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Battery and Fuel Cell Recycling Economics: Calculating Recycling Value with Monte Carlo Simulations

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Executive Summary

Zero emission vehicles have upended traditional business models for vehicles. Typically, internal combustion engine vehicles are purchased, used, and then sold to a second buyer. The residual value, which is an important financial metric, is driven by the service that it can provide to the second buyer. Zero emission vehicles, however, do not yet have an established residual value as very few vehicles have reached end of life. This uncertainty in residual value is problematic because it is an important part of the vehicle's total cost of ownership. The residual value for a zero emission vehicle will be largely driven by the recycling value of the vehicle's battery or fuel cell. This study will analyze mineral content in batteries and fuel cells, examine historic commodity data for these minerals, and use a Monte Carlo simulation to estimate the residual value of recycled batteries and fuel cells.

Keywords: batteries, fuel cell systems, recycle & reuse, mining

1 Introduction

Zero emission vehicles (ZEV) replace the internal combustion engine (ICE) with a lithium ion battery (LIB) or a proton exchange membrane fuel cell (PEMFC). The growth of the e-mobility industry has led to an increase in demand for LIBs and PEMFCs. Since the e-mobility industry is in early stages of development, there are few vehicles that have reached their end of life. However, as these vehicles reach the end of life, there will be large quantities of used LIBs and PEMFCs that will need to be disposed of. This inevitability has sparked questions about how to handle this waste stream. The introduction of ZEVs has also upended traditional business models for commercial vehicles. Fleets normally purchase vehicles, put the vehicles into service, and then sell them at the end of their life. The value that they can sell the vehicle for at the end of life is referred to as residual value. Residual value is calculated as the difference between the original cost of the vehicle and the depreciation that occurs before the vehicle is sold. Residual value is an important metric because it affects the total cost of ownership (TCO), which is vital to creating financial products to finance vehicle purchases.

The residual value of a vehicle is based on the remaining performance that the purchaser can expect to obtain from the used vehicle. ICE vehicles have a residual value because the depreciated vehicle can continue to be used, although likely in a reduced capacity as the vehicle will have accumulated wear and tear. Since ICE vehicles have been in existence for a long time, their residual value is well understood and very predictable.

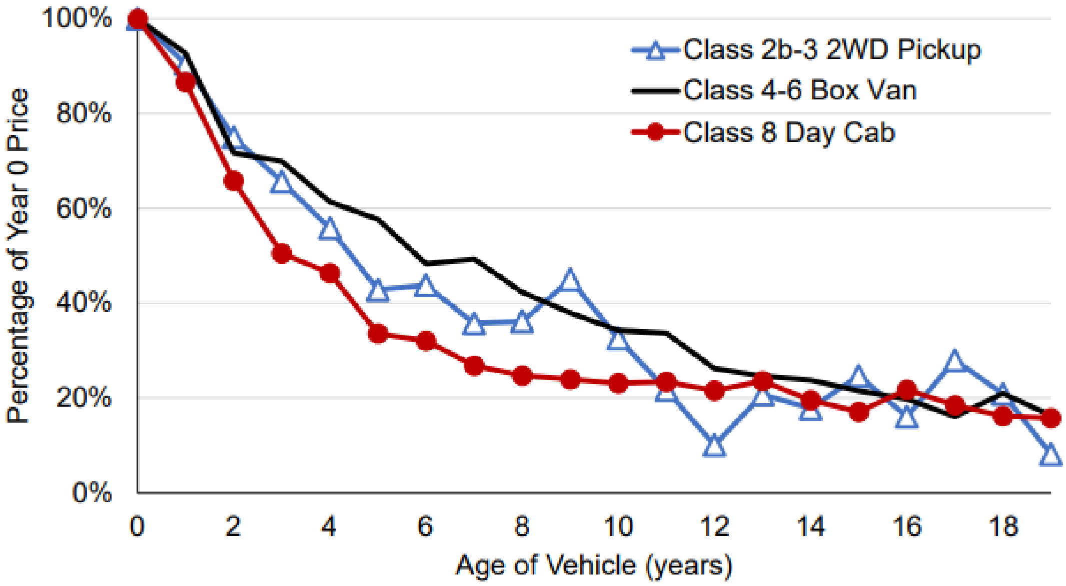

Figure 1: Commercial Vehicle Residual Value [1]

ZEVs, however, do not have an ICE. Instead, these vehicles are considered to have reached their end of life when the state of health of the LIB or PEMFC has degraded to the point where they cannot meet the vehicle's duty cycle. The e-mobility industry generally accepts that this occurs when the state of health reaches 80%. For batteries, this is measured as 80% of the original LIB storage capacity [2]. For PEMFCs, this is measured as 80% of the original voltage [3]. This distinction is important because ZEVs reach their end of life when the power plant is no longer fit for service. Since the vehicle is not useful without the power plant, a ZEV's residual value is heavily influenced by the residual value of the LIB or PEMFC. At this point in time, the residual value of a used LIB or PEMFC is still unclear. This paper will use a financial model to calculate these residual values. The financial model achieves this by calculating the revenues and costs associated with LIB and PEMFC recycling to determine the residual value.

2 Zero Emission Bus Residual Value

Transit buses also have an established residual value in the United States. Many transit buses are funded by the Federal Transit Administration (FTA). Transit buses are generally expected to have a minimum lifetime of 12 years or 500,000 miles. When the buses reach their end of life, they are usually sold to a scrapping company. Transit agencies typically receive less than $10,000 for an end of life ICE transit bus. However, the public transit sector has emerged as an early adopter of zero emission technology in the United States. Zero emission buses (ZEB) have experienced rapid growth. As of 2024, there are 7,028 ZEBs that are funded, on order, or deployed in the United States. 6,453 of these buses are battery electric buses (BEB) and the remaining 575 are fuel cell electric buses (FCEB) [4]. As ZEBs continue to be deployed, the FTA anticipates that there will be a significant number of end of life LIBs and PEMFCs and is interested in understanding the ramifications this will have on bus residual value. CALSTART received funding from the Federal Transit Administration to investigate this topic.

CALSTART identified two major pathways through which a LIB or PEMFC can generate residual value: recycling or second life applications. Recycling occurs when the LIB or PEMFC is broken down into its components, which can then be reintroduced into the supply chain to make new products. Most recycling processes focus on breaking the LIB or PEMFC into raw materials that can then be recovered and sold. The most valuable materials in a LIB are typically the cathode materials, which can include materials such as nickel, cobalt, manganese, and lithium. The most valuable minerals in the PEMFC are platinum and ionomer.

Alternatively, LIBs or PEMFCs can be employed in second life applications. While a LIB or PEMFC is no longer useful for medium- and heavy-duty (MHD) e-mobility applications at their end of life, there is still potential to deploy the LIB or PEMFC in another application. For example, a MHD vehicle battery can potentially be repurposed for use in a stationary battery energy storage system or microgrid.

While both recycling and second life applications are of heavy interest to the public transit industry, this report will focus on recycling. This study will specifically investigate the residual value that can be generated by recycling LIBs and PEMFCs. The recycling value of LIBs and PEMFCs is driven largely by the raw materials and minerals that they contain. Since these raw materials are traded commodities, there can be significant variations in their value based on market conditions, creating uncertainty in their value at any given time. To address this uncertainty, CALSTART employed Monte Carlo simulations to estimate the likely residual value.

3 Battery Recycling Residual Value

There are several methods that can be used to recycle LIBs. However, the dominant recycling method is hydrometallurgy (HMT). HMT is a chemical-based recycling process that uses leaching agents to dissolve battery materials, enabling selective extraction of materials. This process has gained popularity due to its high recovery rates and selectivity in extracting valuable materials. This technique is highly effective at recovering lithium, cobalt, and nickel.

The HMT recycling process involves several stages, the first of which is pre-treatment and crushing. When a battery first gets sent for recycling, it gets discharged to eliminate any electrical hazards. Next, the battery gets disassembled, either mechanically or manually, to separate the components such as casing, electrodes, electrolyte, and separators. Once the batteries are disassembled, they are crushed or shredded to create black mass, which contains valuable materials like lithium, cobalt, nickel, manganese and graphite.

The black mass, although rich in valuable materials, still contains binders like plastics and electrolytes that can interfere with HMT leaching. To combat this, the black mass goes through thermal and/or mechanical pre-treatment, which is where batteries undergo a heat treatment or solvent cleaning to remove volatile components such as binders, plastics, and residual organics. While black mass contains valuable battery metals, these materials are not immediately useable and must be converted to a form where they can reenter the manufacturing supply chain. To achieve this, after the LIBs finish their pretreatment, they undergo leaching. Leaching is a chemical process that dissolves valuable materials from the black mass (a solid) to a liquid solution, typically a strong acid such as sulfuric or hydrochloric acid. These acids react with the materials in the black mass, separating and extracting the valuable materials through chemical reactions.

Since HMT is the dominant recycling method in the United States, the analysis in this section focuses on determining the residual value generated by the HMT recycling process.

3.1 Methodology

CALSTART calculated the residual value that a transit agency can realize by recycling a LIB. This calculation was performed by first calculating the net revenue (NR) from the LIB recycling process. NR was calculated using a model adapted the battery recycling model developed by Lander et al. [5]. This model is specified as follows:

$$NR = R - I - C_{Transportation} - C_{Disassembly} - C_{Recycling} \qquad (1)$$

Where NR is the value of the recycled products from the LIB process, R is recycling revenue, I represents the investment CAPEX, $C_{Transportation}$ represents transportation costs, $C_{Disassembly}$ represents LIB disassembly costs, and $C_{Recycling}$ represents recycling costs. All of these variables were normalized and expressed in terms of revenue or cost per MWh of LIBs.

NR represents the value of the recycled products at the end of the recycling process. However, the LIB recycling company must also make a profit. As a result, the LIB recycling company is assumed to take a profit margin, which is expressed as a percentage of NR. The remaining value is the residual value that is paid to the transit agency. This is expressed as:

$$RV = (1 - p) * NR \qquad (2)$$

Where RV represents residual value realized by the transit agency and p is the LIB recycler profit margin. This model assumes that the recycler profit margin is 25%. RV is also normalized and expressed in terms of value per MWh of LIBs.

3.2 Model Inputs

The LIB recycling model has five primary components including Revenue, Investment, Transportation Costs, Disassembly Costs, and Recycling Process Costs. This section outlines the inputs and parameters that were used to calculate each component.

3.2.1 Revenue

LIB recycling processes generate revenue by recovering raw materials from the battery, which can then be sold. LIBs contain several recoverable materials. However, the most valuable material is the cathode material. Most BEBs in the US use the nickel cobalt manganese (NMC) 622 chemistry. As a result, the LIB recycling process focuses on recovering these materials which can then be resold or put back into the manufacturing process to make new LIBs. This study focuses primarily on revenue generated from cathode materials and lithium. This was calculated as the sum of the revenue from recovered lithium, nickel, cobalt, and manganese.

Each battery metal has its own value that is based on market price. This was calculated per MWh of battery. Each battery metal's value was calculated by taking the product of the metal content (kg of battery metal per kg of recycled LIB), weight of 1 MWh of LIB (assumed to be 6,280 kg based on data collected from the EverBatt model [6]), recovery rate, and metal price (commodity spot prices for the metal based on IMF commodity data [7]).

Data from the EverBatt Model was used to determine the metal content and recovery rates. The table below contains the assumed parameters for each material using HMT:

Table 1: Battery Metal Content and Recovery Rates

Battery Metal	Battery Metal Content (kg of battery metal per kg of recycled LIB)	Recovery Rate (%)
Lithium	0.02	90%
Nickel	0.101	95%
Cobalt	0.034	95%
Manganese	0.031	95%

While the battery metal content and recovery rates are known, there is a high degree of uncertainty in the prices for the minerals. This is due to the fact that these minerals are a commonly traded commodity whose price changes based on market conditions. CALSTART used a Monte Carlo simulation to address this uncertainty. The Monte Carlo simulation predicts battery metals pricing based on historical data and then calculates the average value to determine the expected value. The International Monetary Fund maintains a dataset that tracks the monthly spot price for lithium, nickel, cobalt, and manganese. Prices for all of these metals have historically been volatile. To eliminate the volatility caused by the 2008 Financial Crisis, CALSTART only analyzed data after the 2008 recession ended. This data ranged from July 2009 – March 2025 for nickel and cobalt. The datasets for lithium and manganese began in June 2012 so data from June 2012 – March 2025 was used. This data was used to develop a probability distribution function for prices for each battery metal. CALSTART found that the probability distribution function was best represented as by a gamma distribution. CALSTART then developed a gamma distribution for each metal based on the following parameters to simulate the prices:

Table 2: Battery Metals Price Gamma Distribution Parameters

Parameter	Lithium	Nickel	Cobalt	Manganese
Shape	0.460549205	2.80559229	1.22070671	0.738635
Scale	151,229.2122	2,976.29635	13,849.93506	1,304.536
Threshold	62,376.58	8,298.5	21,721.08	1,476.3

CALSTART used these distributions to draw random samples to simulate the prices of the battery metals. The Monte Carlo simulation consists of 1,000 samples for each battery metal. The simulated platinum prices were converted from dollars per short ton or metric tonne to dollars per kilogram.

The Monte Carlo simulation was then calculated based on the following equation:

$$Battery\ Metal\ Value = \frac{\Sigma_{i=1}^{1000}\ (Metal\ Content\ x\ Battery\ Weight\ x\ Recovery\ Rate\ x\ Metal\ Price_i)}{1000} \quad (3)$$

Where i corresponds to the random samples. This Monte Carlo simulation assumes that metal content, battery weight, and recovery rate remain constant across all simulations. The resulting value represents the expected value of the battery metals recovered from the recycling process. The results from each battery metal were then added together to calculate the total revenue from the battery.

3.2.2 Investment

LIB recycling companies must invest in a recycling facility. Since recycling companies are building dedicated facilities for recycling, their initial investment cost must be amortized over the throughput of the facility. This analysis assumes that the recycling facility has a capacity of 20,000 metric tonnes per year and has a lifetime of 25 years. Based on data from the EverBatt model, the initial capital expenditures (CAPEX) for the preprocessing process is $24,771,584 and $56,265,970 for the material recovery process. This CAPEX was divided by the throughput of the plant over a 25 year life. The throughput was calculated by the following equation:

$$Throughput = \frac{20{,}000\ metric\ tonnes}{1\ year}\ x\ \frac{1{,}000\ kg}{1\ metric\ tonne}\ x\ \frac{1\ MWh\ of\ LIB}{6{,}280\ kg}\ x\ 25\ year\ life \quad (4)$$

The CAPEX was then divided by throughput to calculate investment, expressed as dollars per MWh. This calculation is not discounted and does not take into account time value of money.

3.2.3 Cost of Transportation

After a LIB reaches its end of life, it must be transported to the LIB recycling facility. The cost of transportation for LIBs has several components including the removal cost, packaging cost, and freight cost. Since LIBs are classified by the Environmental Protection Agency as Class 9 hazardous waste, they must be handled by workers with hazardous materials certification. Removal cost corresponds with the labor costs associated with removing and packaging the used LIB for transport. CALSTART assumed that the removal and packaging process would take 5 hours per BEB and labor rates of $22.73 per hour, based on data from the US Bureau of Labor Statistics [8]. Since a single BEB does not contain a MWh of LIBs, this figure was normalized to 1 MWh. In addition to the removal cost, LIBs must be put in special packaging before they can be transported. Based on data from the EverBatt model, the packaging was assumed to cost $0.59 per kg of LIB.

Freight Cost was calculated using a Monte Carlo simulation. Since there are recycling facilities in the US, CALSTART assumed that used LIBs are transported via truck. Furthermore, CALSTART assumed that 1 MWh of LIBs can fit inside of one heavy-duty tractor carrying a 53-foot container. CALSTART calculated freight costs based on the product of distance (assumed to be 400 miles) and the freight rate (cost for transporting the LIB on a per mile basis.

Freight rate was calculated based on dry van spot prices, which refer to the cost of shipping cargo in a 53-foot container using a Clas 8 truck. This data was obtained from DAT Freight & Logistics [9]. Dry van spot prices vary because they are market-based. CALSTART used a Monte Carlo simulation to address this uncertainty. The Monte Carlo simulation used historical data from the DAT Freight & Logistics dataset. This dataset consisted of weekly data from January 2015 – October 2023. This data was used to develop a probability distribution function for platinum prices. CALSTART found that the probability distribution function was best represented as by a gamma distribution. CALSTART then developed a gamma distribution based on the following parameters to simulate the freight pricing:

Table 3: Dry Van Spot Prices Gamma Distribution

Parameter	Value
Shape	1.76819
Scale	0.248179
Threshold	1.321

CALSTART used this distribution to draw random samples to simulate the dry van spot price. The Monte Carlo simulation consists of 1,000 samples. The Monte Carlo simulation was then calculated based on the following equation:

$$Freight\ Cost = \frac{\Sigma_{i=1}^{1000}\ (Distance\ x\ Freight\ Rate_i)}{1000} \qquad (5)$$

Where i corresponds to the random samples. This Monte Carlo simulation assumes that distance remains constant across all simulations.

3.2.4 Cost of Disassembly

After the LIBs arrive at the recycling facility, they need to be disassembled before they are recycled. The disassembly process strips the battery pack down to smaller components, such as modules and cells. Based on data from the EverBatt Model, CALSTART assumes that each LIB requires 4.5 labor hours to disassemble and assumed that the labor rate is $21.14 per hour. CALSTART assumed that each LIB has a capacity of 400 kWh. The labor costs were normalized per MW using the following equation:

$$C_{Disassembly} = \frac{\$21.14}{hour}\ x\ \frac{4.5\ hours}{1\ PEMFC}\ x\ \frac{1000}{400} \qquad (6)$$

3.2.5 Cost of Recycling

After the LIB is disassembled, the recycling process can begin. HMT has several required process inputs. These process inputs were described in the EverBatt Model. CALSTART calculated recycling costs using the following process inputs and costs:

Table 4: HMT Preprocessing Inputs (kg per kg of recycled LIB)

Process Input	Quantity	Cost
NH4OH	0.031	$0.53
HCl	0.012	$0.57
H2O2	0.366	$1.46
NaOH	0.561	$0.45
Sulfuric acid	1.08	$0.08
Soda ash	0.02	$0.14
Water (in gallons)	1	$0.005
Diesel (in MJ)	0.6	$0.0132
Natural gas (in MMBTU)	0.00239	$7.77
Electricity (in kWh)	0.0347	$0.08

These factors were used to calculate the cost of the preprocessing inputs per kg of recycled LIB. They were then multiplied by 6,280 kg, which is the weight of 1 MWh of LIBs to normalize the cost per MWh.

Preprocessing converts the LIBs to black mass. According to the EverBatt Model, preprocessing will produce 0.439 kg of black mass per kg of recycled LIBs. The black mass must go through further processing to recover battery metals. This process requires the following inputs:

Table 5: HMT Material Recovery Inputs (kg per kg of black mass)

Process Input	Quantity	Cost
Lime	1.17	$0.13
Sulfuric Acid	1.26	$0.08
Water (in gallons)	0.6	$0.005

These factors were then multiplied by 2,756.92 kg, which is the weight of the black mass from 1 MWh of LIBs.

3.3 Model Results

The model indicates that an NMC 622 battery that is removed from a BEB at its end of life is worth approximately $14,359 per MWh. Most BEBs in the United States have approximately 400 kWh of LIB. As a result, the residual value of the LIBs from one BEB is expected to be approximately $5,744.

Table 6: HMT Monte Carlo Simulation Results (per MWh)

Component	Cash Flow
Revenue	$33,916
Investment/CAPEX	($1,018)
Cost of Transportation	($4,697)
Cost of Disassembly	($951)
Cost of Recycling	($8,104)
Net Revenue	$19,146
Profit Margin	($4,787)
Residual Value	$14,359

The model indicates that the recycling process costs are the largest cost for HMT. However, transportation costs are also a significant portion of the cost. Transit agencies that are further away from recycling facilities will have to incur larger transportation costs, which will erode the residual value they can obtain from the LIB.

4 Fuel Cell Recycling Residual Value

The useful life of a FCEB is largely driven by the life of the PEMFC. FCEBs are considered to have reached their end of life when the state of health of the PEMFC has degraded to the point where it cannot meet the vehicle's duty cycle. For FCEBs, this is typically benchmarked at 80% of the original voltage [10]. However, depending on the duty-cycle, some fleets might be able to use the FCEB after the PEMFC reaches this level of degradation. Since the FCEB is no longer useful once the PEMFC reaches its end of life, options for selling the FCEB on secondary markets are limited. Since the vehicle is not useful without the PEMFC, the FCEB's residual value is heavily influenced by the residual value of the fuel cell.

When batteries reach their end of life, they can either be employed in second-life applications or recycled. However, based on interviews with industry, second-life PEMFC applications are unlikely to be feasible. As a result, recycling is the primary method for disposing of the PEMFC and generating residual value once it reaches its end of life. PEMFC recycling processes generate residual value by recovering valuable raw materials. The primary raw material that can be recovered is platinum, which is used as a catalyst in the membrane electrode assembly (MEA). The ionomer can also potentially be recovered.

The PEMFC recycling process begins by dismantling the PEMFC. Since the recycling process focuses on the 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 [11]. After the PEMFC is processed, there are multiple recycling methods that can potentially be used.

Pyrohydrometallurgy (PMT), which is also used to recycle batteries, is a recycling method for PEMFCs. PMT involves incinerating the MEA before using a leaching process to recover platinum. The process begins by drying the MEA. This is followed by a calcination process where the MEA is heated to 600°C to incinerate all carbon materials and volatile compounds. The resulting ashes are then leached with nitric acid. Then the solution is heated and hydrochloric acid is added. After this, deionized water and NaOH are added to dissolve the resulting solids, and then formic acid is used to reduce the platinum. It is then dried and filtered to produce a powder containing platinum [12]. However, the incineration process releases fluorocarbon gases, which is a greenhouse gas and depletes atmospheric ozone. The incineration process also requires higher energy inputs than would be required for other recycling methods [13].

PEMFCs can also be recycled using HMT. HMT is also used for battery recycling. HMT dissolves the platinum from the carbon support structure in the MEA and then separating it through precipitation. The process begins with mechanical pretreatment to maximize the surface area that can be attacked in the dissolution process. Then a leaching process is carried out using an aqua regia consisting of hydrochloric acid and nitric acid. After leaching, the resulting solution is filtered to remove carbon particles. The filtered solution is then mixed with NH_4Cl to precipitate platinum as $(NH_4)_2PtCl_6$ before it is filtered again to obtain a platinum solid. The solid can be ignited to form pure platinum or can be mixed with carbon powder to create new electrode ink.

While HMT and PMT methods can recover platinum, they destroy the ionomer. As a result, industry has sought to develop a process that can recover the ionomer as well. Some prospective processes can potentially allow for ionomer recovery. The alcohol solvent process is a prospective recycling method. This process entails applying an alkyl alcohol solution to the MEA. This separates the MEA layers. The solution is then microwaved until the temperature is suitable for dissolving the ionomer. The ionomer is then filtered out of the solution and recovered [14]. BEST4Hy developed a novel alcohol solvent process which involves using a mixture of ethanol and water as the solvent. Dissolution is most effective at a high temperature and pressure, and a pressure autoclave is used to create these conditions. The resulting solution is then put through a centrifuge to remove large grains. The ionomer and platinum-carbon ink are then separated and filtered. HMT can then be used to recover platinum from the catalyst ink. This study assumes that HMT will be combined with the solvent dissolution process to recover both platinum and the ionomer.

4.1 Methodology

CALSTART evaluated the residual value for PEMFCs based on PMT, HMT, and alcohol dissolution. CALSTART utilized the same model that was used for LIB recycling (see Equations 1 and 2 in Section 3.1). However, since PEMFC capacity is measured in MW, residual value for PEMFCs was normalized to MW instead of MWh.

4.2 Model Inputs

The PEMFC recycling model has five primary components including Revenue, Investment, Transportation Costs, Disassembly Costs, and Recycling Process Costs. This section outlines the inputs and parameters that were used to calculate each component.

4.2.1 Revenue

PEMFC recycling processes generate revenue by recovering raw materials from the fuel cell, which can then be sold. PEMFCs contain several recoverable materials. However, the most valuable material is the platinum catalyst. PEMFC recycling processes aim to reconstitute the catalyst into solid platinum, which can then be resold. The value of platinum is the product of platinum loading (kg of platinum per MW), the recovery rate (percentage of platinum that can be recovered), and the platinum price. Based on industry feedback, platinum loading was assumed to be 0.5 kg per MW. Data from Uekert *et al.* [15] was used to determine the platinum recovery rates. The table below contains the assumed recovery rate for each recycling method:

Table 7: Platinum Recovery Rates

Recycling Process	Recovery Rate (%)
PMT	98.3%
HMT	84.9%
Solvent Dissolution	84.9%

While the platinum loading and recovery rates are known, there is a high degree of uncertainty in the platinum price due to the fact that platinum is a commonly traded commodity whose price changes based on market conditions. CALSTART used a Monte Carlo simulation to address this uncertainty. The Monte Carlo simulation predicts platinum price based on historical data and then calculates the average value to determine the expected value. The International Monetary Fund maintains a dataset that tracks the monthly spot price for platinum [16]. Platinum prices have historically been volatile. To eliminate the volatility caused by the 2008 Financial Crisis, CALSTART only analyzed data after the 2008 recession ended. This data ranged from July 2009 – March 2025. This data was used to develop a probability distribution function for platinum prices. CALSTART found that the probability distribution function was best represented as by a gamma distribution. CALSTART then developed a gamma distribution based on the following parameters to simulate the price of platinum:

Table 8: Platinum Spot Price Gamma Distribution Parameters

Parameter	Value
Shape	1.852976
Scale	218.7075
Threshold	752.55

CALSTART used this distribution to draw random samples to simulate the price of platinum. The Monte Carlo simulation consists of 1,000 samples. The simulated platinum prices were converted from dollars per troy ounce to dollars per kilogram.

The Monte Carlo simulation was then calculated based on the following equation:

$$Platinum\ Value = \frac{\Sigma_{i=1}^{1000}\ (Platinum\ Loading\ x\ Recovery\ Rate\ x\ Pt\ Price_i)}{1000} \quad (7)$$

Where i corresponds to the random samples. This Monte Carlo simulation assumes that platinum loading and the recovery rate remain constant across all simulations. The resulting value represents the expected value of the platinum recovered from the recycling process.

While platinum is the primary source of revenue from recycling, the ionomer can potentially be recovered with some recycling processes. While PMT and HMT destroy the ionomer, solvent dissolution can be used to recover the ionomer. According to Uekert *et al* (2024), one MW of PEMFCs contains 30.48 kilograms of ionomer and the solvent dissolution method has a recovery rate of 81% [17]. The value of the recovered ionomer is still unclear at this point in time, as further research needs to be conducted to characterize the recovered material. To model this uncertainty, CALSTART provided a pessimistic and optimistic scenario. The pessimistic scenario assumes that the ionomer has no value and generates $0 per kilogram of revenue. The optimistic scenario assumes that the ionomer is as valuable as virgin ionomer and generates $18 per kilogram of revenue.

Table 9: Ionomer Recovery Rates

Recycling Process	Recovery Rate (%)
PMT	0%
HMT	0%
Solvent Dissolution	81%

The revenue generated from ionomer recovery was added to the revenue generated from platinum recovery.

4.2.2 Investment

Most financial models also take into account the initial CAPEX of the recycling facility. However, PEMFCs are typically recycled in facilities that primarily process other precious metals. Oftentimes these facilities process other materials such as catalytic converters, gold, silver, and other PGMs. Since there are relatively few FCEBs and other fuel cell vehicles on the road, the waste stream of used PEMFCs is not expected to justify the construction of new recycling facilities. Furthermore, PEMFC recycling will probably comprise only a portion of an existing plant's recycling capacity. As a result, the initial CAPEX investment was treated as a sunk cost and was ignored in this analysis.

4.2.3 Cost of Transportation

Unlike used LIBs, PEMFCs are not hazardous waste. As a result, they do not have to be processed by trained hazardous waste handlers and do not require special packaging. Therefore, the cost of transportation for PEMFCs consists entirely of freight costs. Freight costs were calculated using the same methodology outlined in Section 3.2.3 and Equation 5.

4.2.4 Cost of Disassembly

After the PEMFCs arrive at the recycling facility, they need to be disassembled before they are recycled. The disassembly process strips the fuel cell system down to the MEA, which contains the recyclable parts. During this process, balance of plant components such as inverters, blowers, piping, and the thermal management system are removed. CALSTART estimated that each PEMFC requires five labor hours to disassemble and assumed that the labor rate is $21.14 per hour (based on labor rates for Electrical and Electronic Equipment Assemblers [18]). CALSTART assumed that each PEMFC has a capacity of 85 kW. The labor costs were normalized per MW using the following equation:

$$C_{Disassembly} = \frac{\$21.14}{hour}\ x\ \frac{5\ hours}{1\ PEMFC}\ x\ \frac{1000}{85} \qquad (8)$$

4.2.5 Cost of Recycling

After the PEMFC is disassembled, the recycling process can begin. Each recycling method has several required process inputs. These process inputs were described in the research carried out by Uekert et al (2024) [19]. CALSTART calculated recycling costs using the following process inputs and costs:

Table 10: PMT Recycling Inputs (per MW of PEMFC)

Process Input	Quantity	Cost
Electricity	19.4 kWh	$0.0778/kWh
Steam	878 kg	$0.1596/kg
Natural Gas	1,352 kg	$0.1596/kg
HCl	18.7 kg	$0.538/kg
H2O2	22.3 kg	$1.486/kg
NH4Cl	0.684 kg	$0.1025/kg
Process Water	517 kg	$0.0002888/kg
Solid Waste	17.3 kg	$0.0573
Wastewater	.519 kg	$0.0132
Labor	8 hours	$33.71

Table 11: HMT Recycling Inputs (per MW of PEMFC)

Process Input	Quantity	Cost
Electricity	27.9 kWh	$0.0778/kWh
Steam	181 kg	$0.1596/kg
HCl	21.5 kg	$0.538/kg
H2O2	25.6 kg	$1.486/kg
NH4Cl	0.785 kg	$0.1025/kg
Process Water	594 kg	$0.0002888/kg
Solid Waste	199 kg	$0.0573
Wastewater	.596 kg	$0.0132
Labor	8 hours	$33.71

Table 12: Solvent Dissolution Recycling Inputs (per MW of PEMFC)

Process Input	Quantity	Cost
Electricity	0.622 kWh	$0.0778/kWh
Steam	25.8 kg	$0.1596/kg
HCl	0.132 kg	$0.538/kg
H2O2	0.158 kg	$1.486/kg
Butanol	3.04 kg	$1.4/kg
NH4Cl	0.005 kg	$0.1025/kg
Process Water	14.9 kg	$0.0002888/kg
Solid Waste	0.001 kg	$0.0573
Wastewater	.015 kg	$0.0132
Labor	8 hours	$33.71

4.3 Model Results

The results of the Monte Carlo simulations are displayed below. The results show that PMT has the highest residual value. This is largely driven by the fact that PMT has the highest platinum recovery rates. The results for solvent dissolution also demonstrates that the ionomer does not make a large contribution to PEMFC residual value. Even if the recovered ionomer has the same financial value as virgin ionomer, it only increases the residual value by 3%. As a result, platinum recovery is the most important factor in PEMFC residual value.

Table 13: PEMFC Recycling Monte Carlo Simulation Results (per MW)

Component	PMT	HMT	Solvent Dissolution (pessimistic)	Solvent Dissolution (optimistic)
Platinum Revenue	$18,303	$15,808	$15,808	$15,808
Ionomer Revenue	-	-	-	$444
Investment/CAPEX	-	-	-	-
Cost of Transportation	($703)	($703)	($703)	($703)
Cost of Disassembly	($1,244)	($1,244)	($1,244)	($1,244)
Cost of Recycling	($400)	($298)	($421)	($421)
Net Revenue	$15,957	$13,563	$13,440	$13,884
Profit Margin	($3,989)	($3,391)	($3,360)	($3,471)
Residual Value	$11,968	$10,172	$10,080	$10,413

These results also demonstrate that the PEMFC has a relatively low residual value. Based on these results, the PEMFC will have a residual value of less than $1,000 per FCEB. Since a new FCEB costs in excess of $1 million, this implies that that FCEBs will have a low residual value and transit agencies will recover a small percentage of the original cost of the bus.

5 Conclusion and Future Research

This research is important because it contributes to industry's understanding of the economics of LIB and PEMFC recycling. This information is vital for understanding the residual value for end of life ZEBs. Based on this research, LIB and PEMFC recycling appears to yield relatively low residual values, implying that residual value for ZEBs will also be low. Since other MHD vehicles, such as Class 8 trucks, use similar LIB and PEMFC technologies, the authors expect that the results of this study can be generalized to other MHD vehicle segments.

CALSTART intends to build on this research. CALSTART is planning to carry out sensitivity analysis to understand how changes in major inputs in the model affects recycling economics. CALSTART also recognizes that study only investigates residual value from recycling and does not investigate second life applications. CALSTART intends to fill this gap in the research by carrying out future research on the residual value of second life LIBs and PEMFCs.

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References

[1] California Air Resources Board. "Advanced Clean Fleets – Cost Workgroup Cost Data and Methodology Discussion Draft." Available at: https://ww2.arb.ca.gov/sites/default/files/2020-12/201207costdisc_ADA.pdf

[2] Jessica Dunn (2022). Union of Concerned Scientists. "Battery State of Health – What is It? Why is It Important?" Available at: https://blog.ucsusa.org/jessica-dunn/battery-state-of-health-what-is-it-why-is-it-important/

[3] Elliot Padget (2020). US Department of Energy. "On-Road Transit Bus Fuel Cell Stack Durability." Available at: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/20008-fuel-cell-bus-durability.pdf

[4] Hynes, Mike and Lemons, Kaila (2025). Zeroing in on Zero Emission Buses: The US Advanced Technology Transit Bus Index. Available at: https://calstart.org/zio-zebs/

[5] Lander, Laura, Cleaver, Tom, Rajaeifar, Mohammad Ali, Nguyen-Tien, Viet, Elliott, Robert J.R., Heidrich, Oliver, Kendrick, Emma, Edge, Jacqueline Sophie, and Offer, Gregory (2021). Financial viability of electric vehicle lithium-ion battery recycling. *iScience* 24:7, 102787. https://doi.org/10.1016/j.isci.2021.102787

[6] Argonne National Laboratory, EverBatt Model, https://www.anl.gov/amd/everbatt

[7] International Monetary Fund. Primary Commodity Prices, https://www.imf.org/en/Research/commodity-prices

[8] Bureau of Labor Statistics. Hazardous Materials Removal Workers. https://www.bls.gov/oes/2023/may/oes474041.htm

[9] Bureau of Transportation Statistics. https://www.bts.gov/browse-statistical-products-and-data/info-gallery/truck-spot-rates-jan-2015-oct-2023

[10] Padget, Elliot (2020). US Department of Energy. "On-Road Transit Bus Fuel Cell Stack Durability." Available at: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/20008-fuel-cell-bus-durability.pdf

[11] BEST4Hy (2022). Deliverable D1.2: Technical Report on Adaptation of Existing Technology (Hydrometallurgical Process) for PEMFC Material Recovery: Results and Design. Retrieved from https://best4hy-project.eu/wp-content/uploads/2023/03/BEST4Hy_D1.2-Technical-report-for-PEM-fuel-cells.pdf.

[12] Valente, A., Iribarren, D., and Dufour, J. (2019). End of life of fuel cells and hydrogen products: From technologies to strategies. *International Journal of Hydrogen Energy 44: 20965 – 20977*. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360319919302423.

[13] Uekert, T., Wikoff, H., and Badgett, A. (2024). Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy. National Renewable Energy Laboratory, Advanced Sustainable Systems. Retrieved from https://doi.org/10.1002/adsu.202300449.

[14] Valente, A., Iribarren, D., and Dufour, J. (2019). End of life of fuel cells and hydrogen products: From technologies to strategies. International Journal of Hydrogen Energy 44: 20965 – 20977. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360319919302423.

[15] Uekert, T., Wikoff, H., and Badgett, A. (2024). Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy. National Renewable Energy Laboratory, Advanced Sustainable Systems. Retrieved from https://doi.org/10.1002/adsu.202300449.

[16] International Monetary Fund. Primary Commodity Prices, https://www.imf.org/en/Research/commodity-prices

[17] Uekert, T., Wikoff, H., and Badgett, A. (2024). Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy. National Renewable Energy Laboratory, Advanced Sustainable Systems. Retrieved from https://doi.org/10.1002/adsu.202300449.

[18] Bureau of Labor Statistics. Electrical and Electronic Equipment Assemblers, https://www.bls.gov/iag/tgs/iag335.htm#prices

[19] Uekert, T., Wikoff, H., and Badgett, A. (2024). Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy. National Renewable Energy Laboratory, Advanced Sustainable Systems. Retrieved from https://doi.org/10.1002/adsu.202300449.

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