Resources, Conservation & Recycling 174 (2021) 105755

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review

Margaret Slattery [a], Jessica Dunn [a], Alissa Kendall [b,*]

[a] Energy Systems, Energy and Efficiency Institute, University of California Davis, 1605 Tilia St #100, Davis, CA 95616, USA
[b] Department of Civil and Environmental Engineering, University of California Davis, 1 Shields Ave. Davis, CA 95616, USA

ARTICLE INFO

Keywords:
Electric vehicles
Recycling
Battery
Circular economy
Transportation
Battery safety
Reverse logistics

ABSTRACT

The market for electric vehicles (EVs) has grown exponentially over the past decade, largely driven by ambitious sales targets in regions around the world. At end-of-life (EoL), these batteries must be managed properly to maximize reuse and recycling, which requires an efficient and safe collection and transportation system; however, the logistics of transporting EoL batteries are rarely examined in depth in scholarly research. In this paper, we conduct a critical review of the peer-reviewed literature on EV traction battery reuse and recycling to assess how transportation is represented. We find that among 60 studies identified, 70% mentioned collection and transportation as a challenge to battery reuse or recycling, and 63% identified a need for policy or further research related to collection and transportation. Among 17 papers that focus on cost, estimates for transportation costs vary widely among studies, from more than five dollars per kg to less than 30 cents, representing, on average, 41% of the total cost of recycling. Studies that examined the environmental impact of EoL transportation suggest it contributes 1–3.5% of life cycle GHG emissions for a recycled battery. In response to the limited and highly variable treatment of battery EoL transportation, the literature review is followed by contextual information about the United States, including the regulatory framework and existing network for EoL batteries. Recommendations for future study include place-specific research on optimal facility siting that considers both existing and projected infrastructure, and which reflects costs and environmental and social impacts at local scales.

1. Introduction

Recent advancements in lithium-ion batteries (LIBs) have enabled electric vehicles (EVs) to achieve driving ranges that can compete with fuel-powered cars (Fletcher, 2013). The market has grown exponentially over the past decade, and EVs are now a critical component of greenhouse gas (GHG) mitigation targets at state, federal, and international scales (CARB, 2021; IEA, 2020). While EVs represent a promising means of decarbonizing transportation, the material demand associated with LIB production engenders concern about supply chain sustainability and end-of-life (EoL) management. Key value chain inputs such as lithium, cobalt, nickel, and graphite are considered critical or near-critical materials and have negative social and environmental impacts (Banza Lubaba Nkulu et al., 2018; Dunn et al., 2015; Mayyas et al., 2019). At EoL, LIBs must be managed properly to avert environmental damages and to capture the residual value via second-life applications and material recovery. Considering the rapid increase in demand for EV LIBs and the deluge of retired EV LIBs that will occur in the coming decade, there is a growing body of research on the need for circular economy strategies to reduce dependence on mining and refining for battery materials and to manage retired batteries effectively (IEA, 2020); (Rajaeifar et al., 2020); (Skeete et al., 2020).

On the supply and production side, researchers have forecasted expected material demand (Ambrose and Kendall, 2019a; Olivetti et al., 2017) and analyzed the life cycle impact of EV batteries, often highlighting the impact of cathode materials and battery assembly (Ambrose and Kendall, 2019b; Dai et al., 2019; Dunn et al., 2015; Kelly et al., 2019). Studies focusing on EoL have forecasted the volume of the future waste stream (Ai et al., 2019; Baars et al., 2020; J. Dunn et al., 2021; Kirti Richa et al., 2014), discussed the potential impact of reusing batteries in stationary storage applications (Leila Ahmadi et al., 2017; Bobba et al., 2018; Casals et al., 2019; Cusenza et al., 2019), reviewed the status of recycling (Harper et al., 2019; Heelan et al., 2016; Lv et al., 2017; Mossali et al., 2020; Zhang et al., 2018a,b); and compared the

* Corresponding author.
E-mail address: amkendall@ucdavis.edu (A. Kendall).

https://doi.org/10.1016/j.resconrec.2021.105755
Received 8 February 2021; Received in revised form 27 May 2021; Accepted 14 June 2021
Available online 9 July 2021

environmental and economic implications of different recycling pathways (Ciez & Whitacre, 2019; Hendrickson et al., 2015; Richa et al., 2017).

However, before reuse or recycling is possible, LIBs must be removed from the vehicle, potentially stored until enough batteries accumulate for a cost-effective shipment, and be transported to the appropriate facility. Transporting EoL batteries is a critical aspect of the collection phase, and has been identified as a potential barrier to achieving the high collection rates that are necessary for robust reuse and recycling systems (Ahmadi et al., 2014; Hua et al., 2020; Larouche et al., 2020; Thompson et al., 2020; Wang & Yu, 2021). Despite this, the practical logistics of how batteries will get from the point of vehicle retirement to facilities where they will be refurbished, repurposed, or recycled have received far less attention in scholarly research compared to scientific and technical aspects of reuse or recycling (Fan et al., 2020; Melin, 2019; Nordelöf et al., 2019).

This article seeks to understand how transporting used batteries influences the sustainability and cost of EoL management, identify solutions to reduce the impact of the transportation phase, and provide suggestions for accurately representing transportation in future research. First, we present a literature review of peer-reviewed articles about the cost and environmental impact of lithium-ion battery end-of-life, focusing on how, if at all, authors account for collection and transportation. The literature review is then complemented with contextual information about EoL battery transportation, including the regulatory framework and existing network, to identify key areas of concern and make recommendations for future research. While the scope of the papers reviewed is global, the contextual discussion is focused on the United States, as the specific context of collection and transportation varies by region.

2. Methods

Peer-reviewed articles, reviews, conference proceedings, and book chapters were identified through Scopus and Web of Science using the following title, abstract, and keyword search terms:

1 To identify studies on environmental impact: ["lithium-ion batter*" AND "electric vehicle"] AND ["recycl* OR end-of-life" OR "circular economy"] AND ["sustainab*" OR "environment*" OR "impact" OR "life cycle assessment" OR "LCA"]. This yielded 238 results in Scopus and 107 in Web of Science.
2 To identify studies on cost and/or economic analysis: ["lithium-ion batter*" AND "electric vehicle"] AND ["recycl* OR end-of-life" OR "circular economy"] AND ["sustainab*" OR "environment*" OR "impact" OR "life cycle assessment" OR "LCA"]. This yielded 21 results on Scopus and five on Web of Science, most of which overlapped with articles captured in the first search.

Next, we searched within these results for ["transport*" OR "reverse logistics"], which yielded 127 document results for environmental search terms, and 17 for economic. All results were published after 2011. Each article was then individually reviewed for exclusion based on the following criteria:

- Where "transport" referred only to the transportation sector or transport of lithium ions within a battery cell
- Where "transport" referred only to the transportation of materials or batteries during production, but not EoL
- When EoL transport is mentioned only to state that it is excluded from the analysis
- When the article is not about batteries for passenger EVs
- When the article is a technical paper about a specific recycling method

In total, 46 articles mentioning EoL transportation were selected through this process from Scopus and an additional eight from Web of Science. Six more were identified by following in-text citations for a total of 60 documents.[1] Among these, 70% ($n = 42$) mentioned collection and transportation as a challenge to battery reuse and/or recycling, and 63% ($n = 37$) identified a need for policy or further research related to collection and transportation (Fig. 1). 17 papers included EoL transportation in cost analysis, and nine in environmental analysis. These articles were then analyzed to determine how, if at all, authors reported the impact of transportation or specified their assumptions. Finally, we looked at whether the authors explain how batteries are transported, reflect the existing network and infrastructure, or provide suggestions for reducing the burden of transportation.

To provide more insight into the factors influencing the impact of transportation, we also reviewed the relevant regulations and industry landscape in the United States. This section was partially guided by interviews with stakeholders who work in battery transportation and storage.

3. Results

3.1. Economics

Of the 60 articles reviewed, 17 include transportation in an analysis of the cost or economics of recycling (Alfaro-Algaba and Ramirez, 2020; Choubey et al., 2017; Fan et al., 2020; Foster et al., 2014; Hendrickson et al., 2015; Idjis and da Costa, 2016; Li et al., 2018; Ma et al., 2018; Sato and Nakata, 2020, 2021; Sun et al., 2020; Tang et al., 2018; L. Wang et al., 2020a; Wang and Yu, 2021; Wang et al., 2014; Zhang et al., 2018a, b). Of these 17, 11 report the disaggregated transportation cost used in their analysis (Table 1). The average estimated cost of transportation is \$1.54/kg, with values varying widely between studies from \$0.24/kg (Hoyer et al., 2015) to \$5.51/kg (Foster et al., 2014). Six studies reported the cost of transportation as a percent of total recycling cost (or provided sufficient data to conduct this calculation), resulting in an average contribution to total recycling cost of 41%. Fig. 2

The variability in cost estimates and assumptions may be partially attributable to regional differences, as transportation costs will vary based on local fuel and labor costs. However, the majority of articles do not justify or even state key assumptions such as distance traveled or mode of transport, even when transportation is reported to be a significant cost with decisive effects on the economics of recycling (e.g. Idjis and Da Costa, 2016). This makes it impossible to determine the contribution of different cost drivers and the cause of such high variability

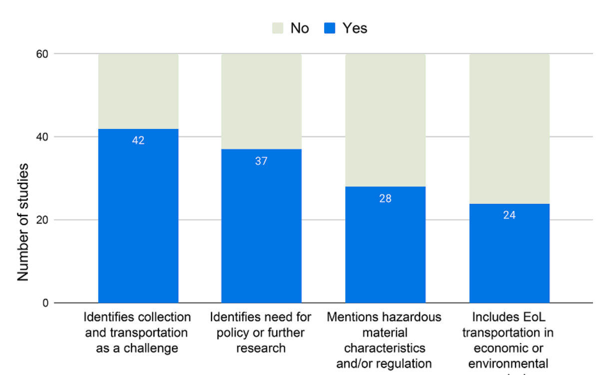

Fig. 1. Breakdown of how transportation is addressed in articles selected for analysis.

[1] The complete list of articles reviewed and corresponding information is included as a spreadsheet in the supplementary materials.

Table 1
Studies that specify a disaggregated transportation cost.

Study	Location	Transport cost	Normalized cost ($/kg)	% of total cost	Additional Assumptions
(Foster et al., 2014)	United States	$2.50/ lb.	$5.51	46%	Transport of a Chevrolet Volt battery (500 lbs) from Detroit to Lancaster, OH. Cost ($2.50/lb.) is quoted from USPS large freight and hazardous materials division.
(X. Wang et al., 2014)	North America	$1120/ton	$1.12	40%	Transportation is assumed to be 40% of variable costs for recycling, which also include collection and processing. Variable costs are $2800, which is the mean of data taken from a variety of older references about the overall cost of battery recycling.
(Hoyer et al., 2015)	Germany	$215.25/ BEV-eq. (330 kg)	$0.71		Cost level assuming one collection facility.
		$72.12/ BEV-eq. (330 kg)	$0.24		Cost level assuming 25 collection facilities.
(Idjis and da Costa, 2016)	European Union	$1660.36/ ton	$1.66		Not stated.
Choubey et al	Unspecified	$3039.50/ ton	$3.04	53%	Not stated.
(Li et al., 2018)	Unspecified	$8.00/ battery-km	NA		Not stated.
(Ma et al., 2018)	Shenzhen	$302.62/ ton	$0.30		Transport cost is obtained from a market investigation in Shenzhen, China, and includes fuel fees and tolls. Cost is estimated at full load circumstances.
(Zhang et al., 2018b)	Unspecified	$411.00/ ton	$0.41	63%	Not stated.
(Alfaro-Algaba & Ramirez, 2020)	Spain	$1096.32/ truckload	NA		Authors estimate the total cost for transporting and handling 500 batteries to be €11,520, which implies that roughly 42 hybrid batteries are shipped per truckload. The weight and capacity of batteries are not specified.
(Dai et al., 2019)	United States	$2.09/ kg	$2.09	38%	Battery travels 50 miles to collection, 50 miles from collection to disassembly, 1000 miles from disassembly to recycler. All transportation is via truck; all materials prior to the recycling process are hazardous, and the shipping cost is estimated to be $1.93/ ton-mile.
(Sun et al., 2020)	China	$36,209.84 (Units unspecified)	NA		Not stated; transportation is included as a component of the initial investment, but the authors do not justify the value of the assumed cost.
(Wang et al., 2020)	China	$158.00/ battery (365 kg)	$0.43	4.8%	Assumes a straight-line distance between the coordinates of collection and recycling facilities in the existing network of a Chinese manufacturer (Chang'an).
(Wang and Wu, 2017)	China	$0.07/ton-km	NA		Based on the average transportation fee for waste LIBs in China.

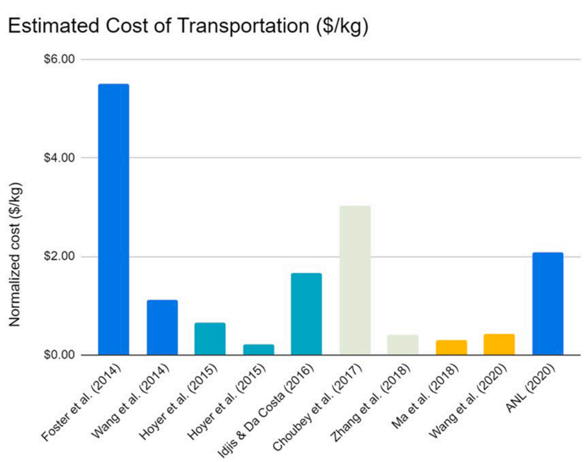

Fig. 2. Cost estimates for EoL transportation. The euro-to-dollar conversion rate is based on the year of publication, using exchange rates from OECD Data. The yuan-to-dollar conversation rate for the publication year was obtained from the US Federal Reserve.

among studies.

Foster et al. (2014), Ma et al. (2018), and Alfaro-Algaba & Ramirez (2020) provide the most detailed explanations behind their assumed cost. Foster et al. specify the battery type and weight (500 lb. Chevrolet Volt battery), estimate the distance traveled based on real-world locations, and obtain a price quote from a specific carrier (the US Postal Service). Notably, their estimated cost is significantly higher than any other study. Ma et al. and Alfaro-Algaba & Ramirez both appear to calculate the cost based on a full truckload, which is important to specify since full truckload shipments are more cost-effective on a per-battery basis. However, to take advantage of the benefits presented by full truckload service, the batteries must be consolidated at a collection point before shipment. For example, achieving the cost presented by Alfaro-Algaba & Ramirez requires 42 hybrid batteries to be shipped per truckload.

More detailed assumptions regarding transportation are also included in the most recent version of EverBatt, a recycling cost and LCA modeling tool from Argonne National Laboratory (Dai et al., 2019). The model uses a shipping cost of $1.93 per ton-mile, which includes a hazardous material insurance premium, based on operational cost data for freight trucking from the American Transportation Research Institute (ATRI). Under the default distance assumptions, this translates to $2.09/kg. The cost difference between EverBatt and Foster et al. may be partially due to EverBatt using operational cost data for motor carriers, while Foster et al. use prices quoted from the US Postal Service.

Several articles include transportation in their analysis, but do not report the cost separately. Fan et al. (2020) state that economic and environmental analysis should include collection and transportation costs and report the results of other studies related to transport. However, they exclude the cost of collection and transportation from the results of their own analysis. Sato & Nakata assume a cost of $94–141 (10,000–15,000 yen) per unit of hybrid vehicle battery for processing and transportation, but processing and transport are not reported separately.

Finally, several studies discuss transportation cost in the context of system optimization. Wang et al. (2020) find that optimizing the recycling network of Chang'an, a Chinese manufacturer, would reduce transportation costs by 22.9%. Interestingly, this study presents by far the lowest value of transportation as a percentage of overall recycling cost: 4.8% as a baseline, or 4% with optimization. These numbers only account for transportation from the collection center to the recycling facility and do not include the initial transportation to the collection center. Hendrickson et al. (2015) use an optimization model to identify the optimal infrastructure siting scenario for battery recycling in California, considering both transportation and capital cost, although they do not specify the value of their assumed transportation cost. Assuming pyrometallurgical recycling, they use sensitivity analysis to examine the tradeoff between transportation cost savings and capital cost expenditures, finding an optimal facility size of 7000 tons per year and associated marginal cost of $37/ton, which includes both capital and transportation costs. To minimize the ton-kilometers traveled between collection and recycling, the authors conclude that the most efficient system is to have two collection points near San Francisco and Los Angeles, with one recycling facility in between.

3.2. Environmental impact

Ten articles accounted for EoL transportation in an assessment of the environmental impact of lithium-ion battery reuse (Mathur et al., 2019; Richa et al., 2017) or recycling (Accardo et al., 2021; Cerdas et al., 2018; Ciez and Whitacre, 2019; Hendrickson et al., 2015; Rahman et al., 2017; Wang et al., 2020; Wang and Yu, 2021; Xiong et al., 2019a). However, only five discuss or report the results separately. These can be generally categorized as studies that report the relative contribution of EoL transport as a percentage of overall emissions (Accardo et al., 2021; Ciez & Whitacre, 2019; Xiong et al., 2019; Hendrickson et al., 2015), and studies that calculate the potential to reduce EoL transportation emissions, either through reuse (Mathur et al., 2019), recycling (Rahman et al., 2017), or system optimization (Hendrickson et al., 2015; Wang et al., 2020).

Where studies report the relative GHG impact of transportation, it is minor, ranging from less than 1% (Accardo et al., 2021) to 3.5% (Ciez & Whitacre, 2019). However, these estimates are relative to the entire life cycle impact of batteries from recycled vs. virgin materials, including production. For example, Ciez & Whitacre use LCA to estimate the greenhouse gas (GHG) emissions and energy inputs associated with batteries produced from recycled materials, comparing pyrometallurgical, hydrometallurgical, and direct physical recycling of different battery chemistries and formats. They include a parametric analysis of transportation impacts, assuming batteries are transported 2500 miles by truck. The authors find that transportation makes a minimal contribution (3.5 - 4%) to the life-cycle greenhouse gas emissions of batteries made from recycled materials. By contrast, Hendrickson et al. focus on EoL and examine life cycle impacts beyond GHG emissions, highlighting the impact of transportation on local air quality. Under their baseline scenario, freight trucking is found to contribute 99% of human health damages from particulate matter (PM), 54% of SO_2 damages, and 62% of total volatile organic compound (VOC) damages. While the authors assume all transportation will be handled by truck, they find that using rail instead could lower the GHG emissions from transportation by 45%.

Mathur et al. and Rahman et al. assess the environmental benefits of reuse and recycling, respectively. Mathur et al. find that reuse reduces emissions from transportation compared to sending batteries directly to recycling, while Rahman et al. find that recycling avoids emissions compared to sending batteries to a landfill. However, in both cases the authors assume that the reuse or recycling facility is co-located with the dismantling facility, which is unrealistic. Wang et al. (2020) assess the benefits of optimizing collection and recycling infrastructure siting, which they find can reduce carbon emissions by 21.8%, mainly due to reduced transportation.

3.3. Hazardous material regulations and producer responsibility

Nearly half ($n = 28$) of the articles reviewed mention the safety hazard associated with transporting LIBs and corresponding regulations. Several papers point out that the complexity of hazardous material transportation regulations is an added cost that complicates battery recycling (e.g. Harper et al., 2019; Thompson et al., 2020; (Ahuja et al., 2020) (Skeete et al., 2020)). Moore et al. (2020) spatially model a second-life deployment scenario in Berlin and identify transport routes that minimize distance to ensure safety compliance, rather than reduce cost. The risk of fire hazard was also mentioned by (Reinhardt et al., 2019) as a motivating factor towards clear legislation allocating liability for second-life batteries.

The other key policy issue is allocating responsibility for collection and transportation (Gaines et al., 2018; Kellner and Goosey, 2020). Under the EU battery directive, the producer is obligated to ensure that batteries placed on the market are properly recycled and set up take-back systems that facilitate collection at no cost to the owner either directly or through a third party acting on their behalf (Hoyer et al., 2015; Kellner and Goosey, 2020; Richa et al., 2017). Car manufacturers or importers are also responsible for the collection, sorting, storage, and transportation of batteries in China under the Provisional Regulation on the Recycling and Reuse of Traction Batteries from New Energy Vehicles (NEV) (Gaines et al., 2018). Clarifying producer responsibility in cases where the battery is repurposed for stationary storage by a third party is identified as a policy need (Richa et al., 2017).

4. Gaps: safety, cost structure, and existing network

To inform future research, the following sub-sections contain detail on the context of how batteries are typically shipped in the United States, including the regulatory framework and required safety protocols, operational cost and pricing, and the existing network of battery recyclers and collectors. The purpose of this section is to provide context-specific parameters that can be used by researchers who are analyzing the situation in North America. Similar information about other regions of interest would be a valuable area for additional study.

4.1. Regulatory framework and safety protocols

In the United States, LIB shipments are regulated by the Department of Transportation (DOT) as a Class 9 ("Miscellaneous") hazardous material. Shipping requirements for LIBs are specified under the DOT Code of Federal Regulations (CFR) §173.185. Batteries that are shipped for disposal are exempted from certain classification and packaging requirements but must be packaged in a manner to prevent short circuits, damage caused by movement or placement within the package, and accidental activation of the equipment (Pipeline and Hazardous Materials Safety Administration, Paragraph (B) (1)). Packages containing LIBs must also meet hazard communication requirements by displaying a lithium battery mark. However, there are no specific placarding requirements for the vehicle transporting them beyond the Class 9 Miscellaneous Waste symbol. This reduces the cost of shipping but also means if there is an accident on the road that leads to a fire, the fact that it is a battery fire requiring special protocol will not be obvious to first responders until they look at the paperwork or package labels.

Damaged or defective batteries are subject to more stringent regulations; they are classified as Packaging Group 1 in the United Nations (UN) Manual of Tests and Criteria, indicating highest danger, and must be shipped in a UN-certified container (Huo et al., 2017). Given that the shape and size of EV batteries vary by make and model, such containers currently must be custom ordered from dangerous goods manufacturers at great expense.

Shipping is typically handled by third-party logistics companies, often through large commonly recognized carriers who have their own guidelines that comply with both federal and international regulations (Huo et al., 2017). However, the responsibility for packaging, marking, labeling, and completing documentation for dangerous goods regulations falls to the party who is holding and wants to ship the battery, not the carrier (FedEx, 2021). The complexity of navigating regulations and following proper safety protocol suggests that shippers with knowledge and experience will be necessary actors in a functioning circular EV EoL system (Kellner and Goosey, 2020).

The United States does not have an extended producer requirement for electric vehicle batteries, so the party responsible for paying the cost of transportation is contract-specific rather than being dictated by policy. This may present an issue in the future as out-of-warranty batteries

Table 2
Studies that report the environmental impact of transportation.

Authors	EOL stage(s)	Geographic focus	Results
(Accardo et al., 2021)	Recycling	European Union	Does not specify the value of EoL transportation impact but states that "transport of batteries contributes less than 1% to all the examined categories."
(Ciez & Whitacre, 2019)	Recycling	United States	Transportation contributes 3.5% of GHG emissions of batteries produced from recycled materials. The study assumes batteries travel 4023 km (2500) miles by truck to reach their destination.
(T.P. Hendrickson et al., 2015)	Recycling	California	Freight trucking contributes 99% of human health damages from particulate matter (PM), 54% of SO_2 damages, and 62% of total volatile organic compound (VOC) damages.
(Rahman et al., 2017)	Recycling	Global/ Unspecified	Transportation emissions are 572 g CO_2 if the battery is not recycled vs 110 g CO_2 with recycling. The impact is based on the fuel consumption (121 L/km) of a diesel pickup with a 500 kg payload. Assumes battery exchange workshop and recycling facility are co-located, distance from exchange workshop to landfill is 20 km, and distance from recycling facility to landfill is 8 km.
(Xiong et al., 2019b)	Recycling	China	Transportation accounts for 2.5% of vehicle cycle energy consumption. EoL transportation is modeled from production plant to service shop (1600 km).
(Mathur et al., 2019)	Reuse, Recycling	United States	Reuse avoids 17.78 kg of CO_2 emissions from transportation compared to direct recycling, assuming that dealership, diagnostic center, and PV industry are co-located. Transport is modeled assuming a light commercial diesel truck using Southwest US transport fuel mix.
(Wang et al., 2020)	Recycling	China	Optimizing the system reduced carbon emissions by 21.8%, mainly due to the reduced need for transportation. Baseline emissions from transportation not reported.

may be dismantled by small auto dismantlers, scrap metal recyclers, or private repair facilities for whom the cost of shipping could be a burden that discourages optimal disposal or dissuades them from acquiring the vehicle in the first place.

4.2. Cost structure

The operational cost of freight transport is dependent on a variety of vehicle-based and driver-based costs. Vehicle-based costs include fuel, vehicle lease or purchase payments, repair and maintenance, insurance, permits and special licenses, and tolls. Driver-based costs are wages and benefits. The operational cost varies by the size and service provided by the motor carrier, as well as by region due to differences in fuel cost, tolls, and labor cost for drivers and repair and maintenance (Williams and Murray, 2020). The cost of shipping is also dependent on the transportation corridor; if the destination is in a remote location, the carrier may not be able to generate revenue through a backhaul shipment and will charge a higher price.

Batteries may be shipped using less-than-truckload (LTL) or full truckload (FTL or TL) services. LTL, which is generally used for shipments up to 15,000 lbs., means the shipper reserves a certain amount of space in a container that is also carrying additional products, and is often charged by weight (Redwood, 2021). FTL means the shipment is transported on a dedicated freight truck and is charged by distance. The operational cost of freight trucking is higher for companies that specialize in LTL (Table 2), and the higher price means the per-unit cost to ship a small quantity of batteries could theoretically exceed the cost of sending an FTL shipment a longer distance in some cases. Furthermore, LTL shipments may be cross-docked, meaning the product is transferred at a terminal from its original truck or rail car to a different outbound vehicle. If this occurs overnight and the terminal is closed, the facility will need to be equipped to properly store dangerous goods and may need approval from the local fire department to store the batteries (Haltrecht, 2020).

This highlights the link and tradeoff between transportation and storage; consolidating batteries at specified collection points may make reverse logistics more efficient as truckload size and volume will affect the cost of shipping. However, storing batteries is costly and associated with its own safety hazards, which could make the prospect of accumulating batteries less attractive depending on the required amount of time. Table 3

4.3. Existing network

Transportation assumptions can be better informed by considering existing infrastructure when assessing recycling pathways. In this sense, it is important to keep track of industry developments, which is not always easy given the fast pace at which the private sector is advancing. Multiple new recycling companies have been announced in the past several years and are now in the pilot phase, most of them using a hydrometallurgical process (Fig. 3). This challenges a common assertion that pyrometallurgical recycling will continue to be the most likely fate for retired LIBs in the United States, which manifests in previous studies' assumptions that batteries will be shipped to a centralized facility in Lancaster, Ohio.

Additional facilities are planned in Gilbert, Arizona; Sonora, Mexico; and Endicott, NY, although the facility in Endicott has been delayed due to local opposition (Kumagai, 2021; NewsChannel, 2021).

5. Discussion

We find that while transportation of EoL batteries is mentioned as an important contributing factor to recycling costs and environmental impacts, it is rarely assessed in detail or with dedicated research. Among papers that do address transportation, important parameters including truckload size, safety precautions, and in some cases even distance are not specified, although all are important to understand and affect the economics and environmental performance of recycling. Conclusive findings on the relative importance of transport to the environmental impact of reuse or recycling are unclear, especially contributions to GHG emissions. Nonetheless, (Hendrickson et al., 2015) demonstrated that transport contributes significantly to human health damages from criteria pollutants, which illustrates the importance of addressing local impacts as well as GHGs. Notably, all articles reviewed (both economic and environmental) assume that batteries will be transported by truck, although rail transport would have a significantly lower environmental impact. While transport via freight truck is the standard practice today, it is not required by law in the United States.

Table 3
Average marginal cost for freight trucking operations in the United States. Marginal cost does not include insurance premium or other added cost from dangerous goods precautions. Source: ATRI, 2020.

Average Marginal Cost ($/km) By Sector		By Region	
LTL	1.15	Midwest	1.05
Specialized	1.15	Northeast	1.15
TL	0.96	Southeast	0.97
Average	1.03	Southwest	0.96
		West	1.01

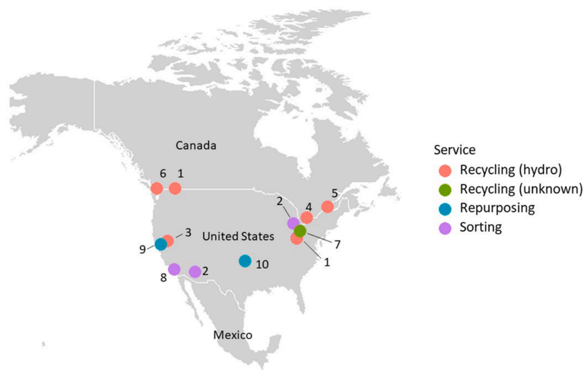

Fig. 3. Lithium-ion battery recycling facilities that are operational, at least at a pilot scale, in North America.

Where it is analyzed in papers discussing cost, transportation significantly affects the economics of recycling, contributing over 40% of recycling cost on average and potentially determining whether or not recycling will be a profitable pursuit. This indicates that the motivation for reducing the burden of transport may be driven by improving the economics of recycling, rather than reducing its corresponding GHG emissions. The relatively minor GHG impact was cited by one study as the basis for excluding EoL transport from environmental analysis ((Ahmadi et al., 2017), and may explain why it was more commonly included in economically focused articles. The insight on cost and spatial impacts demonstrated by Hendrickson et al. (2015), Hoyer et al. (2015), and Wang et al. (2020) points to optimized system design as a promising area for future research. When considering the siting for new facilities, researchers should ensure that the current state of the industry is reflected by seeking out and incorporating knowledge of the existing network.

Strategic facility siting that minimizes distance is the most common suggestion to reduce the cost of transportation or make it more efficient (Gaines et al., 2018; Thompson et al., 2020; Wang et al., 2020; (Kellner and Goosey, 2020); Li et al., 2018). Minimizing transport distance is also preferable from a safety perspective (Kellner and Goosey, 2020; Moore et al., 2020). (Larouche et al., 2020) suggest that companies design smaller local process plants or distributed crushing facilities to shorten transport distance, noting that transporting only black mass to central processing plants would neutralize safety concerns. Facilitating access to accurate information about the battery's state of health (SOH) early on in the chain of custody would also reduce the burden of transportation by ensuring batteries are sent to the appropriate facility (i.e. only batteries with a high SOH are sent for reuse or repurposing) and avoiding unnecessary shipments. This would also lower the cost and environmental impact of repurposing by reducing the number of modules that must be tested onsite (Neubauer et al., 2015; K. Richa et al., 2017).

The regional differences in operational transportation costs indicate that optimization research on infrastructure siting can more effectively inform policy by using place-specific parameters. This would allow for a more accurate estimation of the transportation, capital, and operational expenditures among areas with varying property, energy, fuel, and labor costs, as well as differences in environmental impact due to grid mix or local pollution standards. Researchers should also incorporate qualitative information about areas of interest, in addition to seeking a quantitatively optimal solution. The regulatory environment and cost of operation are likely to affect the feasibility of building a recycling facility in a given location, which should be taken into account when evaluating alternatives. For example, in the United States, the stringency of environmental regulations governing hazardous waste management may vary by state under the Resource Recovery Act, (US EPA, n.d.). This is likely to make certain states more favorable for recycling operations than others.

It is also important to account for the local social and political context and evaluate potential developments with an environmental justice lens. For example, the negative air quality impacts reported by Hendrickson et al. from freight trucking are concentrated in communities surrounding transportation corridors, many of which are known to be environmental justice communities that are disproportionately Black and Latinx (Morello-Frosch et al., 2002). The facilities themselves, while potentially a source of employment and economic benefits, also risk perpetuating historic harm and inequality if local impacts are not accounted for and mitigated. The case of the contested SungEel facility in Endicott, NY exemplifies this tension; in press releases, the company emphasized the economic benefit, while a local activist group (NoBurnBroome) strongly opposed the project due to concerns over the impact of its incineration process on public health (NewsChannel, 2021). Both the environmental impact and the history of the community contributed to the ensuing conflict; NoBurnBroome issued a statement that "SungeEel seems oblivious of the assault on the health of the citizens of Endicott by previous industrial operations," referring to a previous IBM facility in the same location (Connett et al., 2020).

6. Conclusion

To avoid burden-shifting from greenhouse gas emissions to local impacts from mining, refining, and potentially recycling, climate mitigation strategies must include provisions to ensure that vehicle electrification is consistent with the three pillars of sustainability – social, environmental, and economic. As it relates to EoL management, this means batteries should be transported to a facility that incurs the lowest environmental impact and maximum social benefit, in addition to being economically efficient. Identifying the socially, economically, and environmentally optimal EoL system will require knowledge of the transportation path and associated emissions (including local pollutants), as well as the impact of the recycling process and characteristics of the surrounding communities. Analyzing the economic feasibility will require accurately accounting for all potential costs, including collection and transportation. On a practical level, the qualitative intricacies of transportation logistics must be examined in detail to identify opportunities to reduce cost and promote worker safety.

The literature review conducted in this article revealed that while in research about lithium-ion battery recycling, it is common practice to state assumptions related to battery chemistry and material recovery, most papers are less specific regarding collection and transportation, or in many cases omit this phase entirely. This is because most studies focus on the recycling or repurposing process, without discussing the pathway from retirement to treatment facility. Where it is included, the large proportion of transportation costs, substantial cost variance between literature, and lack of detail in the calculations demonstrate there is a crucial information gap in the literature. To address this issue, we recommend that researchers studying battery EoL be deliberate about including transportation and state the reasoning behind their cost assumptions; for example, by using a regionally-specific industry average; specifying the mode of transport, distance, fuel cost, and truckload size; and/or by referring to a quoted price from a specific carrier. The detailed options provided in the latest version of EverBatt can also be used to facilitate future analysis that incorporates transportation in both economic and environmental analysis. Another promising opportunity for future research is regionally optimized system design that identifies preferable facility siting while considering cost, GHG emissions, and local environmental and social impacts.

Finally, given the complexity of safely transporting batteries in compliance with regulations and the economic advantages of shipping batteries in bulk, facilities that collect and store batteries will be a critical component of the EoL ecosystem. The safety, cost, and regulatory considerations of storing batteries would be a valuable area for future study, as would further exploration of the actual pathway between retirement and collection. For example, while Hendrickson et al.

assume batteries will be collected at dealerships, they may also be exported, sold at insurance auctions, purchased, and resold by auto dismantlers, or even used by do-it-yourself enthusiasts in off-grid homes. The details of how this unfolds and who is involved must be understood to craft policy that effectively brings the batteries back into the collection points and recycling facilities of a circular LIB EoL system.

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.

Acknowledgments

Thank you to Jeff Haltrecht of Call2Recycle for providing insight and clarification on the North American battery recycling network. This study was funded, partially or entirely, by a grant from the National Center for Sustainable Transportation (NCST) entitled “Sustainable Management of Retired Electric Vehicle Batteries,” supported by the U. S. Department of Transportation’s University Transportation Centers Program. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange and does not necessarily reflect the official views or policies of the U.S. Government. The U.S. Government assumes no liability for the contents or use thereof.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105755.

References

Accardo, A., Dotelli, G., Musa, M.L., Spessa, E., 2021. Life cycle assessment of an NMC battery for application to electric light-duty commercial vehicles and comparison with a sodium-nickel-chloride battery. Appl. Sci. (Switz.) 11 (3), 1–32. https://doi.org/10.3390/app11031160.

Ahmadi, L., Yip, A., Fowler, M., Young, S.B., Fraser, R.A., 2014. Environmental feasibility of re-use of electric vehicle batteries. Sustain. Energy Technol. Assess. 6, 64–74. https://doi.org/10.1016/j.seta.2014.01.006.

Ahmadi, L., Young, S.B., Fowler, M., Fraser, R.A., Achachlouei, M.A., 2017. A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. Int. J. Life Cycle Assess. 22 (1), 111–124. https://doi.org/10.1007/s11367-015-0959-7.

Ahuja, Jyoti, Dawson, L., Lee, R., 2020. A circular economy for electric vehicle batteries: driving the change. Journal of Property, Planning and Environmental Law 12 (3). https://doi.org/10.1108/JPPEL-02-2020-0011. In press.

Ai, N., Zheng, J., Chen, W.Q., 2019. U.S. end-of-life electric vehicle batteries: dynamic inventory modeling and spatial analysis for regional solutions. Resour. Conserv. Recycl. 145, 208–219. https://doi.org/10.1016/j.resconrec.2019.01.021.

Alfaro-Algaba, M., Ramirez, F.J., 2020. Techno-economic and environmental disassembly planning of lithium-ion electric vehicle battery packs for remanufacturing. Resour. Conserv. Recycl. 154 https://doi.org/10.1016/j.resconrec.2019.104461.

Ambrose, H., Kendall, A., 2019a. Understanding the future of lithium: part 1, resource model. J. Ind. Ecol. https://doi.org/10.1111/jiec.12949.

Ambrose, H., Kendall, A., 2019b. Understanding the future of lithium: part 2, temporally and spatially resolved life-cycle assessment modeling. J. Ind. Ecol. https://doi.org/10.1111/jiec.12942.

Baars, J., Domenech, T., Bleischwitz, R., Melin, H.E., Heidrich, O., 2020. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nat. Sustain. 4 (1), 71–79. https://doi.org/10.1038/s41893-020-00607-0.

Banza Lubaba Nkulu, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N.D., Kayembe-Kitenge, T., Musa Obadia, P., Kyanika Wa Mukoma, D., Lunda Ilunga, J.-.M., Nawrot, T.S., Luboya Numbi, O., Smolders, E., Nemery, B., 2018. Sustainability of artisanal mining of cobalt in DR Congo. Nat. Sustain. 1 (9), 495–504. https://doi.org/10.1038/s41893-018-0139-4.

Bobba, S., Mathieux, F., Ardente, F., Blengini, G.A., Cusenza, M.A., Podias, A., Pfrang, A., 2018. Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. J. Energy Storage 19, 213–225. https://doi.org/10.1016/j.est.2018.07.008.

Redwood Logistics. (2021). LTL (Less than Truckload) vs. FTL (Full Truckload) Shipping Rates. Redwood Logistics. Retrieved from https://www.redwoodlogistics.com/ltl-less-than-truckload-vs-ftl-full-truckload-shipping-rates/ Date accessed: 4 February 2021.

2021 CARB. (2021). Zero-Emission Vehicle Program. California Air Resources Board. Retrieved from https://ww2.arb.ca.gov/our-work/programs/zero-emission-vehicle-program. Date accessed: 25 January 2021.

Dai, Q., Spangenberger, J., Ahmed, S., Gaines, L., Kelly, J. C., & Wang, M. (2019). EverBatt: A closed-loop battery recycling cost and environmental impacts model. Argonne National Laboratory. Retrieved from https://publications.anl.gov/anlpubs/2019/07/153050.pdf Date accessed: 1 July 2021.

Casals, L.C., Amante García, B., & Canal, C. (2019). Second life batteries lifespan: rest of useful life and environmental analysis. J. Environ. Manage.. 10.1016/j.jenvman.2018.11.046.

Cerdas, F., Andrew, S., Thiede, S., Herrmann, C., 2018. Environmental aspects of the recycling of lithium-ion traction batteries. Sustain. Product. Life Cycle Eng. Manag. https://doi.org/10.1007/978-3-319-70572-9_16.

Choubey, P.K., Chung, K.S., Kim, seuk, M., Lee chun, J., Srivastava, R.R., 2017. Advance review on the exploitation of the prominent energy-storage element Lithium. Part II: from sea water and spent lithium ion batteries (LIBs). Miner. Eng. 110, 104–121. https://doi.org/10.1016/j.mineng.2017.04.008.

Ciez, R.E., Whitacre, J.F., 2019. Examining different recycling processes for lithium-ion batteries. Nat. Sustain. 2 (2), 148–156. https://doi.org/10.1038/s41893-019-0222-5.

Connett, P., Chmm, J.R., Connett, E., Fiedler, G., & Kowalski, M.A. (2020). NoBurnBroome Position Paper On the SungEel project Proposed For Endicott (Updated).

Cusenza, M.A., Guarino, F., Longo, S., Ferraro, M., Cellura, M., 2019. Energy and environmental benefits of circular economy strategies: the case study of reusing used batteries from electric vehicles. J. Energy Storage 25. https://doi.org/10.1016/j.est.2019.100845.

Dai, Q., Kelly, J.C., Gaines, L., Wang, M., 2019. Life cycle analysis of lithium-ion batteries for automotive applications. Batteries, 5 (2), 48. https://doi.org/10.3390/batteries5020048.

Dunn, J.B., Gaines, L., Kelly, J.C., James, C., Gallagher, K.G., 2015. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling’s role in its reduction. Energy Environ Sci 8 (1), 158–168. https://doi.org/10.1039/C4EE03029J.

Dunn, J., Slattery, M., Kendall, A., Ambrose, H., & Shen, S. (2021). Circularity of lithium-ion battery materials in electric vehicles. Environ. Sci. Technol.. 10.1021/acs.est.0c07030.

Fan, E., Li, L., Wang, Z., Lin, J., Huang, Y., Yao, Y., Chen, R., Wu, F., 2020. Sustainable recycling technology for Li-ion batteries and beyond: challenges and future prospects. Chem. Rev. 120 (14), 7020–7063. https://doi.org/10.1021/acs.chemrev.9b00535.

FedEx. (2021). How to Ship Batteries. Retrieved from https://www.fedex.com/en-us/shipping/how-to-ship-batteries.html Date accessed: April 2, 2021.

Fletcher, S. (2013). Bottled lightning: superbatteries, electric cars, and the new lithium economy. Choice Rev.Online. 10.5860/choice.49-1488.

Foster, M., Isely, P., Standridge, C.R., Hasan, M.M., 2014. Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries. J. Ind. Eng. Manag. 7 (3), 698–715. https://doi.org/10.3926/jiem.939.

Gaines, L., Richa, K., Spangenberger, J., 2018. Key issues for Li-ion battery recycling. MRS Energy Sustain. 5 (1) https://doi.org/10.1557/mre.2018.13.

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., Anderson, P., 2019. Recycling lithium-ion batteries from electric vehicles. Nature 575 (7781), 75–86. https://doi.org/10.1038/s41586-019-1682-5.

Heelan, J., Gratz, E., Zheng, Z., Wang, Q., Chen, M., Apelian, D., Wang, Y., 2016. Current and prospective Li-ion battery recycling and recovery processes. JOM 68 (10), 2632–2638. https://doi.org/10.1007/s11837-016-1994-y.

Hendrickson, T.P., Kavvada, O., Shah, N., Sathre, R., D Scown, C., 2015. Life-cycle implications and supply chain logistics of electric vehicle battery recycling in California. Environ. Res. Lett. 10 (1) https://doi.org/10.1088/1748-9326/10/1/014011.

Hoyer, C., Kieckhäfer, K., Spengler, T.S., 2015. Technology and capacity planning for the recycling of lithium-ion electric vehicle batteries in Germany. J. Bus. Econ. 85 (5), 505–544. https://doi.org/10.1007/s11573-014-0744-2.

Hua, Y., Zhou, S., Huang, Y., Liu, X., Ling, H., Zhou, X., Zhang, C., Yang, S., 2020. Sustainable value chain of retired lithium-ion batteries for electric vehicles. J. Power Source. 478 https://doi.org/10.1016/j.jpowsour.2020.228753.

Huo, H., Xing, Y., Pecht, M., Züger, B.J., Khare, N., & Vezzini, A. (2017). Safety requirements for transportation of lithium batteries. Energies. 10.3390/en10060793.

Idjis, H., da Costa, P., 2016. Is electric vehicles battery recovery a source of cost or profit? The Automobile Revolution: Towards a New Electro-Mobility Paradigm. Springer International Publishing, pp. 117–134. https://doi.org/10.1007/978-3-319-45838-0_8.

IEA. (2020). Global EV Outlook 2020. https://www.iea.org/reports/global-ev-outlook-2020.

Kellner, R., Goosey, E., 2020. Chapter 9: the recycling of lithium-ion batteries: current and potential approaches. Issue. Environ. Sci. Technol. 49 https://doi.org/10.1039/9781788018784-00246.

Kelly, J.C., Dai, Q., & Wang, M. (2019). Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. Mitigation and Adaptation Strategies For Global Change. 10.1007/s11027-019-09869-2.

Kumagai, J. (2021, January 5). Lithium-ion battery recycling finally takes off in North America and Europe - IEEE spectrum. IEEE Spectr.. https://spectrum.ieee.org/

energy/batteries-storage/lithiumion-battery-recycling-finally-takes-off-in-north-america-and-europe.

Larouche, F., Tedjar, F., Amouzegar, K., Houlachi, G., Bouchard, P., Demopoulos, G.P., Zaghib, K., 2020. Progress and status of hydrometallurgical and direct recycling of Li-Ion batteries and beyond. Materials 13 (3). https://doi.org/10.3390/ma13030801.

Li, L., Dababneh, F., Zhao, J., 2018. Cost-effective supply chain for electric vehicle battery remanufacturing. Appl. Energy 226, 277–286. https://doi.org/10.1016/j.apenergy.2018.05.115.

Lv, W., Wang, Z., Cao, H., Sun, Y., Zhang, Y., & Sun, Z. (2017). A Critical Review and Analysis on the Recycling of Spent Lithium-Ion Batteries. ACS Sustainable Chem. and Eng. (Vol. 6, Issue 2,1504-1521). 10.1021/acssuschemeng.7b03811.

Ma, X., Ma, Y., Zhou, J., Xiong, S., 2018. The recycling of spent power battery: economic benefits and policy suggestions. IOP Confer. Ser. 159 (1), 12017. https://doi.org/10.1088/1755-1315/159/1/012017.

Mathur, N., Deng, S., Singh, S., Yih, Y., Sutherland, J.W., 2019. Evaluating the environmental benefits of implementing Industrial Symbiosis to used electric vehicle batteries. Procedia CIRP 80, 661–666. https://doi.org/10.1016/j.procir.2019.01.074.

Mayyas, A., Steward, D., Mann, M., 2019. The case for recycling: overview and challenges in the material supply chain for automotive li-ion batteries. Sustain. Mater. Technol. 19 https://doi.org/10.1016/j.susmat.2018.e00087.

Melin, H.E. (2019). State of the art in reuse and recycling of lithium-ion batteries-A research review. Report commissioned by the Swedish Energy Agency. Retrieved from https://www.energimyndigheten.se/globalassets/forskning–innovation/overgripande/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf. Date accessed: 25 January 2021.

Moore, E.A., Russell, J.D., Babbitt, C.W., Tomaszewski, B., Clark, S.S., 2020. Spatial modeling of a second-use strategy for electric vehicle batteries to improve disaster resilience and circular economy. Resour. Conserv. Recycl. 160 https://doi.org/10.1016/j.resconrec.2020.104889.

Morello-Frosch, R., Pastor, M., Porras, C., Sadd, J., 2002. Environmental justice and regional inequality in Southern California: implications for furture research. Environ. Health Perspect. 110 (SUPPL. 2), 149–154. https://doi.org/10.1289/ehp.02110s2149.

Mossali, E., Picone, N., Gentilini, L., Rodrìguez, O., Pérez, J.M., Colledani, M., 2020. Lithium-ion batteries towards circular economy: a literature review of opportunities and issues of recycling treatments. J. Environ. Manage. 264, 110500 https://doi.org/10.1016/j.jenvman.2020.110500.

Neubauer, J.S., Wood, E., Pesaran, A., 2015. A Second life for electric vehicle batteries: answering questions on battery degradation and value. SAE Int. J. Mater. Manuf. 8 (2) https://doi.org/10.4271/2015-01-1306.

Nordelöf, A., Poulikidou, S., Chordia, M., Bitencourt de Oliveira, F., Tivander, J., Arvidsson, R., 2019. Methodological approaches to end-of-life modelling in life cycle assessments of lithium-ion batteries. Batteries 5 (3), 51. https://doi.org/10.3390/batteries5030051.

Olivetti, E.A., Ceder, G., Gaustad, G.G., Fu, X., 2017. Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. Joule 1 (2), 229–243. https://doi.org/10.1016/j.joule.2017.08.019.

NewsChannel 34. (2021). Update on Endicott battery recycling project. Binghamton Homepage. Retrieved from https://www.binghamtonhomepage.com/news/update-on-endicott-battery-recycling-project/ Date accessed: 25 January 2021.

Pipeline and Hazardous Materials Safety Administration. (2021). Electronic Code of Federal Regulations (eCFR). Retrieved from https://www.ecfr.gov/cgi-bin/text-idx?SID=463e264d43ab547a929fbe9660f1636d&mc=true&node=se49.2.173_1185&rgn=div8 Date accessed: 7 February 2021.

Rahman, A., Afroz, R., Safrin, M., 2017. Recycling and disposal of lithium batteries: an economical and environmental approach. IIUM Eng. J. 18 (2), 238–252. https://doi.org/10.31436/iiumej.v18i2.773.

Rajaeifar, M., Heidrich, O., Ghadimi, P., Raugei, M., Wu, Y., 2020. Sustainable supply and value chains of electric vehicle batteries. Resources, Conservation, & Recycling 161. https://doi.org/10.1016/j.resconrec.2020.104905.

Reinhardt, R., Christodoulou, I., Gassó-Domingo, S., Amante García, B., 2019. Towards sustainable business models for electric vehicle battery second use: a critical review. J. Environ. Manage. 245, 432–446. https://doi.org/10.1016/j.jenvman.2019.05.095.

Richa, K., Babbitt, C.W., Gaustad, G., 2017a. Eco-efficiency analysis of a lithium-ion battery waste hierarchy inspired by circular economy. J. Ind. Ecol. 21 (3), 715–730. https://doi.org/10.1111/jiec.12607.

Richa, K., Babbitt, C.W., Nenadic, N.G., Gaustad, G., 2017b. Environmental trade-offs across cascading lithium-ion battery life cycles. Int. J. Life Cycle Assess. 22 (1), 66–81. https://doi.org/10.1007/s11367-015-0942-3.

Richa, Kirti, Babbitt, C.W., Gaustad, G., Wang, X., 2014. A future perspective on lithium-ion battery waste flows from electric vehicles. Resour. Conserv. Recycl. 83, 63–76. https://doi.org/10.1016/J.RESCONREC.2013.11.008.

Sato, F.E.K., Nakata, T., 2020. Recoverability analysis of critical materials from electric vehicle lithium-ion batteries through a dynamic fleet-based approach for Japan. Sustain. (Switz.) 12 (1). https://doi.org/10.3390/SU12010147.

Sato, F.E.K., Nakata, T., 2021. Analysis of electric vehicle batteries recoverability through a dynamic fleet based approach. Sustain. Prod. Life Cycle Eng. Manag. https://doi.org/10.1007/978-981-15-6779-7_22.

Skeete, Jean-Paul, Wells, Peter, Dong, Xue, Heidrich, Oliver, Harper, Gavin, 2020. Beyond the EVent horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition. Energy Research & Social Science 69. https://doi.org/10.1016/j.erss.2020.101581. In press.

Sun, B., Su, X., Wang, D., Zhang, L., Liu, Y., Yang, Y., Liang, H., Gong, M., Zhang, W., Jiang, J., 2020. Economic analysis of lithium-ion batteries recycled from electric vehicles for secondary use in power load peak shaving in China. J. Clean. Prod. 276 https://doi.org/10.1016/j.jclepro.2020.123327.

Tang, Y., Zhang, Q., Li, Y., Wang, G., Li, Y., 2018. Recycling mechanisms and policy suggestions for spent electric vehicles' power battery -A case of Beijing. J. Clean. Prod. 186, 388–406. https://doi.org/10.1016/j.jclepro.2018.03.043.

Thompson, D.L., Hartley, J.M., Lambert, S.M., Shiref, M., Harper, G.D.J., Kendrick, E., Anderson, P., Ryder, K.S., Gaines, L., & Abbott, A.P. (2020). The importance of design in lithium ion battery recycling-a critical review. In Green Chemistry (Vol. 22, Issue 22, pp. 7585–7603). Royal Society of Chemistry. 10.1039/d0gc02745f.

US EPA. (n.d.). State Authorization under the Resource Conservation and Recovery Act (RCRA). EPA.Gov. Retrieved February 4, 2021, from https://www.epa.gov/rcra/state-authorization-under-resource-conservation-and-recovery-act-rcra.

Wang, L., Wang, X., Yang, W., 2020. Optimal design of electric vehicle battery recycling network – From the perspective of electric vehicle manufacturers. Appl. Energy 275. https://doi.org/10.1016/j.apenergy.2020.115328.

Wang, S., Yu, J., 2021. A comparative life cycle assessment on lithium-ion battery: case study on electric vehicle battery in China considering battery evolution. Waste Manage. Res. 39 (1), 156–164. https://doi.org/10.1177/0734242X20966637.

Wang, W., Wu, Y., 2017. An overview of recycling and treatment of spent LiFePO<inf>4</inf>batteries in China. Resour. Conserv. Recycl. 127, 233–243. https://doi.org/10.1016/j.resconrec.2017.08.019.

Wang, X., Gaustad, G., Babbitt, C.W., Richa, K., 2014. Economies of scale for future lithium-ion battery recycling infrastructure. Resour. Conserv. Recycl. 83, 53–62. https://doi.org/10.1016/j.resconrec.2013.11.009.

Williams, N., & Murray, D. (2020). An Analysis of the Operational Costs of Trucking: 2020 Update. Report prepared by the American Trucking Research Institution. Retrieved from https://truckingresearch.org/wp-content/uploads/2020/11/ATRI-Operational-Costs-of-Trucking-2020.pdf Date accessed: 7 February 2021.

Xiong, S., Ji, J., Ma, X., 2019a. Comparative life cycle energy and GHG emission analysis for BEVs and PHEVs: a case study in China. Energies 12 (5). https://doi.org/10.3390/en12050834.

Zhang, W., Xu, C., He, W., Li, G., Huang, J., 2018a. A review on management of spent lithium ion batteries and strategy for resource recycling of all components from them. In: Waste Management and Research, 36. SAGE Publications Ltd, pp. 99–112. https://doi.org/10.1177/0734242X17744655.

Zhang, X., Li, L., Fan, E., Xue, Q., Bian, Y., Wu, F., Chen, R., 2018b. Toward sustainable and systematic recycling of spent rechargeable batteries. Chem. Soc. Rev. 47 (19), 7239–7302. https://doi.org/10.1039/c8cs00297e.