ATTACHMENT G: END OF LIFE OPTIONS FOR LITHIUM-ION BATTERIES

Use of lithium-ion batteries in California is growing rapidly in multiple sectors, leading to a growing waste stream. Lithium-ion batteries are hazardous waste and must be treated as such in final disposal to mitigate harm to humans and the environment. Battery recycling and repurposing offer the potential to postpone the cost of disposal, to reduce the state's overall waste stream, to reduce cost and supply constraints to new battery production, and even to provide a second life use case for electricity grid services. The degree of synergy in the state's laws, policies, and knowledge-sharing across the electricity, transportation, and small electronics industries will likely have a major impact on the state's ability to realize these benefits.

The goal of this attachment is to provide the CPUC and its stakeholders an overview of end of life options, their scalability, and their tradeoffs—and an overview of important industry trends and policy ingredients that will influence the sustainability of the lithium-ion battery lifecycle.

This attachment is based on a literature review of industry publications and research papers. We also highlight two business case studies that reflect the industry's current successes and challenges with recycling and repurposing lithium-ion batteries.

We start with an overview of the volume of lithium-ion battery usage and end of life options, with some discussion of technical maturity, tradeoffs, and challenges in practice. We then summarize challenges and uncertainties in business models and economics with a focus on the costs and economic viability of recycling and repurposing options. We conclude with summaries of going-forward policy challenges for spent lithium-ion batteries and of our key observations.

This attachment presents a high-level summary for policy use and it includes simplifications of the underlying science and technical papers. The recent scientific record is rich with insights and suggestions for future study of the lithium-ion battery aging process (degradation) and end of life options. For more detail we recommend review of the publications referenced at the end of this attachment.

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Size and Types of Lithium-Ion Battery Waste Streams

Electricity. In California's electricity industry, stationary energy storage installations are expected to grow by up to 1,900 MW per year of mostly 4-hour lithium-ion storage across all grid domains, with 13,571 MW new capacity by 2032 and 48,600 MW new capacity by 2045. Batteries retired from stationary applications do not present a clear repurposing opportunity and will likely need to be either recycled or disposed of. Due to larger battery system size and regulatory environment, utility-owned and LSE-contracted grid-scale energy storage are relatively straightforward to track and route to the appropriate recycling and disposal channels compared to the transportation and small electronics industries. Smaller and more distributed customer-sited installations that are retired may pose some tracking and collection challenges similar to what we see in transportation today. Assuming a 15-year useful life (which is highly debatable and dependent on actual use case; battery degradation is discussed further throughout this attachment) California's waste stream from large stationary applications would not be expected to ramp up significantly until about 2035.

Transportation. In transportation, however, two factors contribute to the industry's expectation of a spent battery "tsunami" (Reid, 2021) and associated pressures to quickly develop end of life options. The first is EV batteries are used more aggressively than in stationary applications, resulting in faster degradation and a shorter expected useful life. Tesla's EV battery warranty period, for example, is up to eight years and declines based on mileage (Tesla, 2022). The second factor is the rate and depth of EV adoption in some parts of the world, like California, indicates that a wave of spent EV batteries is imminent. Based on historical EV sales (CEC, 2022), in 2026 California will have a stock of almost 400,000 EVs that are 8 years or older, growing thereafter by at least 100,000 vehicles per year. As early as 2026, therefore, California could see major growth in its spent battery waste stream. The timeline of actual EV battery degradation to retirement condition, however, is under observation and could take longer than 8 years. In a 2022 interview a Nissan representative reported that observed battery lives are much longer than originally expected and suggested that batteries could remain useful in EVs for 15–20 years. If this is indicative of the industry as a whole, which remains to be seen, California's wave of spent EV batteries could be postponed to 2033 or later.

Regardless of timing, lithium-ion batteries retired from transportation present a significant volume of potential second life capacity for use in stationary energy storage applications. The state's stock of registered light-duty battery and plug-in hybrid electric vehicles (EVs) on the road reached over 800,000 vehicles by the end of 2021 (CEC, 2022). Future EV stock is expected to grow to up to 10 million vehicles by 2032 in a high bookend scenario (Bahreinian, 2021). Translating these volumes to the electricity industry, spent batteries from 1,000,000 EVs roughly equate to about 7,000 MW/42,000 MWh potential capacity for grid services.[1] How long repurposed batteries would last in their second life is still unclear. How to harvest these batteries for repurposing and ensure they can economically and predictably perform as stationary energy storage over a given period of time also remains to be seen.

Spent EV batteries not (or no longer) suitable for use as stationary energy storage present a major opportunity to recover valuable cathode materials, through recycling, for new battery production. In 2018 California passed Assembly Bill No. 2832 (Dahle), requiring formation of a Lithium-Ion Car Battery Recycling Advisory Group (AB 2832 Advisory Group) to develop recommendations to the state legislature. AB 2832 sets a policy objective to ensure that "… as close to 100% as possible of lithium-ion batteries in

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[1] Assuming 60 kWh original battery capacity per vehicle, 70% capacity degradation at the time of repurposing, and 6-hour charge/discharge rates in stationary use.

the state are reused or recycled at end-of-life in a safe and cost-effective manner." As part of its review, the bill requires the AB 2832 Advisory Group to consider repurposing of EV batteries as stationary energy storage systems.

Small electronics. In small electronics, lithium-ion batteries power a wide variety of devices like cell phones, computers, toothbrushes, and toys. The total volume of small lithium-ion batteries in the state's waste stream is unclear. In the period 2017–2021 California battery recyclers collected about 385,000 pounds per year of lithium-ion batteries (DTSC, 2022). Lithium-ion batteries from e-waste do not represent a significant total volume of energy storage capacity from the electricity industry perspective, but they present a major recycling and hazardous waste management challenge as these batteries easily contaminate general waste streams. Small lithium-ion batteries also present an opportunity to recover valuable cathode materials for new battery production.

Overview of End of Life Options

End of life options for lithium-ion batteries fall into three general categories: recycling, repurposing, and disposal (Figure 1). Repurposing extends the life of a battery in whole, and recycling harvests a subset of materials for use in a new battery. All pathways eventually lead to some form of disposal.

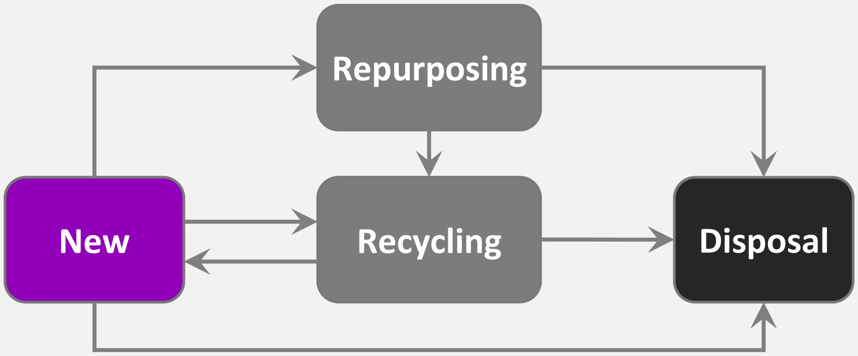


Figure 1: End of life routes for lithium-ion batteries.

Recycling. The cathode material in lithium-ion batteries includes high-value metals such as lithium, cobalt, nickel, vanadium, and manganese. Cathodes represent about half of the cost of the battery cells in an electric vehicle (BNEF, 2021) and are the main driver of the value proposition to recycle or repurpose batteries.

Recycling options reflect three main methods to recovery of cathode materials: direct, pyrometallurgical, and hydrometallurgical (Figure 2). Other critical materials—like the graphite used as the anode in a battery cell—can also be recycled. Scientific literature offers rich exploration of recycling methods and the tradeoffs of each. A meta-analysis of lithium-ion battery recycling research identified almost 700 journal articles published globally and in the 2017–2021 timeframe (Baum et al, 2022).

Direct
Separates and harvests battery materials without breaking down chemical components

Pyrometallurgical
High-temperature process to recover metals, then re-produces cathodes for a new battery

Hydrometallurgical
Pre-processing, then chemical process to recover metals, then re-produces cathodes for a new battery

Figure 2: Prominent methods for recycling lithium-ion batteries.

Direct recycling separates and harvests battery materials without breaking down chemical components, with a focus to recover and recondition cathodes for a new battery. Direct recycling is expected to result in high materials recovery, an attractive value proposition, and relatively low emissions and pollution compared to other recycling methods—but it is in a pilot phase. The main challenge with direct recycling is that it relies on sorting and pre-processing that is so finely tuned to an exact type and chemistry of battery that it cannot scale to accommodate the realities of a diverse waste stream or a waste stream that changes over time as technologies evolve (Chen et al, 2021). Argonne National Laboratory's ReCell Center is leading R&D activities to address this and other challenges with direct recycling.

Pyrometallurgical recycling requires battery pretreatment (e.g., shredding or crushing), utilizes a high-temperature process (on the order of 1,200–1,800°F) to recover metals from a spent battery, then re-produces cathodes for a new battery. This process is used widely in electronics waste processing but not designed specifically for lithium-ion battery recycling. Lithium is particularly difficult to recover with traditional pyrometallurgical recycling methods and new methods are under development for better lithium recovery (Chen et al, 2021). Pyrometallurgical recycling is high cost and results in the worst environmental impacts compared to other lithium-ion battery recycling methods (Mohr et al, 2020).

Hydrometallurgical recycling requires battery pretreatment (e.g., sorting and crushing), separates cathode metals using chemical solutions, then re-produces cathodes for a new battery. Hydrometallurgical recycling produces lower CO2 emissions than pyrometallurgical recycling but it requires wastewater treatment (Mohr et al, 2020 and Mrozik et al, 2021). This type of recycling is viewed as well-suited for lithium-ion batteries, it performs well in terms of materials recovery, and it is potentially economically viable for some cathode chemistries (Yao et al, 2018 and Chen et al, 2021). Hydrometallurgical methods are in use for lithium-ion battery recycling by several companies around the world.

	Direct	Pyrometallurgical	Hydrometallurgical
Commercial readiness (specifically for lithium-ion batteries)	Worst	Better	Best
Value proposition	Best (est.)	Worst	Better
Materials recovery performance	Best (est.)	Worst	Better
Pollution impacts of recycling process	Best (est.)	Worst	Better

Figure 3: Key tradeoffs to lithium-ion battery recycling methods.

Figure 3 summarizes key tradeoffs of lithium-ion battery recycling methods. Although direct recycling has the potential to yield the highest value proposition, have the highest materials recovery performance, and result in the least pollution impacts, it is still in a technology development phase. Hydrometallurgical recycling is in some respects a better option because it performs better than pyrometallurgical recycling across these dimensions, and because is in commercial deployment now.

Many of the challenges with recycling, however, lie in creating clear buyer and seller accountability for proper handling of batteries, and in development of tracking, collection, and transportation processes between the spent battery owner and the recycling facility.

California's AB 2832 Advisory Group, led by the California Environmental Protection Agency (CalEPA), published its final report on EV battery recycling in 2022. The group's two core policy recommendations focus on defining who is responsible for ensuring a battery is properly reused, repurposed, or recycled. Their first recommendation, a "core exchange and vehicle backstop" policy, assigns responsibility of tracking a particular spent battery to (a) the most recent manufacturer of that vehicle/battery and (b) any dismantler who removes the battery from the vehicle. The most recent manufacturer could be the original manufacturer of a new vehicle/battery, a refurbisher, or a repurposer. The second recommendation, a "producer take-back" policy, assigns responsibility to the vehicle manufacturer to take back a spent battery at the customer's request and at no cost.

The AB 2832 Advisory Group also developed 12 supporting policies designed to improve:

- Tracking data for individual batteries and access to individual battery information;
- Development of a reuse, repurposing, and recycling business ecosystem; and
- "Reverse logistics" (e.g., system of collection and transportation of spent batteries to reused, refurbished, or recycled facilities).

Some materials we reviewed mention lead-acid batteries as an example of a mature battery technology and its well-understood recycling and end-of-life processes. MIT, 2022 points out that lead-acid batteries have a "mature supply chain and high recycling rate (>99% in the United States and Europe)"—although recycling and repurposing issues are mostly outside of the scope of that study. Mrozik et al, 2021 warns of the dire consequences of an insufficiently regulated recycling industry when the materials include highly toxic substances like lead. They discuss how the lead-acid recycling industry in some areas are highly polluting with uncontrolled lead emissions.

Repurposing. Lithium-ion battery repurposing options depend on the battery's condition, including its history of thermal, electrical, or mechanical abuse, and to what degree the battery is degraded from its first use. On the topic of repurposing, most literature we reviewed is focused on repurposing electric vehicle (EV) batteries for use as stationary energy storage. This use case is in an early pilot and demonstration phase.

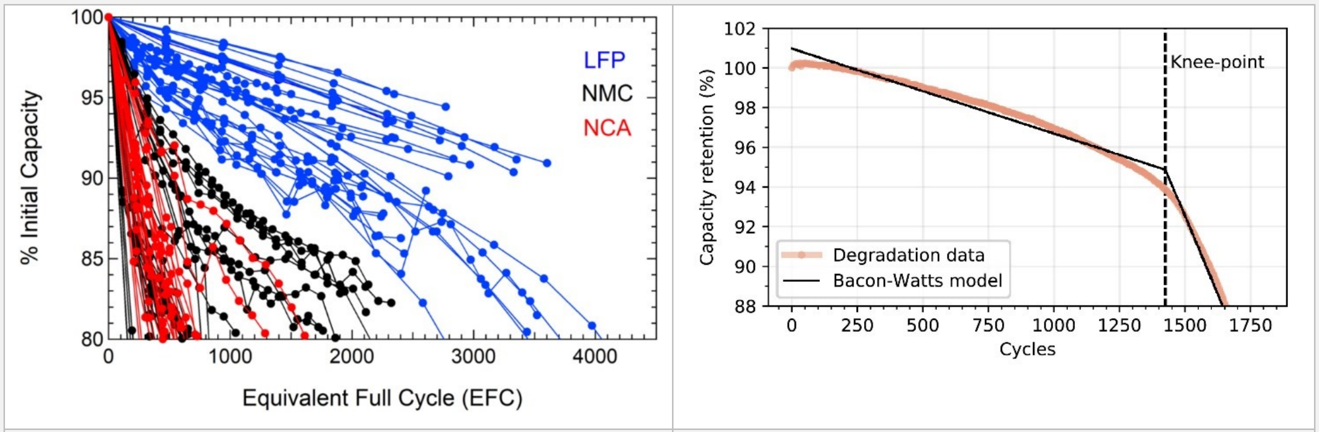
Lithium-ion battery peak (kW) and energy (kWh) capacity degradation is a function of how it is used and of its environmental conditions. Degradation is most simply represented as a single degradation curve, with the number of charge/discharge cycles on the x-axis and the share of functioning capacity on the y-axis (Figure 4, left). Actual degradation varies dramatically depending on actual use of the battery and environmental conditions during its life. Degradation curves typically demonstrate a sharp decrease in the first few cycles, followed by a period of linear degradation, then a rapid decrease after a "knee point" (Fermín-Cuetoa et al, 2020) (Figure 4, right). Exposure to high or low temperatures, overcharge or undercharge with voltage exceeding certain high/low thresholds, and aggressive cycling in low/high state of charge ranges have each been shown to accelerate degradation significantly. Edge et al, 2021 provides a useful summary of the extensive scientific literature on lithium-ion battery degradation.

Factors that accelerate degradation also contribute to increased safety risks. Attachment F (Safety Best Practices) provides examples of safety consequences of under-voltage (e.g., event at Elden Substation in November 2012) and aggressive cycling (e.g., events in South Korea—2017–2018) as well as the importance of power and thermal management systems.

In addition to capacity degradation, loss of a battery's ability to hold a charge reduces its usefulness in secondary applications. Lithium-ion batteries are characterized by relatively low self-discharge rates but a battery's "thermal history" (esp., exposure to high temperatures, even if momentary) can significantly affect its self-discharge rate (Seong et al, 2018) and thus its ability to hold a charge.

Exactly when a battery retires from transportation may depend on each EV user's appetite for reduced battery performance. EV manufacturer warranties provide some indication of broadly-unacceptable battery performance. Tesla, for example, guarantees 70% retention of battery capacity over a warranty period of up to eight years (Tesla, 2022). The AB 2832 Advisory Group notes that battery retirement from EV use is "generally assumed to be between 70–80% [remaining battery capacity]" (AB 2832 Advisory Group, 2021 and Saxena et al., 2015). Batteries below 70% capacity retention may still be useful as stationary energy storage. But it is questionable whether a highly degraded battery—such as one close to or past its knee point—would be sufficiently useful or reliable for stationary energy storage applications.

The highest value stationary energy storage applications are energy time shift, including daily cycles, RA capacity and performance during grid emergencies, and performance as backup power. Stationary energy storage applications do not have the same energy density requirements as an EV and thus an installation can be expanded to a larger footprint with more battery packs to offset reduced capacity of each battery pack. But second use batteries would need to reliably hold a certain state of charge for at least a day to provide energy time shift and RA capacity services, and for several days to provide reliable backup power. Accelerated self-discharge and/or unexpected knee point crossover would be problematic to a battery's ability to provide valuable stationary energy storage use cases.



Capacity degradation curves based on number of full cycles and battery chemistry (Preger et al, 2020)

Estimation of knee-point onset in a capacity degradation curve (Fermín-Cueto et al, 2020)

Figure 4: Examples of lithium-ion battery degradation curves.

The AB 2832 Advisory Group notes that repurposing of EV batteries for use as stationary energy storage "… is a relatively new industry and data about performance is uncertain because of the uneven degradation of battery cells over time…" Currently, no standard data collection or testing methods for determining the quality of second life batteries are in place. The AB 2832 Advisory Group also points out that "the CEC is funding several ongoing demonstration projects in California." As of 2022 these CEC research projects are in an early stage and results are pending.

Disposal. Recycling and repurposing postpone or reduce the waste stream, but battery materials will eventually be disposed of. Two important issues on disposal of lithium-ion batteries as hazardous waste are: (1) the pollution risks of the battery's hazardous materials, and (2) how and to what degree disposal routes are controlled to manage those risks.

Hazardous materials held or produced by spent lithium-ion batteries include hydrogen fluoride and other gases, metals (particularly nickel and cobalt), chemical compounds, and various other reactions with water (e.g., hydrofluoric acid) and other substances that each are highly toxic to humans and to the environment (Mrozik et al, 2021). Pollution pathways include gas and dust release into the air, and soil and water contamination—notably from landfill leachate (Mrozik et al, 2021). Mrozik et al, 2021 offers a more comprehensive discussion of pollution sources, pathways, and consequences.

Appropriate handling and landfilling of lithium-ion batteries from small electronics has proven particularly difficult to control. Small lithium-ion batteries can easily enter general waste or recycling processes undetected and thus result in an uncontrolled release of hazardous materials. Batteries landing in the general waste stream contribute to the rising number of fires originating from lithium-ion batteries in landfills, recycling centers, and waste transportation—causing injury, service disruption, property damage, and release of a variety of toxins (EPA, 2021 and Mrozik et al, 2021). Decomposition in general waste landfills (rather than those designed for hazardous waste) and illegal dumping pollutes even further, notably via leachate that contaminates soil and water (Mrozik et al, 2021). In 2022 California passed two pieces of legislation designed to significantly improve the collection of spent lithium-ion batteries from small electronics for appropriate recycling and disposal routes. Proper disposal of larger batteries from EVs and stationary applications is more straightforward but it is not without challenges. Battery tracking and collection systems that establish regulations, provide easily-accessible routes for disposal, and effectively penalize for non-compliance are important ingredients to a sustainable end-of-life ecosystem.

Value Propositions for Recycling and Repurposing

This section provides a high-level overview of the current status of the economics of lithium-ion battery recycling and repurposing, including a discussion of key risks to the value propositions and how policies can help.

Lander et al, 2021. We highlight this study as a demonstration of the key factors and issues impacting the economics of recycling. The authors expand upon prior technoeconomic studies of recycling EV lithium-ion batteries by estimating the net profitability of direct, hydrometallurgical, and pyrometallurgical recycling domestically (UK-based) versus overseas including transportation costs. They analyze net recycling profits across several lithium-ion chemistries, including the three dominant chemistries lithium-nickel-manganese-cobalt oxide (NMC), lithium-iron-phosphate (LFP), and lithium-nickel-cobalt-aluminum oxide (NCA). They found that viable value propositions are possible, but strongly dependent on "transport distances, wages, [battery] pack design and recycling method" (Lander et al, 2021). Their results also demonstrate the importance of battery chemistry: chemistries with nickel and cobalt (NCA and NMC) produced higher revenue and net recycling profits, all else being equal.

Specific analytical findings in Lander et al, 2021 show that:

- Due to its lower cost, hydrometallurgical recycling yields a higher net profit than pyrometallurgical recycling.
- Domestic hydrometallurgical recycling of NCA and NMC is close to break-even and may be improved through cost economies of scale.
- LFP recycling is not profitable except under the hypothetical direct recycling method.
- Actual battery pack designs significantly affected recycling cost: the cost and complexity of disassembly of a representative commercial LFP pack (Nissan Leaf) made LFP recycling profitability significantly worse.
- Due to a wide range of estimated international transportation costs to specific countries, the profitability of sending materials overseas for recycling is unclear.

Lithium-ion batteries as a mixed waste stream. We do not know how future battery technologies and chemistries will evolve. For now, it is reasonable to expect that the flow of spent lithium-ion batteries will include a variety of battery types, each with a different value proposition for recycling and each requiring a different approach for disassembly, sorting, and other recycling pretreatments. Policies that (a) set the stage for mixed collection and processing streams and (b) help recyclers track and identify differences in battery types out of those mixed streams (such as policies outlined in AB 2832 Advisory Group, 2021), will likely be critical to the recycling ecosystem.

Policy role for attractive recycling value propositions. Battery chemistries with high-value cathodes like nickel and cobalt have a clearer value proposition for recycling, and with it a higher chance that the private sector will develop a recycling ecosystem on its own. Policies can be supportive by improving spent battery tracking, collection, and reverse logistics as emphasized in AB 2832 Advisory Group, 2021. Policies can also help the recycling industry build enough economies of scale to be profitable and build some of that infrastructure and expertise ahead of the upcoming wave of spent EV batteries. For nickel and cobalt specifically, policies that support recycling of these minerals will also help to (a) relieve global supply chain pressures on new battery production and (b) reduce the volumes of these minerals in the waste stream and their pollution risks.

Policy implications of poor recycling value propositions. Battery chemistries without cobalt or nickel, like LFP, appear to have a poor recycling value proposition and thus the private sector is not likely to develop a recycling ecosystem on its own. Battery chemistries in both transportation and in stationary energy storage have begun to trend away from NMC and towards LFP—in part driven by its more stable chemistry and in an effort to improve safety (see **Attachment F (Safety Best Practices)**). LFP battery chemistry is also preferable to NMC from a final disposal perspective due to its lower pollution risks. If California sets goals to reduce the lithium-ion battery waste stream and/or create more of a circular lifecycle for lithium-ion batteries, then relatively strong recycling standards, incentives, and accountability will be needed for battery chemistries like LFP—and possibly for non-cathode materials in any battery. A major recycling innovation like direct recycling—if its high rate of materials recovery and low cost can be proven at commercial scale—would relieve that policy pressure, but the path of this innovation is unclear at this time.

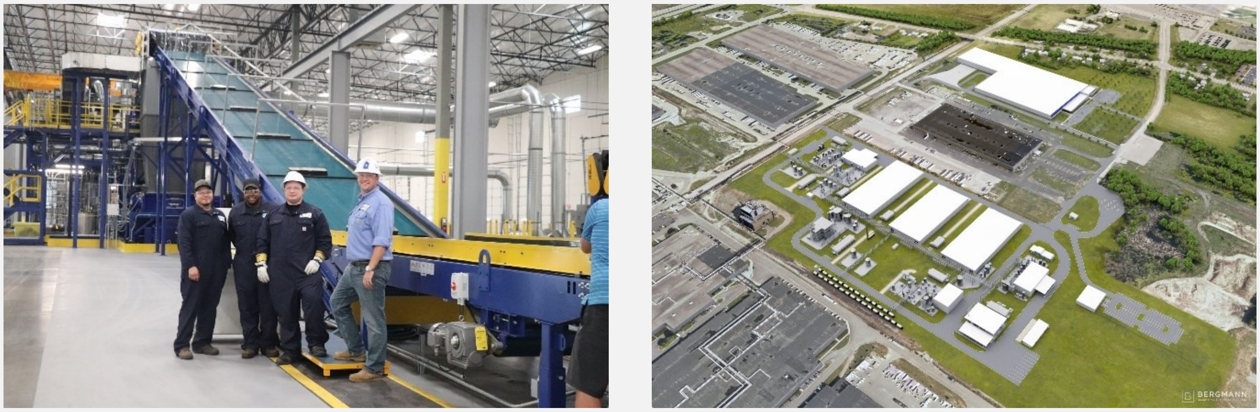
This situation reflects an important tension among the industry's trends in battery types and chemistry, recycling value proposition, and related policy pathways that is reminiscent of challenges in recycling plastics (see Steinbauer, 2021). Just as not all *technically* recyclable plastic polymer types have a viable *financial model* for recycling, not all lithium-ion battery types, chemistries, or materials have a clear recycling value proposition. Although they may be technically recyclable today, many batteries and battery materials are unlikely to actually be recycled without a strong policy framework.

Depending on the state's recycling objectives, policies may need to be developed beyond collection and sorting—to clarify what materials must be recycled and address the economics of the recycling process itself. The goal here would be to ensure those materials are not produced in the first place, and/or actually recycled rather than disposed of after collection and sorting. California's 2021 Circular Economy Package, aimed at addressing the realities of the plastics recycling value proposition and towards building a more circular plastics lifecycle, provides guidance that may be more generally useful for battery recycling. Integration of recycling standards and recycled materials with domestic battery production policies will likely also be an important element to development of a circular lifecycle for lithium-ion batteries.

Recycling Business Case Study: Li-Cycle

Li-Cycle, founded in 2016, is a lithium-ion battery recycling company based in Canada and operating North America and Europe (see li-cycle.com). Over its initial 6 years, Li-Cycle focused on developing the infrastructure and logistics to collect spent lithium-ion battery materials, recover critical cathode minerals (nickel, cobalt, lithium, and manganese), and sell the recovered minerals to the commercial market. Through about 2019 the company was in an initial pilot and demonstration phase. In 2021 Li-Cycle became a publicly-traded company on the New York Stock Exchange (NYSE: LICY), and as of 2022 the company is in an initial investment and commercial expansion phase towards its target annual processing capacity.

At the core of Li-Cycle's recycling infrastructure and logistics is the company's Spoke & Hub Technologies$^{\text{TM}}$ (Figure 5). The "Spokes" are distributed collection points where battery materials are pre-processed into a pulverized "black mass" of electrodes, then sent to a centralized "Hub" for hydrometallurgical processing into mineral powders. Li-Cycle's Spokes are designed to intake a variety of battery formats: "from 'powder to pack', meaning all materials from cathode powder through to full EV packs can be processed…" (FAQs). Li-Cycle also describes its Spoke pre-processing as "battery chemistry agnostic" (2021 Annual Report) which implies some flexibility to adjust to future changes in the recycling value proposition.



Arizona Spoke

New York Hub Design (under construction)

Figure 5: Li-Cycle's Spoke & Hub facilities.

(Images credit: Li-Cycle)

In 2021 Li-Cycle's battery recycling sources by volume were 49% transportation original equipment manufacturers (including recalls), 27% manufacturing scrap, 20% consumer electronics, and 4% energy storage systems (Dec 2021 Investor Presentation). Li-Cycle appears to follow a staged approach to process recycling sources as they evolve over time: first from small electronics, then transportation, then stationary energy storage.

Li-Cycle is implementing an innovative strategy to developing its recycling infrastructure and logistics *ahead* of the industry's expected wave of spent EV batteries. As battery manufacturing has accelerated in recent years, Li-Cycle taps into manufacturing scrap as both a major supply of recyclable materials and as an opportunity to develop relationships with battery manufacturers. Battery manufacturers would ultimately be among the buyers of final Hub products. As of October 2022 Li-Cycle has three operational Spokes in North America, close to battery manufacturing plants. Li-Cycle's first commercial Hub is under construction in Rochester, NY and expected online in 2023.

Li-Cycle's business strategy and key innovations highlight the importance of (a) the value of critical cathode minerals to a viable recycling financial model, (b) the flexibility to pre-process a mixed waste stream, in terms of spent battery source (e.g., small electronics, transportation, stationary), format (e.g., pack design), and chemistry, (c) connecting to a wide range of sources for recyclable materials, and (d) "closing the loop" with battery manufacturers who are buyers of the recycled product.

Value proposition for repurposing.

Repurposing spent EV batteries for use as stationary energy storage is still in an early pilot and demonstration phase. Although the cost to repurpose and to ensure reliable battery performance are unclear, the potential benefits are meaningful.

In Chapter 3 (Moving Forward) we discuss how stationary energy storage can support state goals at a large scale through the high-value energy time shift and RA capacity use cases. Energy storage installed in the distribution and customer grid domains can also provide communities and individual customers who are most vulnerable to grid outages and weather extremes significant additional value as backup generation.

Repurposing studies we reviewed find economics that are favorable but highly dependent on being able to determine battery condition, quality, and performance levels. For example, in 2015 the National Renewable Energy Laboratory (NREL) published a study on barriers to repurposing EV batteries. They find repurposing cost can be as low as $20/kWh nameplate capacity and that second use batteries could last up to 10 years, but these results hinge on the ability to identify and exclude batteries with faulty cells. Similarly, Kamath et al (2020) find that EV batteries repurposed for stationary energy storage yield a lower levelized cost of electricity than new batteries, but that uncertainties in battery quality and availability need be addressed.

The AB 2832 Advisory Group's policy recommendations to improve tracking and information collection on individual batteries can help de-risk repurposing cost and second life battery performance. Even so, used batteries may still be viewed as undesirable or risky by consumers. Depending on the state's waste management goals, additional policies may be needed to further reduce performance risk, reduce the soft costs of collecting and installing re-purposed battery packs, and/or incentivize utilities and customers to use repurposed batteries even when the equivalent cost of a new battery is similar.

Business Case Study: RePurpose Energy

RePurpose Energy, founded in 2018, is a California startup focused on developing testing for used EV batteries, and reassembly and controls for reuse in stationary applications (see www.repurpose.energy). In 2019 they developed a 60 kW/275 kWh demonstration project using a collection of Nissan LEAF battery modules. In 2020 RePurpose Energy began a research project with the California Energy Commission to (a) validate ability to provide resilience services, (b) provide a cost comparison to new batteries, and (c) characterize degradation rates during second life (CEC, n.d.).

RePurpose Energy's commercially-available second-life battery product—a modular 20-foot 1.2 MWh container—is due for launch in 2023. Their technologies are aimed at reducing the costs and risks of repurposing and of battery performance in its second life. RePurpose Energy's technological innovation is based on machine learning models to rapid-test batteries, optimization models for reassembly into a stationary system, and state-of-the-art battery management systems to optimize battery performance.

Going-Forward Policy Challenges for Spent Lithium-Ion Batteries

California has taken important steps to support development of a recycling ecosystem for lithium-ion batteries, but much legal and policy work remains.

The state's number one challenge is to first secure the hazardous waste stream, all the way to final disposal and regardless of recycling and repurposing options. Two bills passed in 2021 (SB 1215 and AB 2440) advance the state's ability to control the waste stream and pollution from lithium-ion batteries in small electronics. Separately, the AB 2832 Advisory Group's policy recommendations to the legislature set the foundation for EV battery tracking and accountability for battery reuse, repurposing, and recycling. Their recommendations could be expanded to dovetail with SB 1215 and AB 2440 and establish regulations to track and route all batteries into appropriate recycling, repurposing, and hazardous waste disposal facilities. Mrozik et al, 2021 also suggests filling key knowledge gaps in pollution impacts, including (but not limited to) seeking a better understanding of what waste streams actually look like and measurement of actual pollution impacts. The aim here is to fully understand, minimize, and hopefully eliminate lithium-ion contamination in human and environmental systems by directing all spent lithium-ion batteries into the appropriate recycling, repurposing, and disposal facilities.

The state's second major challenge is to minimize or postpone the final disposal stream as much as possible. This can reduce pollution risks and relieve expensive new battery supply chain constraints by pushing hazardous materials and of other critical battery materials back into useful applications, in support of a more sustainable and circular lithium-ion battery lifecycle. This is achieved by routing as much of the waste stream towards recycling and repurposing as possible, but it may require the state to define exactly what materials in the waste stream it wants to minimize. Key issues to address include the logistics and economics of recycling and repurposing. And these need to be addressed quickly enough to keep up with the waste stream as it grows over time. The AB 2832 Advisory Group's report includes recommendations that would would improve the availability of individual battery information and reverse logistics to the recycling and repurposing facilities. Other supporting policies include those that help to reduce the costs of recycling and repurposing (including investment in innovations like direct recycling), policies that motivate customers and utilities to demand repurposed batteries and batteries made with recycled materials, policies that provide a procurement backstop if the private financial value proposition remains poor, and policies that discourage first-life use of materials have an unacceptably low recovery and recycling rates.

Key Observations

Lithium-ion batteries are expected to produce a significant and growing stream of hazardous waste from the electricity, transportation, and small electronics industries. In California, growth is expected to accelerate as early as 2026 but as late as mid-2030s if EV batteries last longer than originally expected.

End of life options include recycling, repurposing, and disposal. Recycling and repurposing options are largely in an early pilot and demonstration phase.

Recycling methods include direct, pyrometallurgical, and hydrometallurgical. Recovery of cathode metals is the key value driver of the recycling option.

Hydrometallurgical recycling is currently the most attractive commercially-ready method of recycling due to its lower cost, higher materials recovery, and lower pollution impacts compared to pyrometallurgical recycling. Direct recycling promises significantly lower cost and higher materials recovery—but is still in a technology development phase.

Lithium-ion battery technologies and chemistries are varied, producing a mixed waste stream, and resulting in significant differences in the cost of recycling (e.g., pack disassembly, sorting, and other pre-processing) and in the expected revenues from various recycled materials.

Repurposing of EV batteries for stationary applications is technically feasible, could provide significant grid value, and is potentially scalable to large volumes. However, the overall value proposition is still unclear and in an initial demonstration phase. Uncertainties in battery condition and degradation over its second life pose a significant risk in the viability of second life use cases.

One core objective of disposal laws and policies is to minimize illegal dumping and circulation through general waste streams. Appropriate disposal of batteries from small electronics is particularly challenging. In 2022 California passed two pieces of legislation (SB 1215 and AB 2440) designed address this challenge.

Battery tracking and information, collection, and reverse logistics to its next life stage (recycling, repurposing, or disposal) are key areas for policy development, as emphasized in California's AB 2832 Advisory Group 2022 report to the Legislature.

Recycling processes will need to be closely monitored for pollution impacts, drawing from lessons learned in the lead-acid recycling industry.

Recycling policies will likely need to address the issue of poor recycling value propositions of many types of batteries and battery materials. The state's challenges with plastics recycling and California's 2021 Circular Economy Package legislation can provide guidance for going beyond battery collection and sorting to truly close the loop to a circular battery lifecycle.

Depending on the state's waste management goals, policies may be needed to motivate electricity customers and utilities to use repurposed batteries that are close in cost to new batteries.

Overall, the state faces two major challenges as lithium-ion battery waste streams grow in the near future: (1) to secure the hazardous waste stream all the way to final disposal, and (2) minimize or postpone the final disposal stream in support of a more sustainable and circular lithium-ion battery lifecycle.

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- Cell Phone Recycling Act of 2004
- AB 1125 (Rechargeable Battery Recycling Act of 2006): https://dtsc.ca.gov/ab-1125-rechargeable-battery-recycling-act-fact-sheet/
- SB 1215 (Newman) (Electronic Waste Recycling Act of 2003: covered battery-embedded products)
    - SB 1215 expands California's existing Electronic Waste Recycling Act to include products containing batteries that cannot be easily removed with household tools. This legislation helps to curb the amount of battery-embedded products that are improperly disposed of so that they no longer pose a danger to the companies and employees charged with managing our waste stream.
    - https://sd29.senate.ca.gov/news/press-release/statewide-battery-recycling-programs-created-under-new-law
- AB 2440 (Irwin) (Responsible Battery Recycling Act of 2022): makes 2004 & 2006 legislation inoperative
    - AB 2440 establishes the nation's largest extended-producer responsibility (EPR) battery program. Creating convenient collection and recycling for batteries, this bill will eliminate the threat of fires at waste facilities and the recovery and reuse of the valuable and finite minerals contained in the batteries.
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