

Advances in Repurposing and Recycling of Post-Vehicle-Application Lithium-Ion Batteries



MNTRC Report 12-55



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REPORT 12-55

ADVANCES IN REPURPOSING AND RECYCLING OF POST-VEHICLE-APPLICATION LITHIUM-ION BATTERIES

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16. Abstract Increased electrification of vehicles has increased the use of lithium-ion batteries for energy storage, and raised the issue of what to do with post-vehicle-application batteries. Three possibilities have been identified: 1) remanufacturing for intended reuse in vehicles; 2) repurposing for non-vehicle, stationary storage applications; and 3) recycling, extracting the precious metals, chemicals and other byproducts. Advances in repurposing and recycling are presented, along with a mathematical model that forecasts the manufacturing capacity needed for remanufacturing, repurposing, and recycling. Results obtained by simulating the model show that up to a 25% reduction in the need for new batteries can be achieved through remanufacturing, that the sum of repurposing and remanufacturing capacity is approximately constant across various scenarios encouraging the sharing of resources, and that the need for recycling capacity will be significant by 2030. A repurposing demonstration shows the use of post-vehicle-application batteries to support a semi-portable recycling platform. Energy is collected from solar panels, and dispensed to electrical devices as required. Recycling may be complicated: lithium-ion batteries produced by different manufacturers contain different active materials, particularly for the cathodes. In all cases, however, the collecting foils used in the anodes are copper, and in the cathodes are aluminum. A common recycling process using relatively low acid concentrations, low temperatures, and short time periods was developed and demonstrated.			
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The recycling component of this work was led by Professor Lindsay Corneal of the School of Engineering and Eric Li, a student in the Master of Science in Engineering Program at GVSU. Their work has demonstrated a recycling process able to separate lithium-ion cells into component materials in a relatively benign environment: low temperatures, low concentrations of acid, in a short time.

Repurposing activities were led by Professor Nicholas Baine of the School of Engineering. Ananda Ganapathy, a student in the Master of Business Administration Program at GVSU, supported all technical work. The repurposing of batteries to provide energy storage of a portable recycling center was done in full partnership with Hastings Township, Michigan. The efforts of Kim Walton of the Michigan Alternative and Renewable Energy Center at GVSU, as well as Jim Brown, Hastings Township Supervisor, are appreciated.

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TABLE OF CONTENTS

Executive Summary	1
I. Introduction	3
II. Modeling and Simulation of Future Remanufacturing, Repurposing, and Recycling Manufacturing Capacity	4
Methods	4
Simulation Experiment and Results	10
Summary	13
III. Repurposing	14
Charge and Balance Circuits	14
Mobile Recycling Platform	16
IV. Recycling	21
Results and Discussion	22
Summary and Conclusions	26
V. Summary and Conclusion	27
Abbreviations and Acronyms	29
Endnotes	30
Bibliography	33
About the Authors	36
Peer Review	37

LIST OF FIGURES

1. Remanufactured Battery Capacity (Wh) Over Time	13
2. Balancing Board Schematic	15
3. Charge Circuit Block Diagram	16
4. Mobile Recycling Platform	17
5. Energy Storage and Battery Management System Layout	18
6. Thermal Management	20

LIST OF TABLES

1. Capacity Planning Model Variables	5
2. Comparison of Histogram with Gamma Distribution of Battery Life	7
3. Comparison of Histogram with Gamma Distribution of Battery Life	8
4. Count of Electrified Vehicles by Type	9
5. Average Battery Energy	9
6. Energy in Batteries of Electrified Vehicles	10
7. New and Remanufactured Batteries by Percent Remanufactured – Simulation Results for 2030	11
8. Repurposed and Recycled Batteries by Percent Remanufactured – Simulation Results for 2030	12
9. MRP Power Requirements	17
10. Sonali's PV Array Specs	18
11. Separation Times for Carbon Coatings from Copper Foils from Manufacturer A for Varying H_2SO_4 Concentrations and Temperatures	23
12. Separation Times for Carbon Coatings from Copper Foils from Manufacturer B for Varying H_2SO_4 Concentrations and Temperatures	23
13. Separation Times for Carbon Coatings from Copper Foils from Manufacturer C for Varying H_2SO_4 Concentrations and Temperatures	23
14. Separation Times for Cathode Active Material Coatings from Aluminum Foils from Manufacturer A for Varying HNO_3 Concentrations and Temperatures	24
15. Separation Times for Cathode Active Material Coatings from Aluminum Foils from Manufacturer B for Varying HNO_3 Concentrations and Temperatures	25
16. Separation Times for Cathode Active Material Coatings from Aluminum Foils from Manufacturer C for Varying HNO_3 Concentrations and Temperatures	25

EXECUTIVE SUMMARY

Electrification is driving the need for energy storage on board vehicles, resulting in the use of lithium-ion batteries. What to do with such batteries post-vehicle application is a fundamental question. The three possible strategies are remanufacturing for intended reuse in vehicles, through replacement of any group with damaged cells within the battery; repurposing by reengineering a battery for a stationary storage application; and recycling, disassembling each cell in the battery and safely extracting the precious metals, chemicals, and other byproducts – which are sold on the commodities market or re-introduced into a battery manufacturing process.

Building on previous work, recent advances in the repurposing and recycling of post-vehicle-application lithium-ion batteries are presented. These include an energy storage and management system that supports a semi-portable recycling unit, using repurposed post-vehicle application lithium-ion batteries. Through experimentation, the application of a recently developed recycling technology to lithium-ion batteries from various manufacturers, despite their different chemistries, was validated.

In addition, a mathematical model for forecasting manufacturing capacity for remanufacturing, repurposing, and recycling – as well as simulation procedures for evaluating the model – are presented. The model transforms a forecast of the demand for electric hybrid vehicles of all types into an estimate of the production capacity needed for remanufacturing, repurposing, and recycling post-vehicle-application lithium-ion batteries, as well as that needed for new batteries. The single model parameter is the percentage of such batteries that are remanufactured. The percentage of batteries that are recycled is viewed as a physical constraint on the life of the batteries. The batteries that are not remanufactured, yet can still hold a charge, are available for repurposing.

The simulation experiment design included setting the value of the model parameter: percent remanufactured. Simulation results are obtained for values in the range [0, 85]: 0, 5, 10, ..., 85 for each of the years 2016 through 2030, and support the following conclusions: A full commitment of all post-vehicle-application batteries to remanufacturing results in an approximate reduction of 25% in the demand for new batteries by 2030. The sum of the repurposing and remanufacturing capacities is approximately constant on the order of 3.12M Wh. This supports the idea of building capacity that is flexible between repurposing and remanufacturing tasks. The recycling capacity needed by 2030, regardless of the percentage of post-vehicle-application batteries selected for remanufacturing, is about 2.69M Wh.

The repurposing demonstration involved the development and implementation of an off-grid energy storage system using post-vehicle-application lithium-ion batteries with a suitable battery management system. Apart from the repurposed batteries, the electrical equipment is readily available off the shelf. The energy storage system supports a mobile recycling platform developed in partnership with Hastings Township, Michigan.

The mobile recycling platform consists of two main macro-assemblies: the storage assembly and the power assembly. The storage assembly was developed from a repurposed semi-

truck trailer and contains multiple bins. Recyclable goods are placed into these bins through slots. The recyclable goods, along with the storage bins, can be guided to an exit door through a mechanized lift and rail system. The power assembly consists of an array of solar panels that gather energy, which is stored in the repurposed batteries for use by the electrical equipment employed by the recycling platform. This includes lighting, cooling fans, and monitoring devices.

One complicating factor in recycling is that lithium-ion batteries produced by different manufacturers contain a variety of active materials, especially for the cathodes. However, the collecting foils used in the anodes are always copper; those in the cathodes are always aluminum. So the potential for a common recycling process, which would be highly desirable, exists.

Researchers developed and demonstrated a method to separate the carbon coatings from the copper foils of the anode using sulfuric acid. The reaction between the H_2SO_4 and the copper resulted in degradation of the adhesion of the carbon coatings to the foils; the combination of H_2SO_4 concentration of 0.5mol/L and temperature of 40°C resulted in the shortest time for full separation of the coating, 35 seconds or less.

A method was also identified to separate the coatings from the aluminum foils of the cathodes using nitric acid. The reaction between the HNO_3 and aluminum weakened the adhesion of the cathode coatings to the foils, resulting in their separation. The differences between the lithium-ion batteries chemistries from the three manufacturers resulted in greater variations in the conditions required for full separation of the cathode active material coatings than for the anode coatings. The results of testing various HNO_3 concentrations and temperatures was that full separation of the coatings from the aluminum foils was possible in 83 seconds or less for all chemistries by using an HNO_3 concentration of 2mol/L at 70°C.

Thus a common process for recycling post-vehicle-application batteries of different chemistries from different manufacturers was validated.

I. INTRODUCTION

Standridge and Corneal introduce and demonstrate methods for the remanufacturing, repurposing, and recycling of post-vehicle-application lithium-ion batteries, as well as providing an extensive literature review.¹ Building on this work, recent advances in repurposing and recycling of such batteries are discussed. In addition, a mathematical model for forecasting manufacturing capacity for remanufacturing, repurposing, and recycling – as well as simulation procedures for evaluating the model – are presented.

A lithium-ion battery is a collection of lithium-ion cells that work together through electrical wiring and a control board. The battery may be organized into groups of cells – for example, 12 groups of 8 cells each, in a battery consisting of 96 total cells. Post-vehicle-application means the battery has fallen below regulatory or manufacturer standards for use in vehicles; a small percentage of the cells within the battery may have failed beyond repair. Most such lithium-ion batteries are still viable for use in stationary applications.

Lithium-ion batteries are an efficient energy storage mechanism, and their use in vehicles will continue to expand with electrification. Smith, Earleywine, Wood, and Pesaran estimate the overall life distribution of vehicle-application lithium-ion batteries as having a 95th percentile of 13.2 years, and a maximum of 16-17 years.² The designed vehicle application life of a new lithium-ion battery for the Chevy Volt is eight years.³ Marano et al. independently estimated the same life expectancy as ten years.⁴

Post-vehicle-application lithium-ion batteries therefore have additional value that may be reclaimed in one of three ways, as discussed in Standridge and Corneal:⁵

- *Remanufacturing* for intended reuse in vehicles through replacement of any group with damaged cells within the battery.
- *Repurposing* by reengineering a battery for a non-vehicle, stationary storage application. This usually means reconfiguring the cells within the battery and developing a different control system, as well as repairing any damage (as in remanufacturing).
- *Recycling* via disassembling each cell in the battery and safely extracting the precious metals, chemicals and other byproducts. These are then sold on the commodities market, if profitable to do so, or re-introduced into a battery manufacturing process.

This study involves advancing the technology for repurposing and recycling. The progress made in each area is discussed in turn. In addition, the mathematical model for remanufacturing, repurposing, and recycling forecasting is presented, and simulation results are discussed.

II. MODELING AND SIMULATION OF FUTURE REMANUFACTURING, REPURPOSING, AND RECYCLING MANUFACTURING CAPACITY

Foster, Isely, Standridge, and Hasan presented a simple model that transforms existing forecasts of the number of electric vehicles and plug-in hybrid electric vehicles into the number of post-vehicle-application batteries.⁶ In addition, these authors present cost-benefit analyses that demonstrate remanufacturing is more economical than repurposing, as well as suggesting that recycling is not usually economical. This leads to the conclusion that remanufacturing, repurposing, and recycling must be integrated into a single process for handling post-vehicle-application batteries, and that the cost of recycling must be borne by remanufacturing and repurposing applications.

The work of those authors was extended by the investigators into a full mathematical model to help plan remanufacturing, repurposing, and recycling production capacity, as well as new battery production capacity, given any forecast of the number of electric vehicles and plug-in hybrid electric vehicles. The equations within the model were evaluated using simulation. The results estimate needed capacity over time for various values of a single parameter: the percent of post-vehicle-application batteries that are remanufactured.

Forecasting generally requires using a mathematical model to extrapolate historical data forward in time, making predictions regarding future values of the same quantities. In this case, producing a capacity forecast required extending in time, combining, and rectifying data from the multiple sources for input to the mathematical model. Caution is in order in drawing conclusions from a forecast based on such data: There is little experience with customer demand for all types of electrified vehicles, and uncertainties remain regarding the lifespan, post-vehicle-application potential, and energy range of vehicle-application lithium ion batteries. This creates uncertainty about the values of the model input data, which implies that the capacity values produced by simulating the model should be regarded with some caution. Thus, conclusions have to do with the relationships between the quantities estimated by the simulation instead of the magnitude of these quantities. Experience has shown that such relationships are less affected by uncertainty in model input data than are magnitudes of estimated quantities.

METHODS

The capacity planning model transfers a forecast of the demand for electric hybrid vehicles of all types into an estimate of the production capacity needed for remanufacturing, repurposing, and recycling post-vehicle-application lithium-ion batteries, as well as that needed for new batteries. The single model parameter is the percentage of such batteries that are remanufactured.

The variables used in the model are defined in Table 1.

Table 1. Capacity Planning Model Variables

Variable Name	Definition
$Demand_t$	The demand for hybrid electric vehicle batteries at time t in watt-hours
New_t	The production of new batteries at time t in watt-hours
$Remanufactured_t$	Remanufactured post-vehicle-application batteries at time t in watt-hours
$Repurposed_t$	Repurposed post-vehicle-application batteries at time t in watt-hours
$Recycled_t$	Recycled post-vehicle-application batteries at time t in watt-hours
$MaxLife$	The maximum number of years of vehicle application life of a new battery
$LifeDist(j)$	The percent of new batteries that have a vehicle application life of exactly j years; $j = 1, \dots, MaxLife$
$LifeDistReman(j)$	The percent of remanufactured batteries that have a vehicle application of exactly j years; $j = 1, \dots, MaxLife$
$LifeDistRepurposed(j)$	The percent of repurposed batteries that have a vehicle application of exactly j years; $j = 1, \dots, MaxLife$
$RemanNewPercent_t(j)$	The percent of new batteries at the end of vehicle application life of exactly j years that are remanufactured at time t ; $j = 1, \dots, MaxLife$
$RepurposedNewPercent_t(j)$	The percent of new batteries at the end of vehicle application life of exactly j years that are repurposed at time t ; $j = 1, \dots, MaxLife$
$RecycledNewPercent_t(j)$	The percent of new batteries at the end of vehicle application life of exactly j years that are recycled at time t ; $j = 1, \dots, MaxLife$
$RemanPrevPercent_t(j)$	The percent of batteries originally remanufactured after j years of vehicle application again at the end of vehicle application life that are again remanufactured at time t
$RepurposedPrevPercent_t(j)$	The percent of batteries originally repurposed after j years of vehicle application at the end of repurposing application life that are again repurposed at time t
$Repur2Recycled_t(j)$	The percent of batteries originally repurposed after j years of vehicle application at the end of repurposing application life that are recycled at time t
$Reman2Recycled_t(j)$	The percent of batteries originally remanufactured after j years of vehicle application at the end of vehicle application life that are recycled at time t

Source: Authors' definition of variables, 2015.

At each point in time, the demand for hybrid electric vehicles results in the demand for batteries that may be either new or remanufactured. New batteries are manufactured to make up the difference between demand and the number of remanufactured post-vehicle-application batteries, as shown in equation 1.

$$New_t = Demand_t - Remanufactured_t \quad (\text{Eq. 1})$$

The three primary equations in the model determine the number of post-vehicle-application batteries that are remanufactured, repurposed, and recycled at a point in time. Note that the index i represents the year a vehicle, remanufacturing, or repurposing application began. The index j has to do with battery life in years, which equals $i - (t - MaxLife) + 1$. The summation is over the values of i only.

$$Remanufactured_t = \sum_{i=t-MaxLife}^{t-1} New_i * LifeDist(j) * RemanNewPercent_t(j) + Remanufactured_i * LifeDistReman(j) * RemanPrevPercent_t \quad (\text{Eq. 2})$$

$$\begin{aligned}
 \text{Repurposed}_t = & \sum_{i=t-\text{MaxLife}}^{t-1} \text{New}_i * \text{LifeDist}(j) * \\
 & \text{RepurposedNewPercent}_t(j) + \\
 & \text{Repurposed}_i * \text{LifeDistRepurposed}(j) * \\
 & \text{RepurposedPrevPercent}_t(j)
 \end{aligned}
 \tag{Eq. 3}$$

$$\begin{aligned}
 \text{Recycled}_t = & \sum_{i=t-\text{MaxLife}}^{t-1} \text{New}_i * \text{LifeDist}(j) * \text{RecycledNewPercent}_t(j) + \\
 & \text{Repurposed}_i * \text{LifeDistRepurposed}(j) * \text{Repur2Recycled}_t(j) + \\
 & \text{Remanufactured}_i * \text{LifeDistReman}(j) * \text{Reman2Recycled}_t(j)
 \end{aligned}
 \tag{Eq. 4}$$

Substituting equation 1 into each of equations 2, 3, and 4 results in a set of equations that are not a function of new battery production.

Thus, new battery production capacity is an output of the model, not an input to the model, as are remanufacturing, repurposing, and recycling capacity.

Equation 5 shows the relationship between the percent of batteries that are remanufactured, repurposed, and recycled.

$$\begin{aligned}
 \text{RemanNewPercent}_t(j) + \text{RepurposedNewPercent}_t(j) + \\
 \text{RecycledNewPercent}_t(j) = 1
 \end{aligned}
 \tag{Eq. 5}$$

Equation 5 states that all post-vehicle-application batteries are either remanufactured, repurposed, or recycled. The percentage that is recycled quantifies a physical property: some cells in a post-vehicle-application or repurposed application battery can no longer hold a charge, and must be recycled. The percentage that is remanufactured is the model parameter. Using equation 5, the percentage that is repurposed can be computed.

The model assumptions follow:

- The maximum life of a battery (MaxLife) was set to 15 years, about midway between the 95th percentile and the maximum life estimations given in Smith, Earleywine, Wood, and Pesaran.⁷ These authors estimated the overall life distribution of lithium-ion batteries for vehicles as having a 95th percentile of 13.2 years, and a maximum of 16-17 years.
- A battery will have life for remanufacturing and repurposing applications, as the maximum life of about 15 years is greater than the designed vehicle application life of about 8-10 years.
- End-of-repurposing-life batteries must all be recycled. A stationary storage repurposing application has fewer charge-discharge cycles than a vehicle application, so lithium-ion batteries are premised to last in such applications until unable to hold a charge ($\text{RepurposedPrevPercent}_t(j) = 0$ and $\text{Repur2Recycled}_t(j) = 100\%$ for all t and j). In addition, this implies that an end-of-repurposing application battery cannot be remanufactured for use in a vehicle.

- End-of-remanufacturing-life batteries may be remanufactured a second time or recycled. Our experience with remanufactured batteries is that they display the same performance and thus the same life characteristics as new batteries, and the designed vehicle application life is about one half to two thirds of the maximum life. Thus, a constraint that a battery can be remanufactured at most two times before recycling is reasonable and conservative ($RemanPrevPercent_t(j) = 0$ and $Reman2Recycled_t(j) = 100\%$ for all t and j if the battery was previously remanufactured). This assumption also implies that no remanufactured battery will be repurposed for post-vehicle-application. The result of this constraint in the model is that new battery production will increase in value.

Equation 6 shows an end-of-remanufacturing-life battery must be either repurposed or recycled.

$$RemanPrevPercent_t(j) + Reman2Recycled_t(j) = 1 \tag{Eq. 6}$$

It is therefore sufficient to set the percentage of end-of-remanufacturing-life batteries that is remanufactured (again taking into account the span of vehicle application life as new batteries and as remanufactured batteries) as equivalent to the t and j indices. There is no recorded experience with such batteries, so it was assumed that the older the battery, the less likely the battery could be used in a remanufacturing application, which seems reasonable. So the percentage that was remanufactured was reduced by 5% for each year of battery life, as shown in equation 7.

$$RemanPrevPercent = \max(1 - (Years\ New + Years\ Remanufactured)/10, 0) \tag{Eq. 7}$$

The battery life distribution in histogram form computed by Smith, Earleywine, Wood, and Pesaran⁸ was fit to a gamma distribution with parameters $\alpha = 39.072$ and $\beta = 0.267$. The percentage points and mean reported by these authors were compared to the same quantities of the gamma distribution in Table 2.

Table 2. Comparison of Histogram with Gamma Distribution of Battery Life

Quantity	From Histogram ¹	Gamma Distribution ²
Mean	10.4	10.4
5th percent point	7.8	7.8
95th percent point	13.2	13.4

Source: 1. Smith, K., Earleywine, M., Wood, E. and Pesaran A. "Comparison of Battery Life across Real-world Automotive Drive-cycles." 7th Lithium Battery Power Conference. 7-8 November 2011. <http://www.nrel.gov/docs/fy12osti/53470.pdf> (accessed April 17, 2015).

2. Authors, 2015.

The mean and 5th percentage point are the same. The 95th percentage point of the gamma distribution is 0.2 greater (1.5%). The gamma distribution was used to model battery life.

Because there is little experience with the life of remanufactured and repurposed batteries and no reason to assume that remanufacturing or repurposing changes the life distribution

of a battery, the life distribution following remanufacturing and repurposing was modeled as being the same, $LifeDistReman(j) = LifeDistRepurposed(j)$ for all j .

This single life distribution is computed from the battery life distribution as a conditional distribution depending on the number of years of vehicle application, v , and the total application life of the battery (vehicle application + remanufacturing or repurposing application, u). This conditional distribution is shown in equation 8, which is written in the form given in Devore.⁹

$$P(Life > u | Life > v) = \frac{P(Life > v \cap Life > u)}{P(Life > v)} = \frac{P(Life > u)}{P(Life > v)} \quad (Eq. 8)$$

As previously discussed, Baum provides a forecast of the number of regular hybrid, mild hybrid, plug-in hybrid, and full electric vehicles through 2017, based on production data from 2009 through 2012.¹⁰ Simple regression was used to create a model by which each forecast could be extended through 2030, the end time of the remanufacturing, repurposing, and recycling capacity plan to be produced. The results are shown in Table 3.

Table 3. Comparison of Histogram with Gamma Distribution of Battery Life (x=year-2008)

Vehicle Type	Intercept	Slope	R2
Regular Hybrid	60.9	+142.83	0.9081
Mild Hybrid	4.5	+ 29.42	0.8106
Plug-in Hybrid	18.0	- 38.14	0.9638
Full Electric	15.8	- 32.79	0.8972

Source: Authors' Analysis (2015).

The forecasting model for the total number of electric vehicles of all types produced by the Center for Automotive Research is given in equation 9.¹¹ The number of micro-hybrids can be computed by subtraction from equation nine of the equations in Table 3.

$$Electrified\ Vehicles = 38.46 * (Year - 1990) + 14500 \quad (Eq. 9)$$

The number of electrified vehicles of each type is shown Table 4.

Note that the number of micro-hybrid vehicles is declining slightly over time, as the numbers of the each of the other vehicle types increases.

Table 4. Count of Electrified Vehicles by Type (In Thousands)

Year	Total ¹	Regular Hybrid ²	Mild Hybrid ²	Plug In ²	Full Electric ²	Micro Hybrid ²
2014	15423	574	58	75	78	14638
2015	15462	606	68	97	88	14603
2016	15500	627	66	109	93	14605
2017	15538	635	68	113	95	14627
2018	15577	752	75	142	125	14484
2019	15615	813	79	160	140	14423
2020	15654	874	84	178	156	14362
2021	15692	935	88	196	172	14302
2022	15731	995	93	214	188	14241
2023	15769	1056	97	232	203	14180
2024	15808	1117	102	250	219	14120
2025	15846	1178	106	268	235	14059
2026	15885	1239	111	286	251	13998
2027	15923	1300	115	304	266	13938
2028	15961	1361	120	322	282	13877
2029	16000	1422	124	340	298	13816
2030	16038	1483	129	358	314	13755

Source: 1. Center for Automotive Research. "The Major Determinants of U.S. Automotive Demand: Factors Driving the U.S. Automotive Market and Their Implications for Specialty Equipment and Performance Aftermarket Suppliers." 2009. http://www.globalautoindustry.com/images/CAR_SEMA_demand.pdf (accessed April 17, 2015).

2. Authors' analysis, 2015.

Table 5 shows the average energy in the battery in each type of electrified vehicle as given by Pesaran.¹²

Table 5. Average Battery Energy

Vehicle Type	Power in Wh
Regular Hybrid	135
Mild Hybrid	52.5
Plug In	10000
Full Electric	30000
Micro Hybrid	20

Source: Pesaran, A. "Choices and Requirements of Batteries for EVs, HEVs, PHEVs." Report by: National Renewable Energy Laboratory. 2011. <http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/51474.pdf> (accessed April 17, 2015).

Multiplying the forecast of the number of electrified vehicles shown in Table 4 by the average energy in the battery of each type shown in Table 5 yields the forecast of the amount of battery energy by vehicle type shown in Table 6.

Table 6. Energy in Batteries of Electrified Vehicles (in Wh)

Year	Regular Hybrid	Mild Hybrid	Plug-In	Full Electric	Micro Hybrid	Total
2014	77490	3045	750000	2340000	292761	3463296
2015	81810	3570	970000	2640000	292050	3987430
2016	84645	3465	1090000	2790000	292099	4260209
2017	85725	3570	1130000	2850000	292548	4361843
2018	101497	3916	1418570	3741420	289678	5555081
2019	109719	4153	1598570	4213920	288464	6214825
2020	117940	4390	1778570	4686420	287250	6874570
2021	126162	4627	1958570	5158920	286035	7534314
2022	134383	4864	2138570	5631420	284821	8194059
2023	142605	5101	2318570	6103920	283607	8853803
2024	150826	5338	2498570	6576420	282393	9513548
2025	159048	5576	2678570	7048920	281179	10173292
2026	167269	5813	2858570	7521420	279965	10833037
2027	175491	6050	3038570	7993920	278751	11492781
2028	183712	6287	3218570	8466420	277537	12152526
2029	191934	6524	3398570	8938920	276322	12812270
2030	200155	6761	3578570	9411420	275108	13472015
Percent of Total	1.6%	0.1%	26.1%	68.8%	3.5%	100.0%

Source: Authors' analysis, 2015.

Note that almost 95% of the energy in batteries is forecast to be from fully electric and plug-in electric vehicles.

SIMULATION EXPERIMENT AND RESULTS

The simulation experiment design included setting the value of the model parameter: percent remanufactured. Simulation results are obtained for values in the range [0, 85]: 0, 5, 10, ..., 85 for each of the years 2016 through 2030. The percent recycled is set to 15% based on the work of Jody, Daniels, Duranceau, Pomykala, and Spangenberg.¹³ The percent repurposed is computed using equation 5.

The model represents the percentage remanufactured, the percentage repurposed, and the percentage recycled as potentially varying over time (t) and vehicle application life (j). Due to the lack of history regard the performance of remanufactured and repurposed batteries, the percentage remanufactured was set to the same value for all t. In addition, it was felt that the percentage of batteries needing recycling – as well as those capable of being remanufactured for a vehicle application – would change in time. The former was assumed to increase, and the latter to decrease after four years. For this simulation experiment, 5% was used for both the increase in recycling percentage and the decrease in remanufacturing percentage. This implies that the repurposing percentage remains constant.

The simulation results can be used in computing verification and validation evidence as discuss by Sargent.¹⁴ One such computation is to show that all demand is met with either new or remanufactured batteries for all years for all values of the percentage remanufactured. To

illustrate, consider that in the year 2030 the percentage remanufactured = 50%. The demand is 12,812,270 Wh, which is met by 11,669,588 Wh of new batteries and 1,142,681 Wh of remanufactured batteries.

A second such computation is to show that all batteries reaching the end of application life in each year – whether new, remanufactured, or repurposed – are subsequently remanufactured, repurposed, or recycled. Again to illustrate, consider that in the year 2030 the percentage remanufactured = 50%. The end of application life batteries total 5,868,232 Wh: new, 5,859,351 Wh; remanufactured, 4,573 Wh; repurposed, 4,308 Wh. Of these, 1,142,681 Wh are remanufactured; 2,039,913 Wh are repurposed; and 2,685,637 Wh are recycled.

Table 7 shows how demand is met in 2030 as a function of the percentage remanufactured using a combination of new and remanufactured batteries. The demand in 2030 is forecast to be 12,812,270 Wh.

Note that for 50% remanufactured and above, each increase of 5% in the percentage remanufactured yields an increase of 2.2%-2.3% in the percentage of demand met by remanufactured batteries – up to about 25% for all available post-vehicle-application batteries remanufactured.

Table 8 shows the repurposing and recycling volume as a function of the percentage remanufactured for 2030.

Table 7. New and Remanufactured Batteries by Percent Remanufactured – Simulation Results for 2030

Percent to be remanufactured	New (Wh)	Remanufactured (Wh)	Percent of demand from remanufactured
0	12,812,270	0	0
5	12,812,269	1	0.0
10	12,812,206	63	0.0
15	12,810,876	1,393	0.0
20	12,800,065	12,204	0.1
25	12,756,185	56,085	0.4
30	12,649,101	163,169	1.3
35	12,467,430	344,840	2.7
40	12,226,453	585,816	4.6
45	11,955,320	856,950	6.7
50	11,669,588	1,142,681	8.9
55	11,378,504	1,433,766	11.2
60	11,087,534	1,724,736	13.5
65	10,796,677	2,015,592	15.7
70	10,505,935	2,306,335	18.0
75	10,215,306	2,596,963	20.3
80	9,924,791	2,887,478	22.5
85	9,634,390	3,177,879	24.8

Source: Authors' analysis, 2015.

Table 8. Repurposed and Recycled Batteries by Percent Remanufactured – Simulation Results for 2030

Percent to be remanufactured	Repurposed (Wh)	Recycled (Wh)
0	3,186,925	2,688,642
5	3,186,924	2,688,642
10	3,186,863	2,688,637
15	3,185,484	2,688,548
20	3,174,344	2,688,266
25	3,129,866	2,687,847
30	3,022,114	2,687,405
35	2,839,772	2,686,963
40	2,598,123	2,686,520
45	2,326,318	2,686,078
50	2,039,913	2,685,637
55	1,748,156	2,685,195
60	1,456,513	2,684,754
65	1,164,983	2,684,313
70	873,567	2,683,873
75	582,264	2,683,433
80	291,075	2,682,993
85	0	2,682,553

Source: Authors' analysis, 2015.

Note that the recycled battery volume is nearly constant, varying slightly due to remanufacturing of post-vehicle-application batteries a second time. The repurposed battery volume decreases as the remanufactured battery volume increases, as shown in Table 7.

Figure 1 shows the remanufactured battery capacity needed over time for 85% of post-vehicle-application batteries remanufactured. Note that the need for recycling capacity becomes significant between 2022 and 2024.

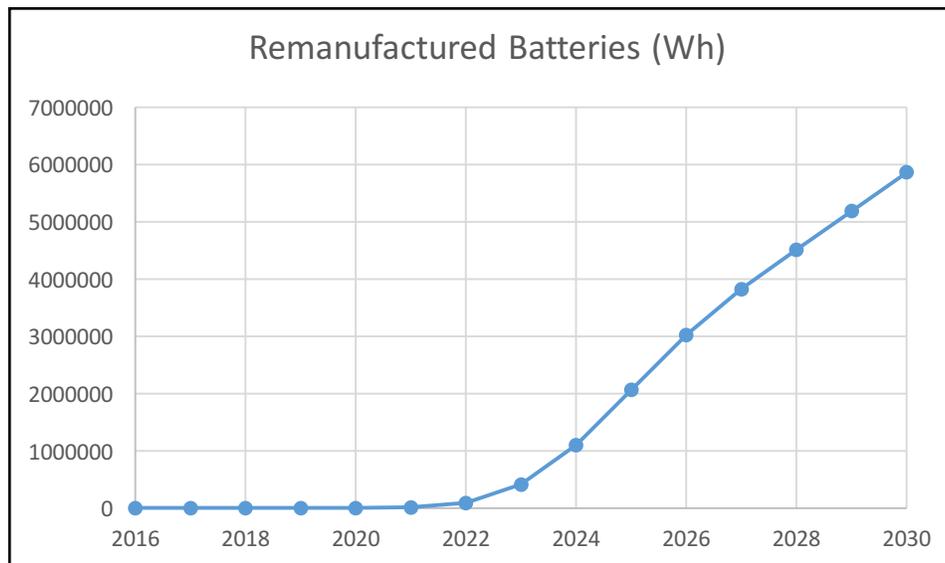


Figure 1. Remanufactured Battery Capacity (Wh) Over Time (Percent remanufactured = 85%)

Source: Authors' analysis, 2015.

SUMMARY

The results in Tables 7 and 8 as well as Figure 1 support the following conclusions: A full commitment of all post-vehicle-application batteries to remanufacturing results in an approximate reduction of 25% in the demand for new batteries by 2030. Such a commitment is supported by Standridge and Corneal, whose analysis concluded that remanufacturing was more economical than repurposing.¹⁵ Such a commitment means that no post-vehicle-application batteries are available for repurposing applications such as stationary storage.

The capacity needed for repurposing decreases as the percentage of post-vehicle-application batteries that are remanufactured increases. However, the sum of the repurposing and remanufacturing capacities is approximately constant on the order of 3.12M Wh. This supports the idea of building capacity that is flexible between repurposing and remanufacturing tasks. Based on the discussion in Foster, Isely, Standridge, and Hasan, such flexibility is reasonable to achieve as activities such as battery testing, disassembly, and controller development are common to both repurposing and remanufacturing.¹⁶

The recycling capacity needed by 2030, regardless of the percentage of post-vehicle-application batteries selected for remanufacturing, is about 2.69 Wh, approximately 85% of the combined repurposing-remanufacturing capacity. Recycling capacity is only 0.23% less for 85% of batteries remanufactured than for no batteries remanufactured. This shows the small impact of remanufacturing a second time post-vehicle-application batteries that were previously remanufactured. For example, in 2030 for the percentage of batteries remanufactured equal to 85%, only 0.05% of the total number of remanufactured batteries were those remanufactured a second time. In addition, the need for recycling becomes significant for the first time between 2022 and 2024, growing steadily over time thereafter.

III. REPURPOSING

Repurposing involves transforming post-vehicle application lithium-ion batteries into another application. In general, we have identified two types of applications: stationary energy storage and replacement of lead-acid batteries. Doing so requires the design and implementation of a battery management system (BMS) that effectively manages the battery charge-discharge cycle and balances the charge among the cells in the battery. Typically, a BMS is uniquely designed for a battery configuration and application.

Few repurposing applications have been reported in the literature. Example applications are discussed by Standridge and Corneal.¹⁷ One of these applications is discussed in more detail by Alexander, Baine, and Corneal.¹⁸ Another application for storing wind energy is discussed by Shokrzadeh and Bibeau.¹⁹

The development and implementation of an off-grid energy storage system using post-vehicle-application lithium-ion batteries with a suitable BMS are discussed. The electrical equipment is all readily available to a general consumer. The energy storage system supports a mobile recycling platform (MRP) for household items such as paper, plastic, cardboard, and the like; it was developed in partnership with Hastings Township, Michigan.

CHARGE AND BALANCE CIRCUITS

There are numerous systems that make use of sealed lead-acid batteries for energy storage such as those on electric golf carts, electric hi-lo forklifts, and electric floor scrubbers. These applications often require replacement of their traditional lead-acid batteries during their product lifetimes; the batteries required are typically 36VDC or 48VDC. The repurposed lithium-ion batteries are nominally 40VDC.

Even with a lower voltage, the lithium-ion batteries are found to provide better performance due to their low internal resistance. The lead-acid batteries, which have a higher open-circuit voltage, can fall to a lower voltage while under load than might the lithium-ion batteries. This is due to the more reactive chemistry of lithium-ion relative to lead-acid.

Lithium-ion batteries, however, need to have a BMS, including a balancer circuit, to ensure that the charge is equal among the cells. Such a circuit is not required for lead-acid batteries. Furthermore, the BMS and balancer circuit from the vehicle application cannot be reused, since an application-specific BMS and balancer circuit are needed. Also, the vehicle application BMS and balancer circuit may be damaged in the process of reconfiguring the batteries as required by the repurposing application. So to ensure the safe operation of the batteries both a cell-balancing circuit and a cell-monitoring circuit must be developed.

To address this issue, a passive cell balancing board was developed; a schematic of this board is shown in Figure 2. It is connected across a cell at connector P1, and bypasses the cell once it is at the maximum charge voltage. This allows for all of the cells to be charged to their maximum voltage and be balanced upon the completion of a charge cycle. In

in addition, the board is connected to the positive and negative contact for each cell group at pins 1 and 2, respectively, of the P1 connector on the right end of the diagram. The goal was to make the circuit as simple and safe as possible.

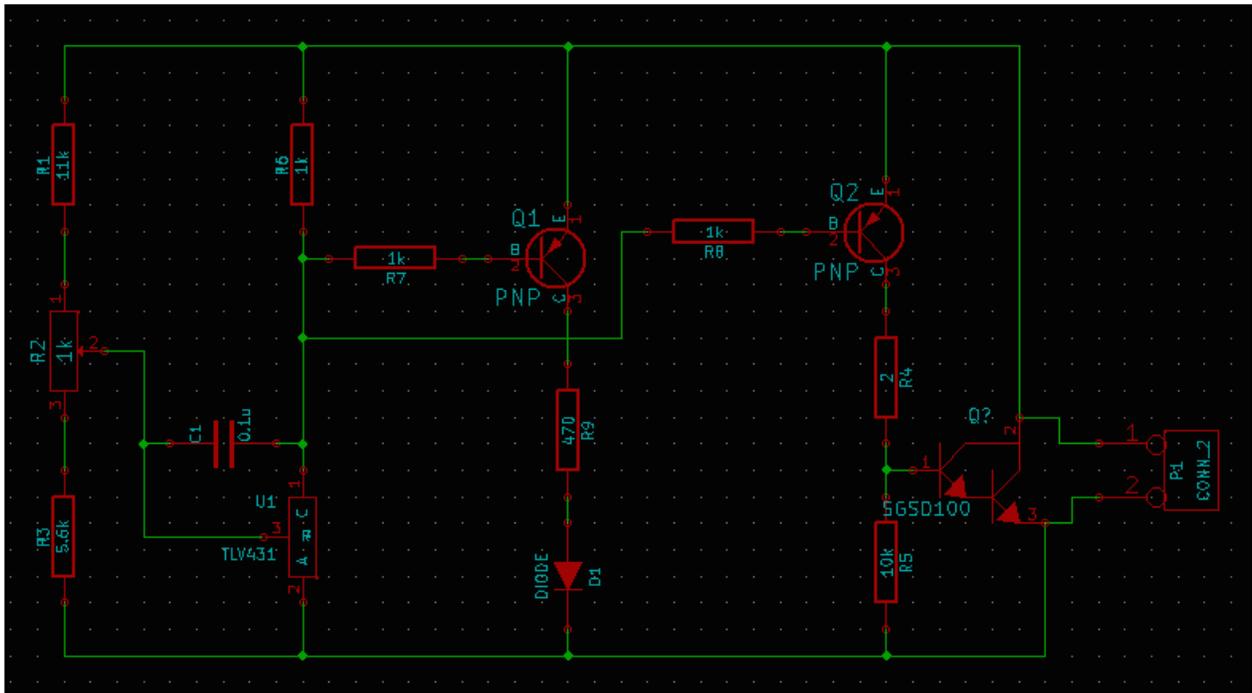


Figure 2. Balancing Board Schematic

Source: Authors' Design, 2015.

In addition to the balancing board, there is a cell voltage monitor that monitors all cell voltages independently and has the ability to open the circuit in the event of a failure. This adds a redundant layer of safety to the system.

To replace a lead-acid battery energy storage system with a repurposed lithium-ion battery energy storage system in the most economically efficient way, it's important to re-use the original chargers and control electronics. Therefore, a simple electronic circuit was designed to interface safely between the battery and the original charger. This circuit works in a fashion similar to that of a fuel pump at a gas station: it allows the charger to charge the batteries up to a set maximum voltage, and then disconnects the charger. This works as long as the battery charger is designed to charge to a higher voltage than the limit set by the charge circuit.

A block diagram of the circuit is shown in Figure 3: A button is pressed to start charging. During charging, the battery voltage is compared to a voltage reference. When the battery voltage exceeds the voltage reference, the circuit is broken and the connection between charger and battery is severed. The charger is only allowed to operate in constant current mode, which allows the existing charger to be used – though some capacity is lost due to the absence of the constant voltage (CV) portion of the charge cycle. (This loss of capacity is small for lithium-ion batteries relative to lead-acid batteries, but it is still worth mentioning.)

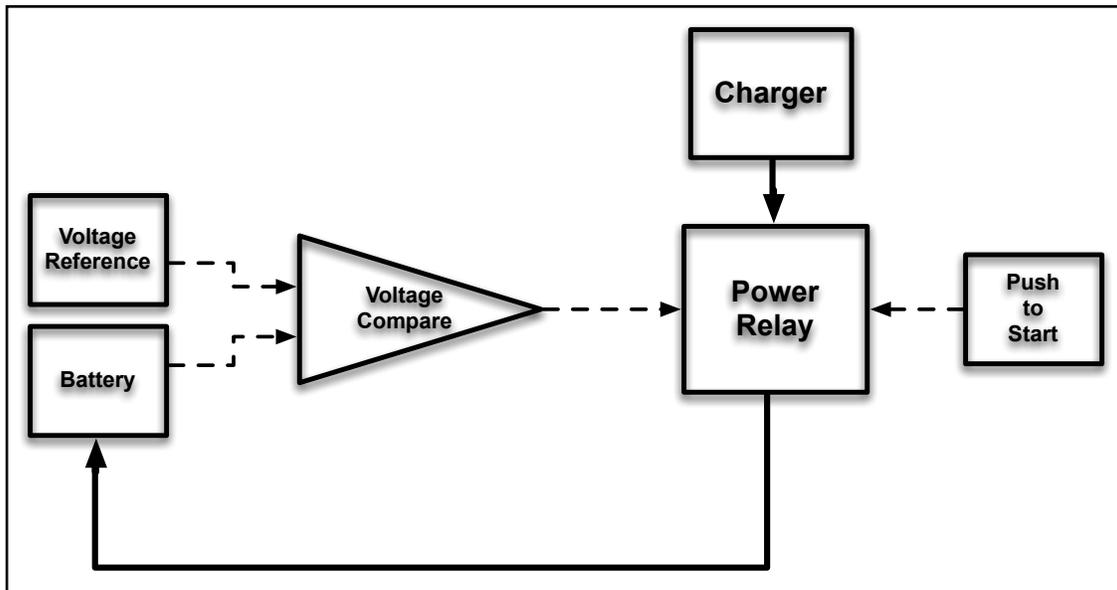


Figure 3. Charge Circuit Block Diagram

Source: Authors' Design, 2015.

MOBILE RECYCLING PLATFORM

The MRP was created in part as a proof of concept for off-grid energy collection and storage. The MRP is a drop-off location for general public recycling that provides residents of a rural community with access to a recycling facility. To be viable in rural and remote areas, the system must be able to run off-grid, using solar power collected and then stored in a battery system. This battery system is made of repurposed lithium-ion batteries.

The MRP consists of two main macro-assemblies: the storage assembly (SA) and the power assembly (PA) as shown in Figure 4. The SA was developed from a repurposed semi-truck trailer. The SA contains multiple bins inside the MRP, into which recyclable goods are placed via slots. The bins can then be guided to an exit door through a mechanized lift and rail system.



Figure 4. Mobile Recycling Platform (MRP)

Source: Authors' photo, 2015.

Energy storage for the recycling platform is accomplished using A123 high-power lithium-ion batteries, model ANR26650m1A, each with a nominal capacity of 2.3 amp-hours and a voltage of 3.3 volts. The batteries are rated to operate in a temperature range of -300C to +600C. The electrical equipment listed in Table 9 is supported, and the electrical light fittings, ratings, and quantity are selected based on the required illumination. One LED floodlight is used to illuminate the interior, and four LED tube lights illuminate the exterior. In order to monitor the level of recyclable goods being collected, five cameras with night vision capability are installed, one for each bin. The wires of the cameras are connected to the DVR to collect data, which is transmitted wirelessly to the monitoring station through a cell phone (plus one backup phone).

Table 9. MRP Power Requirements

Item	Description	Qty	Watts (W)	Hours of use per day (hr)	Total watts (W)	Total watt-Hours (Wh)
Camera	Infra-red, to view bins and trailers	5	2.4	24	12	288
Flood Light	LED, to illuminate trailer inside	1	10	8	10	80
Tube Light	LED, to illuminate trailer outside	4	8	12	32	384
DVR	Record data received from cameras	1	35	24	35	840
Cell Phone	Transmit data and/or creates LAN Network for cameras	6	5.45	24	32.7	784.8
Total	Assuming all units are on an using rated power conditions				121.7	2,376.8
System	Total pack capacity incorporated in the system, assuming environmental factors and BMS minimum battery handling requirements					2.4 kWh 6.7 kWh

Source: Author's design, 2015.

The electrical equipment mentioned in Table 9 is powered by energy generated through solar panels and stored in the repurposed lithium-ion batteries, supported and controlled by the power management system. Together, these constitute the Power Assembly (PA) of the MRP. A complete schematic of power generation, energy storage/management using lithium-ion batteries, and power management (including the charging system, as well as conversion of direct current (DC) to the required alternating current (AC) level) is shown in Figure 5. Each unit in this system is discussed in detail.

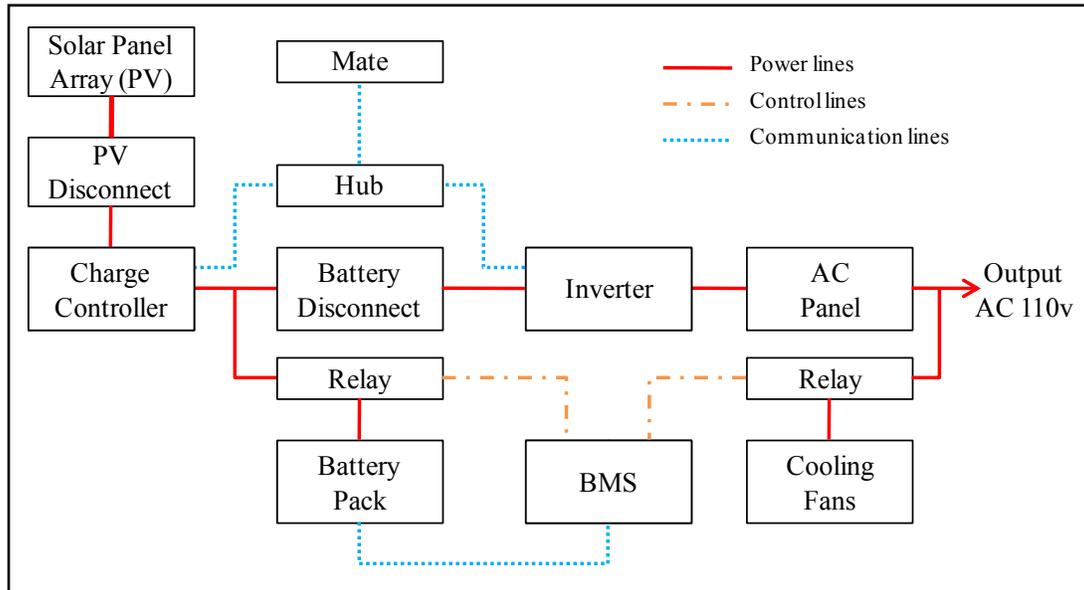


Figure 5. Energy Storage and Battery Management System Layout

Source: Author's design, 2015.

The power generation system consists of eight SS250x type (Sonali-manufactured) photovoltaic (PV) solar panels with the specifications given in Table 10. These panels are mounted over the top of the semi-truck platform, at the angle that maximizes exposure to sunlight, as shown in Figure 2.

Table 10. Sonali's PV Array Specs

Rating	250W, 31.32V, 7.98A
Open-circuit voltage	37.30V
Short-circuit current	8.45A
Inbuilt fuse rating	15A
Configuration	4 series, 2 parallel (2.5KW)

Source: Supplier Data Sheet, 2015.

The ratings and configurations of these solar panels take into account peak power generation capacity, cloud factor, and load to generate the required power for the equipment in the MRP and charge the batteries that make up the energy storage system.

The PV arrays are connected to the charge controller through a PV disconnect switch. This switch is installed to the exterior of the MRP, which is visible and also quickly accessible, in accordance with electrical code requirements. Thus the power assembly can be quickly disconnected from the solar power generation source to service the interior power assembly, and to isolate the power source for handling unsafe incidents.

A charge controller's main function is to optimize a PV array's output, which can fluctuate based on shading and temperature variables. Outback Power's Flexmax-80 (rated current 80A) is used in this system to handle the maximum current flow from the PV arrays.

Elithion's Lithiummate Pro Master BMS is used in this system, and configured to manage the battery. The BMS is rated to operate at 12Vdc, and can control up to 16 batteries – the number used in this system.

The selected BMS has the maximum capacity to manage up to 16 batteries. As mentioned in Table 10, the 2.4 kWh load capacity needs only eight batteries. However, 16 batteries with a total capacity of 6.7 kWh are installed. This provides for future load requirements, as well as providing a safety factor. There is 100% reliance on solar power energy, and at 6.7 kWh battery capacity the power load can be sustained for up to 72 hours without the solar system generating energy.

The first basic purpose of a BMS is to manage the safe charging and discharging of the battery within the technical specifications defined by the battery manufacturer. This includes balancing the charging among the cells in the battery, and leaves room for more charge without overcharging any single cell. Eventually, balancing brings all the cells to the same state of charge (SOC), which is critical for maintaining the life of the each cell and getting the most out of the battery system.

The second basic purpose of the BMS is to manage the operation of batteries in accordance with safe temperature limits, as defined by the manufacturer through a suitable thermal management system. A forced-air system is used in this application: An AC fan (115VAC, 105W, 930CFM) is connected through a duct channel to pull air from the outside of the MRP. The rating of the fan was chosen based on maximum temperature increase in the cell at maximum load, seasonal changes in temperate at the installed location, and the maximum possible internal ambient temperature within the MRP.

The sixteen batteries are stacked in five racks, as shown in Figure 6. The surface planes on which these batteries are placed have cut steel bars spaced adequately to balance the weight of the batteries, and also ensure the appropriate airflow underneath them. This ensures high level of thermal management, cooling the batteries quickly.

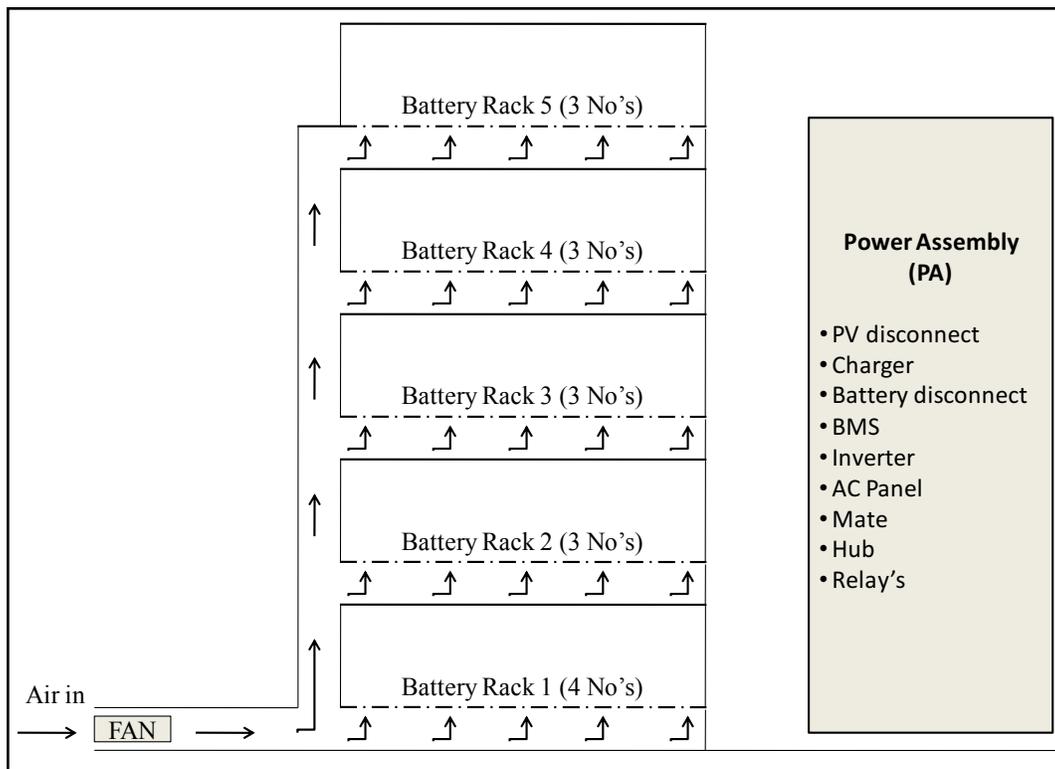


Figure 6. Thermal Management

Source: Author's design, 2015.

The third basic purpose of the BMS is to ensure that the battery operates within safe voltage limits. The voltage levels are monitored through the BMS, and actions are taken as required. It is critical to ensure that any Li-ion cell doesn't fall below its low-voltage limits, as this would result in damage to the cell and diminish its capacity. Two levels of safety are implemented: First, a 60A breaker is mounted in the AC panel to isolate load from the inverter. If this fails, the contactor connected between the battery and inverter will be actuated through the BMS to isolate the battery providing the highest level of safety.

The inverter is connected to the DC energy storage system/DC solar energy system, and converts the power from DC to AC. It also provides true sine wave power output. Both the charger and the inverter are connected through a MATE3 hub.

IV. RECYCLING

The remanufacturing and repurposing of post-vehicle-application lithium-ion batteries extends their useful life. Eventually, however, all such batteries will fail to hold a charge, and thus will need to be recycled as discussed by Standridge and Corneal as well as Li, Corneal, and Standridge.²⁰ Discussions of safely handling batteries for disassembly, as well as detailed disassembly procedures, are given in the former.

The central recycling challenge here is that lithium-ion batteries produced by different manufacturers contain different active materials – though the collecting foils in the anodes are invariably copper, while those in the cathodes are always aluminum.

Copper accounts for approximately 11–15% of the battery by weight, and aluminum accounts for approximately 19–24% of the battery by weight, depending on whether the battery is intended for an electric vehicle (EV), a hybrid electric vehicle (HEV), or a plug-in hybrid electric vehicle (PHEV). By disassembling a battery and separating the coatings from the collecting foils, copper and aluminum can be recovered and recycled. Other components such as steel, plastic, and active materials can either be disposed of or recycled.²¹

Most research being done on the recycling of lithium-ion batteries uses cells with LiCoO_2 as the cathode active material, and focuses on the recovery of cobalt and lithium, with little attention to the copper and aluminum within the cells. These methods incorporate various acid leaching and hydro- and pyro-metallurgical processes and bioleaching techniques.²²

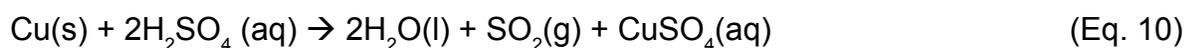
This work focused instead on the separation of the active materials from the copper and aluminum foils. Batteries from three different manufacturers, identified as A, B, and C, with differing chemistries, were studied. A common process was developed and validated.

Batteries from manufacturers A and B were disassembled, and the anode and cathode samples were used to develop and test the recycling process. The materials tested from manufacturer C were scraps of coated foils from the manufacturing process that had never been assembled into cells.

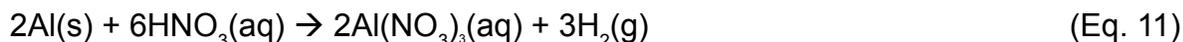
The cathodes were aluminum foils whose coatings are of differing chemistries for each manufacturer. Manufacturers A, B, and C use Lithium Iron Phosphate (LiFePO_4), Lithium Nickel Cobalt Aluminum Oxide (LiNCA), and Lithium Manganese Oxide (LiMn_2O_4), respectively. The anode foils were the same for all manufacturers: copper with a carbon coating.

Acid baths were used to separate the active materials from the foils. By focusing on the reaction with the aluminum and copper rather than the coating materials, it was hypothesized that the same process would be effective for batteries from the different suppliers.

Sulfuric acid (H_2SO_4) was selected because of its reactivity with copper, as shown in equation 10. It was hypothesized that the H_2SO_4 would react with the copper foil, weakening the adhesion of the anode coatings to the foil.



Nitric acid (HNO_3) was selected for the reaction with aluminum as shown in equation 11. The intent was for the HNO_3 to react with the aluminum foil, thereby weakening the adhesion of the carbon coating to the foil.



Because SO_2 and H_2 gases are products of the above reactions, all tests were conducted in a fume hood. Experiments were designed and conducted to find the lowest acid concentration, the lowest temperature, and the shortest time required for full separation of the coatings from the foils for each of the battery chemistries (manufacturers). Such a combination was hypothesized to result in the lowest cost of recycling. Experiments for each battery chemistry were used to determine the shortest separation time for the varying combinations of acid concentration and temperature.

Sulfuric acid has been shown to react with copper in concentrations as low as 0.5 mol/L.²³ Therefore, for separation of the carbon coatings from the copper foils, 50 mL of 2.0 mol/L, 1.0 mol/L, and 0.5 mol/L solutions of sulfuric acid (95.0-98.0%, Sigma-Aldrich Co, St. Louis, MO) were prepared. While stirring, 5g of the coated copper foils were placed in the sulfuric acid solution. The time taken for the coatings to separate from the foils was recorded. Tests were conducted at 25°C, 30°C, 40°C and 50°C. The tests were repeated with samples from each manufacturer.

For separation of the cathode active coatings from the aluminum foils, 50mL of 2.0mol/L, 1.0mol/L, and 0.5mol/L solutions of nitric acid (70%, Sigma-Aldrich Co, St. Louis, MO) were prepared. While stirring, 3g of the coated aluminum foils were placed in the nitric acid solution. The time taken for the coatings to separate from the foils was recorded. Tests were conducted at 25°C, 30°C, 40°C, 50°C, 60°C, and 70°C. The testing combinations were repeated for each manufacturer.

The purpose of the testing was to validate a common process and to establish process parameters for lithium-ion recycling spanning all manufacturers. Thus, if it was found that the samples from a particular manufacturer were separating at faster times, the number of test combinations was reduced. Higher concentrations and temperatures were not tested if the lower concentrations and temperatures for a particular manufacturer were not limiting the separation time when compared to the time required for the samples from the other manufacturers.

RESULTS AND DISCUSSION

Upon immersion of the coated copper foils into the sulfuric acid solutions, bubbles of SO_2 gas formed on the surface. There was also minor heat dissipation (approximately a 4°C temperature rise) during the tests, and the solution turned slightly blue, indicating the formation of copper sulfate (CuSO_4) due to the reaction of the copper with the sulfuric acid. This reaction did cause a degradation of the adhesion of the carbon coating to the copper foils, as was intended. The H_2SO_4 concentrations, temperatures, and times required for full separation of the coating from the copper foils for the samples from manufacturers A, B, and C can be seen in Tables 11, 12 and 13, respectively.

Table 11. Separation Times for Carbon Coatings from Copper Foils from Manufacturer A for Varying H₂SO₄ Concentrations and Temperatures

H ₂ SO ₄ Concentration (mol/L)	Temperature (°C)	Separation Time (sec)
2	25	57
2	30	49
2	40	37
1	25	50
1	30	40
1	40	37
0.5	25	64
0.5	30	47
0.5	40	35

Source: Author's experiment, 2015.

Table 12. Separation Times for Carbon Coatings from Copper Foils from Manufacturer B for Varying H₂SO₄ Concentrations and Temperatures

H ₂ SO ₄ Concentration (mol/L)	Temperature (°C)	Separation Time (sec)
0.5	25	5

Source: Author's experiment, 2015.

Table 13. Separation Times for Carbon Coatings from Copper Foils from Manufacturer C for Varying H₂SO₄ Concentrations and Temperatures

H ₂ SO ₄ Concentration (mol/L)	Temperature (°C)	Separation Time (sec)
2	30	35
2	40	29
2	50	20
1	30	53
1	40	25
1	50	16
0.5	30	58
0.5	40	26

Source: Author's experiment, 2015.

Increasing the H₂SO₄ concentration had very little effect on decreasing the separation times. At temperatures of 25°C and 30°C, increasing the sulfuric acid concentration from 0.5mol/L to 1mol/L and 2mol/L resulted in separation times 7-14 seconds faster for samples from manufacturer A and separation times of 5-23 seconds faster for samples from manufacturer C. However, when the temperature was raised to 50°C, increasing the concentration had no effect on decreasing the separation times.

The separation of the carbon coatings from the copper foils occurred in under 65 seconds for all concentration and temperature conditions tested. The fastest separation time of 5s occurred with the samples from manufacturer B, with an H_2SO_4 concentration of 0.5mol/L and temperature of 25°C. For the samples from the other manufacturers, higher temperatures were required to achieve the fastest separation times. For the samples from manufacturer A, the shortest separation time was 35s, using an H_2SO_4 concentration of 0.5mol/L at a temperature of 40°C. For the samples from manufacturer C, the shortest separation time was 16s at both the 1mol/L and 0.5mol/L concentrations, at a temperature of 50°C.

It was noteworthy that there were separation times for the samples from manufacturer C at lower temperatures that were still below the shortest separation time for the samples from manufacturer A. Using the same H_2SO_4 concentration of 0.5mol/L and temperature of 40°C, as was identified as the optimum condition for the samples from manufacturer A, the separation time for the samples from manufacturer C was 26s. Using common conditions of an H_2SO_4 concentration of 0.5mol/L at a temperature of 40°C results in samples from all manufacturers separating in 35s or less.

Upon immersion of the coated aluminum foils into the nitric acid solutions, bubbles of H_2 gas formed on the surface of the aluminum foils. There was also minor heat dissipation (approximately a 2°C temperature rise) during the tests. The reaction between the HNO_3 and aluminum resulted in a degradation of the adhesion of the cathode coatings to the foils, as was intended. The HNO_3 concentrations, temperatures, and times required for full separation of the coating from the aluminum foils for the samples from manufacturers A, B, and C can be seen in Tables 14, 15, and 16, respectively.

Table 14. Separation Times for Cathode Active Material Coatings from Aluminum Foils from Manufacturer A for Varying HNO_3 Concentrations and Temperatures

HNO_3 Concentration (mol/L)	Temperature (°C)	Separation Time (sec)
2	25	55
2	30	46
1	25	54
1	30	43
1	40	35
0.5	25	67
0.5	30	62
0.5	40	40

Source: Author's experiment, 2015.

Table 15. Separation Times for Cathode Active Material Coatings from Aluminum Foils from Manufacturer B for Varying HNO₃ Concentrations and Temperatures

HNO ₃ Concentration (mol/L)	Temperature (°C)	Separation Time (sec)
2	25	35
2	30	32
2	40	26
1	25	41
1	30	39
1	40	29
0.5	25	44
0.5	30	40
0.5	40	33

Source: Author's experiment, 2015.

Table 16. Separation Times for Cathode Active Material Coatings from Aluminum Foils from Manufacturer C for Varying HNO₃ Concentrations and Temperatures

HNO ₃ Concentration (mol/L)	Temperature (°C)	Separation Time (sec)
2	50	180
2	60	161
2	70	83
1	50	273
1	60	210
1	70	120
0.5	50	>300.00
0.5	60	219

Source: Author's experiment, 2015.

For the conditions tested, the separation of the cathode active material coatings from the aluminum foils tended to take longer than the time required for the separation of the carbon coatings from the copper foils for each manufacturer. The fastest separation time of 26s was achieved with an HNO₃ concentration of 2mol/L at 40°C for the samples from manufacturer B. For the samples from manufacturer A, an HNO₃ concentration of 1mol/L at 40°C resulted in a separation time of 35s. The samples from manufacturer C had much longer separation times than the samples from the other manufacturers. The shortest separation time for the samples from manufacturer C was 83s, using an HNO₃ concentration of 2mol/L at 70°C.

The common condition for the separation of the active materials from the aluminum foils would then be to use an HNO₃ concentration of 2 mol/L at 70°C and the separation would occur in 83s or less for samples from all manufacturers. It would also be possible, however, to use lower temperatures, which would work for the samples from manufacturers A and B but would approximately double the separation time for the samples from manufacturer C. An HNO₃ concentration of 2 mol/L at 50°C would be able to achieve separation for the samples from manufacturer C in 180s (3 min).

SUMMARY AND CONCLUSIONS

The use of acid baths to separate the active material coatings from the collecting foils of post-vehicle-application lithium-ion batteries of varying chemistries from three different manufacturers was evaluated. A process was developed and verified to separate the carbon coatings from the copper foils of the anode using sulfuric acid; the reaction between the H_2SO_4 and the copper resulted in degradation of the adhesion of the carbon coatings to the foils. The combination of H_2SO_4 concentration of 0.5mol/L and temperature of 40°C resulted in the shortest time for full separation of the coating from the foil, 35s or less.

A method was identified to separate coatings from the aluminum foils of the cathodes using nitric acid. The reaction between the HNO_3 and the aluminum weakened the adhesion of the cathode coatings to the foils, resulting in their separation. The differences among the chemistries from the three manufacturers resulted in greater variations in the conditions required for full separation of the cathode active material coatings than of the anode coatings. The results of testing various HNO_3 concentrations and temperatures identified that full separation of the coatings from the aluminum foils was possible in 83s or less for samples from all manufacturers by using an HNO_3 concentration of 2mol/L at 70°C.

These results have shown that it is possible to identify a common acid concentration and temperature that will separate the differing active materials from the current collecting foils in a reasonable length of time (3 min or less). Once separated, the copper and aluminum foils can then be recycled. The next step would be preparing the other components of the cells such as steels, plastics, and the active materials themselves for recycling or disposal.

These results support the idea that it is possible to develop a common process with common parameter values for recycling the valuable materials in post-vehicle-application lithium-ion batteries of varying chemistries after they can no longer be remanufactured or repurposed.

V. SUMMARY AND CONCLUSION

The efficient energy storage provided by lithium-ion batteries suggests that their use in vehicles will continue to expand with electrification, raising the important issue of what to do with post-vehicle-application lithium-ion batteries.

Three possibilities for handling used lithium-ion batteries have been identified: remanufacturing, repurposing, and recycling. A mathematical model estimates the manufacturing capacity needed for each of these activities through the year 2030, as well as new battery production capacity. The model has a single parameter: the percentage of vehicle batteries that are remanufactured for a vehicle application. Demand is met using a combination of new and remanufactured batteries, and encompasses five classes of hybrid vehicles. The distribution of battery life is taken into account.

The model is analyzed using simulation. The results indicate that a full commitment of all post-vehicle-application batteries to remanufacturing results in an approximate reduction of 25% in the demand for new batteries by 2030. In addition, the sum of repurposing and remanufacturing capacities is approximately constant on the order of 3.12M Wh. This supports the idea of building capacity that is flexible between repurposing and remanufacturing tasks. The recycling capacity needed by 2030, regardless of the percentage of post-vehicle-application batteries selected for remanufacturing, is about 2.69M Wh, approximately 85% of the combined repurposing-remanufacturing capacity. The need for recycling becomes significant for the first time between 2022 and 2024, growing steadily over time thereafter.

Advances in repurposing were demonstrated in a joint project with the Hastings Township, MI. An energy storage and management system was constructed to support a mobile recycling platform constructed from a repurposed over-the-road tractor trailer. In this prototype, solar energy is collected using an array of solar panels mounted on the top of the trailer; this energy is stored in a set of repurposed post-vehicle-application lithium-ion batteries. The energy is used to power lighting and monitoring equipment, and a commercial off-the-shelf battery management system was used to control the system.

Advances in recycling focused on showing the applicability of a previously developed approach to post-vehicle-application lithium-ion batteries from different manufacturers with different chemistries. This approach uses acid baths to separate the coatings from the collecting foils: carbon coatings are separated from the copper foils of the anode using sulfuric acid, and the various coatings from the aluminum foils of the cathodes are separated using nitric acid.

These results have shown that it is possible to identify a common acid concentration and temperature that will separate the differing active materials from the current collecting foils in a reasonable length of time (3 min or less), relative low acid concentrations, (2mol/L or less), and relatively low temperatures (70°C or less). Once separated, the copper and aluminum foils can then be recycled. The next step will be to preparing the other components of the cells such as steels, plastics, and the active materials themselves for recycling or disposal.

Future work will involve field-testing and commercial application of the repurposing and recycling methods described above.

ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
BMS	Battery Management System
DC	Direct Current
DVR	Digital Video Recorder
EV	Electric Vehicle
GVSU	Grand Valley State University
H ₂ SO ₄	Sulfuric Acid
HNO ₃	Nitric Acid
H	Hydrogen
kWh	Kilowatt-Hour
LED	Light Emitting Diode
Li	Lithium
Li-ion	Lithium Ion
LiCoO ₂	Lithium Cobalt Oxide
LiFePO ₄	Lithium Iron Phosphate
mol/L	Moles per Liter
MRP	Mobile Recycling Platform
PA	Power Assembly
PHEV	Plug-In Hybrid Electric Vehicle
SA	Storage Assembly
SO ₂	Sulfur Dioxide
V	Volt
Wh	Watt-Hour

ENDNOTES

1. C. Standridge and L. Corneal, "Remanufacturing, Repurposing, and Recycling of Post-Vehicle-Application Lithium-ion Batteries." Mineta National Transit Research Center (2014). <http://transweb.sjsu.edu/project/1137.html>.
2. K. Smith, M. Earleywine, E. Wood, and A. Pesaran, "Comparison of Battery Life Across Real-world Automotive Drive-Cycles" (paper presented at 7th Lithium Battery Power Conference, Las Vegas, NV, November 7-8, 2011). <http://www.nrel.gov/docs/fy12osti/53470.pdf> (accessed April 17, 2015).
3. GM-Volt.com, "Chevy Volt Specs." 2011. <http://gm-volt.com/full-specifications> (accessed January 5, 2015).
4. V. Marano, S. Onori, Y. Guezennec, G. Rizzoni, and N. Madella, "Lithium-ion Batteries Life Estimation for Plug-in Hybrid Electric Vehicles" (paper presented at IEEE Vehicle Power and Propulsion Conference, Dearborn, MI, September 7-11, 2009. doi: 10.1109/VPPC.2009.5289803).
5. C. Standridge and L. Corneal, "Remanufacturing, Repurposing, and Recycling of Post-Vehicle-Application Lithium-ion Batteries," Mineta National Transit Research Center (2014). <http://transweb.sjsu.edu/project/1137.html>.
6. M. Foster, P. Isely, C. Standridge, and M. Hasan, "Feasibility Assessment of Remanufacturing, Repurposing, and Recycling of End of Vehicle Application Lithium-Ion Batteries," *Journal of Industrial Engineering and Management* 7, no. 4 (2014): 698–715. doi:10.3926/jiem.939.
7. K. Smith, M. Earleywine, E. Wood, and A. Pesaran, "Comparison of Battery Life Across Real-world Automotive Drive-Cycles" (paper presented at 7th Lithium Battery Power Conference, November 7-8, 2011). <http://www.nrel.gov/docs/fy12osti/53470.pdf>.
8. Ibid.
9. J. L. Devore, *Probability and Statistics for Engineering and the Sciences*. (Boston, MA: Cengage Learning, 2015).
10. A. Baum, "Mild and Micro Hybrids: Moving Forward Albeit Quietly" (paper presented at NextEnergy Energy Storage Event, Detroit, MI, October 2013). <http://www.nextenergy.org/oct-30-2013-energy-storage-event/> (accessed April 17, 2015).
11. Center for Automotive Research. "The Major Determinants of U.S. Automotive Demand: Factors Driving the U.S. Automotive Market and Their Implications for Specialty Equipment and Performance Aftermarket Suppliers" (paper presented at Specialty Equipment Market Association, Las Vegas, NV, Nov 3–6, 2009). http://www.globalautoindustry.com/images/CAR_SEMA_demand.pdf (accessed April 17, 2015).

12. A. Pesaran, "Choices and Requirements of Batteries for EVs, HEVs, PHEVs," (report by National Renewable Energy Laboratory, 2011). <http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/51474.pdf> (accessed April 17, 2015).
13. B.J. Jody, E.J. Daniels, C.M. Duranceau, J.A. Pomykala, Jr., and J.S. Spangenberg, "End-of-Life Vehicle Recycling: State of the Art of Resource Recovery from Shredder Residue" (publication of Center for Transportation Research, Argonne National Laboratory, September 2010). http://www.es.anl.gov/Energy_systems/CRADA_Team/publications/End%20of%20life%20vehicle%20recycling%20Technology%20review.pdf (accessed August 31, 2013).
14. R.G. Sargent, "Verification and Validation of Simulation Models," *Journal of Simulation* 7 (2013): 12-14. doi:10.1057/jos.2012.20.
15. C. Standridge and L. Corneal, "Remanufacturing, Repurposing, and Recycling of Post-Vehicle-Application Lithium-ion Batteries." Mineta National Transit Research Center (2014). <http://transweb.sjsu.edu/project/1137.html>.
16. M. Foster, P. Isely, C. Standridge, and M. Hasan, "Feasibility Assessment of Remanufacturing, Repurposing, and Recycling of End of Vehicle Application Lithium-Ion Batteries," *Journal of Industrial Engineering and Management* 7, No. 4 (2014): 698–715. doi:10.3926/jiem.939.
17. C. Standridge and L. Corneal, "Remanufacturing, Repurposing, and Recycling of Post-Vehicle-Application Lithium-ion Batteries," Mineta National Transit Research Center (2014). <http://transweb.sjsu.edu/project/1137.html> (accessed April 17, 2015).
18. T. Alexander, N. Baine, and L. Corneal, "Utilizing Repurposed Automotive Lithium Ion Cells for Stationary Energy Storage" (proceedings of the ASEE North Central Section Conference, Cincinnati, OH, April 17-18, 2015). http://people.cst.cmich.edu/yelam1k/asee/proceedings/2015/Paper%20files/Student_Papers/2015_ASEE_NCS_Conference_submission_62.pdf (accessed December 11, 2015).
19. S. Shokrzadeh, and E. Bibeau "Repurposing Batteries of Plug-In Electric Vehicles to Support Renewable Energy Penetration in the Electric Grid," SAE Technical Paper 2012-01-0348. (2012) doi:10.4271/2012-01-0348.
20. C. Standridge and L. Corneal, "Remanufacturing, Repurposing, and Recycling of Post-Vehicle-Application Lithium-ion Batteries"; H. Li, L. M. Corneal, and C. R. Standridge, "Effects of Acid Concentration, Temperature, and Time on Recycling of Post-Vehicle-Application Lithium-Ion Batteries of Varying Chemistries" in *Materials for Renewable and Sustainable Energy* (2015) doi: 10.1007/s40243-015-0048-7.
21. J.B. Dunn, L. Gaines, M. Barnes, J. Sullivan, and M. Wang, *Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle* (Energy Systems Division, Argonne National Laboratory, June 2012). <https://greet.es.anl.gov/publication-lib-lca>.

-
22. G. Dorella and M. Mansur, "A Study of the Separation of Cobalt from Spent Li-Ion Battery Residues," *Journal of Power Sources*, 170 (2007): 210–215; T. Georgi-Maschler, B. Friedrich, R. Weyhe, H. Heegn, and M. Rutz, "Development of a Recycling Process for Li-Ion Batteries," *Journal of Power Sources* 207 (2012): 173–182; M.J. Lain, "Recycling of Lithium Ion Cells and Batteries," *Journal of Power Sources* 97–98 (2001): 736-738; L. Li, J. Ge, R. Chen, F. Wu, S. Chen, and X. Zhang, "Environmental Friendly Leaching Reagent for Cobalt and Lithium Recovery from Spent Lithium-Ion Batteries," *Waste Management* 30 (2010): 2615–2621; B.P. Xin, D. Zhang, X. Zhang, Y. Xia, F. Wu, S. Chen, and L. Li, "Bioleaching Mechanism of Co and Li from Spent Lithium-Ion Battery by the Mixed Culture of Acidophilic Sulfur-Oxidizing and Iron-Oxidizing Bacteria," *Bioresources Technology* 100 (2009): 6163–6169; P. Zhang, T. Yokoyama, O. Itabashi, T. M. Suzuki, and K. Inoue, "Hydrometallurgical Process for Recovery of Metal Values from Spent Lithium-Ion Secondary Batteries," *Hydrometallurgy*, 47 (1998): 259–271.
23. O. Benali, L. Larabi, and Y. Harek, "Inhibiting Effects of 2-mercapto-1-methylimidazole on Copper Corrosion in 0.5 M Sulfuric Acid," *Journal of the Saudi Chemical Society* 14, (2010): 231–235.

BIBLIOGRAPHY

- Alexander, T., N. Baine, and L. Corneal. "Utilizing Repurposed Automotive Lithium Ion Cells for Stationary Energy Storage." Proceedings of the 2015 ASEE North Central Section Conference, 2015. http://people.cst.cmich.edu/yelam1k/asee/proceedings/2015/Paper%20files/Student_Papers/2015_ASEE_NCS_Conference_submission_62.pdf (accessed December 11, 2015).
- Baum, A. "Mild and Micro Hybrids: Moving Forward Albeit Quietly." Presented at NextEnergy Energy Storage Event, October 30, 2013. <http://www.nextenergy.org/oct-30-2013-energy-storage-event/> (accessed April 17, 2015).
- Benali, O., L. Larabi and Y. Harek. "Inhibiting Effects of 2-mercapto-1-methylimidazole on Copper Corrosion in 0.5 M Sulfuric Acid." *Journal of the Saudi Chemical Society* 14 (2010): 231–235.
- Center for Automotive Research. "The Major Determinants of U.S. Automotive Demand: Factors Driving the U.S. Automotive Market and Their Implications for Specialty Equipment and Performance Aftermarket Suppliers." Paper presented at Specialty Equipment Market Association, Las Vegas, NV, Nov 3–6, 2009. http://www.globalautoindustry.com/images/CAR_SEMA_demand.pdf (accessed April 17, 2015).
- Center for Climate and Energy Solutions. *Federal Vehicle Standards*. 2013. <http://www.c2es.org/federal/executive/vehicle-standards> (accessed October 1, 2013).
- Devore, J. L. *Probability and Statistics for Engineering and the Sciences*. Boston, MA: Cengage Learning, 2015.
- Dorella, G., and M. Mansur. "A Study of the Separation of Cobalt from Spent Li-Ion Battery Residues." *Journal of Power Sources* 170 (2007): 210–215.
- Dunn, J.B., L. Gaines, M. Barnes, J. Sullivan, and M. Wang. *Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle*. Energy Systems Division, Argonne National Laboratory Publication, June 2012. <https://greet.es.anl.gov/publication-lib-lca> (accessed April 20, 2015).
- Foster, M., P. Isely, C. Standridge, and M. Hasan. "Feasibility Assessment of Remanufacturing, Repurposing, and Recycling of End of Vehicle Application Lithium-Ion Batteries." *Journal of Industrial Engineering and Management* 7, no. 4 (2014): 698–715. doi:10.3926/jiem.939.
- Georgi-Maschler, T., B. Friedrich, R. Weyhe, H. Heegn, and M. Rutz. "Development of a Recycling Process for Li-Ion Batteries." *Journal of Power Sources* 207 (2012): 173–182.

- GM-Volt.com. "Chevy Volt Specs." 2011. <http://gm-volt.com/full-specifications> (accessed January 5, 2015).
- Jody, B.J., E.J. Daniels, C.M. Duranceau, J.A. Pomykala Jr., and J.S. Spangenberg. "End-of-Life Vehicle Recycling: State of the Art of Resource Recovery from Shredder Residue." Center for Transportation Research, Argonne National Laboratory Publication, September 2010. http://www.es.anl.gov/Energy_systems/CRADA_Team/publications/End%20of%20life%20vehicle%20recycling%20Technology%20review.pdf (accessed August 31, 2013).
- Lain, M.J. "Recycling of Lithium Ion Cells and Batteries." *Journal of Power Sources* 97–98 (2001): 736–738.
- Li, H., L. M. Corneal, and C. R. Standridge. "Effects of Acid Concentration, Temperature, and Time on Recycling of Post-Vehicle-Application Lithium-Ion Batteries of Varying Chemistries." *Materials for Renewable and Sustainable Energy* (2015) doi: 10.1007/s40243-015-0048-7.
- Li, L., J. Ge, R. Chen, F. Wu, S. Chen, and X. Zhang. "Environmental Friendly Leaching Reagent for Cobalt and Lithium Recovery from Spent Lithium-Ion Batteries." *Waste Management* 30 (2010): 2615–2621.
- Marano, V., Onori, S., Guezennec, Y., Rizzoni, G. and Madella, N. "Lithium-ion Batteries Life Estimation for Plug-in Hybrid Electric Vehicles." Presented at IEEE Vehicle Power and Propulsion Conference, Dearborn, MI, September 7–11, 2009. doi: 10.1109/VPPC.2009.5289803.
- Pesaran, A. "Choices and Requirements of Batteries for EVs, HEVs, PHEVs." Report by National Renewable Energy Laboratory, 2011. <http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/51474.pdf> (accessed April 17, 2015).
- Sargent, R. G. "Verification and Validation of Simulation Models." *Journal of Simulation* 7 (2013): 12-14. doi:10.1057/jos.2012.20
- Shokrzadeh, S. and E. Bibeau. "Repurposing Batteries of Plug-In Electric Vehicles to Support Renewable Energy Penetration in the Electric Grid." SAE Technical Paper 2012-01-0348. (2012) doi:10.4271/2012-01-0348.
- Smith, K., Earleywine, M., Wood, E. and Pesaran A. "Comparison of Battery Life across Real-World Automotive Drive-Cycles." Presented at 7th Lithium Battery Power Conference, Las Vegas, NV, November 7-8, 2011. <http://www.nrel.gov/docs/fy12osti/53470.pdf> (accessed April 17, 2015).
- Standridge, C. and L. Corneal. "Remanufacturing, Repurposing, and Recycling of Post-Vehicle-Application Lithium-ion Batteries." Mineta National Transit Research Center, 2014. <http://transweb.sjsu.edu/project/1137.html>

- Xin, B.P., D. Zhang, X. Zhang, Y. Xia, F. Wu, S. Chen, and L. Li. "Bioleaching Mechanism of Co and Li from Spent Lithium-Ion Battery by the Mixed Culture of Acidophilic Sulfur-Oxidizing and Iron-Oxidizing Bacteria." *Bioresources Technology* 100 (2009): 6163–6169.
- Zhang, P., T. Yokoyama, O. Itabashi, T. M. Suzuki, and K. Inoue. "Hydrometallurgical Process for Recovery of Metal Values from Spent Lithium-Ion Secondary Batteries." *Hydrometallurgy*, 47 (1998): 259–271.

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