Title

Where Do Batteries Go When They Die? An Assessment of Battery Disposal Strategies for Battery Electric Buses

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UCLA Institute of Transportation Studies

Where Do Batteries Go When They Die?

An Assessment of Battery Disposal Strategies for Battery Electric Buses

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Client: WSP Global Inc.

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Disclaimer

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Where Do Batteries Go When They Die? An Assessment of Battery Disposal Strategies for Battery Electric Buses

UCLA Institute of Transportation Studies

A comprehensive project submitted in partial satisfaction of the requirements for the degree Master of Urban and Regional Planning.

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Executive Summary

Transit agencies across the United States, especially in California, are looking to electrify their bus fleets. These electrification efforts support sustainability goals and shift our public transportation systems away from being powered by fossil fuels. Most transit agencies are still in the process of acquiring new battery electric buses (BEB). However, concerns have begun to arise surrounding best practices for retiring BEBs at the end of their useful lives.

The US electric vehicle (EV) battery recycling market is still nascent but experts are optimistic, predicting that a “circular economy” for batteries will be established in the near future. This innovative approach would see the materials found in used EV batteries recycled and used to manufacture new EV batteries, providing significant environmental benefits. With a large number of buses slated to be replaced with BEBs, sustainable disposal of these BEBs is crucial to the creation of this promising circular battery economy.

This report takes a proactive approach, presenting the current conditions surrounding BEB retirement, making educated predictions on the near future conditions of the used EV battery market, and providing comprehensive policy recommendations to all stakeholders. This thorough research aims to facilitate a successful transition to a circular battery economy, ensuring all parties are well-informed and prepared for the changes ahead.

The report opens with a comprehensive literature review on the current state of BEB adoption by transit agencies, recent technological advancements, and legislative mandates supporting the electrification of public transit bus fleets. This establishes a baseline context of the field for readers unfamiliar with EV technology.

The following section catalogs the challenges and opportunities associated with BEBs identified by transit agencies. This information was gathered through interviews with subject matter experts at three Californian transit agencies currently in the process of electrifying their bus fleets. There is significant optimism from transit agencies about the opportunities presented by used BEB batteries, especially the prospect of utilizing used BEB batteries as stationary electric storage.

This report then presents the perspective of BEB manufacturers regarding the disposal of BEB batteries and future plans for additional services. Similar to the previous section, this content was gathered through interviews with three major BEB manufacturing companies. These companies are looking to adapt their business models to reflect the changing needs of their customers, mostly by offering various levels of additional support and changing battery designs that can be easily removed and swapped.

The report then analyzes the current outlook of the EV battery recycling and reuse industry by analyzing existing literature and market research. Generally, all signs point to significant growth in the US EV battery recycling and stationary storage markets.

Lastly, this report concludes with a series of policy recommendations for transit agencies, BEB OEMs, and policymakers. The recommendations mainly revolve around establishing greater standardization in EV batteries, reusing spent batteries in novel applications, and promoting closer coordination between stakeholders.

This report is an introduction to the complex world of battery disposal. Given the rapidly changing industry, this report serves as a point-in-time analysis of BEB disposal strategies. As the field evolves, much of the information in this report is subject to change in the near future.

Acronyms and Definitions

Alternating Current	AC
American National Standards Institute	ANSI
Battery Electric Storage Systems	BESS
Battery Management System	BMS
Battery Electric Buses	BEB
California Air Resources Board	CARB
Compressed Natural Gas	CNG
Direct Current	DC
Electric Vehicle	EV
End Of Life	EoL
Federal Transit Authority	FTA
Fuel Cell Electric Bus	FCEB
Innovative Clean Transit	ICT
Internal Combustion Engine	ICE
International Council On Clean Transportation	ICCT
International Energy Agency	IEA
Kilowatt	kW
Lithium Iron Phosphate	LFP
Los Angeles County Metropolitan Transportation Authority	LA Metro
Los Angeles Department Of Transportation	LADOT
Metropolitan Transportation Commission	MTC
Nickel Manganese Cobalt	NMC
Nickel-Cobalt-Aluminum	NCA
Original Equipment Manufacturers	OEM

Renewable Natural Gas	RNG
San Francisco Municipal Transportation Agency	SFMTA
Southern California Edison	SCE
Electric Power Research Institute	EPRI
United States	US
United States Department Of Energy	DOE
United States Department Of Transportation	USDOT
United States Environmental Protection Agency	EPA
Zero-Emission Bus	ZEB

3 Literature Review

California Air Resources Board (CARB) public meeting.

Source: ***CalMatters, 2022***

Topics covered in this chapter:

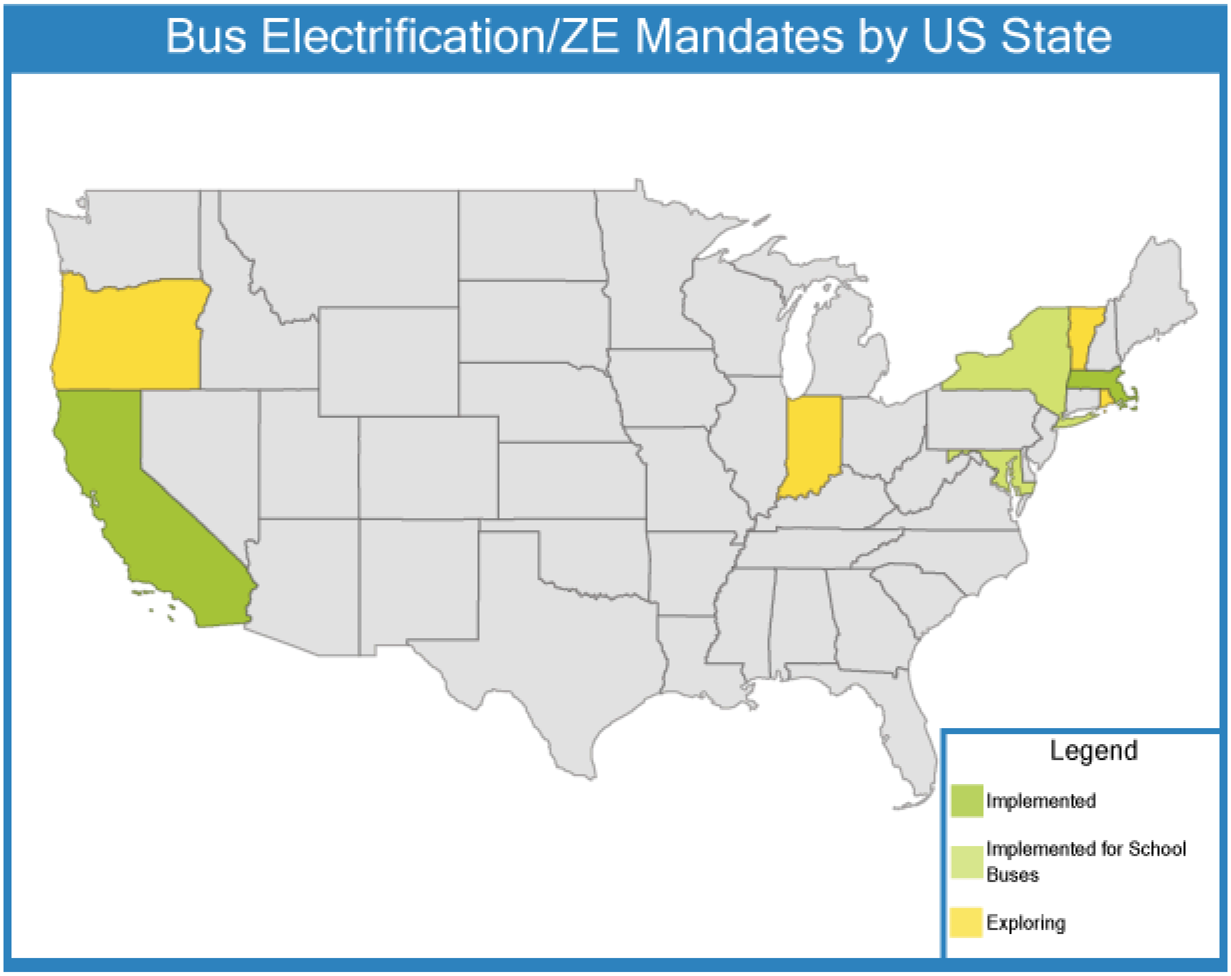
- Why and how rapidly are battery electric buses (BEB) coming to market?
- Common battery concerns
- Existing battery chemistry and performance
- Experimental battery reuse opportunities
- The need for operational resilience for electrified transit fleets

3.1 The Growing Electric Bus Market

In the coming years, transit agencies across the United States (US) will adopt zero-emission buses (ZEB) to replace aging and polluting internal combustion engine (ICE) bus fleets. While the US federal government has not mandated ZEBs, many states have developed legislation to catalyze the adoption of ZEB technology. California, in particular, is a leader in adopting ZEB technology, requiring that all transit agencies transition to a 100% ZEB fleet by 2040 and that all transit bus sales be ZEB starting in 2029 (California Air Resources Board (CARB) | Innovative Clean Transit (ICT) Regulation, 2018a). Given that the transportation sector is one of the major pollution sources, CARB has prioritized legislation and regulations that transitions commercial medium- and heavy-duty following the path of greatest feasibility. Transit buses are one of the first “beachheads" in CARB’s plan to facilitate the electrification of commercial vehicles in California. Transit agencies are less reliant on profit to determine infrastructure upgrades, and there are a significant number of zero emission vehicles which can replace existing fleets. CARB hopes that this jumpstarts manufacturing capacity and technology innovations for other medium- and heavy-duty commercial vehicles (CALSTART, 2022). According to the ICT regulation, a ZEB is a bus with zero tailpipe emissions and is either a battery electric bus (BEB) or a fuel cell electric bus (FCEB) (CARB | ICT Regulation, 2018a). CARB defines FCEBs as an electric bus that stores hydrogen in fuel cells onboard which is used to generate electricity and charge the bus’ battery (CARB | ICT Regulation, 2018a). This report does not focus on FCEBs, as they are less common outside of California, contain smaller batteries than most BEBs, and have been adopted in relatively low numbers at the time of writing.

BEBs are one of the most common forms of ZEBs on the market today. BEBs use electric motors powered by large onboard batteries that are charged in two primary ways. The first being traditional “slow” Alternating Current (AC) charging, usually done overnight at bus yards, which charges a BEB over the course of four to eight hours, typically overnight. The second charging method is “fast” Direct Current (DC) charging, usually used during bus layovers, which significantly recharge a bus’s battery over a matter of minutes. Besides California, other states nationwide are also interested in battery electric technology for transit and school buses, with several smaller local and county-level jurisdictions experimenting with BEBs. The map below displays the US states with ZEB mandates.

Figure 1. Map of state-level bus electrification and zero emission mandates as of May 2024.



Source: United States Department of Energy (DOE), 2024

Transit agencies which are adopting BEBs into their fleets are unclear on how the retirement process for these buses may differ from the process of retiring ICE buses. In particular, transit agencies do not know the full extent of the challenges and opportunities presented by the large, high energy capacity batteries which BEBs use. This report primarily focuses on end of life (EoL) batteries, which are defined by this report as any BEB's battery which have been removed, had its capacity degraded, and will no longer be used in a BEB. There are multiple times during a BEB's life in which a transit agency will need to determine what to do with an EoL battery, such as after a BEB's mid-life battery replacement. However, the main question is what to do about a BEB's EoL battery after the retirement of the bus. It is in this situation that the transit agency has the least assistance available to them, as the manufacturer's warranty will have expired by that time. This is a major question to answer, as there will be a large number of these BEBs which will be going through the retirement process in the coming years. In California alone, there are about 12,000 buses operated by transit agencies that will be transitioned to zero-emissions technology (CARB, 2018b). To address transit agencies' concerns, this report reviews and analyzes the current state of disposal strategies for BEBs from the perspective of transit agencies, BEB original equipment manufacturers (OEMs), battery recyclers, and battery reusers. For the purposes of this report, BEB OEM refers to the organization or company which assembles the bus. This report also offers specific guidance to transit agencies that are in the process of decommissioning their first BEBs. Lastly, the report closes with a series of policy recommendations aimed at regional, state, and national agencies to promote more sustainable disposal strategies as BEB technology becomes more widely adopted. Material for this report was collected through interviews with subject matter experts at San Francisco Municipal Transportation Agency (SFMTA), Los Angeles County Metropolitan Transportation Authority (LA Metro), Los Angeles Department of Transportation (LADOT), Nova Bus, Gillig, and New Flyer.

3.2 Estimated Lifetimes for Battery Electric Buses

Under current Federal Transit Authority (FTA) guidelines, to receive federal funding support, transit agencies must operate a standard 40-foot transit bus for a minimum of 12 years or 500,000 miles, whichever comes first (United States Department of Transportation (USDOT), 2015). With regular maintenance, internal combustion engine buses (ICEB), such as diesel-hybrids or buses with powertrains fueled by diesel or compressed natural gas (CNG), have comfortably met and even exceeded these lifetime minimums. Currently, some major OEMs of BEBs can provide up to a 12-year warranty on all components of the buses (International Council on Clean Transportation (ICCT), 2020) (New Flyer, 2022) (Proterra, 2018). Batteries, on the other hand, typically have a separate warranty from the BEB OEM, which may not cover the entire life of the bus. Battery warranties can cover the battery for set period time or maximum electricity throughput. Currently, there is no public information whether or not BEB OEMs are willing to purchase batteries from agencies once the bus has reached its useful life, outside of the bus or battery manufacturer's warranty. Not all BEB OEMs have committed to providing a full life warranty. In the cases that this warranty is not long enough, it may pose a problem to transit agencies that are very sensitive to the costs associated with replacement and disposal.

Currently, unless a BEB is involved in a serious traffic collision, transit agencies are required to keep their BEBs operational until they reach the FTA mandated minimum lifespan (USDOT, 2015). If a battery needs replacement while still under warranty, this does not pose a significant problem for the transit agency as the disposal of the battery will be handled by the bus and battery manufacturer. However, should the battery be rendered unusable out of warranty but before the FTA's minimum lifespan, it then becomes the transit agency's responsibility to dispose of the EoL battery and source a replacement. Typically, more than one set of batteries is needed to maintain the necessary range throughout the entire life of a BEB. For that reason, most BEBs receive a mid-life battery replacement about six to eight years into service. The party responsible for paying for the mid-life battery replacement and ownership of the EoL battery is determined during procurement negotiations between the transit agency and the bus manufacturer. Used batteries replaced during the mid-life battery replacement can still serve a useful purpose for transit agencies. Given the large initial capacities of the batteries, while they may not be able to power a bus, they may have another life in the secondary uses explored in this report.

Transit agencies have an unclear picture on how long they can expect a BEB's battery to last. BEBs are new to the transportation sector, the field data on their battery lifespans is unsurprisingly sparse. Current estimates for battery lifetimes for BEBs lie between 8 and 12 years, but they are typically replaced before the end of their useful lifetimes. The life of a battery depends on the number of cycles endured by the battery and the calendar age of the battery, as it deteriorates in storage depending on factors such as ambient temperature (McGrath et al., 2022). In a study attempting to determine the number of cycles until reaching 80% of the original capacity of a battery, researchers found that Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP) batteries could endure 2,500 and 9,000 cycles, respectively (Preger et al., 2020). Both chemistries are common in bus battery architectures, and buses typically have one or two cycles per day. When a bus battery has degraded to 80% of its original capacity, it is generally considered to have reached the end of its useful life (BloombergNEF, 2018).

3.3 Growing Interest in Battery Reuse, Recycling, and Refurbishment

There are a variety of reuse opportunities for degraded bus batteries. The incorporation of EoL battery electric storage systems (BESS) has gained a lot of traction from policymakers and companies alike in recent years as the most promising reuse option. A BESS is an electrochemical device that stores electricity from the power grid or from a power plant, and then discharges that electricity at a later time (Bowen et al., 2019). Given the primary cost for a BESS is the battery, incorporating an electric vehicles' (EV) EoL battery provides significant cost savings. The use of BESS has also been explored by private companies. The Sumitomo Corporation and Nissan have begun to use EoL batteries in commercial-scale BESS. General Motors (GM) has also produced its own pilot, focusing on using EoL batteries in a microgrid backup system (Casey, 2014). In 2019, Toyota and 7-Eleven Japan started an experimental project to power two commercial locations with a hydrogen power generation system and a BESS (7-Eleven Japan Co., Ltd. & Toyota Motor Corporation, 2018). Current estimations for an EoL battery's market values place them at between $38 to $132 per kilowatt hour (kWh) (Elkind et al., 2014). In some cases, researchers estimate it will cost more to repurpose these batteries in reuse projects than the minerals inside are worth, with some estimates placing a repurposing cost at $50 per kWh (Elkind et al., 2014). While various theoretical examples exist for second-life batteries, the full field of possibilities has yet to be determined. Beyond experimental projects, little is known about what the second-life battery market may look like in the near future. Therefore, this report mainly focuses on BESS and explores some uses for BESSs relevant to transit agencies and local/county governments.

Much of the conversation on battery disposal has been on reusing batteries due to concerns about the feasibility of recycling them, however it remains an appealing disposal strategy. Many transit agencies are hopeful that they can recover some costs in the recycling process. However, this depends entirely on the chemistry of the batteries and the recycling technology available at the recycling facilities closest to the transit agency. Additionally, it is likely that recycling these batteries would also increase carbon emissions and possibly pollute the environment with harmful chemicals. (Elkind et al., 2014) (Ciez & Whitacre, 2019) Additionally, current lithium-ion battery recycling techniques are not optimized to recycle entire EoL vehicle battery packs. Instead, the majority of the battery recycling industry is currently focused on manufacturing scrap. Manufacturing scrap mostly consists of individual battery cells which did not meet a battery manufacturer's standards and are subsequently disposed of. EoL batteries from EVs will become the major recycling feedstock around the year 2040. At that point, the recycling industry will grow dramatically, possibly providing a steady stream of materials for new battery manufacturing and increasing the value of EoL batteries (Weigl & Mann, 2023). The current recycling landscape is nebulous in the United States; much of the field's information is concealed as "trade secrets." Given these circumstances, it's imperative to maximize these batteries' useful life before resorting to recycling them.

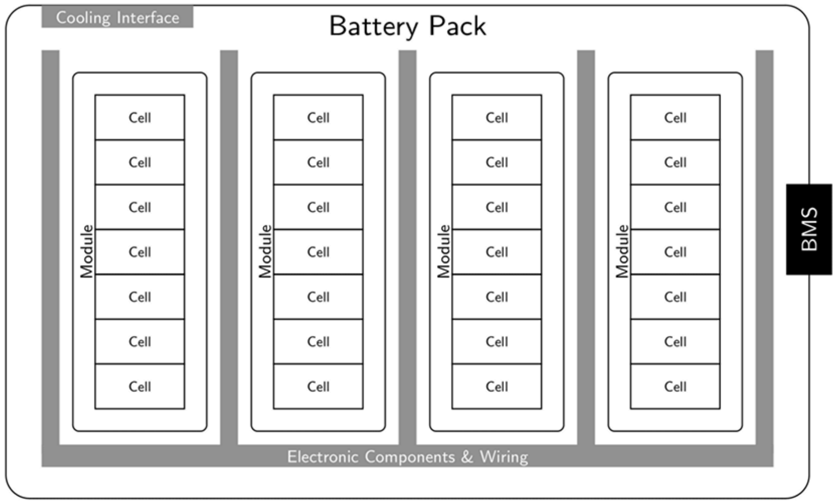
EoL batteries can also be refurbished in a process called relithiation, using the lithium recovered by recycling. The process promises to restore battery capacity through a chemical process to add new lithium to the battery’s cathode in just 10 minutes with minimal harmful byproducts (Wu et al., 2021). Currently it is only feasible in conjunction with direct recycling, a novel recycling process which disassembles EoL batteries by hand rather than through chemical, thermal, or hydrometallurgical means (Dunn, 2023). Some of the literature has estimated that as the number of batteries that are produced increases, the costs of relithiation will decrease exponentially as economies of scale come into play. One study estimated that once the battery production of a given chemistry reaches 1,500 tonnes metric tons annually, the costs of relithiation will be minimized due to economies of scale. That same study found that the cost of relithiatizing 50% of a battery's capacity with new lithium would cost $6 per kilogram (kg) of cathode for nickel manganese cobalt (NMC) and nickel-cobalt-aluminum (NCA) batteries. However, the costs of relithiatizing an LFP battery would be on par with manufacturing an entirely new one (Ciez & Whitacre, 2019, 148–156). Relithiation could be an important strategy during the mid-life replacement of a BEB's battery and could solve concerns regarding a theoretical lack of compatible replacement batteries. However, the relithiation process has not yet been expanded to commercial scale and it is likely not economically viable in the short term, until more EoL EV batteries are slated to be recycled in the future. For that reason, this report does not explore refurbishment in depth as a disposal strategy.

3.4 The Need for Emergency Backup Capacity and the Opportunity for Battery Electric Storage Systems

Power outages and grid resiliency are becoming more of a concern for transit agencies as bus fleets electrify. The three primary grid resiliency strategies have been identified by the American Public Transit Association, which include establishing multiple connections to the grid, the establishment of backup electric generators, and the creation of microgrids with battery storage (Blair et al., 2020). The current policies surrounding grid resilience are lacking. Emergency power requirements for transit agencies have yet to be established in a standardized manner. Electric utilities currently have priority users which exempt customers such as hospitals, rail operators, and other essential services from rolling power outages; bus operators are not currently identified as priority users (Southern California Edison (SCE), 2016). Policy surrounding emergency power for transit agencies will likely be updated in the near future. Transit agencies provide lifeline and essential services in the case of a major event (power outage, natural disasters, etc.). Typically transit agencies play a key role in emergency management and access to a consistent source of electricity is a priority (Metropolitan Transportation Commission (MTC), 2018). Requirements for emergency operational capabilities have yet to be standardized across jurisdictions. Most transit agencies do see the value in having access to some backup power storage or generation capability, although desired capacity varies wildly from 100% of operational needs down to just 25%. The Federal Transit Administration (FTA) advises transit agencies to consider implementing BESSs to lower demand charges and provide backup power in case of power outages in their “Guidebook for Deploying Battery Electric Buses”. In addition, it also advises transit agencies to include language encouraging the reuse of EoL batteries in BESSs in procurement contracts to reduce unexpected challenges with battery disposal (FTA & Center for Urban Transportation Research, 2023).

A few firms in the US already offer services to reuse EoL batteries in BESS systems. Companies such as RePurpose Energy, and B2U provide services to reuse EoL EV batteries for low-cost BESSs. A typical BEB contains multiple battery packs. Each battery pack contains multiple battery modules, which are filled with individual battery cells bonded together by welds or adhesive. A Battery Management System (BMS) controls all the internals of the battery through the use of a controller area network. The BMS and its associated algorithms are essential for keeping a battery in working order, and manufacturers are generally reluctant to share details regarding them (Sandberg, 2023). A diagram for a typical EV battery pack is presented below.

Figure 2. Diagram of an EV battery pack.



Source: Sandberg, 2023

Companies reusing EoL batteries for BESSs typically disassemble battery packs down to the module level. The modules are then diagnosed and reconfigured in a BESS to optimize efficiency often with a new BMS. The BESS is then placed into a shipping container or similar battery enclosure. Depending on the design of the battery, it may not be possible to break down a pack into its individual modules while maintaining interoperability. In that case, reuse companies can take a simpler approach by combining batteries at the pack level rather than the module level. However, combining modules is the preferred method which enables a longer lifetime for the BESSs and a higher energy density (Slattery et al., 2024). Each company uses a different technique, but follows similar principles to ones described here.

4 Transit Agency Concerns

LA Metro bus operators.

Source: LA Metro, 2024

Topics covered in this chapter:

- Plans for electrification
- Existing plans for EoL batteries
- Limits on traditional disposal strategies
- Common themes from transit agency interviews

4.0.1 Agency Descriptions

Content for this chapter was sourced from a series of interviews with transit operators around California. Only California operators were interviewed, as these agencies have the strictest ZE mandates and the most experience with BEB technology. Each transit operator was specifically chosen to capture the wide range of transit providers that can be found across the country. Each interviewed operator has unique challenges and circumstances that can provide important lessons to other transit operators that are in similar situations. A description of the characteristics of each transit operator can be found below.

Table 1. Description of Interviewed Transit Agencies

	SFMTA	LA Metro	LADOT
Planned Number of BEBs	600	2,100	410
Number of Bus Facilities	7	10	3
Jurisdiction Level	Joint City and County	County	City
Report Defined Agency Size	Medium	Large	Small
CARB ICT Defined Agency Size	Large	Large	Large
Annual Budget 2024	$1.47 Billion [a]	$9.0 Billion [b]	$216.8 Million [c]

[a] *source: https://www.sfmta.com/projects/sfmta-budget-planning-fiscal-years-2023-2024*
[b] *source: https://www.wmata.com/initiatives/budget/fy2024-budget.cfm*
[c] *source: https://cao.lacity.gov/budget/index.htm*

4.1 Current State of Battery Adoption

4.1.1 Fleet Specifications

Most transit operators, especially in California, have already developed CARB Rollout Plans, transition plans that outline what technology (such as hydrogen, BEB, or trolleybus) will help them achieve 100% zero-emission fleets. These transition plans typically explore the challenges and concerns the agency may have with different ZE technologies. Rollout plans carefully lay out the plans for vehicle procurement, infrastructure build out, and fuel cost management (CARB, 2020). After much careful consideration of their options, many agencies have chosen BEBs for their relative maturity compared to hydrogen fuel cell electric buses and economic feasibility compared to trolleybuses. Primarily, the most significant challenge to address is range. To overcome these challenges, transit agencies work closely with BEB OEMs to specify the performance requirements they need for their buses. From interviews with transit agencies, the following bus specifications were highlighted:

Table 2. Agency Determined BEB Specifications

	SFMTA	LA Metro	LADOT
Current 40’ BEB Battery Capacity	525-600 kWh	360 kWh	400 kWh
Current 60’ BEB Battery Capacity	600-720 kWh	590 kWh	N/A
Acceptable Level of Degraded Capacity Compared to Full Capacity	80%	Dependent on route	70%
Specified BEB Range Minimum	N/A	150 miles	200 miles

4.1.2 Utility and Energy Usage Considerations

Given the relatively large energy capacities of these batteries, an equally large amount of power (kW) is needed to charge buses without impacting service. Transit agencies are working closely with utilities to guarantee enough power. However, the relationship and the specific utility that serves the agency directly impacts the agency's electrification goals. All three agencies have access to a publicly owned utility typically to provide power. SFMTA typically relies on power generated by Hetch Hetchy Power, a public utility, and transmission infrastructure owned by a private company, Pacific Gas and Electric. Both LADOT and LA Metro have facilities powered by the Los Angeles Department of Water and Power, a public entity. LA Metro has a few facilities powered by Southern California Edison, a private company. They stated that the utility upgrade process has been more straightforward for them than for agencies that rely on a private utility. Assuming that there is a consensus on priorities, access to a public utility can reduce complicated negotiations and contracts to a simple memorandum of understanding. A unified direction, especially one established by the top level executive branch, is a powerful force to accelerate public sector bureaucracy. Private utilities, while historically are more risk-averse to experimenting with new technologies and business models, have identified the potential in working closely with transit agencies to electrify their fleets. LA Metro in particular has had success in partnering with Southern California Edison for their electrification efforts The following points on electrification were highlighted through interviews:

Table 3. Transit Agency Electrification Plans and Electricity Sources

	SFMTA	**LA Metro**	**LADOT**
Utility Type	Public [d]	Mixed	Public
Existing or Planned Electricity Generation	Yes, Hetch Hetchy plant and planned solar	Yes, solar and planned clean CNG generators	Yes, planned and existing solar
Planned Fleet Wide Peak Energy Usage	23.6 MW [e]	171 MW [f]	22.6 MW [g]
Considering Microgrids with BESS	Yes, 5 facilities x 3-4 MW	Yes	Yes, 4 facilities x 1.1 MW

[d] *Privatized transmission infrastructure*
[e] *source:* *https://www.sfmta.com/sites/default/files/reports-and-documents/2021/06/sfmta_zeb_task_2_facility_needs_final_report_2.pdf*
[f] *source:* *https://ww2.arb.ca.gov/sites/default/files/2021-09/LAMetroRolloutPlanADA.pdf*
[g] *source:https://ww2.arb.ca.gov/sites/default/files/2020-12/LADOT_ROP_Reso_ADA12172020.pdf*

As most transit agencies are just beginning to buy BEBs, there will be a period of time before addressing the influx of used batteries is an issue. We can expect an influx of used batteries from these buses' mid-life refurbishment about six years later. There will also be another influx of used batteries when these buses are retired an additional six years later. Some agencies have found even better performance than initially expected from their batteries, so this timeline might be able to be pushed back even further. In addition, while most agencies may try to replace their batteries once they reach 80% of their original capacity, once they are out of warranty, transit agencies may consider continually using them on less strenuous routes until they hit 65-70%. Transit agencies must develop comprehensive plans to retire BEBs and dispose of batteries in ways that align with their goals and objectives.

4.2 Assumptions on Secondary Bus and Battery Market by Transit Agencies

4.2.1 Traditional Bus Retirement practices

Due to existing regulations, transit agencies are prioritizing BEB implementation and adoption - the afterlife of the batteries have not been at the forefront of agencies' decision-making. Agencies are much more preoccupied with adopting this technology first and have some assumptions about what disposal will look like. First, they are confident that regardless of future conditions, they will always be able to find a buyer as they have done in the past. Many agencies believe the process will resemble the retirement process for diesel or compressed natural gas (CNG) buses. The typical process for retiring buses usually involves auctioning off the buses to the highest bidder. Typically, the buses sell for between $5,000 and $15,000, depreciating about 90% of their original value. In addition, non-operational buses that must be towed cost the transit agency about $3 per mile (MacKechnie, 2019). Once sold off, the new owners of a used bus may use it for scrap or spare parts, collected by hobbyists, or continue service for private usage. On rare occasions, some buses end up in other countries worldwide, continuing to provide transit service. Sometimes, these buses are even donated free of charge due to their lack of value. Nongovernment organizations convert these buses for portable showers, mobile libraries, emergency evacuation vehicles, and local shuttles (Fitzgerald, 2017).

There is reason to doubt that these standard practices can continue with the adoption of BEBs. Previously, SFMTA has successfully auctioned off its hybrid buses to secondary markets. However, these small purpose-built buses excelled at climbing steep terrain, an attribute that is valuable outside of its hybrid powertrain. In addition, charging is optional for these buses, which can still run on fossil fuels (SFMTA, 2023). BEBs, on the other hand, require significant capital investment in charging infrastructure to be used, which is likely to cost more than the value of the BEB itself. These additional costs severely limit the potential for these buses to be reused by entities without charging infrastructure already in place. In addition, the battery in these BEBs will likely need to be replaced, which will incur additional costs for the buyer. It is unlikely that BEBs will be suitable for any use outside of providing transportation as a typical transit bus.

4.2.2 BEB Retirement considerations

While, in theory, Californian BEBs may be sold off to agencies beginning their electrification plans, that, too, is an unlikely scenario. Given that the FTA only assists in purchasing new buses, it is unlikely that any US transit agencies will buy a used BEB. However, used BEBs could be used in private bus fleets. The recent Advanced Clean Fleets regulations has mandated that private bus fleets with two axles must consist of 100% ZEBs by 2036 and fleets with more than two axles must consist of 100% ZEBs by 2039 (CARB, 2023). Private transportation providers in other states may also have internal sustainability goals; which could incentivize the purchase of a used BEB outside of California. Given the aforementioned high infrastructure capital and battery replacement costs, it is unlikely that any foreign transit agency would be interested in purchasing a used BEB over a diesel or CNG bus.

The last option for retiring BEBs is to disassemble them and sell the parts individually. In conversations with transit agencies, all of them were confident in their maintenance staff's ability to safely separate the batteries and individual components from their BEB, regardless of whether their maintenance was done in-house or contracted out. Once retired, every portion of the BEB besides the battery can be scrapped through traditional channels. In addition, once the battery has been removed, it is possible to retrofit a BEB frame with an alternative powertrain. Transportation of these parts for sale will be extremely difficult for transit agencies. While scrap metal dealers are common in cities of all sizes, the larger concern lies with the batteries. Once removed from the bus, these batteries are considered hazardous waste, which adds additional costs (United States Environmental Protection Agency (EPA), 2023a). Argonne National Laboratory generally assumes the costs of shipping a used EV battery, including the hazardous material insurance premium, is an average of $1.93 per ton mile (Dai et al., 2019). One literature review of 17 battery transportation cost estimates found that the average cost of transportation is about 41% of the cost of recycling a battery, and is dependent on the transportation mode, battery condition, and volume of batteries shipped (Slattery et al., 2021). In addition, battery recyclers that can handle these large EV batteries are not found in all parts of the US which increases transportation costs to ship batteries to far off recyclers.

If a transit agency wants to sell the battery of a retired BEB, the transportation costs alone may cost more than the battery is worth. More information on battery recycling is discussed in this report's "Secondary Battery Market Landscape" section. All these points give necessary information on how transit agencies should approach retiring a BEB at the end of its life. The section "Determining the Value of a Used Electric Bus" provides some guiding recommendations

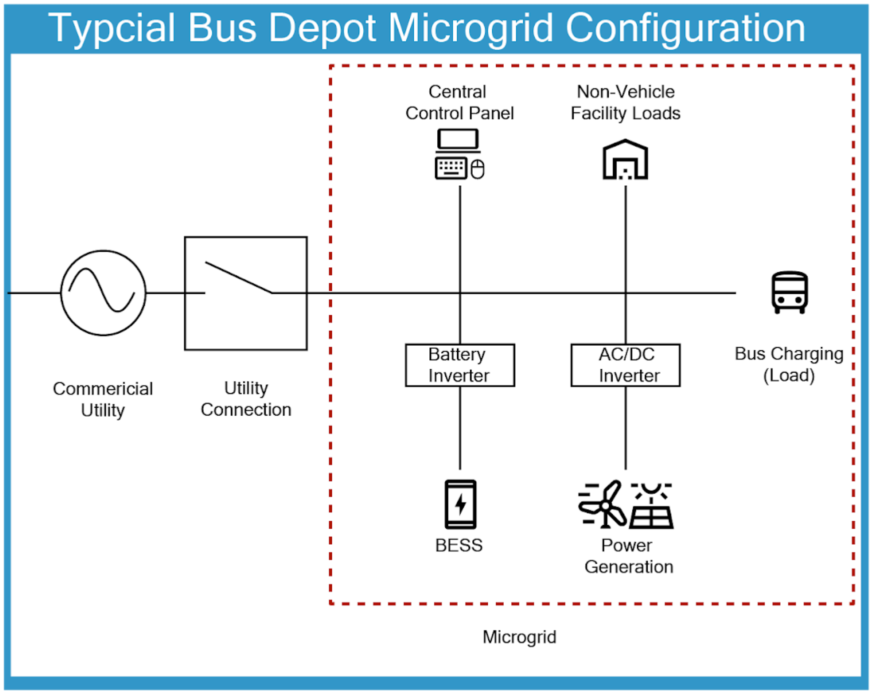
4.3 Transit Agency Interest in Alternative Disposal Methods

If selling off these buses in their entirety is not feasible, all the transit agencies were interested in exploring other options to reuse their batteries. There are conversations happening across the field discussing the potential of reusing batteries in BESS. BESS has many uses depending on how they are integrated into the grid. Microgrids, in particular, benefit greatly from BESS. Microgrids are small networks of electricity users and generators connected to the commercial electric grid but can also work independently. Each transit agency was quick to highlight the need for the creation of microgrids to support a ZE fleet transition; however, their approaches differed greatly.

4.3.1 Emergency Power and Grid Resiliency

One of the largest challenges to implementing a fleet with many BEBs is that there is very little operational flexibility should the grid go offline. An entire fleet of BEBs draws tremendous power from the grid. Much more power is used by a BEB bus depot than could ever be generated from on-site electricity generation such as rooftop solar. This presents an opportunity for BESS in microgrid configurations, which could support charging buses during emergencies. Used BEB batteries are an ideal feedstock for BESS systems at transit agencies, given the typical battery's large electric capacity even after significant degradation and minimal transport costs, because the used batteries would already be at their final destinations. An "off the shelf" new BESS modular system could provide 3.7 MWh of storage in a 20' container, costing about $180/kWh in 2024 (Roskin, 2024). Assuming a BEB has 500kWh of average storage, BESS could achieve a similar level of capacity with EoL battery packs from just 10 BEBs. A typical microgrid setup is displayed by the diagram below.

Figure 3. Typical configuration for a microgrid found at a bus depot.



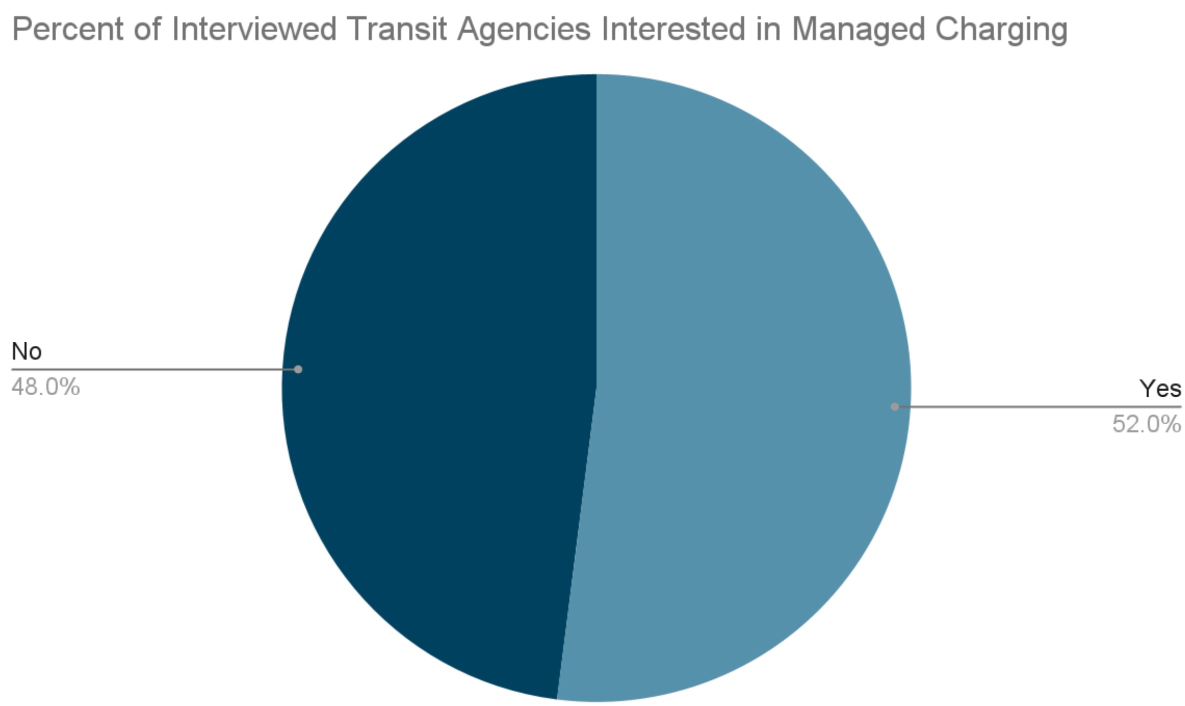
As climate change accelerates and transit agencies are faced with more natural disasters, planning for climate resiliency has been a key theme across the US (Nugent, 2022). There is no standardization on requirements or best practices for how much capacity to plan for. SFMTA was the only agency interviewed with definite plans for emergency operational capacity. They plan to have 20% of the fleet available during an emergency, requiring approximately 3-4 MW of power at every bus facility. LADOT and LA Metro also have plans for emergency capacity, but how much emergency operational capacity they would need to have is still being determined.

LA Metro is also considering other resilience measures. LA Metro has a large amount of CNG infrastructure at many of its facilities. They are actively exploring the implementation of CNG electric generators, which could be powered by “renewable natural gas” (RNG). RNG is natural gas gathered from agriculture, landfills, wastewater, or food waste decomposition, which, when captured and burned, produces a net negative amount of greenhouse gasses. This would make significantly more electricity than solar generation during a blackout and reduce the BESS capacity needed. However, this is a monetarily and spatially intense project, which may not be feasible for all transit agencies. As of this writing, all requirements for emergency power have been regulated at the city and county levels. However, state and/or federal agencies will likely step into this responsibility as more transit agencies adopt ZE technology.

4.3.2 Increasing Efficiency and Reducing Charging Costs

BESSs are useful for emergencies and can also be used as part of the daily charging infrastructure. Managed charging is when the charging schedule for BEBs is spread out to focus charging during periods of low grid demand and reduce the peak draw from the grid, a common practice when dealing with large BEB fleets. Managed charging can reduce electricity costs and the needed investment in utility upgrades for transit agencies. BESSs can be implemented in microgrids to be charged during periods of low electricity rates and high electricity generation. Subsequently, the stored electricity can be used to charge BEB fleets during high electricity rates and high demand. BESSs present the opportunity to have more stable electricity distribution, provide greater efficiency, and lessen the demand on the electricity grid. Many transit agencies have already realized this potential. The following figure displays the results from an FTA survey of 25 electrifying transit agencies.

Figure 4. Survey results regarding interest in managed charging for BEBs.



Source: FTA, 2023

It is clear that transit agencies are not relying on BESS – alone – as a strategy for battery reuse. The transit agencies were hopeful that BEB OEMs or other companies could handle much of the hard work of repurposing BEB batteries in BESSs. While transit agencies are generally confident they have the equipment and ability to remove these large batteries, reusing them requires specialized knowledge and planning with their respective utilities. However, as of present, no BEB OEM offers services for retired buses. More perspective on this issue is expanded upon in the "Bus Manufacturer Perspective" section.

4.3.3 Non-Transit Opportunities

Another potential strategy is transferring ownership of EoL to other agencies – while it was not proposed by the interviewed agencies, it may be a potential disposal opportunity in the future. Similar to working with municipal utilities for utility upgrades, the transfer of these batteries could also be done through a simple memorandum of understanding transferring ownership between agencies. BESSs have a world of potential outside of the transportation industry. BESSs have obvious uses for municipal utilities, such as transmitting stored electricity generated during low-demand periods. California has already acknowledged the importance of BESSs as part of the plan to switch to more renewable emergency sources (CALMAC, 2016). BESSs can also serve jurisdictions that have public housing authorities and be installed to power large residential buildings. This would increase the grid resiliency for the residents of the building and possibly reduce utility costs if used in conjunction with rooftop solar. And, of course, BESSs can be invaluable to any municipal emergency services, such as law enforcement, fire, and healthcare, which need to remain operational regardless of the status of the grid. In conjunction with onsite electricity generation, BESSs can form the backbone of stable microgrids, which could significantly improve resiliency. These are just a few possible uses for BESSs; they have many other creative uses across multiple fields. It is unclear if other public agencies know about the potential of these batteries for reuse in BESSs. However, cooperation could bring substantial benefits for both parties, reducing disposal costs and uncertainty for transit agencies and decreasing project costs for cooperating agencies. Possible plans for inter-agency collaboration are outlined in the recommendations section.

5 Bus Manufacturer Perspective

New Flyer's Anniston, Alabama manufacturing facility.

Source: Business Alabama, 2020

Topics covered in this chapter:

- Battery design choices and philosophies
- Plans for future battery services
- Common themes from BEB OEM interviews

5.0.1 The Changing Bus Manufacturer Landscape

The BEB OEM landscape is rapidly changing. Bus manufacturing has long been a stable industry of established firms with a long history of manufacturing diesel, CNG, and hybrid buses. Many firms expected that the transition to ZE powertrains would be easy. However, that is proving not to be the case. Proterra and El Dorado were originally considered major players in the field but have or are currently leaving the BEB market due to financial hardship (De Socio, 2023) (Wanek, 2024). The BEB market is rapidly consolidating, which means the plans for individual companies are now more impactful than they had been previously. For this report, Nova Bus, Gillig, and New Flyer were interviewed on various topics surrounding the current design choices of their buses and their planned future business models. The interviewed OEMs combined hold a majority of the BEB market share, and their responses reflect the direction of the industry as a whole. Nova Bus announced its exit from the US market in 2025. However, they will remain a major player in Canada. BYD was the only major BEB OEM in the US market that did not respond to an interview request. The future of BYD as a major BEB OEM is uncertain due to the Buy America requirements in the National Defense Authorization Act for Fiscal Year 2020 and 2024 bars federal assistance for buses and EV batteries made by companies from countries determined to be non-market or on the priority watch list which includes china, BYD’s country of origin (National Defense Authorization Act for Fiscal Year 2024, 2023) (National Defense Authorization Act for Fiscal Year 2020, 2019). BYD has a US-based factory in Lancaster, California and is making significant investments to try to fall in line with buy america requirements (BYD USA, 2020). Given the significant regulatory challenges for BYD, their future outlook is uncertain.

5.1 Battery Design and Philosophies

Most bus OEMs do not manufacture their own batteries. Instead, they purchase standardized battery packs from third party vendors. While the batteries may have similar internal chemistries, each battery vendor uses proprietary hardware and software in their battery management systems (BMS) to control the charge and discharge rate. BMSs are the crucial onboard computer of a battery pack, which both communicates with the bus' electrical system and manages the battery's condition. BMSs being proprietary makes it nearly impossible to swap internal modules and have battery packs "communicate" across battery manufacturers. The ability to communicate between packs is essential if transit agencies want to mix and match batteries from different bus OEMs in a reuse project. In addition, the technology of these batteries is rapidly changing and iterating from year to year. The battery technology in a given BEB model is often changed from vehicle generation to generation, and sometimes even between batches, depending on technological advancements, transit agency requests, and changes in the supply chain. Of the three interviewed OEMs, only Gillig requires their battery vendor to have an internal sustainability and recycling plan. The following table details the current battery specifications for the interviewed OEMs.

Table 4. Interviewed OEM BEB Battery Design Description

	Nova Bus	Gillig	New Flyer
Cell form factor	8650 Cylindrical Cell	21700 Cylindrical Cell	Pouch and Prismatic Cell
Cell bonding type	Welding	Adhesive and microwire bonding	Laser tab welding
Cell Chemistry	NMC	NMC	NMC
Battery Vendor	Akasol (Recently acquired by Borg Warner)	Borg Warner	American Battery Solutions
Battery Warranties	2, 6, or 12 years	6 year standard, can be extended up to 12 years	6 years or 175 MWhr throughput, whichever comes first

While battery vendors determine the internal configuration and technology inside a battery pack, the bus manufacturer determines where and the battery pack placement in the bus. Every BEB typically contains multiple battery packs placed in the rear, under the floor, or on the roof. From conversations with BEB OEMs, they all emphasized their dedication to creating easily removable batteries on their buses. Most importantly, all batteries are removable by transit agency maintenance staff simply by removing a few bolts and lifting them out of the frame using a maintenance crane commonly found in bus maintenance facilities. BEB OEMs are looking to make the process even easier in the future. Currently, the light maintenance of batteries is handled by field technicians sent by the BEB OEM. For more intense repairs, the battery is sent back to the vendor. However, Nova Bus, in particular, was interested in training their customers to handle “level 3” repairs. This training would allow transit agency maintenance staff to swap modules inside battery packs. Overall, the industry is heading in a direction that gives more flexibility to transit agencies. However, there are still major roadblocks regarding proprietary technology inside BEB batteries.

5.2 Manufacturer Plans for Entering the Battery Recycling and Reuse Market

Bus OEMs recognize the large market for used batteries, which will open soon. Nova Bus and Gillig, in particular, are looking to expand their business in the used batteries market, while New Flyer was more skeptical of the potential. Nova Bus and its parent company, Volvo, are currently looking to partner with battery recyclers to dispose of used BEB batteries. Volvo is also looking to expand its capabilities to remanufacture used or damaged batteries to be reused in BEBs. Volvo is also looking to offer new spare parts by expanding beyond mechanical components and begin selling battery components directly to their customers. Gillig is currently in the early stages of integrating BEB batteries collected during the mid-life refurbishment process to be used as feedstock for second-use products. The largest hurdle identified was having enough used batteries available for a stable supply. Ideally, heavily degraded batteries would be sold to circular life recyclers, and batteries with significant capacity remaining could be used in stationary applications. Gillig is skeptical that the benefits from this process will outweigh the costs associated with removing the batteries, transporting them, and paying for the replacement battery. New Flyer was the least enthusiastic about second-life uses for batteries, only committing to acting as a mediator for transit agencies and recyclers. They are currently looking for a recycler that could recycle and scrap the entire BEB rather than the battery and remaining parts separately. New Flyer does recognize some of the opportunities that BEB batteries present and is interested in partnering with experts in the microgrid field while internally taking a more project management approach.

All interviewed bus OEMs expect their clients to do a mid-life (six-year) battery swap regardless of capacity degradation as a maintenance precaution. However, whether this falls under warranty or is paid out of pocket by the transit agency is settled during contract negotiations for the BEB initial acquisition. Gillig, in particular, had some concerns with this process. They claimed that because battery technology has been advancing so rapidly, with a new technological breakthrough roughly every three years, there might not be a new battery compatible with BEBs needing refurbishment. To counteract this, Gillig is working closely with their battery partners to retrofit newer battery technology to work in older BEBs. This would involve heavy OEM participation in the retrofit process to change core pieces of the bus, including the frame, wiring harness, and connectors. None of the interviewed OEMs had plans to buy back used batteries at the end of a BEB's useful life.

6 Secondary Battery Market Landscape

3D rendering of a BESS microgrid setup.

Source: istock.com, 2023

Topics covered in this chapter:

- Description of US BEB battery recycling capacity and capabilities
- Description of recycling and reuse methods
- Market outlook of the secondary battery market
- Government support for EV batteries

6.1 Current Conditions and Transparency of the Field

For the purposes of this report, the secondary market is defined as the commercial uses for EoL EV batteries, the most common uses discussed in this section are battery recycling and repurposing. Disposing of BEB batteries entails a similar process to recycling lithium batteries found in light duty vehicles or other consumer products. Not all recycling facilities are equipped to handle them, due to the large size of EV batteries compared to those found in consumer products. Battery recycling for EVs poses a serious concern for all stakeholders, especially as to whether the United States has enough recycling capacity to handle all the EVs on the road today and into the future. Additionally, the field of battery recycling is mostly out of the public eye, which brings some concerns to citizens about its prospects. The general US public has some concerns about what the disposal of these EV batteries might entail. A 2022 survey conducted by ascend elements, a battery recycling company, found that 71% of US adults are concerned about end-of-life EV batteries ending up in landfills (Ascend Elements, 2023).

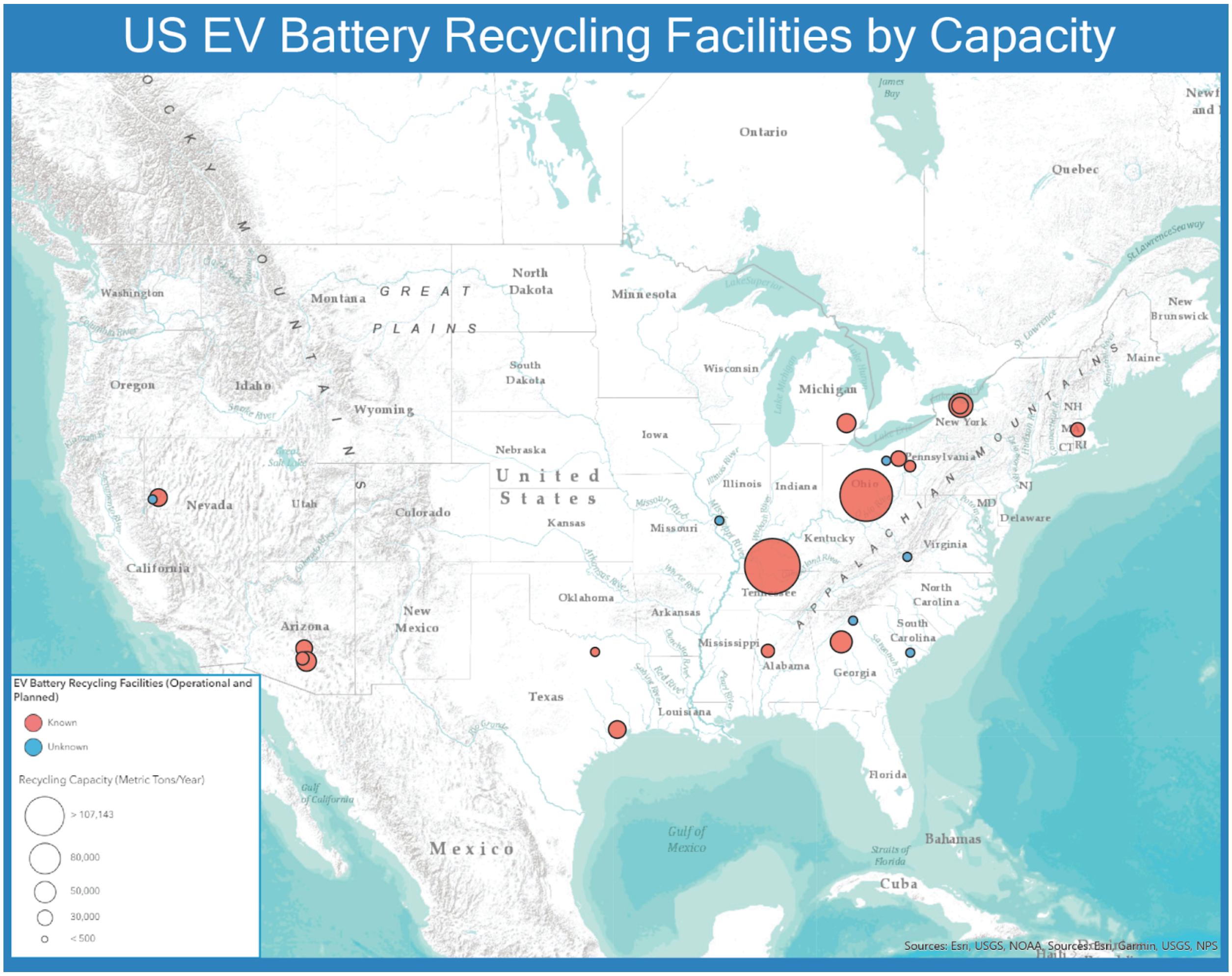
Given the murky nature of the industry today, this section establishes a baseline understanding of the field both as it is today as well as some speculation as to what it may look like in the near future. Additionally, this section provides some context for the historical trends of similar lithium ion battery technology and government investments in battery recycling. The content for this section sources its material from a wide literature review of market forecasts, government reports, and an exhaustive internet search.

6.2 Scale of Investment and Market Forecasts

6.2.1 The Present Day Conditions

There are three primary ways an EV's (including BEBs) lithium ion battery can enter the end of life "network". They can be disposed of through an OEMs warranty process: used batteries of this category can be refurbished for reuse in other vehicles, repurposed for stationary usages, or be sent to a recycling facility to recover the precious material. EV batteries retired due to a collision typically become the property of the insurance company. They are then sent to vehicle dismantlers which typically sell all the individual usable components for spare parts; the rest of the unusable metal is typically sold for scrap. Lastly, EV batteries can reach the end of their lives out of warranty, then leaving the responsibility to the owner of the vehicle (Slattery et al., 2024). This is true for both private EVs and BEVs. When recycled, the battery packs are disassembled and the foils and casing of the batteries are scrapped. The remaining parts, including the anode and the cathode, are shredded into "black mass" which is then processed to extract as much valuable material as possible, sometimes being sent out of the country (EPA, 2023b). Each battery recycler uses a unique technique to do this, but the two main commercial processes are hydrometallurgical or pyrometallurgical in nature. The former relying on high pressure liquid and the latter using a thermal treatment, although most recycling firms use a combination of the two (Slattery et al., 2024). Neither process is ideal, as they have their own trade-offs in terms of environmental impacts and in terms of retrieving materials for remanufacture. Currently, hydrometallurgical recycling is preferable over pyrometallurgical recycling due to its lower energy use, lower greenhouse gas emissions, and a higher lithium material recovery rate, better for high value NMC batteries. Direct recycling is a novel recycling method which involves disassembling batteries by hand, ideal for lower value LFP batteries and manufacturing scrap, and may gain more popularity as EV battery recycling throughput increases (Dunn, 2023). EV battery recyclers are not found widespread throughout the US, however the number of these facilities continues to grow. The map below details the location of both existing and planned battery recycler and reuse facilities across the United States.

Figure 4. Map of operational and planned EV battery recycling facilities as of May 2024.



Detailed descriptions of the recycling facilities can be found in the appendix.

The full table of US EV battery recycling facilities can be found in the appendix. This equates to about 652,293 metric tonnes of installed and announced EV lithium-ion battery recycling capacity per year, and about 105,150 metric tonnes of currently installed EV lithium-ion battery recycling capacity as of September 2023 (Tankou & Hall, 2023). For context, a single average BEB could have over a tonne of battery packs on board (Tesar et al., 2020).

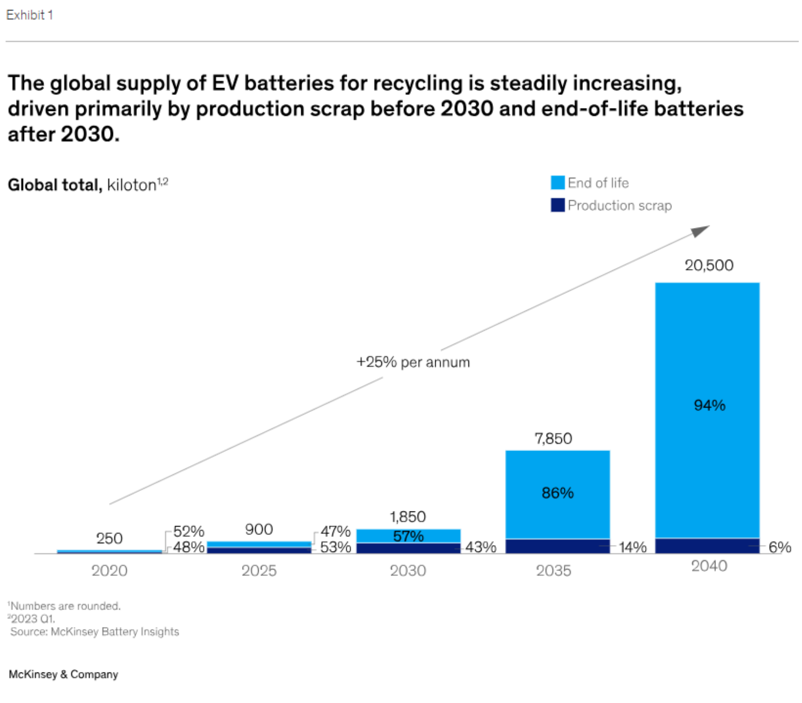
The reuse industry for end of life EV lithium ion batteries is extremely nascent, and the primary application is in Battery Electric Storage Systems, or BESSs. A BESS is an electrochemical device that stores electricity from the power grid or from a power plant, and then discharges that electricity at a later time (Bowen et al., 2019). Integration into BESSs is a prime reuse strategy due to the cost savings associated with using a used battery, and the flexibility of BESSs to use lower energy density batteries compared to transportation uses. A sample of current companies offering these services include: B2U Storage Solutions, RePurpose Energy, Smartville, Inc., BattGenie, and Element Energy. These companies are primarily from California, due to the large amount of EVs on the road compared to other states and the large amount of support from the state of California. California in particular has multiple demonstration projects from pilot to commercial-scale to help stakeholders understand the potential of the technology (Kendall et al., 2022). A low volume of retiring EVs is the primary cause attributed to the slow growth of the reuse industry. Nissan Leafs, one of the first mass produced EVs in the US, have just now begun to reach the end of their warranty periods (Slattery et al., 2024). As more models of EVs come to retirement age, we can expect more reuse projects to become common across the US.

The lack of available used batteries is not the only challenge that must be overcome to spur greater reuse of batteries in a BESS. One large challenge for reuse projects is access to module-level information from end-of-life EV batteries. For a reuse project to be feasible, battery reusers need to have information on the state of health (SOH) of EV batteries at the batter pack and module level, historical charging data, access to the BMS, and a history of prior fire code certifications (e.g., SAE J2929, UL1642) before a reuser can consider purchasing an end of life battery. While EV batteries already receive fire safety certifications during manufacturing, they require additional certification to be used in a BESS. UL9540A is the standard certification for used EV batteries so that they may be used in BESSs. In addition, only two facilities in the world have the UL1974 certification to use used EV batteries in BESSs (This certification is not necessary, but assists in getting projects through local permitting processes) (Slattery et al., 2024). Those two recipient companies are Moment Energy, a Canadian company, and Tokyo-based 4R Energy, a joint venture between Nissan and Sumitomo (Murray, 2023). Currently, is it difficult to diagnose used EV batteries to determine their eligibility in non-destructive ways and the typical diagnostic method requires significant manual labor. This may make it difficult for transit agencies to know what end-of-life batteries could be reused in BESS projects without risking their viability (Faessler, 2021). Lastly, end of life batteries used in reuse projects will still need to be recycled once the battery capacity is degraded beyond a usable point.

6.2.2 Predicted future conditions

The success and expansion of the EoL battery secondary market depends on recycled material achieving price parity compared to new raw material in the future (Mayyas et al., 2018b). As mentioned previously, the biggest hurdle towards achieving price parity is the lack of EoL to achieve economies of scale in the recycling industry. Once economies of scale are established for battery recycling, the National Renewable Energy Laboratory (NREL) predicts that the cost savings from using recycled materials could reach up to 43% of the cost of cathodes made from newly mined materials (Mayyas et al., 2018a). Battery manufacturers have already identified the potential of sourcing batteries materials from recyclers due to their price stability compared to the more volatile mining markets (Mayyas et al., 2018a). Given that the US does not have enough domestic supply of battery materials to meet manufacturing demand, recycling batteries has a high potential to fill that material gap (Mann, 2019). Market indicators point to a large increase in the availability of EoL batteries to reach economies of scale for recycling in the near future. Mckinsey & Company, a management consulting firm, are predicting a significant increase in the global availability of EoL batteries for recycling, displayed in the figure below.

Figure 5. Expected growth in the global availability of EoL EV batteries.

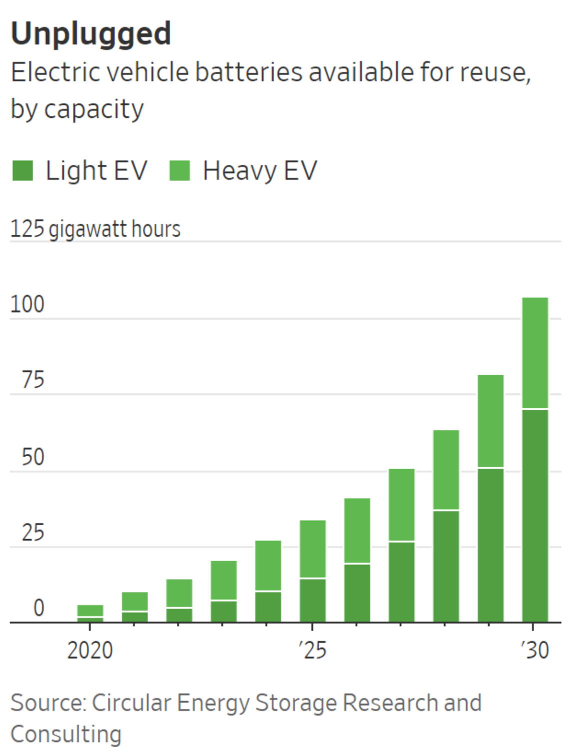


Source: Mckinsey & Company, 2023.

Mckinsey & Company predict a significant growth rate of 25% year over year growth in the market, mostly attributed to the transition to EVs in the private automobile industry, improvements to recycling processes, and a desire by companies to source more manufacturing material from recycling (Mckinsey & Company, 2023). This positive growth however, is reliant on battery chemistries remaining consistent in the future. Given the innovative nature of the battery technology industry, the dominant battery chemistry will likely change in the next decade; this would necessitate a change in recycling processes, reducing the viability of a circular recycling economy (Mayyas et al., 2018a). Future battery chemistries are likely to use less cobalt, a material often recovered from EoL batteries due to its high value (Mayyas et al., 2018a). In addition, future breakthroughs in battery chemistries may lead battery chemistries to significantly change. New battery chemistries could add a large array of new materials to EV batteries, including silicon, silicon oxide, or sulfur (S&P Global, 2020). Regardless of future changes to battery chemistries, the recycling market as a whole is expected to have significant growth and a positive outlook.

Similarly, the BESS market is expected to grow expeditiously in the coming years. This can generally be attributed to the growth of renewable energy in the US, and a larger priority of grid resiliency. Current market predictions estimate that the market will grow between 10.5% and 20.1% every year, with the overall market reaching a value above $50 billion by 2031 (ResearchAndMarkets.com, 2024) (IndustryArc, 2024). The growth of the overall BESS market does not guarantee growth in the usage of EoL in BESSs. Given that new battery prices are expected to drop, the appeal of reusing EoL batteries may not be as strong in the future after accounting for their decreased capacity (DeRousseau et al., 2017). Until those price drops are realized, EoL batteries will be a cost efficient feedstock for BESSs (DeRousseau et al., 2017). The Wall Street Journal predicts that the availability of EoL batteries which could be used in BESSs will grow significantly in the near term, up to 107.5 Gigawatt hours of capacity by 2030. This is displayed in the figure below.

Figure 6. Expected growth in the availability of EoL EV batteries for reuse in the US market.



Source: (Holger & Petroni, 2022).

The prevalence of reusable EoL batteries is the primary element necessary for the establishment of a robust reuse BESS industry.

There are significant ongoing discussions across the US to update the fire codes for BESSs. While most of these implemented and proposed changes don't necessarily make it easier to use EoL batteries for BESSs, they are slated to significantly increase safety and reduce fires from lithium batteries (The Electric Power Research Institute (EPRI), 2023). This in turn, may make it easier to construct BESSs and assuage public concerns. While the overall BESSs is heading in a positive direction, the adoption of EoL batteries, a main feedstock for these projects, is not certain. Given the unique circumstances of transit agencies, the trends of the overall markets may not be as important as the immediate needs of the agency when determining whether to use new or EoL batteries in BESSs.

6.3 Government Funding and Support

Significant funding has been made available, primarily by the federal government, to support the growing EV battery industry in the US. The 2022 Infrastructure Investment and Jobs Act is the most recent and largest source of funding for battery recycling and reuse projects. Over two funding phases, the DOE has made $5.42 billion available to fund domestic manufacturing of EV battery materials, including recycling (DOE, 2022a) (DOE, 2023b). As of the writing of this report, only the first phase has announced its awardees. The Cirba Solutions battery recycling facility in Lancaster, Ohio was the only awardee focused on recycling, receiving $74.9 million dollars to establish the largest battery recycling facility in the US (DOE, 2022b). The 2022 Infrastructure Investment and Jobs Act has reserved $325 million for BESS projects, including the Communities Accessing Resilient Energy Storage (CARES) which utilizes used EV batteries for BESS projects in two affordable housing communities (DOE, 2023a). Besides incentivizing the establishment of new battery facilities, significant support has been given for battery research initiatives. The Department of Energy has continuously supported battery research, but has recently announced an additional $131 million boost in funding for 2024 applicants (DOE, 2024). California has made a significant investment of $27 million towards 20 battery related research projects (Office of the Governor California, 2023). Overall, there is significant recognition of the need to support the domestic US battery market.

Outside of funding, discussion exists at the federal level for the establishment of new regulations regarding battery recycling policy. While other jurisdictions like the EU have established recycled content minimums for battery manufacture and have placed the onus on recycling on the battery manufacturer, the US is now beginning to enact similar legislation (Dunn et al., 2022) (DIRECTIVE 2000/53/EC, 2000). For example, the Strategic EV Management Act of 2022 requires multiple federal agencies to work on guidelines for “reusing and recycling” batteries from vehicles retired from the federal fleet (The Office of Senator Mitt Romney, 2022). New Jersey is the first US state to extend some of the responsibility of recycling to EV battery manufacturers, requiring them to establish “take-back” programs for batteries sold in the state (Gorjala & More, 2024). These regulations are typically referred to as Extended Producer Responsibility (EPR) laws. Through the Infrastructure Investment and Jobs Act, the DOE has been directed to establish a task force which will develop an “extended battery producer responsibility framework” to address battery design, transport, and recycling, possibly extending EPR laws nationwide (International Energy Agency (IEA), 2023). The Inflation Reduction Act is also expected to have an effect on the EV battery recycling market, as it has mandated that new EVs that receive tax credit must have 80% of their battery’s “critical minerals" be sourced domestically (Internal Review Service (IRS), 2024). Given that battery material recycled in the US also counts to this minimum, the legislation may spur additional demand for EoL battery recycling but more support is necessary to support the expected demand for material (Trost & Dunn, 2023).

7 Recommendations

LADOT solar-powered bus depot.

Source: Chardevs.com, 2021

Topics covered in this chapter:

- Recommendations to transit agencies for disposal of BEBs
- Advice for BEB manufacturers to succeed in the US market
- Policy necessary to spur the growth of US battery recyclers and reusers

7.0.1 Stakeholder Cooperation

The mass adoption of BEBs may bring substantial challenges, but the US has the ability to establish a circular battery economy with proper coordination between transit agencies, policymakers, bus manufacturers, recyclers, and reusers. California, in particular, can serve as a model for sustainability and climate resiliency in future jurisdictions transitioning to zero-emission transportation technologies. The content in this chapter is addressed to three separate audiences. The first section is meant to serve as a guide for transit agencies exploring strategies for BEB disposal. Recommendations provided in this section are based on the current conditions of the BEB market, focusing primarily on best practices for BEB procurement and retirement. The following section details high-level policy recommendations to promote greater transparency, encourage industry cooperation, and lower disposal costs. The last section provides recommendations on how BEB manufacturers can capitalize upon the potential of the used battery market described throughout the report.

7.1 Suggested Policies and Guidelines for Transit Agencies

7.1.1 Procurement Considerations for Reuse Projects

The most critical period for the success of BEB battery reuse projects is during the procurement of new BEBs. As many agencies are still acquiring BEBs for their fleets, there is a lot of opportunity for preparatory actions to facilitate battery reuse projects in the future. Ideally, a transit agency should purchase as many buses from the same manufacturer as possible. Large orders of bulk BEBs will also be helpful in guaranteeing a sizable feedstock for reuse projects. Transit agencies should stipulate in their procurement contracts that the battery technology inside their BEBs is uniform and consistent. Taking these steps is essential to guarantee compatibility between batteries. Acquiring bulk orders of BEBs can also help obtain spare parts that can be swapped between vehicles as they age.

Ideally, agencies should create an emergency operation plan for their BEB fleet before procuring additional vehicles. As BEB technology becomes more common in the coming years, state or federal regulators will require agencies to provide a minimum operational capacity during emergencies and blackouts. Establishing these plans before they are required can reduce costs by utilizing used BEB batteries for BESSs rather than purchasing new stationary batteries. This could have major cost-saving benefits since batteries will likely be the most expensive component in any backup system. Agencies should work with local emergency and disaster management services to establish a minimum operational capacity, ideally with approximately 15% to 25% of the fleet operational during blackouts. As well, transit agencies should work with state utility regulators to ensure that transit agencies are considered priority users to minimize service disruptions during rolling blackouts. During the contract negotiations, transit agencies can set the battery specifications to match their needs to build these BESS, assuming that at 80% of their original capacity, they will be transitioned to stationary uses. Agencies should utilize the contract negotiation period to emphasize that they intend to reuse batteries in secondary projects at the end of their useful life and place additional recycling responsibilities on the BEB OEMs. This will help BEB OEMs understand a transit agency's needs, encourage them to expand their second-use business offerings, and ensure that they provide technical support throughout a BEB's life.

7.1.2 Disposal Coordination

The point at which a BEB is no longer useful will depend on the individual bus's leftover range, battery degradation, age, and the route characteristics of the transit system. Once a bus can no longer service any routes or has reached 12 years of age, the transit agency should consider retiring the bus. For buses with extensive battery degradation (less than 60% of their original capacity), transit agencies should primarily consider recycling. While in the future there exists the potential for retired BEBs to be worth more, the most valuable BEB from SFMTA's fleet, a 2007 Orion 40' Electric Hybrid Transit Bus, was sent to auction in California and was sold for $3,600 (Bar None Auction, 2020). Transit agencies should expect a similar return, adjusted for inflation if they auction their buses intact. Transit agencies will need to carefully calculate whether a fully intact or disassembled bus will net the largest return.

Before the first midlife refurbishment of a BEB fleet's battery, transit agencies should develop a comprehensive battery disposal plan. This plan should set out the following:

- Determine standard levels of degradation for determining battery reuse or recycle pathways. Batteries with higher capacities should preferably be reused, while batteries with greater degradation and damaged components should be recycled.
- Identify the nearest metal scrap yards and battery recyclers to determine transportation costs.
- Attempt to establish competitive bulk scrap prices with recyclers to counter fluctuations in the market.
- Reserve an amount of used BEB batteries to be reused to satisfy emergency BESS needs at transit agency facilities.
- Coordinate with other city/county departments to explore opportunities to establish BESSs at other public facilities. Ideal departments for coordination include publicly owned utilities, housing authorities, and emergency service providers such as police, fire, and medical departments. Regional nonprofits and NGOs may also benefit from

access to low-cost, high-capacity batteries, which may help a jurisdiction reach its environmental and climate goals.

- Locate safe storage locations at bus depots and other maintenance facilities to store separated bus batteries.
- Partner with contractors or BEB OEMs that can reuse BEB batteries in BESSs or build internal capacity to take on these projects.
- Select BESS technology, which allows for swapping in larger-capacity batteries as battery technology continues to improve.

Given the large capacities of these batteries, a transit agency will likely be able to satisfy their needs for batteries as part of BESSs with batteries reused from their first batch of BEB. There will be a significant surplus of lightly degraded bus batteries as transit agencies continue to adopt this technology and older BEBs are retired. This presents new opportunities for innovative projects and partnerships utilizing BEB batteries as a resource. These batteries will continue to degrade while used in BESSs, and transit agencies will continue acquiring new BEBs. For that reason, a comprehensive disposal plan will create pathways for continually replacing BESS batteries with used BEB batteries. Non-Californian transit agencies have a significant advantage in this respect, as strict zero-emission transition requirements do not bind them and can take a more conservative approach to this technology's adoption. As California transit agencies continue to innovate as forerunners in the field, other agencies should pay attention to the challenges that must be overcome and proactively address them.

7.2 Battery Recycling and Regulation Policy Recommendations

At the federal and state levels, there must be a significant number of new guidelines and regulations in the lithium battery field as the industry approaches critical mass. As reported by the National Renewable Energy Laboratory, the lack of regulation on battery recycling at the national level leads to a significant number of lithium batteries ending up in landfills (Mayyas et al., 2018a). First and foremost, there must be a significant push for greater transparency and reporting for the battery recycling industry. Battery recycling is an entirely private enterprise with few requirements or desires to share their recycling practices. Throughout the development of this report, I encountered significant interest from members of the public concerned about the recycling process, specifically about environmental impacts. Greater transparency would promote more trust in the technology and assuage environmental concerns.

Additionally, policymakers should fund additional research in new and innovative battery reuse and recycling strategies. While battery recycling incentives as part of the Inflation Reduction Act are a good start, significant progress must be made on new battery pathways. In particular, supporting battery reuse start-ups, especially those based in California, could greatly reduce costs for public agencies interested in reuse projects across the country. New funding for research on battery recycling techniques at national laboratories, research universities, and private firms could lead to new breakthroughs to reduce recycling economic and environmental costs. This is especially important given that even reused batteries will eventually be recycled.

Given that California is adopting lithium battery technology in the transportation industry faster than any other US state, California transit agencies, in particular, can act as a leader in the field and as a testing ground for battery disposal strategies that may be adopted nationwide. The state already has a history of being a leader in environmental policy, especially in the transportation sector. The California Air Resource Board imposes significantly stricter vehicle pollution regulations than its federal equivalent. In addition, the state allocates significant funding to environmentally friendly transportation programs through its robust cap and trade policy.

Establishing standardized open-source software for BMS could unlock huge potential and opportunities for battery reuse and make it easier. At a minimum, standardized BMS software should facilitate communication between battery packs from different manufacturers. It would also allow for the use of different manufacturers' battery modules to interact with each other within a battery pack. Standards for such software could be created cooperatively with leading battery, BEB manufacturers, and the American National Standards Institute (ANSI). The Federal Transit Administration (FTA) could require implementing such standardized software on all new transit buses approved for federal funding. Similarly, standardized labeling and battery classifications for battery chemistries would assist recyclers in sorting received batteries (Zanoletti et al., 2024). The US could mimic regulations from the European Union to mandate recycled content standards in newly manufactured EV batteries to spur demand for battery recycling (Dunn et al., 2022). The US could also place greater responsibility on BEB battery manufacturers to handle the recycling process for EoL batteries as is done for EVs in the EU (DIRECTIVE 2000/53/EC, 2000). Lastly, the establishment of national-level government battery recycling centers distributed across the country would help to create a network of recycling infrastructure, and address the high transportation costs associated with transporting EoL batteries long distances (Zanoletti et al., 2024).

As an aside, if policymakers are able to regulate the development of heavy-duty vehicle batteries successfully, it would be the second time the US has been able to mitigate the problems related to vehicle battery recycling. There are many lessons to be learned from the history of lead-acid batteries used in almost every light-duty vehicle in the US today. In the present day, 99% of all lead-acid batteries are recycled. This can be attributed to the highly standardized nature of the batteries, which allows them to be recycled easily and swapped with any other battery brand. Starting in the 1980s, the US applied strict environmental regulations on battery recyclers, forcing them to become extremely efficient and produce significantly less pollution. As a result, lead acid batteries are part of a circular economy that could also be replicated for lithium batteries (Turner, 2022).

7.3 Opportunities for Bus Manufacturers

Bus manufacturers play a crucial part in the BEB battery reuse and recycling landscape, especially as many bus OEMs are exploring expanding to new markets and offering new services. Transit agencies rely on the expertise of bus OEMs to guide them on all things battery, which gives OEMs unique opportunities to provide new services. As BEBs become a greater portion of a transit agency's fleet, agencies interested in reusing those batteries are incentivized to maintain "brand loyalty" and select one primary BEB provider. Increasingly, in-house reuse capabilities and partnerships with 3rd party BESS builders will be essential to secure business with transit agencies of all sizes. From conversations with BEB OEMs, the profitability of battery disposal and reuse services is likely to be close to profit neutral. Despite a lack of direct profit, OEMs able to offer these services will be significantly more appealing to transit agencies. Transit agencies face complex bureaucratic and contracting challenges when handling used BEB batteries alone. Offering straightforward disposal services, including assistance in battery recycling, is a surefire way to gain repeat customers. Lastly, maintaining a supply of older-generation or retrofitted batteries is imperative for midlife refurbishments and repairs. OEMs should have access to at least one additional compatible battery for each BEB sold. No transit agency wants to be forced to retire a BEB before it achieves 12 years of service.

Bus battery design is also a key component in facilitating BEB batteries' easy disposal and reuse. BEB OEMs should continue to work towards easier removability and greater modularity of their battery packs. In particular, moving away from individual cells bound with adhesives can improve recyclability. Moving towards utilizing water-soluble adhesives inside battery modules, as well as standardizing screw connections and module junctions can simplify the recycling process (Zanoletti et al., 2024). Additionally, maintaining selected battery technology between BEB manufacturing batches can make reuse projects easier to implement. BEB OEMs should work with battery vendors and other BEB OEMs to establish open-source standards for BMS, especially regarding software. The current lack of interoperability between battery OEM BMSs makes it easier to repurpose end of life batteries in BESSs on the battery pack level. However, if the BMS was standardized, it would make it easier to repurpose batteries in BESSs on the module level, which would give these systems higher energy densities and longer lifetimes (Slattery et al., 2024). The US will likely adopt some form of EV battery standard soon, and beginning conversations today will make the transition easier. This will also ensure that the specific features of the established BMS standard reflect individual BEB OEM priorities. OEMs that do not adapt to the changing BEB market are increasingly at risk of being locked out. Multiple OEMs have already declared bankruptcy or left the BEB market; OEMs that do not change course are at risk of sharing the same fate.

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Appendix A - Table of EV Battery Recycling Facilities

Address	Company Name	Facility Location	Source	Recycling Capacity (Metric Tons/Year)
1669 Lake Ave, Rochester, New York 14615, United States	Li-Cycle	Rochester, New York	https://li-cycle.com/rochester-hub/	35000
4461 E Nunneley Rd, Gilbert, AZ 85296, United States	Li-Cycle	Phoenix, Arizona	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	18000
1601 Boone Blvd. Northport (Tuscaloosa), AL 35476	Li-Cycle	Tuscaloosa, Alabama	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	10000
1 Inmetco Dr, Ellwood City, Pennsylvania 16117, United States	International Metals Reclamation Company	Elwood City, Pennsylvania	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	6000
7515 Hill Road Northwest, Canal Winchester, Ohio 43110, United States	Omega Harvested Metallurgical	Winchester, Ohio	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	?

4930 Holtz Drive, Wixom, Michigan 48393, United States	Cirba Solutions	Wixom, Michigan	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	23000
1872 Pratt Drive, Blacksburg, Virginia 24060, United States	Li Industries	Blacksburg, Virginia	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	?
133 Flanders Road, Westborough, Massachusetts 01581, United States	Ascend Elements	Westborough, Massachusetts	https://www.renewableenergymagazine.com/electric_hybrid_vehicles/ascend-elements-and-elemental-strategic-metals-establish-20240409#:~:text=The%20facility%20has%20the%20capacity,approximately%2028%2C000%20EV%20batteries%20annually.	12000
100 Latona Road, Greece, New York 14615, United States	Li-Cycle	Rochester, New York	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	18000
9176 Industrial Blvd NE, Covington, Georgia 30014, United States	Ascend Elements	Covington, Georgia	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	30000
6505 John Rivers Rd, Hopkinsville, Kentucky 42240, United States	Ascend Elements	Hopkinsville, Kentucky	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	107143

2425 West Loop South Suite 501 Houston, TX 77027 USA	Ace Green Recycling	Houston area, Texas	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	20000
1474 North v I P Boulevard, Casa Grande, Arizona 85122, United States	Ecobat	Casa Grande, Arizona	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	10000
1007 Wild Horse Canyon Dr, McCarran, NV 89437	Redwood Materials	Reno, Nevada	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	?
Camp Hall in Berkeley County, South Carolina	Redwood Materials	Berkeley County, South Carolina	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	?
7491 OH-45, Warren, OH 44481	Li-Cycle	Lordstown, Ohio	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	15000
GA-17 and Hayes Wilbank Rd Toccoa, GA 30577	SungEel HiTech	Hayestone Brady Industrial Park	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	?
295 Quarry Road Southeast, Lancaster, Ohio 43130, United States	Cirba Solutions	Lancaster, Ohio	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	100000

1300 West Battaglia Drive, Eloy, Arizona 85131, United States	Cirba Solutions	Eloy, Arizona	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	25000
395 Logan Ln, Fernley, NV 89408	American Battery Technology Company	Fernley, Nevada	https://theicct.org/wp-content/uploads/2023/09/EV-battery-recycling-plants-in-the-United-States-v4.pdf	20000
10 FOX INDUSTRIAL DRIVE, MADISON, ILLINOIS 62060	Interco	Madison, Illinois	https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf	?
2101 Couch Dr, McKinney, TX 75069	Princeton NuEnergy	McKinney, Texas	https://entrepreneurs.princeton.edu/news/2022/princeton-nuenergy-takes-massive-strides-new-factory-texas-and-partnership-wistron	500
600 East Exchange Street, Akron, Ohio 44306, United States	Recycling Coordinators	Akron, Ohio	https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf	?