review sections of the paper. Elaine also helped with literature review and focused on the results interpretation and limitations sections of the report.

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