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A Review of Current Zero Emission Bus End of Life Strategies

Katrina Sutton[1,2], Bryan Lee[2], Katelyn Tomaszewski[2], Lais Caldeira[2]
[1] *Katrina Sutton (corresponding author), ksutton@calstart.org*
[2] *CALSTART, 48 S Chester Ave, Pasadena, CA 91106 USA*

Executive Summary

As of 2023, there are 6,147 full-sized zero emission transit buses (ZEBs) in the United States. Important consideration needs to be given to best manage batteries and fuel cells following the ZEBs' end of life as more vehicles enter into service. This paper intends to provide an overview of the current state of the market for end of life and residual values of zero-emission vehicle components. It finds that batteries and fuel cells need to be carefully considered in terms of second life applications, recycling value, and technology hurtles to determine what option is best suited.

Keywords: Heavy Duty electric Vehicles & Buses, Recycle & Re-use, Design for second life, Materials for EVs, Fuel Cell Systems

1 Introduction

This study evaluates the end-of-life management for zero-emission buses (ZEBs). At the end of life, 12-years or 500,000 miles, transit agencies have typically disposed of internal combustion engine (ICE) buses by reselling them on secondary markets or selling them for scrap [1]. Scrap refers to old or damaged parts, like battery packs, motors, or body components, that are no longer usable in the bus but can still be reused, or recycled for valuable materials like lithium, nickel, or copper. This allows the transit agency to derive a residual value, the estimated worth at the vehicle at its end of life, from the used bus and recuperate some of the initial purchase costs of the bus. ZEBs, however, contain a battery and/or fuel cell instead of a traditional engine. Batteries and fuel cells open up new opportunities in end-of-life management. Once removed from an end-of-life ZEB, these components can potentially be useful in second-life applications such as stationary energy storage and generation, though this research remains ongoing. Alternatively, batteries and fuel cells can be recycled, which entails breaking them down into raw materials that are reintroduced into the supply chain to make new batteries and fuel cells. Both second-life applications and recycling offer transit agencies a new avenue for deriving residual value. However, the exact residual value remains unknown because, at the time of writing, few ZEBs have reached their end of life.

This study aims to investigate current and prospective end-of-life management processes and practices for both batteries and fuel cells in ZEBs. This report fundamentally seeks to answer the following research questions:

1. How do transit agencies currently dispose of ICE buses and how do they plan to dispose of ZEBs when they reach their end of life?
2. What end-of-life management practices and processes are available for batteries used in

battery-electric buses (BEBs)?

3. What end-of-life management practices and processes are available for fuel cells used in fuel cell electric buses (FCEBs)?

2 Methodology

CALSTART examined current ZEB end-of-life management practices and developed recommendations for further research and knowledge sharing. Researchers used a literature search, a transit agency survey, and stakeholder interviews to gather quantitative and qualitative data. Research on battery and fuel cell end-of-life management included a review of technical documents from sources such as U.S. Department of Energy, American Institute of Chemical Engineers, HyTechCycling, National Renewable Energy Laboratory, BEST4Hy, Argonne National Laboratory. Additional information was also gathered from interviews with industry stakeholders to gain their perspectives on ZEB end-of-life practices, including transit agencies, vehicle manufacturers, battery manufacturers, fuel cell manufacturers, and recycling companies.

3 ZEB End of Life and Recyclability Overview

As more ZEBs are deployed, they will reach end-of-life and must be decommissioned appropriately. Both second-life applications and recycling offer transit agencies a new avenue for deriving residual value. However, the exact residual value remains unknown because, at the time of writing, few ZEBs have reached their end-of-life. This paper focuses on the batteries and fuel cells of the ZEBs and does not explore other components of ZEBs because these are the most expensive components of the vehicle [2].

Batteries are a vital technology in ZEBs, storing and supplying power needed for propulsion and other auxiliary functions like heating, cooling, and ventilation. Unlike conventional diesel-powered buses, ZEBs use lithium-ion batteries (LIB), which are electrochemical devices that store energy and can be charged and discharged. BEBs and FCEBs both utilize LIBs. BEBs use LIBs as the primary source of power. FCEBs typically include both a fuel cell and a LIB. In a FCEB, the primary source of power is the hydrogen fuel cell, which generates electricity to drive the motor, while the LIB supports power delivery during acceleration and captures energy through regenerative braking. The relative size of the fuel cell and LIB depends on the operational demands, or duty cycle, of a ZEB. As of July 2024, 7,028 ZEBs are now funded, ordered, delivered, or deployed in the United States. Of these ZEBs, 6,453 are BEBs, [3] making BEBs the dominant ZEB technology. The remaining 575 buses are FCEBs. As we continue to see the adoption of ZEBs and FCEBs scale, the transit industry is expected to see a significant increase in batteries entering the end-of-life market, specifically from BEBs deployed in the mid-2010s and FCEBs equipped with on board battery systems.

This section provides an overview of battery and fuel cell technologies. The battery subsection details battery chemistries, pack design, recycling processes, and second life applications. The fuel cell subsection details degradation, material recovery, recycling, and second life applications.

3.1 Battery End of Life and Residual Value

Battery end-of-life management is important for transit agencies that have deployed BEBs, and to a lesser extent FCEBs. The battery is the most expensive component in a BEB. As a result, the residual value of the LIB will be a major aspect of a BEB’s residual value. Transit agencies have a few options for LIB end-of-life management: LIB recycling or second-life applications. Several factors affect LIB end-of-life management, including chemistries, pack design and properties, and state of health.

Chemical composition fundamentally shapes LIB safety and performance, dictating stability, efficiency, and susceptibility to thermal failure. Transit vehicle manufacturers (TVMs) match battery chemistries with the expected duty cycle for a ZEB. [4]

For BEBs, since the LIB provides the sole source of power, it must have capacity to store a large amount of energy to maximize range, making high energy density crucial for LIBs. TVMs typically install high-capacity batteries in BEBs serve as the primary energy source, while FCEBs are equipped with smaller battery systems that support power delivery and regenerative breaking.

TVMs favor batteries with a cathode of nickel, manganese, cobalt (NMC) for their high energy density and power output, making them well-suited for long-range transit buses and high-performance BEBs; however, their higher thermal instability necessitates robust battery management and cooling systems to prevent overheating.

ZEBs are significantly larger and heavier than standard electric cars, so they require a more powerful battery system to meet the rigorous requirements of public transportation. TVMs optimize the design of these batteries not only for their initial life in the vehicle but to also provide benefits in second-life applications and/or recycling possibilities. Battery sizes for ZEBs typically range from 150 kilowatt-hours (kWh) to over 500 kWh, depending on the specific needs of the fleet in terms of range and overall size of the bus.

Modularity is another key feature in ZEB battery design. TVMs often build bus battery packs in a modular format, allowing individual modules to be replaced or repurposed more easily. When batteries are no longer optimal for use in a BEB, individual modules retain sufficient capacity and can be reconfigured or recombined for new applications such as energy storage systems (ESS). This modularity reduces the cost and complexity of reusing batteries for a new purpose.

One challenge that LIBs face is battery degradation. Degradation results from repeated charge and discharge, thermal stressors, and high current demands. With proper management, these batteries can retain 70-80% of their capacity even after several years of service, making them still viable for second-life applications. [5]

3.1.1 Battery State of Health

State of health (SOH) is an important factor in LIB end-of-life management. SOH is the remaining energy storage capacity in the battery measured as a percentage. For example, a battery with 100% SOH has the same energy storage capacity as a new battery. An SOH of 80% means that the battery has 80% of its original storage capacity. SOH is directly connected to degradation and has major ramifications on vehicle performance, as lower SOH reduces the range of the vehicle. The transit industry generally considers 80% SOH to represent the end of life for an LIB in electric mobility applications. The LIB’s internal resistance, meaning how much the battery resists the flow of electricity inside it, can also increase as the battery degrades. LIBs with an internal resistance 200% higher than the initial internal resistance is also considered to have reached its end-of-life. [6]

Calculating SOH is an important aspect of end-of-life management because it determines what can be done with the LIB at end-of-life. However, since different batteries face different operating conditions during their lives (e.g., ambient temperature, discharge rates, average state of charge, depth of discharge, etc.), LIBs with the same SOH can have varying levels of internal degradation and therefore a different remaining useful life. [7] If the SOH is too low or the LIB has other internal damage, then it would not be a good candidate for second-life applications and should be recycled instead. SOH can also be used to estimate the LIB's remaining life. As a result, accurately calculating SOH and the internal characteristics of the LIB is very important before attempting to repurpose the battery. [6] However, in many cases, degradation is not linear, and cases of both decreasing degradation rates over time (sublinear degradation) and increasing degradation rates over time (superlinear degradation) have been observed. [7] Due to the multiple degradation pathways an LIB can take, estimating SOH and the number of cycles remaining in its life can be difficult. [7]

When the LIB operates within a ZEB, the TVM typically uses software that estimates SOH. [8] However, once the LIB is removed from the ZEB, calculating SOH is difficult without access to the TVM’s proprietary software. Without the software, the main method of calculating SOH involves putting the LIB through a full charging and discharging cycle to measure capacity. This process takes approximately four hours [9] and is typically performed alongside other tests to understand the internal state of the battery. UL 1974 provides a standard for which tests should be carried out to determine the LIB's suitability for second-life applications. These tests include: visual inspection, open circuit voltage, high voltage isolation, capacity, internal resistance, BMS controls and protection components, discharging and charge cycling.

3.2 Battery Recycling and Materials Recovery

Recycling is one potential method for disposing of an LIB at its end of life. Two pathways exist for recycling a LIB.

The first pathway entails breaking down the LIB to its raw materials. Since BEB batteries often use a lot of glue and welding, taking them apart for recycling is challenging and labor intensive. Afterwards, the raw materials are reintroduced as a feedstock, which means they're used as the basic input materials, to manufacture new LIBs.

The second method is direct recycling, where major components of the LIB, such as the anode or cathode, are reused or refurbished without being broken down into raw materials. The intent of both recycling pathways is to reuse the materials from the original LIB in a new LIB product.

A battery contains many precious minerals. The type of minerals varies based on the chemistry of the LIB, which are named after the chemistry of the cathode. The fundamental element in LIB chemistry is lithium, popular for its high electrochemical potential and light weight. In batteries, lithium provides the high energy density required to power large vehicles over extended ranges, making it an important component. Lithium is present in both the cathode as a solid and in the electrolyte as an ion. Graphite also plays a critical role in a battery as an important element of the anode because of its stability and good conductivity. Copper is also essential and used for battery connections and electrical wiring.

3.2.1 Battery Second Life Applications

When LIBs reach an SOH that no longer meets the power and energy demands of a typical bus operation, they are still likely to have considerable storage capacity remaining. This remaining capacity poses an opportunity to use these batteries in second-life, or new nonautomotive, applications.[1] Figure 1**Error! Reference source not found.** shows the life cycle of an EV battery with second-life application.

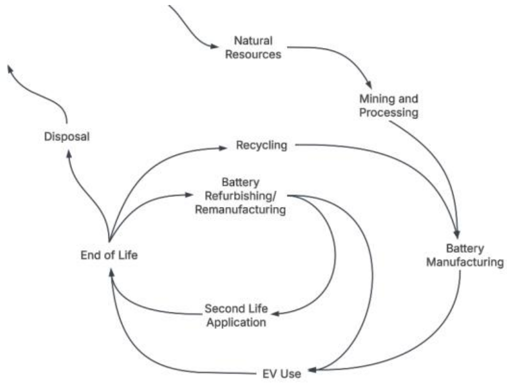

Figure 1: Life Cycle of EV Battery Pack with Second-Life Application

When an LIB is no longer suitable for a ZEB application, the batteries may still have around 70-80% of usable energy capacity. With new ZEB battery packs ranging from 150 kWh to over 500 kWh, this equates to 105 kWh to 400 kWh remaining. Second-life applications are attractive because it allows the battery to continue providing energy services, which is the most financially lucrative use for the battery.

[1] Refurbishing or remanufacturing a battery to return them to their original EV application would not characterize a second-life application for the purpose of this report.

Furthermore, EV batteries typically have a high level of adhesives and welding, which make them difficult and labor-intensive to disassemble for recycling.

Battery second-life applications include stationary energy storage, which can provide additional resilience to the grid and operations where deployed. Services can support behind-the-meter customers, such as residential, commercial, or industrial installations, provide backup power, or be used for peak shaving or load shifting to reduce electricity costs. Supporting charging stations could be an example of this type of application. It can also be used in front-of-the-meter applications when employed by utility companies for frequency regulation and voltage support, or when employed by renewable power plants for local energy storage of excessive energy generation.[6] An LIB's ability to provide these services depends on its ability to interconnect to the grid. Utilities enforce regulations regarding the interconnection of distributed energy resources, such as batteries, to the grid. As a result, second-life LIBs will need to meet utility requirements. For example, investor-owned utilities in California enforce Rule 21, which mandates that grid-connected batteries comply with UL 1741 and IEEE 929. [10]

Second-life applications can be done at the pack, module, or cell level. Before being deployed at its new use, the battery and its components must be diagnosed and tested. After that, a technical viability analysis should be conducted to identify if and in what setting or configuration these batteries could be applied in a second-life use. Then, they are usually sorted according to their chemical, electrical, and SOH and reconfigured by stacking the batteries packs or into refurbished batteries made from used modules or cells. Each configuration has its own advantages and disadvantages in terms of reconfiguration costs, time, performance, and monitoring ease when operating in a second-life application. [6] The financial benefits the second-life LIB provide depend on the application and the grid services it will provide. Furthermore, the longevity of the LIB in a second-life application will also vary based on the application. Research indicates that second-life LIBs used in peak shaving for EV charging stations can last for 30 years, whereas a second-life LIB used to store and discharge excess energy from a solar photovoltaic system can last up to 12 years. [11]

Despite the potential economic and environmental benefits of repurposing retired ZEB batteries for second-life applications, important challenges remain to prove its viability. One major concern is battery degradation. Studies have shown that batteries tend to suffer rapid aging after reaching the 80% SOH mark and begin to fail and degrade faster. [12] This could significantly limit an LIB's remaining lifespan and pose reliability issues for second-life applications.

Another challenge is managing heterogeneous battery packs. Each retired battery may have different chemical composition, electrical properties, and self-discharging rates, making it difficult to ensure consistent and secure operation. This demands rigorous testing and sorting to properly allocate and set the batteries for second-life use. However, the lack of standardized battery diagnostics complicates the assessment of SOH and the establishment of best practices for repurposing these batteries.

Lastly, automakers and industry stakeholders have raised other critical issues: responsibility and liability. It remains unclear in some cases who is accountable for the second-life batteries, ensuring the safety, performance, and appropriate disposal at the end of the second use.

3.3 Fuel Cell End of Life and Residual Value

Fuel cells are electrochemical devices that are similar to batteries in that they convert chemical energy into electricity, but unlike batteries, they require a constant supply of fuel and oxygen to operate. However, unlike a battery, which contains the chemicals it uses to produce electricity, a fuel cell requires external fuel to produce electricity. Multiple types of fuel cells can use different fuels, but proton exchange membrane fuel cells (PEMFC) are the most prominent fuel cell technology. PEMFCs, which consume hydrogen, are the type of fuel cell used in electric mobility applications, including for fuel cell electric buses (FCEBs).

To date, BEBs has been the dominant ZEB technology. As of July 2024, 7,028 ZEBs have been funded, ordered, delivered, or deployed in the United States. Of these ZEBs, 575 are FCEBs. [3]

As with BEBs, the powertrain is expected to be the highest-value component in an FCEB. As a result, the residual value of the PEMFC is expected to be a major factor in the bus's residual value at end-of-life. The PEMFC's residual value will likely be determined by its value in a second-life application or through recycling. There have been efforts to advance PEMFC end-of-life applications. In March 2024, DOE announced $50 million in funding for the American Institute of Chemical Engineers to lead the H2CIRC consortium. This consortium will investigate pathways for recovering, recycling, and reuse of materials and components in PEMFCs. [13] This section will investigate the current state of the market for PEMFC second-life applications and recycling.

3.4 Fuel Cell End of Life and Degradation Mechanisms

Like batteries, PEMFCs experience degradation over the course of their lifetime. This is measured by decreases in the voltage provided by the PEMFC system. Decreased voltage directly affects fuel cell power output. This can result in decreased performance of the FCEB (e.g., not being able to provide enough power to drive on hilly routes) and decreased fuel economy. At a certain point, the PEMFC stack is considered to be at its end-of-life and needs to be replaced to ensure that the FCEB can meet its duty cycle. For the purpose of transit applications, DOE considers 20% voltage degradation to be the end of life of a PEMFC. As of 2021, DOE determined that this occurs at 17,000 hours of operating time. DOE established a terminal objective for PEMFCs in transit applications to achieve a life of 25,000 hours of operating time. This would equate to an approximately 6-year lifetime for the fuel cell, after which the FCEB would need to receive a new fuel cell stack to last the full 12-year lifetime of the bus.

3.4.1 Fuel Cell Recycling and Materials Recovery

Recycling is one potential method for disposing a fuel cell at its end of life. This process entails breaking down the materials in the PEMFC to raw materials so they can be reused in either new PEMFCs or even in other products. Recyclers can attempt to recycle either individual components of the PEMFC or the entire PEMFC. The economic feasibility of recycling is determined by factors such as the value of the materials that can be extracted, the quality/useability of the recovered material, the relative cost of new or virgin material, and the costs of the recycling process. The utility of recycling can also be driven by non-financial factors such as emissions or pollution produced by the recycling process.

Since the viability of recycling is driven largely by the value of the materials that can be extracted, components that have high material value are good candidates for recycling. HyTechCycling, which was funded by the European Union, is a research consortium that investigated end-of-life options for fuel cells, including PEMFCs. The consortium identified platinum metal groups (PGMs) in the catalyst layers as a high value material that can potentially be recycled. The consortium also identified bipolar plates made of aluminum or metal alloys as high value materials. HyTechCycling also identified the PEM electrolyte, which is made of perfluorosulphonic acid (PFSA) as a medium value material. [14] As a result, research into PEMFC recycling has focused primarily on these items.

The catalyst layers are the highest value component within a PEMFC. Research from DOE projects that the catalyst layers will constitute a majority of the PEMFC cost, regardless of production volumes and economies of scale.[15] As a result, the catalyst layer is a good candidate for recycling. The catalyst layers are so valuable because they contain PGMs that can be extracted through recycling processes. Valente et al. (2019) estimates that the platinum content is approximately 0.5 – 1 g per kW. [16] DOE estimates that there are 0.06 kg of platinum per MW in the anode and 0.12 kg of platinum per MW in the cathode. [17] FCEBs typically have a PEMFC that is 100 kW. Industry has made efforts to reduce PGM content in PEMFCs to reduce the cost of the fuel cell and to prevent reliance on a scarce metal.

PGMs are a valuable commodity traded on markets. For example, as of August 2024, platinum was trading at $944.00 per troy ounce, which is the equivalent of over $30,000 per kg. [18]

3.4.2 Current PEMFC Recycling Methods

Before a PEMFC can be recycled, it must be dismantled. Since the recycling process focuses on the membrane electrode assembly (MEA), this typically involves removing all other materials from the fuel cell. The first step is to disassemble the bipolar plates before cutting the rubber gasket that seals the cell. After that, the gas diffusion layer is peeled away, leaving the catalyst layer behind. The catalyst layer is then shredded into smaller pieces before the PGM recovery process begins. [19]

3.4.3 Fuel Cell Second Life Applications

While PEMFCs and batteries provide energy through an electrochemical process, PEMFCs differ from batteries in that they generate electricity rather than releasing stored energy. However, despite this difference, due to the degradation mechanisms of fuel cells previously described, their efficiency or safety is often compromised by the time they reach the end of their life in a vehicle. This limits their potential for second-life applications.

A second-life use for fuel cells would likely involve repurposing them as an alternative energy source, such as backup power generators. There is little information available in the literature on this topic, and such applications are considered unlikely.

4 Transit Agency Feedback

CALSTART engaged with representatives from transit agencies to understand their perspectives on battery and PEMFC end-of-life management. The project team gathered survey data from 20 transit agencies to understand the perspectives of those that have less operational experience with ZEBs.

CALSTART distributed a survey to transit agencies across North America to understand their perspectives on ZEB end of life. This survey focused on how transit agencies have historically disposed of their buses at end of life, the residual value they have received for their disposed buses, and their attitudes toward ZEB end-of-life management. The data from these surveys is intended to establish a benchmark for how transit agencies navigate bus end-of-life issues.

CALSTART surveyed 20 transit agencies about how they currently dispose of their ICE buses and how they plan to dispose of ZEBs when they reach their end of life.

The results (Figure 2) show that most transit agencies have historically disposed of ICE buses by reselling them on secondary markets or auctioning the vehicles off. Some transit agencies have also historically sold their ICE buses for scrap. However, how transit agencies intend to dispose of ZEBs varies. While a majority of transit agencies still intend to resell or auction their ZEBs, others are unsure of how they will dispose of the ZEBs. This likely reflects the fact that very few ZEBs have yet to reach end of life, and much uncertainty exists about options for disposing of batteries. Some transit agencies also expressed an interest in recycling the battery or employing the battery in a second-life stationary energy storage application.

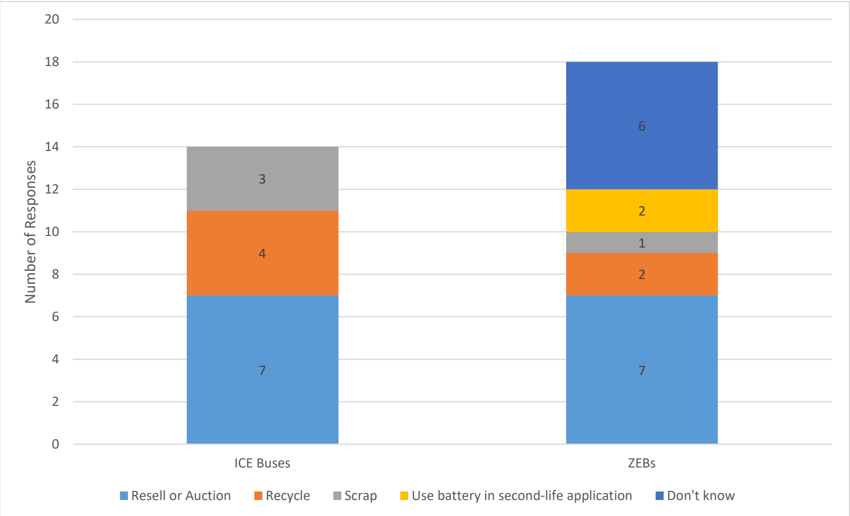

Figure 2: Bus End-of-Life Disposal

CALSTART also collected data on the residual value that transit agencies have historically received for their ICE buses (Figure 3). Most transit agencies reported receiving fairly low levels of revenue from disposing of the bus, with a majority receiving between $2,001 and $5,000 for an ICE bus. No transit agency reported receiving more than $10,000, and many transit agencies received no compensation at all. Some transit agencies also reported that the compensation for their buses can vary based on market conditions and/or the results of the auction.

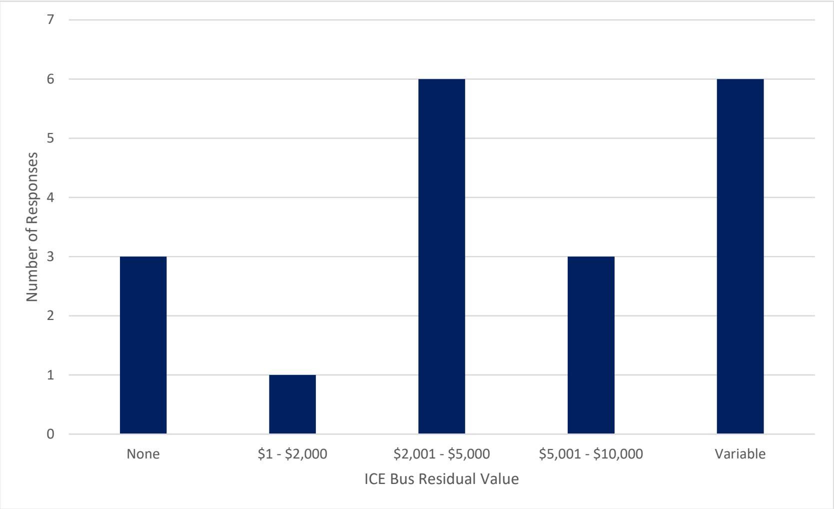

Figure 3: ICE Bus Residual Value

CALSTART also surveyed transit agencies on who they believe should be responsible for managing the battery and/or fuel cell at end of life (Figure 4). The majority of transit agencies believe that the battery manufacturer should be responsible for battery end-of-life management.

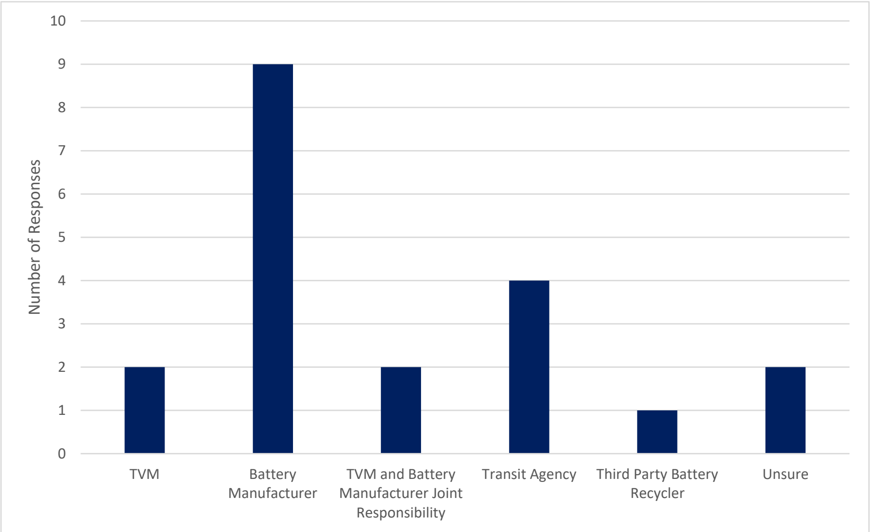

Figure 4: Opinions on Responsibility for End-of-Life Management

5 Battery End of Life Industry Feedback

The battery end-of-life sector is rapidly growing. Multiple companies operate in the end-of-life market. The battery recycling sector appears poised for rapid growth. Many battery recycling companies are expanding their facilities to increase their recycling capacity. Battery recycling companies reported that they have recycled few batteries from ZEBs, but they are anticipating that the used battery feedstock will increase in the next few years as ZEBs start reaching their end of life. Many of the recycling companies are focusing on recycling smaller batteries, such as those found in electric scooters, until more electric mobility batteries become available.

Battery recyclers prefer to recycle NMC batteries because they contain higher quantities of high-value metals. Many TVMs employ NMC batteries on their buses and will continue to do so for the foreseeable future. This stands in contrast to the electric car industry, where manufacturers are increasingly switching to the LFP chemistry which have lower mineral value content. As a result, ZEB batteries are expected to be a lucrative market for the battery recycling industry.

Battery manufacturers also appear supportive of battery recycling. This study uncovered several barriers to battery recycling, including information sharing about batteries and battery construction. Battery manufacturers are aware of these barriers and have taken steps to address these challenges.

The outlook for second-life batteries is less clear. The process for manufacturing second-life batteries is not as established as battery recycling processes. Whereas the battery recycling industry has established multiple commercial plants, the battery second-life sector is largely still in the demonstration phase and has not yet reached scale. The economics of second-life batteries are also still unclear. The results and operational data from the current second-life battery demonstrations will be vital to answering questions about economic valuation and the expected duration of second-life batteries.

6 Fuel Cell Industry Feedback

While recycling processes for PEMFCs have been developed, the PEMFC recycling sector is currently in its nascency. At this point in time, relatively few PEMFCs have reached their end of life. A key question for the transit industry is how much residual value can be extracted from the PEMFC at its end of life. Industry consensus is that the PEMFC cannot be used in a second-life application, meaning that the only avenue for extracting residual value is through recycling. Based on industry feedback, the dominant recycling process is currently PMT with alcohol solvent dissolution as a possible emerging process. The recycling value of the PEMFC through these processes is not well understood. Answering this question is important because it affects the economics of FCEBs. If the recycling value for PEMFCs is higher than the current scrapping value for buses, it could allow transit agencies to realize more value at the end of the bus's useful life.

A key challenge to establishing the recycling value is that recyclers have little experience recycling PEMFCs from FCEBs. Much of the waste stream recyclers have processed to date has been from fuel cell-powered forklifts, meaning that there is little real-world data on FCEB PEMFC residual value. As a result, a study that quantifies the expected residual value for PEMFC recycling would be beneficial for the transit industry.

Industry is seeking more PEMFCs to recycle and has enough recycling capacity to increase their operations when the waste stream scales up. However, industry has expressed concerns about the uncertainty of future waste streams. Some vehicle manufacturers and PEMFC manufacturers have offered to take the fuel cells back at the end of life. However, it is unclear what they will do with the used PEMFCs and which recycling process will be used to dispose of them. As a result, the amount of PEMFC waste stream that will be available in the future is unclear. PEMFC recycling is also highly relevant to PEM electrolyzer recycling as both devices have PGM and an ionomer in the MEA. The main difference between them is that electrolyzer MEAs also contain Iridium, which is not present in PEMFC MEAs. As a result, electrolyzers also represent a market opportunity for PEMFC recyclers.

7 Research Finds and Recommendations

This research found that ZEBs at end-of-life have significant potential to be valuable to the transit industry, but many unknowns still need to be considered. The residual value of a battery pack is highly dependent on the battery chemistry and mineral content. The packaging design varies among battery and vehicle manufacturers, which can cause issues for second-life and recycling companies. SOH or number of cycles is used in determining when a battery should be retired from its first life. A battery is typically considered no longer suitable in vehicle applications when 80% of the usable capacity remains. However, quantifying when a battery is no longer suitable for second-life applications remains unknown, and currently different metrics exist to make that determination.

There are a few different ways to recycle batteries. Materials recovery is vital to create a battery circular economy, but it is not clear how much of the recycled materials stays in the U.S. or is sent abroad. Selling the recycled material in the U.S. would help to secure future supplies of these materials.

Grid and building storage have emerged as prime second-life battery applications. Industry certifications are important to meet to ensure a safe and reliable battery deployment. Battery recyclers appear to have more potential feedstock coming down the line as more ZEBs reach their end of life. The results and operational data from the current second-life battery demonstrations will be vital to answering questions about economic valuation and the expected duration of second-life batteries.

The PEMFC in a FCEB is valuable due to its materials. The ionomer and PGM can be broken down and extracted. PEMFC recyclers have less certain potential feedstock in the future due to the relatively few FCEBs that have been deployed. However, some PEMFC recyclers have other revenue generators (e.g., catalytic converter recycling, recycling PEMFCs from cars and forklifts) that they can pursue while they await FCEBs to reach their end of life.

A key challenge to establish residual value is that recyclers have little experience recycling PEMFCs from FCEBs. Industry has expressed concerns about the uncertainty of future waste streams. Some vehicle manufacturers and PEMFC manufacturers have offered to take the fuel cells back at their end of life. However, it is unclear what they will do with the used PEMFCs and which recycling process will be used to dispose of them. As a result, the amount of PEMFC waste stream that will be available in the future is unclear. Industry consensus is that second-life applications for PEMFCs does not exist.

To receive federal funding for a replacement vehicle, transit agencies must ensure that the existing federally funded vehicle has reached its useful end of life and is properly disposed of in accordance with the Federal Transit Administration (FTA) guidelines. [20] As a result, transit agencies cannot remove parts of these buses before sale. This restriction does not apply to buses that were purchased with local funding. This regulation makes it difficult for transit agencies to remove the LIB from their buses to recycle or use them in second-life applications.

Transit fleet RFPs are increasingly asking for end-of-life solutions for vehicles, showing that users are looking to TVMs for solutions. Notably, all stakeholders expressed a willingness to collaborate and support the facilitation of these end-of-life strategies. Many TVMs have established partnerships with battery recycling companies and will help to facilitate the transfer of used batteries to the recyclers. The responsibility of transporting the batteries varies depending on the relationship between the parties.

Based on this research, CALSTART developed several recommendations when considering how to handle decommissioned ZEBs:

- Materials Recovery
    - BEBs – The battery is considered the most expensive part of the BEB. Safely and efficiently recovering the battery from the BEB will be crucial. Once the battery is removed, breaking it down into usable components, either for recycling or second-life applications, should happen in the U.S. Keeping the materials in the country allows for better control over the minerals and promotes a national circular economy.
    - FCEBs – In PEMFCs, the PMG appears to be the most valuable part of the FCEB. Industry has determined that the only available avenue for PEMFCs' end of life of is recycling. However, very few fuel cells have been recycled to date. More research should be conducted to quantify the value of these materials to aid in the circular economy of ZEBs.

- Battery State-of-Health Metrics – To assess a battery's feasibility for second-life applications or recycling, a universal methodology of determining SOH needs to be established. This will allow companies and transit agencies to understand how much life remains in the battery and make it possible to assign value to it. The economics of second-life batteries are heavily dependent on the price of a new LIB and the SOH of the used battery. Having established SOH metrics can also increase safety and allow for more tangible warranties on the batteries.
- Ownership – A ZEB is owned by both the transit agency and FTA when federal dollars are spent to purchase the vehicle. Instead of requiring the transit agency to sell or scrap the bus in its entirety, allowing the transit agency to keep the part of the bus as spare parts or sell to a third party interested in the vehicle's parts for second-life applications can increase the value and usefulness of the bus.

8 Acknowledgments

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10 Presenter Biography

Katrina Sutton is a technical project manager at CALSTART specializing in zero-emission bus technologies and infrastructure. She received a M.S. in Transportation Technology and Policy at UC Davis in 2020 and a B.S. in Environmental Science and Management from UC Davis in 2015. Her research interests include zero-emission buses, barriers to EV adoption, EV education, charging management strategies, charging etiquette, long distance BEV travel, and climate change mitigation. Proud owner of one 2022 Hyundai Ioniq5, one cat, and sixteen PV solar modules.