End of Life EV Battery Policy Simulator: A dynamic systems, mixed-methods approach

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A Research Report from the National Center for Sustainable Transportation

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16. Abstract
Lithium-ion batteries (LIBs) are the enabling technology for modern electric vehicles (EVs), allowing them to reach driving ranges and costs comparable to internal combustion engine vehicles, an important development with EVs being integral to greenhouse gas mitigation efforts. However, LIB advancements include the use of rapidly evolving and chemically diverse batteries as well as larger battery packs, raising concerns about battery production sustainability as well as battery end-of-life (EoL). This study seeks to respond to these concerns by analyzing potential pathways for EoL EV batteries, quantifies flows of retiring EV battery materials, proposes economically and environmentally preferable LIB EoL strategies, and recommends pertinent policies with an emphasis on environmental justice. The researchers used a loosely coupled dynamic systems model that utilized life cycle assessment and material flow analysis and a mixed methods research approach. They find that the U.S. can make significant gains in securing supply chains for critical materials and decrease life cycle environmental impacts through the adoption of Recycled Content Standard policies similar to those found in the European Union. In addition, they examine the currently understood waste hierarchy in the context of LIB technology. Comparing immediate recycling to repurposing and reusing, they find that repurposing and reusing reduces life cycle environmental impacts relative to recycling. This project also includes an investigation of EoL battery collection and transportation and the vehicle afterlife ecosystem, as well as general stakeholders in the LiB life cycle, informed by expert interviews and a case study of a developing lithium industry in Imperial, California.

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February 2024

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EXECUTIVE SUMMARY

Electric Vehicles (EVs) are a critical component of greenhouse gas (GHG) mitigation targets at state, federal, and even international scales (*1*). Lithium-ion batteries (LIBs) are the enabling technology for today's EVs, allowing for driving ranges and costs that are nearly competitive with internal combustion engine vehicles. However, the advancements in LIBs that have enabled today's EVs include rapidly evolving and increasingly diverse battery chemistries and larger battery packs, which engender concerns about the sustainability of battery production and battery end-of-life (EoL). For example, at production, key inputs to batteries such as lithium, cobalt, and graphite are considered critical or near-critical materials and have negative social and environmental impacts. At EoL EV LIBs present environmental and safety concerns, but may also have residual value in second-life applications or as sources of recycled materials. Few EVs or EV batteries are being retired from the fleet today, so there is an opportunity to anticipate and address the needs for a safe and sustainable system for managing EoL EV LIBs.

This research project was conceived to understand the future flows of EV batteries, their fate and EoL and the policies and decisions that lead to environmentally and socially preferable outcomes. In particular, this research identifies the potential pathways for future EoL EV batteries, quantifies flows of retiring EV battery materials in the U.S., determines environmentally and economically preferable EV LIB EoL strategies, and creates recommendations for policies that can help achieve them. To accomplish this goal, we created a loosely coupled dynamic systems model (DSM) that embeds industrial ecology analytical methods (life cycle assessment - LCA and material flow analysis - MFA), and use a mixed methods research approach (i.e., an approach that includes both qualitative and quantitative research methods) to gather data and information on the EV and LIB EoL industry. As part of this research, the concerns of communities likely to be effected by the siting of extractive or industrial activities associated with LIB production are documented and analyzed as well.

The rest of this report described the research undertaken as part of this project. Because much has been published in peer-reviewed journal articles (*2*–*5*), this report summarizes the results of published research, directing readers to peer-reviewed journal articles for more in-depth discussion of methods and findings. This avoids the risk of duplicating information already published and copyrighted, and provides a concise summary of the work completed under this project. All of the published articles are publicly available via open-source publication agreements and thus accessible to all readers. The following paragraphs summarize key research outcomes from this project.

The quantitative modeling work undertaken in the project focused on decision support for the fate and management of EoL EV batteries. Two primary research thrusts and products from this work were generated: (i) an assessment of the feasibility, cost and environmental benefits of a

U.S. Recycled Content Standard (RCS) policy; and (ii) a LCA examining the relative environmental performance of recycling without repurposing versus repurposing prior to recycling an EoL EV battery considering changing technologies.

The first research thrust showed EV LIB recycling can decrease life cycle environmental impacts and assist in securing domestic supply chains (*2*). However, despite being the third largest market for EVs, the U.S. is alone among other large EV markets for its lack of policies requiring recycling of batteries at EoL. Looking to the European Union's comprehensive Battery Regulation, which includes RCSs, the research conducted in this project calculates feasible RCSs for the U.S. Using a 95% confidence interval, results show that 11–12% of cobalt, 7–8% of lithium, and 10–12% of nickel demand in 2030 and 15–18%, 9–11%, and 15–17%, respectively, in 2035, could be met by recycling the retired supply of EV LIBs assuming closed-loop recycling within the U.S. While domestic recycling can be profitable at scale and reduce environmental impacts, it is more expensive than exporting to the world's current leader in LIB recycling, China. Consequently, policy is likely needed to ensure LIBs are recycled domestically.

The second thrust focused on comparing EoL alternatives for EV LIBs, with a particular focus on understanding how changes in battery chemistry and design, such as reducing or eliminating cobalt in LIB cathodes or substituting silicone for graphite in LIB anodes, might effect these decisions (*3*). Reusing, repurposing, and recycling all mitigate battery impacts by either extending their life or generating recycled content for future batteries. However, extending in-use lifetimes delays the availability of recycled material for new batteries. This research assesses whether technological innovations change the currently understood waste hierarchy, which prioritizes reuse or repurposing prior to recycling. Retired high-cobalt batteries could supply their constituent materials sooner if recycled immediately and be used in lower-cobalt, higher-performing batteries. The assessment applies LCA two end-of-life management routes for a high-cobalt LIB: first, recycling immediately after use in an EV, and second, repurposing the LIB in a stationary storage application followed by recycling. Findings show that reuse reduces life cycle environmental impacts relative to immediate recycling. Thus, the waste hierarchy holds, even as LIB technology rapidly advances.

Complementing the quantitative modeling approaches described above, two qualitative research thrusts were undertaken. The first charts the EV LIB reuse and recycling network in the United States (U.S.) using expert elicitation. Despite the increasing scrutiny of EV batteries from environmental, social and governance perspectives, the actual process whereby EoL batteries are collected or transported are commonly omitted from discourse and research, thus this work provides the first scholarly work examining this process. 29 experts were interviewed from sectors including automotive dismantling, auto auctions, battery recycling, dealerships, collection and storage, and representatives of the automotive manufacturing industry. The research results include a comprehensive flow diagram illustrating the vehicle and LIB EoL industrial ecosystem, and elucidates some of the anticipated changes and concerns that experts see for the transition from EoL internal combustion engine vehicles to EVs. This research is documented in Slattery et al., 2024 (*5*).

The second qualitative research project focused on understanding the priorities and concerns of frontline community affected by the LIB supply chain. This research initially intended to create a social-LCA (S-LCA) for LIBs. However, as research progressed it became evident that the data and methods were not mature enough for S-LCA. Instead, the research sought to identify the priorities and concerns of frontline communities to support environmental justice research and action [4]. As a case study, textual analysis of public meetings about a developing lithium industry in Imperial, California was conducted. The results show that water consumption, public health impacts, local employment, and opportunities to participate are high-priority topics for community members. Participants in community-focused meetings were mainly interested in the local impacts of the process, whereas state-led discussions focused on the sustainability of direct lithium extraction compared to conventional production methods. To address the priorities of frontline communities, future LCAs of LIBs and other environmental assessments can be responsive to communities' concerns. For example, evaluating water consumption in the context of regional availability, including local air emissions and waste streams, and monitoring the impact on local employment over time to ensure the promises made during development accrue to communities.

Introduction

Electric Vehicles (EVs) are a critical component of greenhouse gas (GHG) mitigation targets at state, federal, and even international scales (*1*). Recent technological advancements and cost reductions in lithium-ion batteries (LIBs) have facilitated the development of EVs that achieve a competitive driving range with fuel-powered cars. However, these advancements include rapidly evolving and increasingly diverse battery chemistries and larger battery packs, which engender concerns about the sustainability of battery production and battery end-of-life (EoL). For example, at production, key inputs such as lithium, cobalt, and graphite are considered critical or near-critical materials and have negative social and environmental impacts, and at EoL EV LIBs present environmental and safety concerns, but also may have residual value in second-life applications or as sources of recycled materials.

Despite the environmental value of recycling and recovering LIB materials, there are potentially significant barriers already evident for a robust, purely market-driven reuse and recycling sector. For example, LIB recycling is not necessarily profitable due to the high cost of material recovery in comparison to the price of raw materials and the high cost of EoL battery transport (*6*). For instance, the past few years has seen increased use of lithium-iron-phosphate (LFP) batteries, with major automakers including Tesla and Rivian announcing LFP-based models. LFP batteries don't use cobalt, which means they have a lower environmental footprint during production, but a lower commodity value for recyclers. Meanwhile, reusing batteries in second-life applications (i.e., repurposing) faces similar challenges, as the value of the repurposed storage system must exceed the cost of acquiring and processing retired EV LIBs.

Requirements reuse and recycling of EV LIBs in the United States (U.S.) have yet to be directed by policy. California, home to the largest number of EVs and EV LIBs in the U.S., has yet to develop its own state-level EV battery EoL policy (*7*). However, a Lithium-ion Car Battery Advisory Group was established in 2020 by AB 2832,a legislative action that mandated the Group to recommend policies for maximizing the reuse and recycling of EV batteries [8]. The final report included a list of recommended policies to assign responsibility for recycling under different scenarios and remove barriers to reuse and recycling, and suggested areas for future study.

The broad goal of this research was to identify the potential pathways for future EoL EV batteries, quantify flows of EV battery materials, determine environmentally and economically preferable EV LIB EoL strategies, and create recommendations for policies that can help achieve them. To accomplish this goal, we created a loosely coupled dynamic systems model (DSM) that embeds industrial ecology analytical methods (life cycle assessment - LCA and material flow analysis - MFA), and use a mixed methods research (MMR) approach (i.e., an approach that includes both qualitative and quantitative research methods) to gather data and information on the EV and LIB afterlife industry and process. MFA is implemented to estimate the total demand for new EV batteries and the flow of retired EV batteries in the U.S. over time. This modeling is used to estimate the potential for recycled content in future batteries, and coupled with cost estimates to illustrate the benefits of recycling. This mode Because this research attempts to understand and model processes that are either poorly defined or not yet in existence, expert elicitation of professionals in the vehicle and battery EoL industry is used to understand how EV batteries are currently managed and expectations of professionals on what the future will look like. A different qualitative research approach, textual analysis, is used to understand community concerns regarding LIB mineral production.

An MMR approach is required because previous studies have simply assumed that EV LIBs are returned to the dealership, and then sent to a final disposal site (*9*). However, there is a lack of knowledge on actual EV EoL processes, especially as the EV market grows and the number of older, out-of-warranty EV batteries and vehicles increase. In addition, given the safety concerns associated with aged or damaged LIBs, for example due to increased risk of thermal runaway, the safety and livelihood of those individuals and organizations that manage aged or damaged batteries stand to change as vehicles become electrified. It is therefore critical that the input and experiences of the people who physically interact with EoL LIBs be considered when crafting a LIB EoL policy. To understand the experiences, knowledge, and perceptions of these stakeholders, and learn about the vehicle afterlife ecosystem from those who operate it, this study includes qualitative research conducted with auto dismantlers, recyclers, original equipment manufacturers (OEMs), and car dealership personnel. This report also documents the quantitative analysis outcomes of this research including EoL battery material flow analysis and life cycle impacts of alternative EoL management options.

The structure of this report documents the outcomes for each of the Tasks proposed as part of the initial project. These tasks are as follows (detailed description of subtasks available in Appendix 1):

Task 1: Literature review and secondary data gathering for model development, with a focus on review of recycling technologies and potentials as well as relevant policies for reuse and recycling.

Task 2: Development of a simplified Dynamic Systems Model (DSM), focused on product and material flows, to be used in Task 4.

Task 3: Qualitative research interviewing stakeholders associated with EoL vehicles and EoL EV batteries.

Task 4: Complete DSM and couple with LCA and technoeconomic modeling.

Task 5: Data Management Plan

Task 6: Policy and Practice Impact Plan, and Final Reporting Requirements

The rest of this report is dedicated to the outcomes of each Task, and a conclusion and recommendations for future work. Tasks 1-4 are research tasks. Task 1 is the only task whose research has not been otherwise published or documented in a peer-reviewed journal article. Because much of the research completed in this project has been published in peer-reviewed journal articles in peer-reviewed journals, this report summarizes the results of the research that is published, directing readers to peer-reviewed journal articles for more in-depth discussion of methods and findings. This avoids the risk of duplicating information that is already published and copyrighted, and provides a concise summary of all the work completed under this project. All of these journal articles are publicly available via open-source publication agreements and thus accessible to all readers.

Currently published articles include:

- Dunn, J., K. Ritter, J.M. Velázquez, A. Kendall. (2023). Should high-cobalt EV batteries be repurposed? Using LCA to assess the impact of technological innovation on the waste hierarchy. *Journal of Industrial Ecology*, 00, 1–14. https://doi.org/10.1111/jiec.13414
- Dunn, J., A. Kendall, M. Slattery. (2022). Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. *Resources Conservation and Recycling*, vol. 185, p. 106488. https://doi.org/10.1016/j.resconrec.2022.106488
- Slattery, M., A. Kendall, N. Helal, ML Whittaker. (2023). What do frontline communities want to know about lithium extraction? Identifying research areas to support environmental justice in Lithium Valley, California. *Energy Research & Social Science*, vol. 99, 103043. https://doi.org/10.1016/j.erss.2023.103043
- Slattery M, Dunn J, Kendall A* (2023) Charting the electric vehicle battery reuse and recycling network in North America. Waste Management 174: 76-87, DOI: https://doi.org/10.1016/j.wasman.2023.11.018

Task 1: Literature Review and Secondary Data Gathering for Model Development

The life cycle of EVs and their batteries has been well-studied, but in part because of the nascency of the technology, many earlier studies addressing the life cycle impacts of EVs either omitted or treated very simply the EoL processes required after vehicle or battery retirement (*6*). Figure 1 below illustrates potential EoL pathways for EV batteries, and shows the many possible EoL fates for batteries including reuse, repurposing and refurbishment prior to final disposition. Even under conditions where batteries are reused or repurposed, or undergo refurbishment prior to reuse, the ultimate fate for every battery should be recycling to ensure maximum recovery of secondary materials. The landscape from a technology perspective is changing for LIB recycling, which has implications for the economics and ultimate recovery rates.

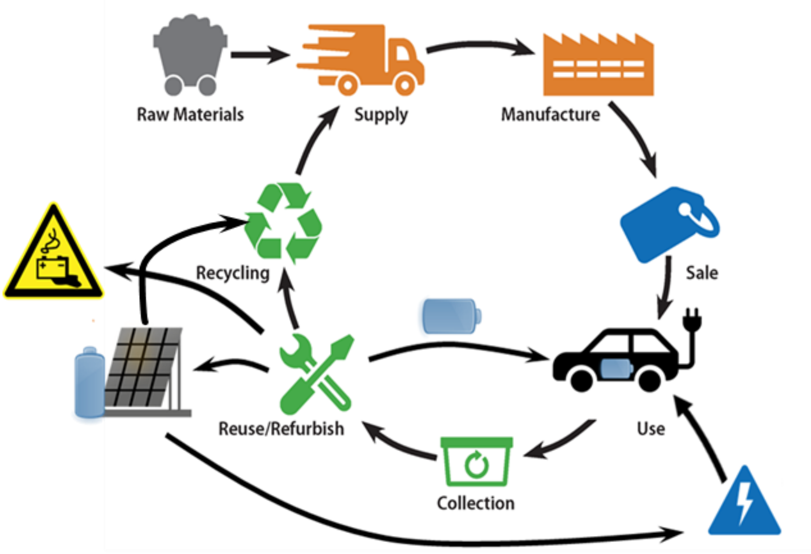

Figure 1. The EV battery life cycle. Note that the use phase may occur in multiple markets due to used vehicle trade. Image adapted from US EPA (*10,11*)**.**

Review of recycling technologies and potentials

Recycling can be broken down into two main components: collection, and material recovery. This section describes processes and pathways for recovering recyclable materials from lithium electric vehicles batteries.

To recycle an EV battery, the battery pack is first discharged and in most cases dismantled down to the module level (*12*). From this point, battery modules can undergo mechanical pre-treatment or pyrometallurgy. Both processes may be followed by a secondary hydrometallurgical process to recover individual metals. Commercial processes focus on recovering cobalt and nickel, in addition to more easily recycled metals (aluminum, copper, and steel).

In most cases, recovered materials require further refining and/or chemical synthesis to be reused as inputs for new lithium batteries. .Which materials are recovered in usable form depends on their commodity value; for example, Historically, lithium was rarely recovered in practice as it requires an extra processing step and had a relatively low commodity price, around USD $8/kg, compared to USD $30/kg for cobalt (*13,14*). However, lithium prices have increased substantially since this study began, and recyclers in China commercially recover lithium hydroxide.

In most cases, recovered materials require further refining or chemical synthesis to be reused as inputs for new lithium batteries. Currently, recovered materials are often used in other products (what is referred to as open-loop recycling systems). The sections below provide a summary of recycling terminology and descriptions of recycling steps in order to provide context to the research conducted in this project.

Recycling Terminology

Closed- and Open- Loop Recycling

In ***closed-loop recycling***, material recovered during recycling is used to manufacture the same product. For LIB cathode recycling to be closed-loop, the constituent material must be refined, then resynthesized into a new cathode compound. Synthesis of the cathode active material is a critical step in the manufacturing process and the synthesized cathode active material is often the highest cost input to cell production. There is currently a knowledge gap regarding remanufacturing techniques and the quality of resynthesized cathode materials, as the technology is still being developed (*15*).

Open-Loop recycling means recovered materials are used as inputs in a different product system. For example, recovered aluminum or steel alloys may be remelted to form different alloys for use in other industries. This is known as “functional recycling.” Open-loop can also mean nonfunctional recycling, which occurs when the recovered metal has been mixed with other elements and can no longer be used for its original purpose.

Recycling Pathways for Lithium-ion Batteries

Different recycling pathways yield different products, and are sometimes combined to yield similar final products. All recycling pathways require pre-treatment steps which typically include discharging of the battery and dismantling of some kind.

Mechanical Pre-Treatment: After packs are discharged and dismantled, batteries are mechanically shredded. Materials are sorted into plastic fluff, metal-enriched liquid, and metal solids. After sorting, most copper, aluminum, and steel casings are recovered. The remaining material is often referred to as ‘black mass’ and has relatively high concentrations of nickel, cobalt, lithium, and manganese. From there, materials can be recovered through hydrometallurgical processes.

Pyrometallurgical Recycling: Modules are smelted in a high-temperature furnace (~1500°C) to produce a concentrated alloy containing cobalt, nickel, and copper. These metals can then be extracted using a hydrometallurgical process. The lithium and manganese end up in a slag that can be directly used in the construction industry or processed further to recover lithium (*16*).

Hydrometallurgical Recycling: A chemical process involving leaching, removal of impurities, and separation. Leaching may be followed by solvent extraction and/or chemical precipitation to recover lithium, nickel, and cobalt.

Direct Cathode Recycling**:** Any combination of the processes described above where cathode materials are recovered in a suitable condition to be directly used in battery production, without breaking them down into individual material elements. The ReCell Center at Argonne National Laboratory is leading research and development in this area (*17*).

Recycling Metrics

To clearly discuss recycling policy, it is important to understand the distinctions between common metrics used to describe recycling rates and efficiencies. The following definitions are adapted from terminology used in Graedel et al., 2011 (*18*):

- ***Collection rate:*** Proportion of EoL products that are collected and enter the recycling chain.
- ***Recovery rate/process efficiency rate****:* Proportion of collected material recovered in usable form
- ***EOL recycling rate:*** Proportion of all EoL product material that is recovered by recycling; dependent on both process efficiency and collection rate.
- ***Recycled content****:* Fraction of a product's manufacturing inputs that are recycled as opposed to virgin material.

Industry Landscape

The existing LIB recycling industry has developed around recycling consumer electronics, with the majority of recycling taking place in China, followed by South Korea (*15*). Pilot and commercial facilities are operational to a smaller extent in Europe, North America, and Canada, although many are in the pilot stage or do not operate at full throughput capacity. The development of recycling is further taking off globally in response to EV demand and the expected increase of EV battery retirements in the next decade. The majority of feedstock for recycling is currently consumer electronics and battery manufacturing scrap, but retired EVs are expected to contribute the bulk of their input in the future (*19*).

North America is part of this rapidly growing market. There are several operational facilities that produce battery grade materials ready to be put back into the battery manufacturing process, such as Interco and Redwood Materials. Others currently specialize in pretreatment, producing black mass that can be further refined into battery-grade material, including Li-Cycle and Cirba Solutions. These companies have plans to expand their operation to produce battery grade materials in the U.S., with plants that are planned to be operational in 2023.

For reference, Table 1 describes planned and operational facilities in North America as of March 2022.

Table 1. Lithium-ion battery recycling facilities in North America (*8*).

Company	Location(s)	Current capacity (metric tons/year)	Planned total capacity (metric tons/year)
American Battery Technologies	Fernley, Nevada	-	20,000
American Manganese	Vancouver, British Columbia	-	182.5
Ascend Elements	Worcester, Massachusetts Novi, Michigan; Covington, Georgia	Unknown	30,000
Interco	Madison, Illinois	24,000	Unknown
Li-cycle Corporation	Rochester, N.Y. (spoke) Kingston, Ontario (spoke) Phoenix, Arizona (spoke) Tuscaloosa, Alabama (spoke) Rochester, N.Y. (hub)	5,000 5,000 - - -	5,000 5,000 10,000 5,000 60,000
Lithion	Ajou, Quebec; Planned locations unknown	200	7,500
Princeton NuEnergy	Dallas, Texas	-	Unknown
Recycling Coordinators	Akron, Ohio	Unknown	Unknown
Redwood Materials (Carney, 2021)	Carson City, Nevada; Reno, Nevada	18,100	Unknown
Cirba Solutions	Lancaster, Ohio and Trail, British Columbia	4,500	4500
Umicore Canada Inc. (Umicore, no date)	Fort Saskatchewan, Alberta	Unknown	Unknown

Current Policies Affecting the End-of-Life of Electric Vehicle Batteries

Policies targeting the EoL of a product life cycle, including EV LIBs, can take on a variety of forms, and depending on their goals (or unintended consequences) can shape more than just disposal processes. EoL policies can drive changes to design and manufacturing, lead to reuse and remanufacturing, and support recycling. Broadly, policies can designate a responsible party for the proper disposal of the LIB, they can focus on producers implementing changes at the design phase, and they can take approaches that combine both, often framed around the concept of circularity.

Policies focused on the responsible party also usually designate the route for ultimate disposition of a battery (recycling vs. landfill). Extended producer responsibility (EPR) is used in many regions to hold the producer liable for the costs and planning of collection and disposal, directing this responsibility away from the government and consumer. This is also intended to influence the manufacturers to plan for EoL throughout the design phase and the reverse logistics process. Alternatively, policies such as landfill bans automatically place responsibility on the final consumer, relying on the government to create a designated pathway for disposal that is accessible by the consumer. In either producer or consumer-oriented policies, reporting the collection rate, recycling rate, and materials recovered requires tracking and enforcement by government entities, and is necessary to observe the success or failure of a policy.

Policies such as labeling of chemistries, design for recycling (DfR), or standardization of design are used to encourage specific changes that producers can implement that both decrease costs and increase safety of disassembly, remanufacturing, and recycling. Tracing the source of materials used in manufacturing is a life cycle-based initiative that has been encouraged by the Global Battery Alliance. While it is not specifically aimed at facilitating EoL, it is related, insofar as tracing and recycling materials share the common goal of decreasing the social and environmental impact of producing LIBs.

Alternatively, instead of implementing requirements, government grants can be used to boost the recycling and repurposing industry through research, development, and demonstration. This market-based approach is aimed to increase the availability of recycling capacity and the technological capabilities to make recycling the economical choice.

Below, a summary by region of active LIB EoL policies is provided for the three biggest EV markets in the world: the EU, China, and the U.S., including California. As is evident in these descriptions, the approaches are very different (*20*).

European Union

The Battery Directive (Directive 2006/66/EC), enacted in 2006, covers the recycling and disposal of lithium-ion batteries. The Battery Directive uses extended producer responsibility, which requires producers to be responsible for the cost of collection, transportation, and recycling of their products. The Battery Directive was originally created to manage nickel-cadmium and lead acid batteries. Lithium-ion batteries fall under the ‘other’ category, for which the policy requires 50% of the battery weight to be recycled (*21*).

However, after a detailed review of the Directive, its successes and failures, and the emergence of entirely new chemistries and large-format applications for batteries (like EVs) since its original conception, the European Commission proposed in 2020 and approved at the end of 2022, a new European Battery Regulation that focuses not just on managing batteries at their end of life, but pursues the development of a battery manufacturing industry that can lead to regional circularity in battery materials and reduce or eliminate dependencies on other parts of the world.

The broad scope of this policy, and its many parts, are intended to provide a comprehensive policy to bring the entire EV battery value chain (including recycling and material recovery) to Europe (*22*). The final approved regulation is intended to take a circular economy approach, considering the production, use and disposal of batteries. For example, it requires manufacturers to create new batteries that include recycled material content, consider the supply chain impacts of production, considering carbon footprint and social and environmental impacts across the battery material and supply chains, but also improve access to information during battery operation and after via "digital battery passport," and requires extended producer responsibility for battery EoL management (*23*). In addition, the European Commission launched a multi-industry European Battery Alliance (EBA) in 2017 to address the challenges associated with a high influx of lithium-ion batteries. EBA is composed of 250 European and non-European stakeholders representing the entire battery value chain The European Commission also announced a Strategic Action Plan on Batteries identifying the following priority areas to promote a sustainable battery industry (*24*).

- Secure access to materials (raw materials from resource-rich countries *and* via domestic recycling)
- Create a list of critical materials
- Assess the potential for EU sourcing secondary raw materials
- Use appropriate trade policy instruments (such as free trade agreements) to ensure fair and sustainable extraction and promote socially responsible mining
- Support European battery manufacturing
- Strengthen leadership in EU research and innovation
- Develop a skilled workforce
- Support sustainability of EU battery cell manufacturing industry (i.e. incentivize the use of renewables in the production process)

EBA is currently developing the Battery Passport to prolong the lifespan of the battery and provide clear and transparent information of the battery health for enhanced end-of-life management. This data is important in determining if the battery should be repurposed or recycled after the first use, as well as providing repurposers a definite and detailed battery health before purchasing and testing. The hardware is installed on the EV and monitors the battery's charge cycle, temperature, and usage patterns in real-time, while also transmitting this information to the cloud (*25*).

China

In 2016, China enacted the Promotion Plan for Extended Producer Responsibility System which proposed the creation of a recycling system of lithium-ion batteries based on the extended producer responsibility principles. China has implemented a Pilot EV Recycling Initiative in 17 cities/regions, controlling the number of new enterprises involved in recycling to make full use of existing infrastructure. In addition, they launched a Battery Traceability Management Platform to better track EV batteries throughout their life cycle.

In 2018, China enacted the Interim Measures for the Management of Recycling and Utilisation of Power Batteries of New Energy Vehicles which requires manufacturers to work with recycling companies to improve the recycling process, by labeling batteries and encouraging design for recycling. A guide for the collection, storage, and testing of batteries was also released to guide in the development of a safe repurposing industry. This is the most ambitious package of electric vehicle lithium-ion battery policy to-date.

United States

The U.S. does not have a national recycling or EoL EV lithium-ion battery policy. They have instead taken a market-based approach by supplying grants for the research, development, and demonstration of battery recycling and repurposing. The 2021 Bipartisan Infrastructure Law dedicated funds to ramp up battery end of life processing in the United States. Ten projects have been named the recipients of 73.9 million dollars from the Bipartisan Infrastructure Law (*26*). Five of the recipients are dedicated to repurposing batteries, with projects spanning from using repurposed batteries to enable rural EV charging, to technological improvements to repurposed battery monitoring and control at the cell level. Five of the recipients are focused on recycling, with the projects including the build up of domestic recycling capacity and innovation for combining recycling with mine waste reclamation.

There are also national regulations in the U.S. that cover the transporting and handling of batteries. The Mercury-Containing and Rechargeable Battery Management Act ('the Battery Act') of 1996 mandates states to manage the disposal of batteries at least to the federal Universal Waste regulations level noted in Title 40 of the Code of Federal Regulations in part 273 (FR Doc. 95-11143)[1]. Lithium-ion batteries are considered to be hazardous and categorized as universal waste due to flammability (§ 261.21(a)(2)). The U.S. Department of Transportation regulates the shipment of live and/or discharged lithium-ion batteries (49 CFR, paragraph 173.185(j)). Table 2 documents the relevant regulations in California, some of which are applicable nationally, and other which are specific to the state.

States have begun implementing their own lithium-ion battery EoL requirements. New York (NY Env Cons L § 27-1801), Minnesota (MN Rev Stat § 325E.125), and New Jersey (NJ Rev Stat §

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[1] Stated in § 273.2(b)(3), batteries (defined in §273.9) must exhibit a characteristic of a hazardous waste (found in § 261 Subpart C), in order to be covered under § 273 as a universal waste.

13:1E-99.65 (2018)) have required collection and recycling through extended producer responsibility principles. Due to the lack of reporting, the success of these laws is unknown, although the lack of enforcement has likely resulted in low recycling rates (IEA, 2020).

Within the U.S., California may have the most to gain by implementing comprehensive policy for EoL batteries, given its leadership in adopting EVs. The California Lithium-ion Battery Advisory Group convened by legislatures released their report in March of 2022 outlining potential policy options to increase EV battery recycling in the state. Senator Allen has proposed bill Senate Bill 615 in 2023 which aims to implement some of these policies.

Table 2. Regulations relevant to the proper disposal of lithium-ion batteries within California. These regulations are parsed by the regulated activity. Please note many regulations are applicable to more than one activity and are therefore listed more than once. (CFR: Code of Federal Regulations. CPUC: California Public Utilities Commission. CCR: California Code of Regulations. IEEE: Institute of Electrical and Electronics Engineers. NFPA: National Fire Protection Association. OSHA: Occupational Safety and Health Administration. RCRA: Resource Conservation and Recovery Act. UL: Underwriters Laboratories).

Regulated activity	Relevant regulations
Dismantling	Facility licensing requirements: California Vehicle Code Division 5 Storage fire codes: NFPA 855, Chapter 14
Transportation	Hazardous Material transportation: 49 CFR §173.185 (special consideration for damaged batteries)
Storage	Storage fire codes: NFPA 855, Chapter 14 Universal waste laws: 40 CFR §273.15 CA Universal Waste Laws: Chapters 12-16 title 22 of CCR
Disassembly	High voltage equipment and personnel safety references: NFPA 70B/E; IEEE C2 and IEEE 3007.3; OSHA 29 CFR 1926 and 1910 Storage fire codes: NFPA 855, Chapter 14 Universal waste laws: 40 CFR §273.15 CA Universal Waste Laws: Chapters 12-16 title 22 of CCR
Energy Storage System (ESS) Installation	Interconnection: CPUC Rule 21, CAISO/FERC Tariffs Electrical storage requirements: California Fire Code 1206; NFP 855; International Fire Code
Hazardous Waste Treatment	Universal waste laws: 40 CFR §273**,** Subpart E Permitting requirements: 40 CFR §§124 and 270 Standards for hazardous waste treatment, storage, and disposal facilities: 40 CFR parts 264, 265, 266, 268, 270, and 124 Notification requirement: section 3010 of RCRA. CA Universal Waste Laws: Chapters 12-16 title 22 of CCR CA specific: Health and safety division 20 chapter 6.5
Export	UN, EPA

Task 2: Development of a Dynamic Systems Model for Representing the Stocks and Flows of Electric Vehicle Lithium-Ion Batteries

The MFA is the foundation for much of the quantitative analysis conducted in this research project. The final model, which couples MFA with LCA and technoeconomic analysis (TEA), is described in more detail in the reporting for Task 4. Here we simply describe the structure for the MFA model development.

The model is used to estimate the circularity potential of pack-level materials under evolving cathode chemistries and what they would mean for a U.S. recycled content standard (RCS) for EV batteries (*2*). The interest in a RCS emerges from its inclusion in the European Union's Battery Regulation and its discussion as a potential policy recommendation from the California AB 2832 Lithium Car Battery Advisory Group (although it is not a policy that was ultimately supported by the Advisory Group) (*8*).

MFA Methods and Model Development

A dynamic systems model approach is used to create a US MFA to forecast future supply and demand of LIB materials for light-, medium-, and heavy-duty vehicles sold in the U.S. Figure 2 illustrates the MFA framework coded in R software, which calculates the demand, stock, and reclaimed materials for the years 2010 to 2050. This analysis includes forecasts of electric vehicle (EV) sales, battery capacity, cathode chemistry market share, battery lifespan, second-life use, collection rate, and recycling efficiency (see Table 3).

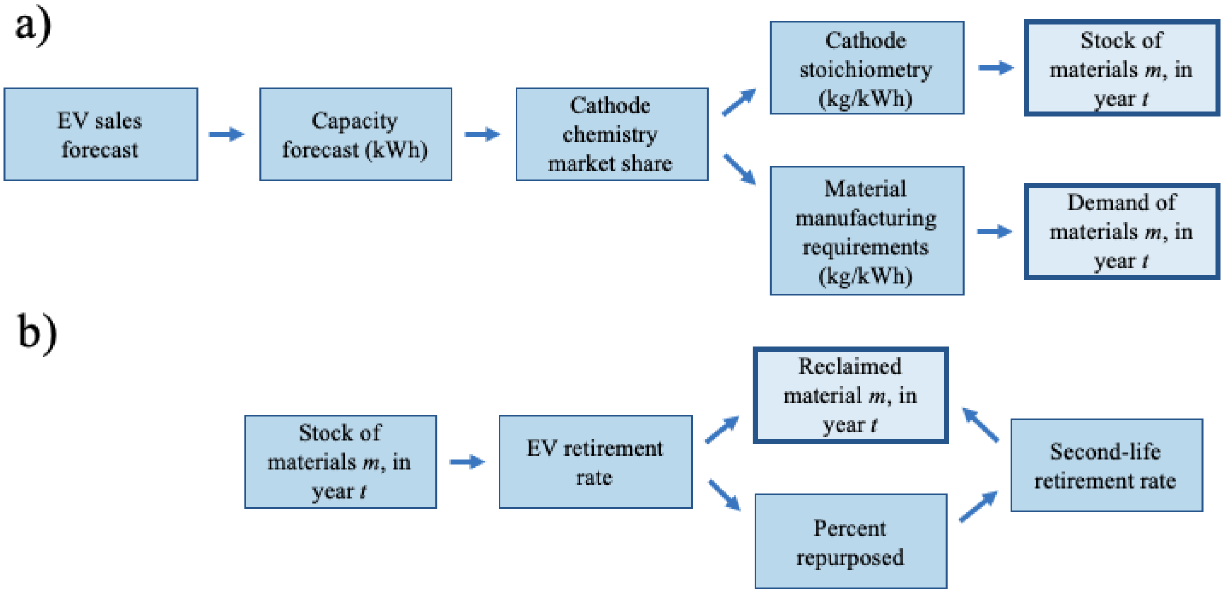


Figure 2. The process for calculating the stock and flow of LIB materials in the MFA model. a) The stock of materials reflects the materials in-use, and the demand reflects the material requirements for manufacturing. b) Using the stock of materials calculated in part a, this process calculates the reclaimed material available at a future date.

Table 3. Scenarios used in the stock and flow model. Reproduced from Table 1 in Dunn et al. 2022 (*2*)**.**

Model input	**Scenarios**
EV sales forecast	Two scenarios taken from the IEA (*1*): Stated Policies Scenario (STEPS) And Sustainable Development Scenario (SDS)
Cathode chemistry forecast	Two scenarios taken from Xu et al (*27*). NCX: Chemistries containing nickel and cobalt dominant in 2050 LFP: Lithium-iron-phosphate (LFP) chemistry dominant in 2050
Percent repurposed	10%, 25%, 50%
Failure rate of 2nd life	A lognormal distribution that uses the number of cycles per year (365 cycles, 183 cycles, and 92 cycles)
Recycling process	Hydrometallurgical, pyrometallurgical, and direct recycling

Task 3: Qualitative Research for Understanding the EV EoL network and flow: Expert Elicitation

Charting the electric vehicle battery reuse and recycling network in North America

Despite the increasing scrutiny of EV batteries from environmental, social and governance perspectives, the actual process whereby EoL batteries are collected or transported are commonly omitted from discourse on these topics or included in vague terms (*28*). While technical aspects of reuse and recycling continue to be extensively studied and reviewed, the logistics of collection and transportation are less commonly a focus of research, and when they are, they often treated simplistically (*6*). As a result, there is a knowledge gap regarding the pathways EV batteries retired today will follow once they are removed from a vehicle. North America is particularly vulnerable to this uncertainty because afterlife vehicle management, for all vehicles (whether EV or internal combustion engine), is a market-driven industry and the fate of LIBs is not dictated by policy.

To address this knowledge gap expert elicitation was used to create a flow diagram illustrating EV battery EoL pathways and to understand the concerns and priorities of individuals who are part of the EoL battery industry. Then, experts were invited to discuss how they thought the replacement of internal combustion engine vehicles with battery electric ones would affect steps in the vehicle EoL pathways. 29 experts were interviewed from sectors including automotive dismantling, auto auctions, battery recycling, dealerships, collection and storage, and representatives of the automotive manufacturing industry.

One product of this research, a flow diagram illustrating EoL pathways for EV batteries in the U.S. and Canada, has already been requested by interviewees to use in their own presentations and communications, illustrating the gap it has filled (Figure 3).

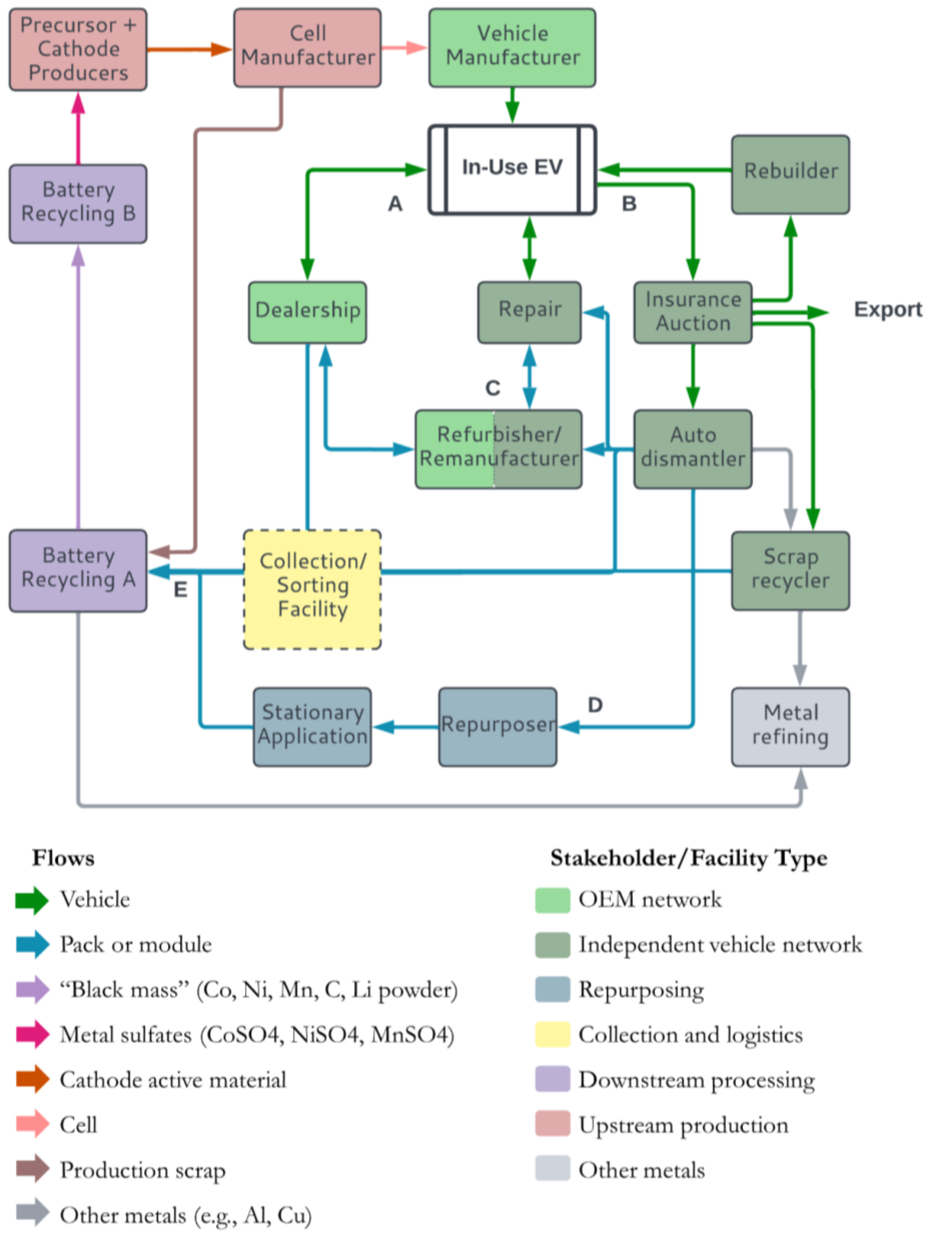


Figure 3. Product flows from EOL batteries. "A" represents batteries that are returned under warranty. "B" represents batteries that are removed due to a car collision. "C" represents batteries that are remanufactured or refurbished and reused in another vehicle, which could be performed within the dealership/OEM network (represented by the light green color) or by an independent operator (dark green). "D" represents batteries that do not have sufficient SOH for reuse in another vehicle but are repurposed as stationary storage. Batteries without remaining usable life may be aggregated at a collection facility or sent directly to a recycler. "E" represents all retired batteries and production scrap that are sent to a battery recycler. Battery recycling consists of two steps: pre-treatment ("Battery Recycling A") and material recovery ("Battery Recycling B"). This figure is reproduced from Slattery et al (*5*).

Some of the key conclusions reached based on this research are as follows: Policy can make the EOL network more efficient by facilitating access to information about battery condition and design, incentivizing domestic manufacturing, and implementing measures to ensure batteries are collected and recycled in the event that material recovery is not profitable. In addition, state and federal governments can help the workforce adapt by developing high-voltage training programs for sectors that have historically processed EOL internal combustion engine vehicles.

Outcome of Task 3

The results of this work are published in the journal *Waste Management* (5), available here: https://doi.org/10.1016/j.wasman.2023.11.018. Due to restrictions on publishing underlying data based on interviewee confidentiality, all relevant information and publishable data is part of the manuscript.

Task 4: MFA, LCA and TEA for Decision Support: Exploring U.S. Recycled Content Standards for EV Batteries, Prioritization of Reuse versus Recycling, and Expanding the Scope of Battery LCA

Reporting on task 4 is divided into three sections, each reflecting a peer-reviewed article that has been published. The first article uses the coupled LCA-MFA to understand the potentials for recycled content to meet material demands for new batteries assuming a closed U.S. battery ecosystem. LCA and TEA are then used to estimate the costs and environmental impacts/benefits of recycled content standards for the U.S. The second paper focuses more closely on environmental impacts (via LCA) of EoL alternatives to inform prioritization of EoL pathways for spent EV batteries, answering the question of whether we should immediately recycle spent batteries to generate recycled material to be used in newer, more efficient batteries, or keep the battery in use in a second-life application. The third paper focuses on understanding the priorities of frontline communities who experience the direct impacts of battery production to inform how LCAs of lithium production (a critical material for lithium-ion batteries) should be conducted. This work could be extended for any extractive mineral process needed to support the battery supply chain.

Electric vehicle lithium-ion battery recycled content standards for the U.S. – targets, costs, and environmental impacts

MFA has proven to be a powerful tool for understanding the material demand and waste material supply for EV batteries in previous work (e.g., *29*). As described in the outcomes of Task 2, the MFA model developed in this project focused on the U.S. and was used to develop possible recycled content standards for U.S. EV batteries. However, to interrogate the viability and performance of such a standard, the MFA was coupled with LCA modeling to characterize environmental impacts and technoeconomic analysis (TEA) to estimate the economic costs and benefits (*2*). It did so by coupling two of existing models, GREET and EverBatt, both developed by Argonne National Laboratory with the MFA model developed in this project (*30,31*). The approach is described in greater detail below, and the article is available open-source at the following URL: https://doi.org/10.1016/j.resconrec.2022.106488.

Background and Motivation

RCS is one potential policy mechanism for encouraging recycling and minimizing the dependency on virgin material for future batteries, which can help reduce the myriad social and environmental impacts associated with mining. It also creates a market and a premium for recycled materials, making recycling more profitable and ensuring that some recovered material is refined to a quality where true closed loop circularity is possible. In fact, the European Union has included an RCS in their new Battery Regulation (*32*). The U.S., however, does not have any comprehensive policy to support or require recycling of batteries, nor does it have requirements for using recycled materials.

In previous research, we showed that in the future, recycled materials could make up around a half of the demand for new battery production for many critical materials, but particularly

Cobalt (*29*). Here we focus in on the U.S., and include light, medium and heavy-duty EV battery demand and secondary supply, to estimate a feasible RCS for the U.S. assuming a domestic closed loop recycling system, and then couple this with the results of TEA and LCA modeling to estimate the environmental benefits and economic cost of implementing such a policy.

Approach

Economics of recycling

To determine the relationship between LIB material prices, materials stocks, and recycling was calculated using the Argonne National Lab EverBatt model (*33*). The model provides a platform to calculate the cost of recycling at various economies of scales (material stock), cathode chemistry market share, recycling process, and location of recycling. The cost of recycling is given in the unit of 1 kg of pack-level retired LIB and then compared with the value of recovered materials.

The cost of recycling is calculated for the scenarios listed in Table 1, along with a varying facility throughput from 1,000 to 50,000 metric tons per year, and the following three location and transportation scenarios:

A. **Domestic – truck scenario:** The LIB is recycled within the U.S., and transportation is done via truck.
B. **Domestic – train scenario:** The LIB is recycled within the U.S., and transportation is done via train and truck.
C. **China – truck and barge scenario:** The LIB is transported from the U.S. to a recycling facility in China via barge and truck.

A sensitivity analysis was used to evaluate the impact of recycling cost and material value inputs on the profitability of hydrometallurgical, pyrometallurgical, and direct recycling. The following inputs were both increased and decreased by 20% within the EverBatt model: the value of cobalt, the value of nickel, the value of lithium, the distance transported, the hourly labor wage, and the equipment cost.

Environmental impacts of recycling

The environmental impacts of collection and transportation, disassembly, and recycling, were taken from EverBatt which uses data from The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET) (*34*). To calculate the environmental impacts abated, the amount of recovered materials from 1 kg of battery recycled at the end-of-life was taken from EverBatt and the pollution from manufacturing these materials from virgin resources was calculated using data from GREET.

Results

The analysis conducted in this article evaluates 108 scenarios and uses a 95% confidence interval to calculate appropriate standards for the U.S. Using a 95% confidence interval, results show that 11–12% of cobalt, 7–8% of lithium, and 10–12% of nickel demand in 2030 and 15–

18%, 9–11%, and 15–17%, respectively, in 2035, could be met by retired supply assuming closed-loop recycling. In addition, this analysis demonstrates recycling domestically is profitable but more expensive than exporting batteries to be recycled within China, although recycling domestically results in a lower environmental impact. Finally, this research concludes that due to the higher cost of recycling within the U.S., policy is likely needed to ensure critical materials are recycled and retained domestically.

This work has been published in *Resources Conservation and Recycling* and is available open-source at the following URL: https://doi.org/10.1016/j.resconrec.2022.106488.

Should high cobalt EV batteries be repurposed? Assessing the impact of technological innovation on the waste hierarchy

Background and motivation

An LIB is comprised of five critical components: cathode, anode, separator, electrolyte and cell container. The cathode can be made from a variety material combinations; all include lithium oxide combined with one more transition metals which include cobalt, nickel, manganese and iron (*8*). Cathode chemistries including cobalt have been popular because of their performance, but cobalt has been a particularly problematic material from the standpoint of environmental, social and governance (ESG) issues. In particularly, the high dependency on cobalt mined in the Democratic Republic of the Congo has long been known to cause human rights violations including child labor and unsafe working conditions (*35*). As a result of ESG concern and the relatively high cost of cobalt, the EV LIB market has seen a trend away from cobalt-intensive chemistries towards low- or no-cobalt cathode chemistries. Thus a retired battery produced ten years ago might include enough cobalt to supply multiple equivalent capacity batteries today were it recycled with high recovery rates. In addition to cathode chemistry evolution, which has been ongoing since the inception of LIBs, a change to anode materials is also on the horizon, moving from graphite, which is ubiquitous in the LIB market, to silicon-based anodes.

The concept of a waste hierarchy, which is essentially a prioritization of how to best use end-of-life products or materials, dictates that products should be kept in their highest and best use, thus it prioritizes reuse and repurposing prior to, for example, recycling. Reusing, repurposing, and recycling batteries mitigate impacts by extending the lifespan and displacing or delaying demand for a new product, or reducing reliance on virgin materials by providing recycled materials for use in new products. However, in the context of rapidly changing chemistry, a battery retired today might have sufficient cobalt for multiple new batteries.

This research assesses whether technological change and innovations in EV batteries could change the understood waste hierarchy, which prioritizes reuse or repurposing prior to recycling.

Approach

This research uses LCA to evaluate if recycling should be prioritized for batteries with a high cobalt content, or if their lifespan should be extended through repurposing on the basis of life cycle environmental impacts. The analysis focuses on two scenarios or pathways; the recycling pathway where a spent EV battery removed from its vehicle at 80% state-of-health (SOH) is sent directly to recycling, or the repurposing pathway where the spent battery is sent for repurposing and finds use in a second-life application for stationary storage.

Because the two pathways do not provide the same service, the system of analysis had to grow to develop to equivalent systems for comparison. In the recycling pathway, a new battery is assumed to be manufactured to provide stationary storage services. Figure 1 in Dunn et al. 2023 illustrates the two pathways modeled in this study (*3*), and is reproduced as Figure 4 in this report. The difference in lifetime between a new battery and a repurposed battery is considered in the analysis on the basis of kWh of throughput.

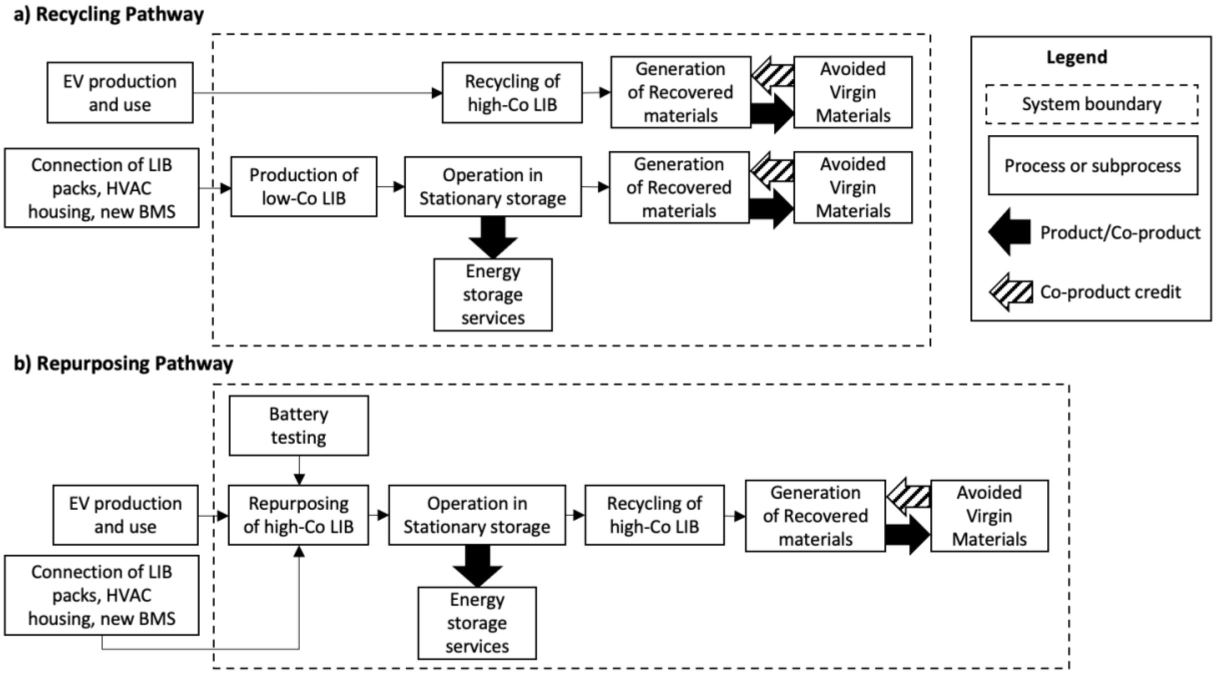


Figure 4. The two pathways modeling in this LCA are a) the Recycling Scenarios and b) the Repurposing Scenarios (reproduced from Figure 1, (*3*)).

The LCA model used data from previously published LCAs to define the foreground system for an NMC111 LIB (*36*). NMC111 batteries contain cathodes with nickel, manganese and cobalt in equal proportions, and are considered high-cobalt chemistries compared to contemporary NMC chemistries which can use the same metals in proportions of 6:2:2 and 8:1:1 for nickel, manganese and cobalt, respectively. To model these lower-cobalt battery we had to alter the production data. We then linked the foreground data for modeled batteries to reference LCI datasets from ecoinvent, a widely used commercial LCI database (*37*).

In addition to conducting LCAs of batteries, modeling the processes used to recycle or repurpose them were also required, and additional scenario analyses were undertaken that required additional modeling. The scenarios for the recycling pathway included four cathode alternatives addressing different chemistries of the retiring EV battery and produced battery (e.g. material from an NMC111 recycled into an NMC811), two scenarios for anode (either graphite or silicon thin film), and recycled content levels for the battery. Three scenarios were explored for the repurposing scenarios that focused solely on the cathode chemistry (NMC111, NMC622, and NMC811).

The impact assessment step of the LCA was conducted using ReCiPe2016 midpoint and endpoint characterization factors for a suite of impacts, ReCiPe2008 was also used to allow comparison to earlier studies.

Results

In all scenarios, repurposing a spent EV battery first results in reduced environmental impact, indicating that regardless of the cathode chemistry of the initial battery, getting value from the retired battery in a repurposed application is typically environmentally preferable. This means that even in the context of rapidly developing technology, the waste hierarchy seems to hold. However, the Repurposing Pathway impacts are highly dependent on three interconnected influencers: capacity fade, efficiency fade, and electricity production source (since repurposed batteries are assumed to be used in a stationary storage application for electricity).

What do frontline communities want to know about lithium extraction? Identifying research areas to support environmental justice in Lithium Valley, California

Background

When we initially began this project, we envisioned conducting an LCA related to EV batteries that encompassed not only environmental indicators, but also social indicators—referred to as Social LCA (SLCA). However, as we began to investigate the available data and SLCA approaches, we realized that SLCA was not going to deliver on our ultimate goal to embed principles of environmental and energy justice in our research. After researching available approaches, we ultimately settled on combining LCA with community-engaged approaches. A community-engaged approach can integrate concepts of procedural environmental justice in the research process and product. Procedural justice emerges from a trivalent understanding of environmental justice, adopted by many in the energy justice community as well, where environmental justice is understood to be based on three tenets; distributive, recognition, and procedural justice. Procedural justice addresses whether affected communities can genuinely participate in decision-making processes that affect them—for example in decisions about the siting of polluting facilities. Engaging community and embedding their priorities in the LCA process does not achieve procedural justice goals; however, it can provide responsive environmental impact information for communities affected by industrial developments and facilitate procedural justice. This work was initially started as part of this NCST project, and then work continued after the lead graduate student researcher working on this task, Margaret

(Meg) Slattery, was awarded a fellowship from Lawrence Berkeley National Laboratory to continue and expand on this work.

Approach

We undertook a case study in Imperial Valley, California where existing geothermal power facilities will begin to extract lithium from the hot geothermal brines they pump up from deep brine reservoirs. These brines are rich in salts, including lithium and other potentially valuable minerals including manganese and zinc. This region has earned the name "Lithium Valley" for the potentially large development that will occur around lithium production in the coming years and decades. While an EV battery is comprised of many materials, lithium is the only critical battery material that cannot be substituted, and will continue to be in demand even as LIB chemistries evolve.

The following questions guided the approach taken in this research:

- "What are the potential benefits and burdens of developing a lithium industry in Imperial County?
- What information exists about these impacts, and how are they represented in research about other lithium developments?
- How can these impacts be studied and communicated to empower all stakeholders to participate in decision-making processes and facilitate a just distribution of impacts?" (p. 2, (*4*))

The primary methods used to gather relevant data and information applied content analysis to government-led public meeting transcripts and notes from community meetings to identify the impacts of greatest concern to community members. These concerns were then compared to the impact of greatest interest expressed in government-lead public meetings to understand the synergies and conflicts between the two groups. The government-led meetings occurred under the auspices of the Lithium Valley Commission (LVC). The LVC was created under AB 1657, which required the creation of a Blue-Ribbon Commission of 14 appointees responsible for "reviewing, investigating, and analyzing certain issues and potential incentives ... regarding lithium extraction and use in California" (*38*).

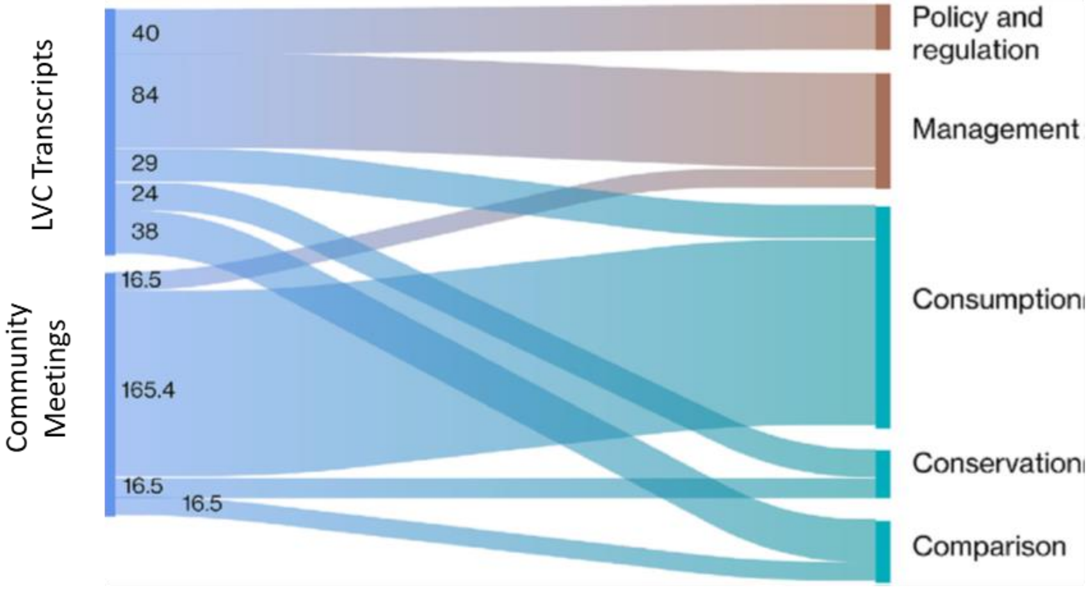
In addition to content analysis, publicly available information such as Environmental Impact Reports, and peer-reviewed literature were examined to create a body of knowledge on the expected environmental impacts associated with lithium extraction in Imperial County. This second step was undertaken to identify gaps in existing research and information, and the research and information needed to address the concerns of communities.

Results

Results from content analysis of meetings show some shared priorities among the LVC and potentially affected communities; water, public health, employment, and infrastructure. However, the two groups discussed these topics differently. For example, for water, communities were most concerned about how much water would be used by lithium extraction facilities, given the region's existing water quality and availability challenges. The LVC mostly discussed water management and policy.

Similarly, for public health, community members were most concern with impacts they might experience, while the LVC was more focused on themes like protective mechanisms, potential for lithium extraction to improve public health and the existing public health conditions. Figure 5 illustrates the findings for water and public health.

a) Water



b) Public Health

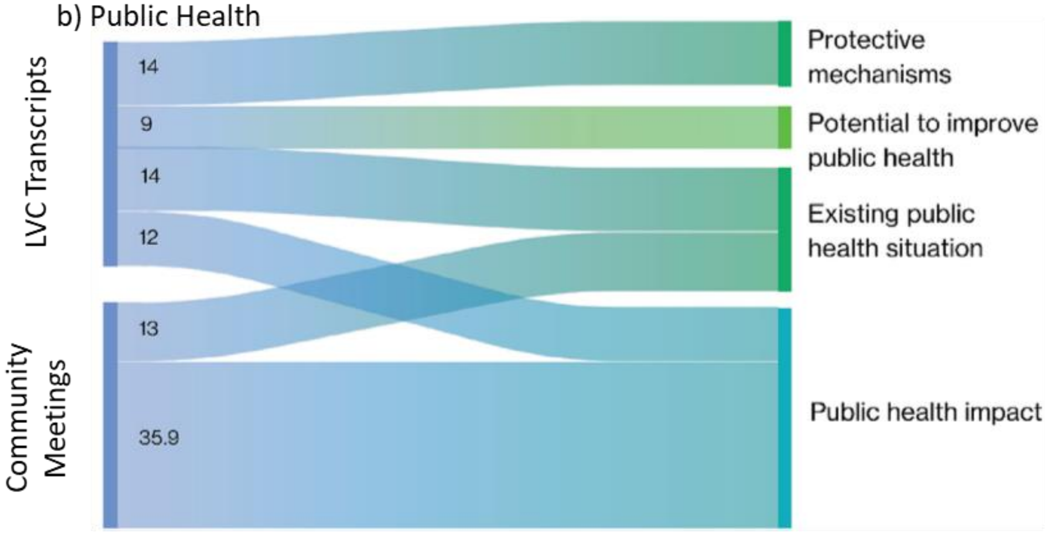


Figure 5. Textual analysis results for community meetings and LVC transcripts for water and public health related themes. Adapted from Figures 2 and 3 in (*4*).

For the other key topic of interest, employment, there were few differences observed in the frequency of themes. However, the tone of the comments were different. For example, community members were particularly concerned that promised job creation would be temporary such as for construction rather than long-term positions, while the LCV meetings mostly focused on job creation and its benefits.

Other themes addressed in the publication associated with this research include infrastructure, as well as the geography of lithium valley, local ecology impacts, greenhouse gas emissions, seismicity risks, and impacts on the cost of living and risks to local residents due to accidents at the facility. Other issues brought up in community meetings included community engagement, the need information about the process, impacts, etc. not provided by industry, but by a trusted third-party.

The lack of independent and trusted information and evaluation is a barrier to achieving environmental justice, and there are multiple challenges to developing the required information. In the particular case of Lithium Valley, the industrial development will be using technology that has not been commercially used elsewhere, meaning that any operation-related impacts have to be predicted rather than measured, and the details of this technology are confidential business secrets, an additional barrier to independent research. In addition, the kinds of information currently required, which includes an EIR provided by the industry, does not actually address public health, a key concern for community members.

This research demonstrated an approach to collecting and publishing stakeholder perspectives that might otherwise not be included in academic literature, a shortcoming if we are going to include community voices in guiding research. In publishing the priorities of these groups future research, whether conducted in an academic, government, or NGO context, can better respond to community priorities, thereby contributing to procedural justice and some key ideals of procedural justice include free, prior, and *informed* consent.

Outcomes of Task 4

The research and outcomes of this task are documented in two peer-reviewed journal articles (*3,4*), available at the following URLs: https://doi.org/10.1111/jiec.13414, and https://doi.org/10.1016/j.erss.2023.103043, respectively.

Conclusions and Future Work

For years, researchers have focused on the need to scale EV deployment, and on calculating the life cycle GHG performance of EVs, all important for achieving climate change mitigation targets. The LIBs used in EVs, arguably the linchpin technology in making EVs competitive with ICEs, have come under increasing scrutiny because of concerns over critical materials they depend on (e.g., (*39*), ESG concerns in their supply chains (*40–42*), their contribution to life cycle GHG emissions (*43*), and because they are single largest cost component in an EV. All of these issues are important, but they largely ignore the EoL risks and opportunities for LIBs retired from EVs. This research was proposed to address this gap in knowledge and research. The problem of battery material supply and EoL risks have only become more urgent, and are engendering new questions about how to decarbonize transport while protecting frontline and indigenous communities, and how to manage batteries at their EoL. The reality is that achieving global mitigation targets, will cause local impacts and harms to communities. This tension is inevitable, and should guide future research priorities.

Future work includes the development of a more comprehensive global MFA battery materials which will be linked to specific mineral resources/mines. This is crucial for understanding where and who will be affected by the battery supply chain. At the same time, the scrutiny of the lithium ion battery supply chain (and reverse supply chain at end of life) is unprecedented and unequaled. The omission of similar scrutiny for the oil and gas supply chains, or other supply chains crucial for internal combustion engine vehicles, implies batteries are worse. We hope to develop parallel knowledge and work to be able to contextualize the findings of battery mineral supply chains. Finally, current and continuing research has explored the question of how to reduce demand for EVs and EV batteries, while achieving mitigation targets [cite climate and community report]. This means expanding our systems of analysis and functional unit away from a vehicle, or kWh of battery, to provision of mobility at regional or societal scales.

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Data Summary

Products of Research

Research products include four peer-reviewed articles.[2] All include an acknowledgement to this project in accordance with NCST language, and all published articles are available open-source from the publisher. In addition, specific data products were generated to provide as much transparency and reproducibility as possible, and all have been archived either as an appendix or supplementary file with the peer-reviewed article, or have been archived in the Dryad UC Library repository as described below.

Data collected for and generated by Material Flow Analysis modeling, Techno-Economic Analysis, and Life Cycle Assessment, and code used to create the MFA model are described and published in two peer-reviewed journal articles (*2,3*), which reference the data archived in the Dryad UC Library as described below in *Data Format and Content*.

In the work done for the article "What do frontline communities want to know about lithium extraction? Identifying research areas to support environmental justice in Lithium Valley, California" (*4*), all relevant data are published in the journal article, including the code book used for transcript analysis, available here: https://ars.els-cdn.com/content/image/1-s2.0-S2214629623001032-mmc1.docx.

The results of the qualitative research from expert elicitation of individuals involved in the EoL vehicle industry are documented in the published journal article (*5*); however, the underlying data cannot be published or archived due to confidentiality requirements. Thus all relevant data is part of the published peer-reviewed journal article.

Data Format and Content

All publications are available from their respective publishers as PDF files. The appendix file associated with (*4*) is available from the publisher as a .docx file. All data files are stored in CSV files, all code files are stored as .R files. R is an open-source software and CSV files are compatible with any spreadsheet software.

Data Access and Sharing

Data associated with the MFA-TEA model and Recycled Content Standards Calculations (as documented in *2*) are available in the Dryad UC Library Repository: https://doi.org/10.25338/B8792H

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[2] The published articles are available at the following URLs: https://doi.org/10.1016/j.resconrec.2022.106488, https://doi.org/10.1111/jiec.13414, https://doi.org/10.1016/j.erss.2023.103043, https://doi.org/10.1016/j.wasman.2023.11.018

Data associated with the Lithium-ion battery end-of-life life cycle assessment (as documented in [34]) are available in the Dryad UC Library Repository: https://doi.org/10.25338/B8S92G

Additional data including the foreground data used in the LCA, and the underlying data for figures and charts associated with the publication are available as supplementary information archived by the publishing journal: https://onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1111%2Fjiec.13414&file=jiec13414-sup-0002-SuppMat2.xlsx

https://onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1111%2Fjiec.13414&file=jiec13414-sup-0001-SuppMat1.docx

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Appendix 1. Detailed Task Descriptions

Task 1: Literature review and secondary data gathering for model development (completed year 1)

Deliverable 1A: Literature review of reuse and recycling technologies and potentials. This includes the development of simplified engineering models or direct appropriation of input and output flows from previous studies or models. The review will include economic and environmental impacts from several reverse logistic scenarios (e.g., centralized vs. non-centralized facilities) and the scale of EoL stocks. The safety concerns associated with recycling, reuse, and the undetermined path of storing, disposing in landfills, or exporting will also be researched.

Deliverable 1B: Literature review of real or proposed battery EoL policies and their impacts. Potential policy levers such as design for recycling, reverse logistics, product standardization, recycling mandates, producer take-back, and financial incentives will be reviewed. The potential impact on the electricity grid from an uptake in reuse will be included in this review. Data on their potential environmental and economic impact will be aggregated.

Task 2: Development of a simplified Dynamic Systems Model (DSM) (completed year 1)

Deliverable 2A: Development of a simplified DSM

Task 3: Qualitative research interviewing first responders/ reverse logistic stakeholders on the safety of LIB.

Deliverable 3A: Develop and submit IRB approval documents including data collection plan, privacy measures, etc. (completed year 1)

Deliverable 3B: Development and initial contact of a target list of interviewees, and outreach

Deliverable 3C: Interview of target stakeholders, documentation and analysis of results.

Deliverable 3C Requirements: White paper disseminating findings from qualitative study

Deliverable 3D: Recommendations on how DSM inputs and parameters should be adjusted to reflect on-the-ground reality

Task 4: Develop complete DSM and couple with LCA

Deliverable 4A: Develop complete stock and flow model for EV LIBs for the U.S. This will require operationalizing data collected in Task 1 to represent the material flows between subsystems and model the relationships between material prices, material stocks, production, recycling, reuse, and waste.

Deliverable 4B: Export or couple the Vensim model with Python to allow for integration of DSM and LCA.

Deliverable 4C: Integration of recommendations from task 3D

Deliverable 4D: Model policy scenarios and analyze the impact of policies discussed in the literature (see task 1B).

Task 5: Data Management Plan

Deliverable 5A: Quarterly data management meetings for project team to assure proper archiving and data back-up plans are in place

Deliverable 5B: Archiving of data in Dryad (https://datadryad.org/stash)

Task 6: Policy and Practice Impact Plan, and Final Reporting Requirements

Deliverable 6A: Year 1 report and webinar

Deliverable 6B: Year 2 report, webinar, and policy brief

Deliverable 6B Requirements: A research report documenting cumulative research and findings from the 2-year project period. A webinar focused on DSM model findings and associated policy recommendations. A policy brief summarizing policy recommendations.