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

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ABSTRACT

Lithium-ion battery recycling can decrease life cycle environmental impacts of electric vehicles (EVs) and assist in securing domestic supply chains. However, the US, the third largest market for EVs, has no policies for recycling of batteries at their end-of-life. The European Union has proposed recycled content standards (RCSs) to help drive a circular battery ecosystem. This analysis calculates feasible RCSs for the US based on future sale projections, techno-economic assessment, life cycle assessment, and material flow analysis. 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. While domestic recycling can be profitable at scale and reduce environmental impacts, it is more expensive than exporting to China for recycling. Consequently, policy is likely needed to ensure critical materials are recycled domestically.

Introduction

On-road transportation has been a substantial contributor to degraded air quality and global warming emissions. Electrifying this sector can mitigate air pollution and contribute to achieving international climate goals, and electric vehicles (EVs) powered by lithium-ion batteries (LIBs) play a crucial role (Rogelj et al., 2018). While LIBs are an essential technology for pollution mitigation, they are also material-intensive and hazardous at their end-of-life (EoL) (International Energy Agency, 2020; The White House, 2021). The repurposing and recycling of these batteries can avert potential environmental and social impacts of LIB production from virgin materials and provide a domestic source of raw materials (Richa et al., 2017; The White House, 2021). The supply of recycled materials only represents a small portion of total battery material demand in the short term, but has the potential to represent over 50% of future cobalt, a critical material in LIBs (Dunn et al., 2021).

One potential policy lever to encourage recycling is a recycled content standard (RCS). RCSs mandate a percent of constituent material in a product to be from recovered sources, which can increase recycling rates by creating a market for the reclaimed material. The United State (US) has implemented this type of standard for the newsprint, plastic, and glass industries (Aunan and Martin, 1994), but has not passed or proposed RCSs for LIBs; however, the European Union (EU), an important EV LIB market, has included an RCS as part of their revised battery regulation (European Commission, 2020).

While federal LIB EoL policy has yet to be passed, the US has begun exploring the national interest of establishing a secure LIB supply chain. The Biden Administration's Executive Order (E.O.) 14,017, "America's Supply Chains," required a 100-day analysis of supply chains within the US, including large capacity LIBs. This report states the US battery supply chain is highly exposed to risk and the US currently cannot supply all materials domestically. The report further concludes that this risk is an adverse side effect of the historical prioritization of efficiency and low cost over sustainability, thus resulting in reliance on low-cost providers overseas, instead of investing in a domestic supply.

In the vacuum of federal policy, states within the US are exploring policies to increase the recycling rates of LIBs. The State of California's 2019 Assembly passed Bill No. 2832 which created a stakeholder advisory group tasked with recommending policy to the 2022 legislature that will lead to as close to 100% reuse and recycling as possible of EoL EV batteries (Dahle, 2018). The advisory group discussed RCSs, although they did not recommend it as a policy, expressing hesitancy due to a lack of knowledge around the optimal level of RCSs for the US,

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and an unknown cost of recycling (Kendall et al., 2022).

There is currently no academic literature that analyzes the proposed EU RCSs, calculates appropriate standards for the US, or assesses the environmental and economic use of these standards for LIBs. Prior analyses have estimated the future demand of materials to manufacture LIBs for the US (Richa et al., 2014a; Shafique et al., 2022; C. C. Xu et al., 2020), China (Liu et al., 2021; Shafique et al., 2022; Song et al., 2019), the EU (Baars et al., 2021), and South Korea (Kim et al., 2018), as well as the circularity potential of these materials (i.e., the potential for retired supplies to meet the material demand) (Baars et al., 2021; Dunn et al., 2021; Richa et al., 2014a; C. Xu et al., 2020). These estimates have demonstrated the potential for the recovered materials from retired EVs to provide a substantial source of supply. Dunn et al. (2021) forecast a wide range of circularity potentials for the US in 2040 for the materials cobalt (35% to 93%), lithium (35% to 68%), nickel (35% to 69%), manganese (29% to 64%), and aluminum (34% to 64%). Xu et al., 2020a estimate a wide range of global circularity potentials in 2050 for lithium (>30% to 50%), cobalt (>40% to 70%), and nickel (>30% to 55%). These large spreads from both Dunn et al. and Xu et al. are due to uncertainty in the future cathode market shares, sales forecasts, and the portion of batteries used in second-life applications. While these circularity estimates are informative, they are based exclusively on the quantity of material available and do not reflect economic feasibility or realistic collection and processing recovery rates. A more tightly defined range representing the near-term circularity potential is needed to guide policy discussions and developments. Thus, this research estimates feasible US RCS for cobalt, lithium, and nickel, that can serve as targets in the discussion or development of RCSs for light-, medium- and heavy-duty EV LIBs in the US market.

Feasibility of RCS is explored by estimation of the cost and environmental impacts, which include life cycle emissions of CO_2e, SO_X, and NO_X, from recycling LIB materials to battery grade quality. Prior research has demonstrated that recycling is environmentally preferable over landfill disposal, with differing impacts dependent on the recycling process, cathode chemistry, and carbon intensity of the grid (Ciez and Whitacre, 2019; Dunn et al., 2012; Ellingsen et al., 2014; Gaines, 2018; Gaines et al., 2010; Mohr et al., 2020; Rajaeifar et al., 2021). This paper adds to the LCA literature by calculating the environmental impacts of recycling LIBs retired in the US, either domestically or in China. In addition, the economics of recycling a mixed cathode chemistry stream of LIBs is calculated. While it is currently disputed if recycling of LIBs is profitable, previous research has attempted to capture the economics of LIB recycling (table S1) (Bernhart, 2019; Ciez and Whitacre, 2019; Foster et al., 2014; Gaines and Cuenca, 2000; Hanlon, 2016; Ma et al., 2018; Mossali et al., 2020; Qiao et al., 2019; Rahman et al., 2017; Standridge et al., 2016; Steward et al., 2019; Wang et al., 2014; Wang, 2020; Xiong et al., 2020). Choubey et al. (2017) is the only study to analyze a mixed cathode stream, reporting a profit from hydrometallurgical processing.

In our analysis, three different recycling processes are considered: hydrometallurgical, pyrometallurgical, and direct recycling. These results are then compared with the material value and avoided emissions of recovered materials. Because the cost and environmental impact of recycling is a function of where recycling occurs, three scenarios are modeled that consider the location of recycling and mode of transportation, an aspect that has historically been overlooked in LIB EoL cost estimates (Slattery et al., 2021). Recycling is modeled to occur in the US under two possible transport modes, truck or train, or is modeled to occur in China. China is currently the only market with significant LIB recycling infrastructure.

Materials and methods

Estimates of feasible RCS for cobalt, nickel, and lithium used in LIB traction batteries are calculated for the US using material flow analysis (MFA) from 2020 to 2050. Results from the MFA are then used in the Argonne National Lab's EverBatt (Argonne National Lab, 2021a) and GREET (Argonne National Lab, 2021b) models to estimate the cost and environmental impact of recycling the batteries retired until 2050.

Material flow analysis

MFA is used to forecast the demand for new materials and the quantity of retired and reclaimed materials for light-, medium-, and heavy-duty vehicles until 2050 (figure S1). The demand for new materials is calculated based on EV sales, capacity of batteries, cathode chemistry, and manufacturing requirements. The quantity of materials reclaimed from recycling is calculated based on the EV lifespan, LIBs used in a second-life application, second-life lifespan, recycling process, collection rate, and manufacturing scrap rate. Scenario analysis is used due to the uncertainty of these inputs, resulting in 864 different scenarios as described in Table 1.

EV sales data and forecast

The historical sales data for light-, medium-, and heavy-duty EVs and plug-in hybrid EVs is gathered from EV Volumes (2020). To predict future sales, two scenarios are considered based on the IEA MoMo forecast for light-, medium- and heavy-duty vehicles (figure S2). The first is based on MoMo's STEPS, which represents the policies and goals of the US. The second scenario is based on MoMo's SDS, which ensures sharp reductions in air pollutants and meet the global climate goals of the Paris Agreement (International Energy Agency, 2020).

Cathode chemistry

Cathode chemistry is based on historical EV Volumes data until 2020 and a forecast for future years (EV Volumes, 2020). From 2021 to 2050 the forecast represents the two scenarios NCX and LFP from C. Xu et al. (2020). The NCX scenario has the chemistries containing nickel and cobalt (e.g., NMC 632, NMC 811, and NCA) as the dominant cathode chemistries, while the LFP scenario has lithium iron phosphate (LFP) as dominant. The 2050 cathode chemistry percentages are taken from each scenario and linear interpellation was used from 2021 until 2050 (figure S3 and table S2).

Battery capacity

The average battery capacity is calculated using EV Volumes data from 2010 to 2020 (EV Volumes, 2020). From 2020 to 2050 regression analysis is used to forecast the light-duty sector. The heavy- and medium-duty forecast was created using linear interpolation to a 600 kWh battery in 2050 (figure S4).

Table 1
Scenarios used in the material flow analysis.

Model input	Scenarios
EV sales forecast	Two scenarios taken from the International Energy Agency's Mobility Model (IEA MoMo) (International Energy Agency, 2020) (Figure S2) 1) Stated Policies Scenario (STEPS) 2) Sustainable Development Scenario (SDS)
Cathode chemistry forecast	Two scenarios taken from Xu et al. (C. C. Xu et al., 2020) (figure S3) 1) NCX: Chemistries containing nickel and cobalt dominant in 2050 2) LFP: Lithium-iron-phosphate (LFP) chemistry dominant in 2050
Percent repurposed	10%, 25%, 50%
Failure rate of 2nd life	A lognormal distribution that is based on the average cycles completed per year: 365 cycles, 183 cycles, and 92 cycles
Recycling process	Hydrometallurgical, pyrometallurgical, and direct recycling
Collection rate	1)Step increase from 65% in 2025 to 90% in 2050 by 5% increments 2)Flat collection rate from 2020 to 2050 analyzed for 7 different rates/scenarios: 65%, 70%, 75%, 80%, 85%, 90%, 95%.

EV lifespan

A Weibull distribution is used to estimate EV lifespan. The average lifespan used for light-duty vehicles is 15 years while the average lifespan used for medium- and heavy-duty vehicles is 10 years (Staff, 2016; Statista, 2016).

Second-life use and lifespan

Due to the infancy of the second-life industry, the percent of batteries that will be repurposed and the lifespan of second-life battery systems is uncertain. This analysis uses several scenarios for the repurposing and the failure rate of second-life batteries (table 1).

The failure rate is calculated using a lognormal distribution of cyclical aging based on cyclical aging research of failure rates by Johnen et al. (2020) ($\mu = 7.038$ and $\sigma=0.064$ when EoL = 50% capacity). In Johnen et al. (2020) batteries are charged and discharged between a minimum and maximum state of charge. The probability of failure is based on the number of equivalent full cycles completed, thus scenarios representing various applications are calculated based on the average cycles completed per year (see table 1).

Collection rate

The collection rate of LIBs represents the percentage of LIBs retiring that are collected and eventually recycled. Collection rates are uncertain due to a lack of reporting and uncertain export rates. Due to this uncertainty, the collection rate is evaluated under several scenarios. First, a flat rate for all years is assessed for the following levels: 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95%. Then, an increasing collection rate is assessed, replicating the EU requirements of 65% in 2025 and 70% in 2030, increasing by 5% increments every five years until 95% is met and held constant. It is assumed recyclers will accept all cathode chemistries collected. The cathode chemistry of batteries and scrap collected for recycling are represented in figure S5.

Recycling processes and efficiency

The recycling processes included in this analysis are hydrometallurgy, pyrometallurgy, and direct recycling. Each use different methods for metal recovery, result in different yields, and produce different products.

Pyrometallurgical processing has been common in the recycling of electronics for metals recovery. Prior to pyrometallurgical treatment, batteries can be mechanically treated by sorting and crushing, and then subjected to temperatures of 150 to 500 °C to remove electrolyte and organic solvent. The pyrometallurgical process consists of heating the LIB to temperatures of 1400 to 1700 °C to create a copper-nickel–cobalt–iron alloy of the recovered materials and a slag of the unrecovered materials, including lithium. The alloy produced is a mixture of metals, but can be run through an additional hydrometallurgical process to recover the constituent target materials of cobalt, nickel, and copper (Assefi et al., 2020).

The hydrometallurgical recycling process also requires pretreatment, which typically consists of discharging, dismantling and/or mechanical crushing, and sorting the following from the rest of the materials: active cathode, anode, electrolyte, copper foils, and aluminum foils. Next, the electrolyte is recovered, and the cathode active materials are separated from the aluminum foil by a dissolution process using organic solvents. The hydrometallurgical process then begins by leaching with inorganic or organic acids to create a solvent containing the materials. The materials cobalt, nickel, manganese, and lithium are then recovered from the solution using solvent extraction, chemical precipitation and/or electrochemical deposition (Yao et al., 2018)

The direct recycling method similarly begins with discharging, physical separation, electrolyte recovery, and delamination. At this point, the anode and cathode are separated using froth flotation, followed by binder removal, and then relithiation. Relithiation processes are still in the research and development stage. Several different methods are being researched, including thermal, hydrothermal, redox mediator, ionothermal, and electrothermal processes. In addition, the ReCell center is currently researching the possibility of upcycling cathodes to different stoichiometry, for example taking an NMC111 cathode and upcycling the cathode to an NMC811 cathode (Gaines et al., 2021).

The recycling efficiencies for pyrometallurgy, hydrometallurgy, and direct recycling are taken from the Argonne National Lab model, EverBatt, and are included in table S3 (Argonne National Lab, 2021a).

Material loss during manufacturing

The demand of materials is calculated based on the sales, capacity of batteries, and the cathode chemistry. To properly calculate the demanded materials, the material loss during manufacturing must be included. The Argonne National Lab BatPac model estimates a yield rate of 92.2% for all cathode materials, a number also used by Ciez and Whitacre (2017), and which is adopted here as well (Argonne National Laboratory, 2020; Ciez and Whitacre, 2017). In addition to the loss of cathode materials, 5% of finished cells are discarded in the final manufacturing step due their inability to retain a charge (Ciez and Whitacre, 2017). This loss is included in the sales forecast as well as the available materials for recycling.

Recycled content standards

Recycled content is the fraction of recovered material within a product. To calculate the recycled content that could be achieved for future LIBs, the supply of recovered material and the demand of materials for manufacturing needs to be determined. The recycled content is calculated for all scenarios listed in table 1 from 2020 to 2050. This model assumes a closed loop recycling system for US batteries.

Equation 1 is used to calculate the recovered material *(m)* of nickel, cobalt, and lithium, for the year *(t)* from 2020 to 2050, for a given scenario *(s)* listed in table 1, and for each recycling process (r) of pyrometallurgy, hydrometallurgy, or direct recycling. The recovered material is calculated by taking the retired supply for the year *(t)*, material *(m)*, and the scenario *(s)*, and multiplying it by the material *(m)* recycling efficiency of the recycling process *(r)*.

$$m = material: \ nickel, \ cobalt, \ and \ lithium$$

$$t = year: \ 2020 \ to \ 2050$$

$$r = recycling \ process \\ : \ pyrometallurgy, \ hydrometallurgy, \ and \ direct \ recycling$$

$$s = scenario; the \ scenarios \ listed \ in \ table$$

$$\sum retired \ supply_{t,m,s} * collection \ rate * recycling \ efficiency_{m,r} \\ = reclaimed \ material_{t,m,r,s} \tag{E1}$$

Equation 2 calculates the manufacturing material demand for each material *(m)* and year *(t)* by multiplying the material demand by 1 plus the material loss, thereby accounting for the additional material needed to manufacture the batteries.

$$\sum material \ demand_{t,m,s} * (1 + manufacturing \ loss)_{t,m} \\ = manufacturing \ material \ demand_{t,m,s} \tag{E2}$$

In Equation 3, the recovered materials (E1) is divided by the manufacturing demand (E2) to calculate the percent of recycled content. This calculation is done for each material *(m)*, year *(t)*, recycling process *(r)*, and scenario *(s)*.

$$\sum \frac{recovered \ material_{t,m,r,s}}{manufacturing \ material \ demand_{t,m,s}} = recycled \ content \ (\%)_{t,m,r,s} \tag{E3}$$

After the RCS for all the scenarios and materials are calculated, a 95% confidence interval is used to calculate a feasible RCS bound. The impact of the scenarios to the RCS are then analyzed. Based on this analysis, the final RCS uses an incremental collection rate beginning with 65% in 2025 and increasing to 90% in 2050, all other scenarios are included in the final RCS calculation except the use of pyrometallurgical recycling. The RCS targets assume the recycled material is battery grade, meaning batteries do not need to be designed around using lower grade material in manufacturing. This assumption is supported by industry declarations, such as the creation of battery cathode material by NorthVolt (2021) and the announcement of a partnership between Tesla and Redwood Materials (Korosec, 2022).

Cost & environmental impact of recycling

The cost and environmental impacts of recycling were determined using the EverBatt and GREET models (Argonne National Lab, 2021a, 2021b). The cathode chemistry market share of retired batteries from the MFA was used to determine the cost and environmental impact of recycling 1 kg of pack-level LIB materials for each year and scenario (Fig. 1). The avoided emissions from using recovered materials were determined by taking the materials recovered and calculating the equivalent virgin material impacts using the GREET life cycle inventory.

EverBatt and GREET are limited by the ability to calculate results for only one scenario at a time. To calculate results for this study, EverBatt was run iteratively 2604 times using a macro to determine the scenario outputs. The transportation distance, mode of transportation, location of recycling, and recycling facility size were varied.

The default settings in EverBatt were kept (table S4), except for the dollar value of materials, the labor rate of LIB disassembly in China, and the amount recyclers pay, or are paid, for LIBs at their EoL (i.e. the recycling fee). The value of materials represents an average price from USGS between 2016 and 2020 (table S5 - S8). The labor rate for LIB disassembly is $7.50 when occurring in China. This was calculated by using the ratio of US to China labor rates during the recycling phase. The recycling fee has been changed to zero for all chemistries to compare the value of recovered materials and the cost to recycle, without inflating profit or loss by including an additional transaction between the supplier and recycler. In addition, these values are removed because the source and process EverBatt used to calculate these values are not reported. This points to another limitation of the EverBatt model; not all inputs have an explanation and documented source. While these limitations exist, the models provide detailed and changeable variables that significantly aided in creating the scenarios in this analysis.

Location and transportation scenarios

Three scenarios representing the location of recycling, transportation distance, and mode of transportation are used to calculate the cost and environmental impact of recycling in EverBatt.

1) **Domestic – truck scenario:** The LIB is recycled within the US and transported via truck. The distance from end-use to collection is 50 miles, collection to disassembly is 50 miles, and from disassembly to recycler is 1000 miles.
2) **Domestic—train scenario:** The LIB is recycled within the US and transported via train and truck (U.S. Department of Transportation, 2021). The distance from end-use to collection is 50 miles via truck, collection to disassembly is 50 miles via truck, and from disassembly to recycler is 1000 miles via train.
3) **China—truck and ocean tanker scenario:** The LIB is transported from the US to a recycling facility in China via ocean tanker. The distance from end-use to collection is 50 miles and collection to disassembly is 50 miles, both via truck. The batteries are shipped from Los Angeles to Shanghai, China which is 19,270 nautical miles. It is assumed the battery will be trucked an average of 260 miles to the LA port and then 740 miles from Shanghai to the Hunan province where Brunp recycling is located.

Recycling facility yearly throughput

The facility throughput per year is varied from 1000 to 10,000 t (t) per year, increasing by 1000 increments, and then from 10,000 to 50,000 t per year, increasing by 10,000 t increments.

Disassembly

The level of disassembly is dependent on the recycling process used. Pyrometallurgical recycling can begin at the module level. Hydrometallurgical is discussed in academic literature as requiring disassembling to the cell level, although recyclers, such as Li-cycle, state their process disassembles to the module level (Karidis, 2020). This analysis assesses the economics of hydrometallurgical and pyrometallurgical recycling when disassembled to the module level. Direct recycling is still in the development stage and must be disassembled to the cell level.

In EverBatt, disassembly is modelled to be performed by hand, thus the cost consists mostly of labor. Recycling in the US is estimated to cost $50 per hour and recycling in China is estimated to be $7.50 per hour. Due to the lack of battery standardization, it is difficult to automate this step. Research is currently underway for self-learning robotics to

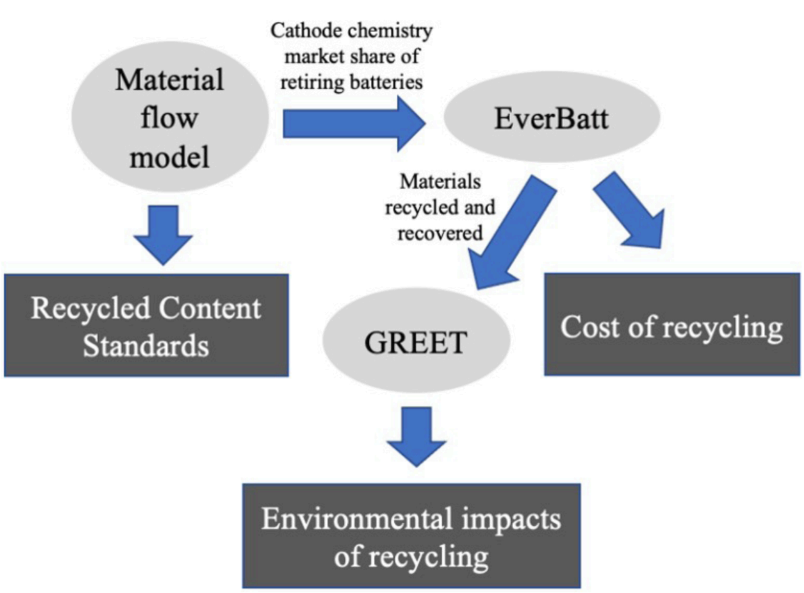

Fig. 1. The interconnection of models used to determine the RCS, cost, and environmental impacts of recycling. The material flow model determined the RCS and the cathode chemistry market share of retiring batteries. The cathode chemistry market share was then input into the EverBatt model to determine the cost of recycling. GREET is integrated into EverBatt to determine the environmental impact of recycling. Finally, the EverBatt outputs of recovered materials were used to calculate the avoided impacts of virgin materials using life cycle inventories from GREET.

potentially decrease the cost of this labor-intensive process (Neumann et al., 2022).

Recycling profit sensitivity analysis

Sensitivity analysis was used to evaluate the impact of recycling cost and material value on the profitability of recycling. The following inputs were both increased and decreased by 20% within the EverBatt model: value of cobalt, value of nickel, value of lithium, distance transported, hourly labor wage, and equipment cost. Due to the high volatility of commodity prices, the impact of cobalt, nickel, lithium, and manganese at their high and low prices since 2000 was additionally analyzed (table S5 – S8, equation S1 – S3).

Environmental impact of recycling

The environmental impacts of collection and transportation, disassembly, and recycling, were calculated with EverBatt using data from GREET (Argonne National Lab, 2021b). To calculate the environmental impacts avoided, the amount of recovered materials from 1 kg of battery recycled at EoL was taken from EverBatt, and the pollution from manufacturing these materials from virgin resources was calculated using GREET.

Results

Achievable recycled content standards

Achievable RCSs for the US are estimated to be between 11 and 12% for cobalt, 7–8% for lithium, and 10–12% for nickel in 2030, which then increase to 45–52%, 22–27%, and 40–46% respectively, in 2050 (Fig. 2). If the RCS for each of the scenarios is evaluated independently, the cathode chemistry forecast, sales forecast, collection rate, and type of recycling, are the largest influencers (figure S6 to S11).

The cathode scenarios significantly alter the estimated RCS for cobalt and nickel; the NCX dominant scenario results in a lower percentage (35–37% for cobalt and 32–34% for nickel in 2050) compared to the LFP dominant scenario (49–53% for cobalt and 43–45% for nickel in 2050). This is due to higher demand when cathodes containing cobalt and nickel are dominant (table S10). The sales scenarios influence the RCS for all materials, with slower future growth in material demand for the SDS scenario, which results in a higher RCS (55–58% for cobalt and 48–51% for nickel in 2050) than the STEPS scenario (32–33% for cobalt and 29–30% in 2050) (table S11). In addition to the sales and cathode forecasts, the collection rate determines the amount of material available for recycling; a higher collection rate results in a higher RCS.

Another important and uncertain variable in future material recovery is the mix of recycling processes in operation. Pyrometallurgical recycling does not recover lithium, and when it is removed from the RCS estimation, the confidence interval for lithium is highest (table S12).

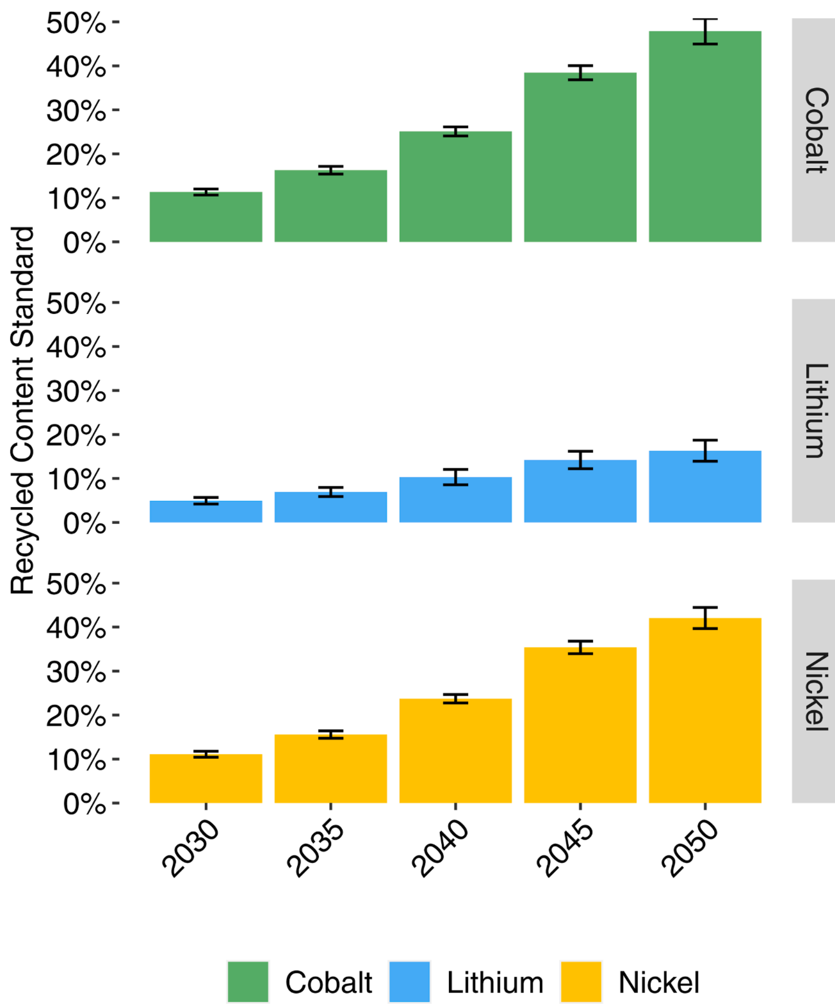

Fig. 2. Achievable recycled content standards for lithium-ion batteries in the US. The error bars represent with 95% confidence the proposed RCS. Full results are in table S9.

Due to the phasing out of pyrometallurgical recycling, it is not used to estimate achievable RCS for the US.

Recycling cost

The total cost of recycling LIBs at their EoL includes their transportation, collection, disassembly, and recycling. The cost of recycling is highly affected by economies of scale and costs decrease exponentially until the throughput of the facility reaches ~10,000 t/year (figure S12). The location of recycling, mode of transportation, and level of disassembly also impact costs (Fig. 3). China has a lower recycling cost, despite the added transport distance, due to a lower cost of labor and equipment costs. Fig. 3 includes three steps of disassembly: removal from the car, disassembly to module level, and disassembly to the cell level. While all disassembly costs are included in Fig. 3, hydrometallurgical does not always need to be disassembled further than the module level (Karidis, 2020). These high costs associated with disassembly are one of the reasons research has focused on mechanical disassembly, design for recycling, and beginning pre-treatment with the least amount of handling (Neumann et al., 2022).

Recovered material value

The recovered material value is highly dependent on the materials recovered and commodity pricing. Direct recycling recovers the most value by recovering the whole cathode, reducing the need for further processing before it can be used as an input to battery manufacturing. In addition, the cathode chemistry mix of retiring materials changes the amount of high value materials such as cobalt and nickel within the batteries. Since the NCX scenario contains a constant cobalt and nickel supply, the value stays higher than the LFP scenario (Fig. 4). In the LFP scenario, the number of cobalt-containing cathodes decreases overtime, replaced by iron, a material that is not recovered.

The economics of recycling lithium-ion batteries

All recycling processes are profitable after material throughput thresholds are met. Based on the EverBatt cost assumptions, recycling in the US in 2020 became profitable at or above ~8000 t/year for hydrometallurgical, ~7000 t/year for direct, and ~20,000 t/year for pyrometallurgical recycling, while using truck transportation. The location of recycling has a considerable impact to the cost of recycling due to the lower cost of labor in China. Recycling in China is profitable at throughput levels of ~3000 t/year, ~3000 t/year, ~4000 t/year, respectively.

Fig. 4 demonstrates the effect of evolutions in cathode chemistry; the value of recovered materials in the LFP scenario declines over time, while the NCX scenario stays relatively constant. This divergence is due to the LFP chemistry not containing the two highest valued materials, cobalt and nickel. Thus, the NCX scenario is economical for all years in the hydrometallurgical scenario, and LFP is only economical until 2028–2031. These results align with more recent analysis that demonstrate a profit from using hydrometallurgy to recycle cobalt containing chemistries (Choubey et al., 2017). These results suggest lower profitability than those documented by Choubey et al. (2017); the cost of recycling is relatively similar and the value of recovered materials in our analysis is considerably lower.

Direct recycling is profitable in the NCX scenario and is the most economical recycling process in the LFP scenario. While direct recycling is more costly, there is high value in recovering the whole cathode. This increased value leads to profitability in the LFP scenario until 2038. Despite direct recycling being the preferable choice for LFP, recycling of the LFP chemistry independently is not profitable. C. Xu et al. (2020) has different findings, demonstrating a net profit from recycling LFP due to the exclusion of disassembly and transportation costs.

Despite this overall higher expense for domestic processing in comparison to the recycling in China, US-based recycling can still be a profitable venture when the recycling mix includes some NMC chemistries. Cost estimates are in table S13.

Sensitivity analysis

A sensitivity analysis was applied to evaluate the impact of recycling cost and material value inputs on the profitability of recycling. When inputs were both increased and decreased by 20% within the EverBatt model, the value of cobalt has the largest impact on hydrometallurgical recycling profit in 2020 and the cost of labor has the largest impact on direct recycling profit. In 2050, nickel is the most influential parameter for hydrometallurgical recycling profit in the NCX scenario. This is a direct result of the decreased use of cobalt and increased use of nickel over time in NCX chemistries. The cost of labor is the most influential parameter for all other scenarios in 2050 due to the use of manual disassembly (figure S13).

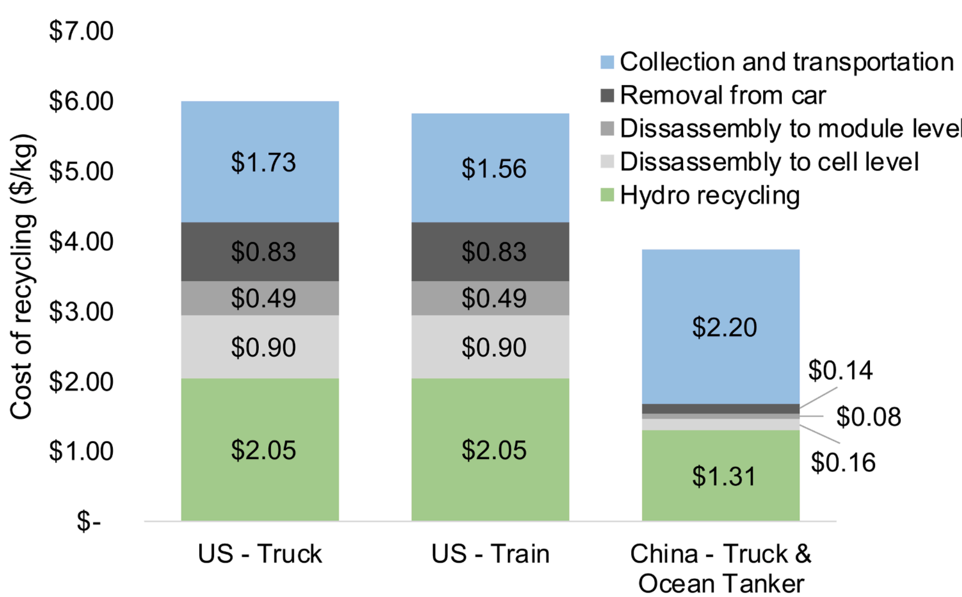

Fig. 3. The cost ($/kg) of a hydrometallurgical recycling facility in 2020 broken out by the cost of disassembly, the cost of hydrometallurgical recycling, and the cost of collection and transportation.

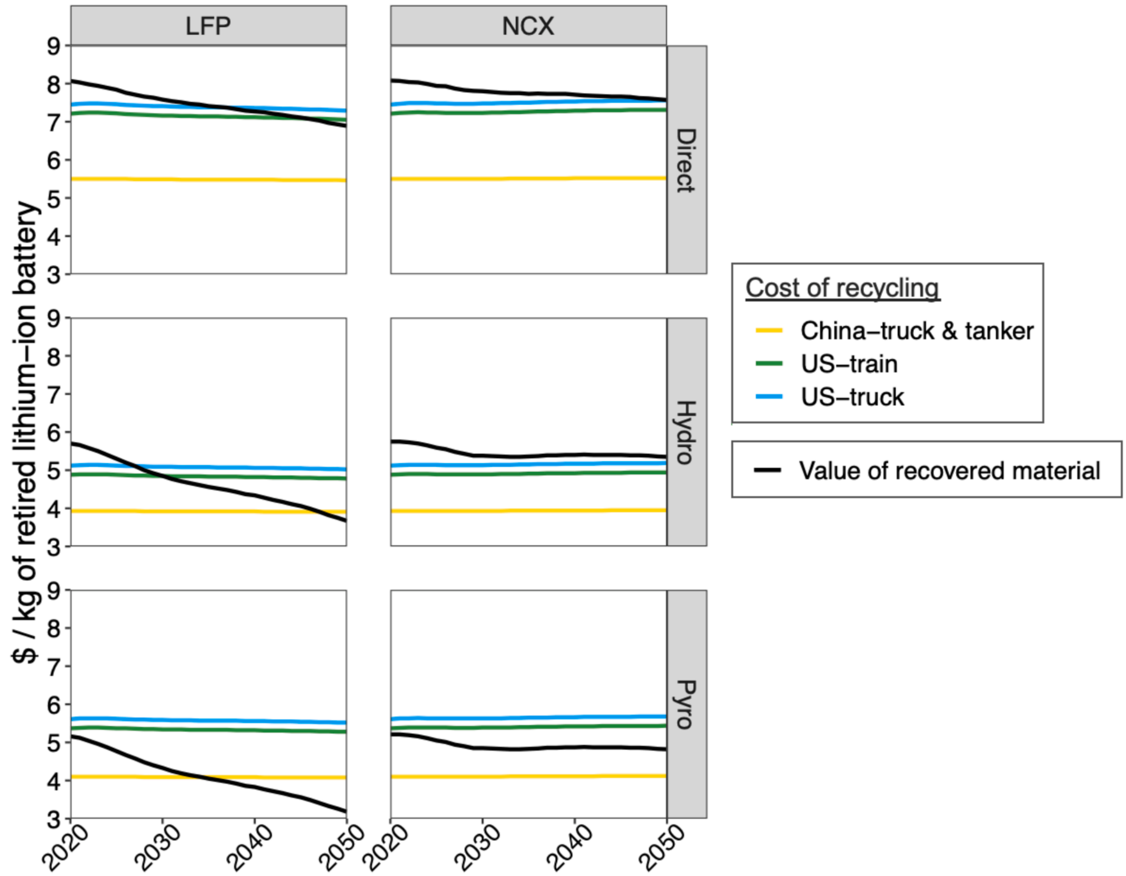

Fig. 4. The economics of recycling lithium-ion batteries. The cost of recycling 1 kg of retired materials in a 10,000 t/year facility (solid lines) and the value of recovered materials (dashed line). The material value and the cost of processing are held constant to 2020 values and does not consider the economies of learning.

In addition, the impact of modeling cobalt, nickel, lithium, and manganese at their historic high and low prices since 2000 was analyzed. Nickel had the largest impact on profitability both in 2020 and 2050 due to the historical high of $42.44 per kg in 2006. While the LFP dominant scenario has only a small amount of nickel-containing chemistry, it has a larger impact than the other materials due to the comparably higher value increase. These results demonstrate high sensitivity of the LIB recycling industry to potentially volatile commodity prices, as well as significance of the industry's increased reliance on nickel. Results are in table S14 and the data repository.

Scale of retirement in the US and infrastructure build-out

An estimated 3000 to 10,000 t of LIB battery packs retired in 2020, too small of a quantity to support the necessary throughput for more than one facility to run at breakeven, if handling only retired EV batteries. Currently, manufacturing scrap and consumer electronics are the bulk of materials processed by LIB recyclers (Carney, 2021). EV LIB retirement rapidly increases to 19,000 - 73,000 t in 2025, 71,000 - 404, 000 t in 2030, and 1.2 – 8.5 million t in 2050 (table S15). This rapid increase demonstrates that increased recycling capacity is likely necessary to support the near future LIB retirement (table S16). These estimates are larger than those previously reported by Richa et al. (2014b) of 14,000 - 193,000 t in 2030 and 38,000 – 344,000 t in 2040 which only consider light-duty vehicles, assumes a smaller battery capacity of 29–51 kWh, and a lower EV sales forecast taken from the US Energy Information Administration's 2012 estimates.

Environmental impacts of recycling lithium-ion batteries

As found in several previous studies, recovered material from recycling is environmentally less intensive than producing material from virgin ore (Fig. 5) (Ciez and Whitacre, 2019; Dunn et al., 2015; Mohr et al., 2020; Richa et al., 2017). This analysis concludes recycling in the US results in less pollution than recycling in China because of a shorter transportation distance and a less fossil fuel intensive electricity grid. Transportation is modelled as 1000 miles by truck and 19,270 nautical miles by ocean tanker when recycling LIBs in China and a shorter distance of 1000 miles by truck when recycling in the US. The electricity grid emissions factor is modelled at 760 g CO_2e/kWh in China and at 449 g CO_2e/kWh in the US (Argonne National Lab, 2021b).

Pyrometallurgical processing results in more CO_2e emissions than the other recycling technologies, while hydrometallurgy results in higher SO_X emissions. Direct and hydrometallurgical recycling recover more material than pyrometallurgical, thus offsetting more virgin material and associated emissions. This is contradictory to the results found by Richa et al. (2017), which showed hydrometallurgical recycling to offset less emissions. The difference is primarily due to Richa et al.'s assumption that manganese is not recovered by hydrometallurgical processing. Ciez and Whitacre (2019) show pyrometallurgical recycling and the recycling of LFP do not result in avoided emissions. Differences among their study and this one are largely due to their scope, which includes the manufacturing of the whole cell, while this analysis only accounts for the emissions of manufacturing the recovered materials.

Limitations of study

The impact of emerging technologies such as solid-state, lithium-

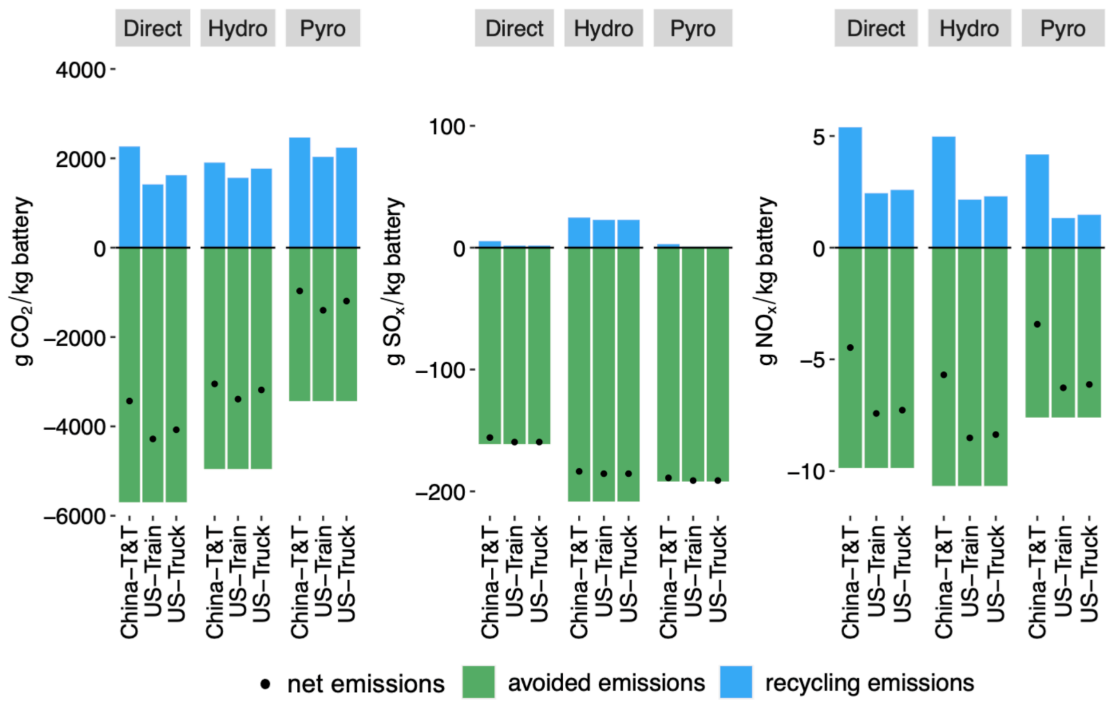

Fig. 5. The environmental impact of recycling lithium-ion batteries in 2020. The avoided emissions represent the environmental impacts if the materials recovered were from virgin ore (green), the recycling emissions are the emissions resulting from the recycling process (blue), and the net emissions represent the emissions saved because materials were recycled instead of mined. The x-axis represents the location and transportation scenarios. Recycling in China and transporting via truck and ocean tanker is abbreviated to "China- T&T".

sulfur, or sodium-ion batteries was not included in this analysis. If the dominant technology changes, the relevancy and level of RCS will need to be reconsidered. For example, solid-state batteries which are currently under development, would drastically decrease the demand for critical materials, therefore the current retiring supply would provide recovered materials for a higher feasible RCS (Watanabe et al., 2019). This is not the case for lithium, if it replaces graphite in the anode for solid-state batteries. In addition, the recycling processes will likely require modification. In the case of solid-state batteries, even if the same materials for recovery are desired, modifications are required due to the presence of a solid electrolyte such as glass or ceramic (Schwich et al., 2020).

We also do not include the potential impact of recycled materials from other product systems; for example, consumer electronics or stationary storage. While the LIB market is historically dominated by consumer electronic sales, and therefore is currently the bulk of retired supply, EV sales are now the large majority (Bloomberg New Energy Finance (BNEF), 2019). If consumer electronics were included in this analysis, they would likely increase the cobalt RCS due to lithium cobalt oxide being the common cathode chemistry (Fu et al., 2020; Gaines et al., 2021). Stationary storage is currently a comparably small market, equal to an estimated 3% (1688 MWh) of total EV capacity in 2019 (U.S. Energy Information Administration, 2021). This is forecasted to increase along with EVs to be equal to about 3–5% of total EV sales until 2050 (664 GWh for 2–6 hour storage) (Frazier et al., 2020).

Lastly, the purity of material recovered impacts the value of materials, and recent studies show the shredding versus disassembling reduces purity, thus changing the economics (Thompson et al., 2021). While this is an important finding, it has not been considered in this analysis.

Discussion

RCS and other international policies to increase material circularity

This research calculates feasible RCSs in the US to be 11–12% for cobalt, 7–8% for lithium, and 10–11% for nickel in 2030, which increase to 15–18% for cobalt, 9–11% for lithium, and 15–17% for nickel in 2035. These are slightly different from the proposed EU standards of 12% for cobalt, 4% for lithium, and 4% for nickel in 2030, and 20%, 10%, and 12%, respectively, in 2035. The variance between regions is likely due to political considerations and different calculation inputs. To reach the EU RCS for lithium, a process which recovers the material must be used. This indicates a push away from pyrometallurgical and towards hydrometallurgical and direct recycling. Future recycled lithium availability will depend on whether hydrometallurgical continues to be the dominant technology. Cathode chemistry trends will likely determine if battery manufacturers prefer cathodes recovered through direct recycling or their constituent materials through hydrometallurgical recycling. Trends towards LFP will likely indicate direct recycling is preferable due to the constituent materials having relatively low values. Both processes are desirable in a trend towards NMC811 due to the high value of materials and the ability to upcycle. The high cobalt chemistries currently phasing out, such as NMC111, are upcycled by adding nickel to achieve a lower ratio of cobalt in the recovered cathode (Gaines and Wang, 2021).

In addition to RCS, the EU has proposed several policy mechanisms to achieve a circular economy, including extended producer responsibility, collection rates, material recovery rates, and emission requirements. The proposed EU collection rates are those used in this analysis, at 65% in 2025 and 75% in 2030 (European Commission, 2020). Considering the EU is the second largest EV market in the world, these policies will impact EV manufacturers globally (Melin et al., 2021). If the US does not implement similar requirements, the battery and material suppliers unwilling to reduce social and environmental impacts may divert their attention to sales in the US, while the companies focused on a sustainable supply chain may focus their efforts on the EU. Policy harmonization across regions could engender a global shift in supply chain and manufacturing requirements, thus positively decreasing the regulatory uncertainty for manufacturers.

There are other policy mechanisms that can also increase battery circularity. Government subsidization of recycling matched with a recycling requirement has been demonstrated by China, resulting in the growth of the industry (International Energy Agency, 2020). Another route for increasing recycling is creating a collection and recycling program funded by environmental collection fees charged at the time of sale. This has not been demonstrated for any LIB recycling program, although is a solution for e-waste in California (California Department of Tax and Fee Administration, 2021).

Closed-loop recycling assumptions and real-world demonstrations

The potential circularity reported in this analysis assumes closed-loop recycling, in which battery materials recovered from LIB waste are used in manufacturing LIBs. While RCS may encourage a circular economy on a global scale, it will only contribute to a domestic circular economy if manufacturing is done domestically. The current lack of cathode manufacturing in the US means recovered materials may be exported or used by other industries.

Due to the criticality of these materials, it is advantageous for the US to develop a domestic cathode manufacturing industry and thus increase material security. Northvolt, located in Sweden, has a closed-loop system which combines LIB recycling and manufacturing (Northvolt, 2021). Within the US, Redwood Materials, a hydrometallurgical recycler, recently announced they are building capacity to manufacture cathode and copper foil from recovered materials, which will be sold to Panasonic, the battery supplier to Tesla (Carney, 2021; Korosec, 2022). If other US-based recyclers and EV manufacturers follow suit, the industry has the potential to create a closed-loop system for secondary material generated from retired LIBs.

LIB recycling economics and global material flows

This analysis shows recycling in China is less expensive than in the US, although domestic recycling in the US is still profitable at economies of scale (table S1). The known recycling facilities planned for development all have capacities over the calculated economical threshold in this paper, excluding pilot facilities. Not previously discussed in this analysis is the spoke and hub model, a method used by Li-cycle. In this method, LIBs are shredded at a smaller facility (5000 t/year spokes), then aggregated at a larger facility (60,000 t/year hub) which performs hydrometallurgical recycling.

The cathode chemistry, and specifically the amount of cobalt, also significantly affects the economics of recycling. The sensitivity analysis demonstrates when cobalt batteries are a significant portion of the waste stream, the value of cobalt is the largest influencer of profits. As the portion of cobalt declines, the value of nickel and the cost of labor becomes more influential. This is especially important considering recent warnings of future class 1 nickel shortages due a lack of necessary processing capacity to support rapidly increasing demand from LIBs (Campagnol et al., 2017; The White House, 2021).

While the cost of recycling in the US is higher than recycling in China, domestic recycling results in lower emissions due to decreased transportation and a cleaner electricity source. The uptake of EVs is based on the need to reduce climate change and emissions from transportation, therefore it is essential to apply those principles to the EoL as well. One opportunity to achieve lower impact and cost is mode shifting from truck to train transportation. LIB EoL transportation by train is not common practice, but it does result in the least environmental impact and also reduces transportation costs.

Conclusion

This research calculates achievable RCSs for the US that can support decision-making in the policymaking process. The analysis finds recycling is economical in the near term. While domestic recycling is ideal to increase energy material security and lower the life cycle environmental impact of these materials, the recycling of LIBs in China is less expensive than in the US. The LIB recycling facility capacity in the US will also have to rapidly increase to support future retirements, if domestic recycle of EV batteries is a priority. To ensure that recovered materials stay domestic, recycling facility development must also be coupled with the development of cathode and battery manufacturing capacity within the US (The White House, 2021). Therefore, policy is likely necessary to ensure the market does not result in exporting of retired batteries or their critical materials.

Materials availability

The materials available are in the supplementary materials and the repository. The code and datasets used to generate these results are made available in the Dryad repository: https://datadryad.org/stash/share/X_DM7T32Z5pJPlaB1ibqXBjAxZL4BU3JxmNgDmC7nbI

Author contributions

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Alissa Kendall: Supervision, funding acquisition, writing – review and editing

Margaret Slattery: Conceptualization, writing – review and editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All data and code used to generate these results are available in the supplementary materials Dryad repository: https://datadryad.org/stash/share/X_DM7T32Z5pJPlaB1ibqXBjAxZL4BU3JxmNgDmC7nbI

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106488.

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