




Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries

J. Neubauer, K. Smith, E. Wood, and A. Pesaran

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February 2015

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List of Acronyms

°C	degree Celsius
B2U	Battery Second Use
BEV	battery electric vehicle
BEV75	battery electric vehicle with a 75-mile electric range
BLAST-V	Battery Lifetime Analysis and Simulation Tool for Vehicles
BLS	U.S. Bureau of Labor Statistics
BOL	beginning of life
BOS	balance of systems
DOD	depth of discharge
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPRI	Electric Power Research Institute
ESS	energy storage system
EV	electric vehicle
GW	gigawatt
GWh	gigawatt-hour
kW	kilowatt
kWh	kilowatt-hour
L	liter
Li-ion	lithium ion
MW	megawatt
NiMH	nickel-metal-hydride
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
OEM	original equipment manufacturer
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PHEV20	plug-in hybrid electric vehicle with a 20-mile electric range
PVT	present value of throughput
Q1	capacity loss due to calendar effects
Q2	capacity loss due to cycling effect
R1	resistance growth due to calendar effects
R2	resistance growth due to cycling effects
SOC	state of charge
SOH	state of health
TWh	terawatt-hour
UPS	uninterruptible power source
Wh	watt-hour
ZEV	zero emissions vehicle

Executive Summary

Market penetration of plug-in electric vehicles (PEVs), which could significantly decrease the nation's dependence on foreign oil and emissions of greenhouse gases, is presently restricted by the high cost of batteries. Deployment of grid-connected energy storage systems, which could increase the reliability, efficiency, and cleanliness of the grid, is similarly inhibited by the cost of batteries. Battery second use (B2U) strategies—in which a single battery first serves an automotive application, then once deemed appropriate is redeployed into a secondary market—could help address both issues. By extracting additional services and revenue from the battery in a post-vehicle application, the total lifetime value of the battery is increased, and the cost of the battery can be reduced to both the primary and secondary users.

Recognizing this potential, the U.S. Department of Energy's (DOE's) Vehicle Technologies Office has funded the National Renewable Energy Laboratory (NREL) to investigate the feasibility of and major barriers to the second use of modern lithium-ion PEV batteries. The resultant research identified and answered three high-level questions critical to understanding the viability of B2U:

1. **When will used automotive batteries become available, and how healthy will they be?**

   A detailed analysis was conducted of battery degradation in automotive service, of the economics of battery replacement in automotive service, and of battery degradation in a second use. It was found that there is little to no economic incentive to replace a PEV battery prior to the end of the original vehicle's service life (approximately 15 years), at which point the battery will have approximately 70% of its initial capacity remaining. The subsequent second use service life is highly sensitive to the second life duty cycle, climate, battery thermal management, and other factors, but could potentially exceed 10 years under favorable conditions.

2. **What is required to repurpose used automotive batteries, and how much will it cost?**

   Application of a battery repurposer business model found that repurposing facilities can likely be dedicated to batteries from a single model of PEV, avoiding the complexities of repurposing heterogeneous batteries, and efficiently operate on a regional scale, avoiding the added costs of nationwide battery collection. Technician labor is a major cost element of repurposing operations that must be minimized. As such, it is economically impractical to replace faulty cells within modules, and thus minimizing purchases of modules containing faulty cells is critical. Use of vehicle diagnostics data to support used battery purchases is therefore of great value to repurposers. When such data is available, repurposing costs can be as low as \$20/kWh-nameplate.

3. **How will repurposed automotive batteries be used, how long will they last, and what is their value?**

   Both economic (cost of repurposed batteries, value of service provided) and market size (supply of repurposed batteries, demand for service) factors were addressed to identify suitable applications. It was found that the potential supply of second use batteries can overwhelm the depth of many markets for second use batteries (often by an order of

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magnitude or more). The most promising application identified for second use batteries is to replace grid-connected combustion turbine peaker plants and provide peak-shaving services. In comparison to automotive service, use in this application will entail relatively benign duty cycles, generally much less than one cycle per day with discharge durations of greater than one hour. Under these conditions, it is anticipated that second use battery lifetimes will be on the order of 10 years. While the value to the original automotive battery owner is restricted primarily to the elimination of end of service costs (battery extraction, disposal, recycling, etc.), the value to the broader community could be significant: decreased cost of peaker plant operation on the order of 10% to 20%, reduction of greenhouse gas emissions and fossil fuel consumption, and deferral of battery recycling.

Together, the answers to these questions suggest that the second use of PEV batteries is both viable and valuable. However, the economic margins that make second use viable are often small, and thus several factors could affect this conclusion. Availability of onboard diagnostics data and accurate assessments of automotive and second use battery degradation stand out in particular. The authors therefore propose the following recommendations to support the future viability of widespread B2U practices:

- **Automotive and Battery OEMs**

  Automotive and battery OEMs should include onboard diagnostic capabilities that accurately track the capacity of individual cells (or parallel groups thereof) and pledge to share this data with repurposers. This will enable accurate identification of a battery's value and its viability for second use service. In addition, degradation and related statistics from automotive service should be quantified and shared.

- **Systems Integrators and Installers**

  Systems integrators and installers should work to develop large megawatt-scale ESS solutions for repurposed PEV batteries that minimize integration, BOS, and installation costs. These systems should monitor the health of individual modules and enable efficient replacement of individual faulty or end-of-life modules in the field.

- **Utilities and Regulators**

  Utilities and regulators should develop policies that encourage the use of ESS, particularly as peaker plant replacements, and that will support access to sufficiently large markets for repurposed batteries. Guidelines should be defined for minimum required system durations in these roles. Enabling the use of assets with durations as little as 1 hour would also be helpful. Demonstrating both new and repurposed batteries in these roles will be critical.

- **Laboratories, Universities, Future Repurposers, and other Third Parties**

  Battery degradation in both the automotive and second use environments is a critical uncertainty in the analysis of B2U strategies. Quantifying degradation of battery packs in first and second uses and developing tools to assess SOH and predict future battery degradation are therefore of great value to the field. Repurposing processed batteries should be demonstrated to confirm that a product of adequate reliability can be provided

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at low cost. Life cycle analyses that show the overall benefit to society of B2U strategies are important to demonstrate value that may not be captured in economic calculations.

If these recommendations can be implemented, it is quite possible that B2U could become an important part of both the automotive and electricity industries. While the analyses herein suggest that B2U has little ability to reduce the upfront cost of PEVs, it can eliminate end-of-service costs for the automotive battery owner and provide low- to zero-emission peaking services to electric utilities, reducing cost, use of fossil fuels, and greenhouse gas emissions. Thus, the overall benefit to society can be quite large. The authors are hopeful that government, industry, and academia will recognize these benefits and continue to push this important research area forward.

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1 Introduction

1.1 Motivation

Increased market share of plug-in electric vehicles (PEVs) is one major strategy to reduce the nation's dependence on foreign oil and emissions of greenhouse gases by improving the overall fuel efficiency and cleanliness of vehicles in the United States. However, accelerated market penetration of PEVs is presently restricted by the high cost of batteries. It has been estimated that an approximate 50% reduction in 2010 battery costs is necessary to equalize the economics of owning PEVs and conventionally fueled vehicles [1, 2].

Deployment of grid-connected energy storage systems (ESSs), which could increase the reliability, efficiency, and cleanliness of the grid, is similarly inhibited by the cost of batteries. Over the past few years, mandates and incentives for energy storage have increased dramatically to overcome this barrier. For example, in 2010 the California legislature passed Assembly Bill 2514, which resulted in the California Public Utilities Commission releasing a procurement target for 1.325 gigawatts (GW) of energy storage in the state by 2020 [3]. Approximately 15% of this allotment has been planned for customer-sited, behind-the-meter storage [4], further encouraged by California's Self-Generation Incentive Program, which offers up to $1.62 per watt installed [5].

Research, development, and manufacturing ramp-up efforts are underway to reduce battery costs by lowering material costs, enhancing process efficiencies, and increasing production volumes. However, it is also advisable to pursue increasing the total value of services provided by a battery over its lifetime. If PEV batteries have substantial performance capability left at the end of their automotive service life, additional value could be extracted by committing them to other energy storage applications following automotive use. By extracting additional services and revenue from the battery in this post-vehicle application, the total lifetime value of the battery is increased, and the cost of the battery can be shared between the primary and secondary users. We term this strategy battery second use (B2U).

Recognizing this potential, the U.S. Department of Energy's (DOE's) Vehicle Technologies Office has funded the National Renewable Energy Laboratory (NREL) to investigate the feasibility of and major barriers to the second use of modern lithium-ion (Li-ion) PEV batteries. The primary motivation of this study is to assess the value of B2U to the automotive community.

1.2 Previous Studies: 1990 to 2008

California's first zero emissions vehicle (ZEV) mandate was enacted in 1990, targeting 2% and 10% of California's annual vehicle sales to be ZEVs by 1998 and 2003, respectively [6]. Significant development of electric vehicles (EVs) resulted, including the proposal of B2U strategies to reduce the impact of battery cost. Several studies were published as a result, the first of which was Argonne National Laboratory's "Electric Vehicle Battery 2nd Use study," conducted for the United States Advanced Battery Consortium [7]. The purpose of this effort was to quantify the degradation of aged nickel-metal-hydride (NiMH) batteries and compare it to that of lead-acid batteries in response to four different duty cycles. Three of these duty cycles—utility load management, commercial and industrial off-road vehicles, and uninterruptible power sources (UPSs)—were representative of anticipated second use applications. While the number of cases was limited and the test durations were shorter than might be expected for an actual second-use service life, the NiMH batteries demonstrated comparable and often superior performance to their lead-acid counterparts. The data demonstrated that used automotive NiMH batteries could potentially meet the requirements of non-automotive energy storage applications and compete with the incumbent technology in terms of performance, thus motivating further study.

Sandia National Laboratories' report *Technical and Economic Feasibility of Applying Used EV Batteries in Stationary Applications* explored the value of applications for second-use NiMH batteries, as well as built an economic model to calculate the costs of repurposing them [8]. The study concluded that there were no "insurmountable technical barriers to the implementation of a second use scheme" using NiMH batteries, but highlighted the benefits of battery module standardization, the large effect that repurposing labor costs plays in repurposed battery selling prices, the absence of a means to apply second use value to the original automotive owners, and the impacts of uncertainty in forecasting battery degradation on warranty terms and value determination. It identified transmission support, light commercial load following, residential load following, and distributed node telecommunications backup power as the most likely applications for second use NiMH batteries, pointing out that the economics appeared viable, but that balance of systems (BOS) costs—in particular, inverters—were a large component of total installed costs. The report recommended considerable demonstration testing to address substantial uncertainties in performance and lifetime.

The Electric Power Research Institute's (EPRI's) report *Market Feasibility for Nickel Metal Hydride and Other Advanced Electric Vehicle Batteries in Selected Stationary Applications* compared the viability of lead acid, NiMH, Li-ion, and lithium polymer batteries in utility control/switchgear, telecom backup power, and UPS applications [9]. Although the focus of the study was on expanding the market for existing EV battery technology to reduce production costs, it also discussed opportunities and challenges for EV battery second use. Specifically, the authors called out the importance of understanding repurposing activities and costs, solving warranty issues, and crediting the original automotive owner with second use value, satisfying technical requirements of the second use application, and understanding battery performance and degradation throughout and subsequent to its automotive service life.

1.3 Previous Studies: 2008 to 2014

When California changed its ZEV requirements in 2003 [6], automakers shifted their focus to hybrid EVs and interest in B2U declined. However, by 2008, California had changed the ZEV program back to an emphasis on PEVs, and battery technology had advanced from NiMH to Li-ion to make EV performance more attractive to consumers. This reignited interest in B2U strategies as a means of reducing the cost of EVs and postponing battery recycling, resulting in many new published studies. Among these are the authors' own studies initiated in 2010 at the request of the DOE Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Office. These include development of a framework for bounding repurposed battery salvage value [10–12], analyzing the ability of battery second use credits to reduce the upfront cost of PEVs [11, 12], calculating the costs of repurposing automotive Li-ion batteries [12], evaluating the economics and market potential of second use batteries in numerous grid applications for energy storage [11–14], and testing of aged batteries in likely second use applications [15].

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These works found B2U strategies are highly likely to be viable, but success will be sensitive to battery degradation rates and identifying large markets that can consume the sizeable quantities of second use storage anticipated is important.

A California Energy Commission-funded study by the University of California, Davis compared the requirements of PEV designs with requirements for stationary energy storage applications and concluded, like previous studies, that light commercial load leveling, telecommunications backup, and residential load leveling appear best suited to second use batteries [16]. The California Energy Commission also concluded that demonstrating economic viability and guaranteeing second use lifetime would be the principal challenges for successful second use operations. A subsequent study by the same group on battery cycle life tested both new and used Li-ion cells and found that while the energy density of aged cells may only be reduced by 10%–20% by automotive service, the power capability may be degraded by a much larger factor [17]. They also observed that the resistance of used cells increases more rapidly than that of new cells when cycled at high temperature. These points led to the conclusion that second use batteries are best suited for applications with lower power-to-energy ratios.

The Office of Electricity funded a second use study by Oak Ridge National Laboratory that focused on assessing repurposing costs, BOS costs, and generated revenue in grid applications [18]. The analysis predicted shipping costs on the order of $100 per kilowatt-hour [kWh]-nameplate as the dominant cost of repurposing. The report then compared its computed repurposing costs to the revenues of many grid applications in search of viable and profitable second use scenarios, concluding with the recommendations to evaluate emerging policies that may impact second use strategies and to demonstrate second use batteries in field applications.

The Mineta National Transit Research Consortium compared three post-automotive options for PEV batteries: remanufacturing for reuse in vehicles, repurposing for alternative applications, and recycling [19]. It investigated the potential supply of retired PEV batteries, finding that quantities were large enough to justify one or more of these efforts; however, a basis for this justification was not disclosed. An economic model of remanufacturing predicted that this is economically preferable to manufacturing new batteries where new batteries exceed a cost of approximately $260/kWh-nameplate to build. Repurposing, on the other hand, was predicted to cost between $83 and $114/kWh, but was not compared to cost requirements for likely second use applications. The study also briefly demonstrated a simple repurposed battery system. Recycling was found to be economically infeasible.

A report on battery second use from Navigant Research [20] identifies risks with shipping (all batteries removed from vehicles in the United States and Europe are presently classified as hazardous waste), competition from low-cost Li-ion batteries in the future, possible resistance from utilities due to requirements for high reliability and long product life, high sensitivity of B2U economics to battery degradation, and repurposing challenges due to control of battery management systems. The report goes on to make projections of B2U supply and revenue based on general assumptions of vehicle sales, battery wear and service life in automotive and second use applications, and new and repurposed battery selling prices. The report concludes with strong recommendations to eliminate regulatory hurdles, address issues with battery management systems and data logging in automotive service, and demonstrating the performance of second use systems.

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A thesis by Bowler [21] considered myriad factors affecting second use—including the overall second use value chain, systems architectures in the automobile and second use application, and the impact of policy—and conducts extensive Monte Carlo simulations to assess the potential impact of these factors. The thesis concludes that under many combinations of assumptions, B2U is economically unviable. It finds that B2U economics are most sensitive to battery degradation in the automotive and secondary service, illuminating the importance of degradation prediction capabilities and properly matching retired automotive batteries with appropriate second use applications. Finally, where B2U strategies are economically viable, this study finds that the value of B2U is not to discount initial PEV prices, but rather to provide economic and environmental benefits of other second-use players.

Numerous additional studies concerning B2U have also been published. Wolfs considered the potential supply of and demand for second use batteries, inverter architectures for their deployment on the grid, battery life in second use service, and the economic value of such systems in Australia's short-term energy market [22]. Others have investigated specific B2U strategies, including a University of California – Berkeley study on the impact of second use strategies on automotive battery lease payments [23] assuming batteries accrued revenue from combined peak power, spinning reserves and regulation grid-support services while also receiving credits for carbon reduction; analyses of repurposed batteries providing regulation services [24] and commercial facility energy time shifting [25]; and a comparison of B2U with vehicle-to-grid services [26]. Cicconi and Landi [27] and Ahmadi et al. [28] looked at B2U in the context of life cycle assessments, the later finding that repurposing plug-in hybrid electric vehicle (PHEV) batteries to replace natural gas-powered peaker plants could effectively match the carbon dioxide reductions provided by vehicle electrification, doubling the overall environmental benefits provided by the battery. Other reports summarize other primary B2U research and interviews with people in the field to qualitatively document factors expected to affect B2U strategies [29, 30, 31].

1.4 Gaps in the Literature

There are numerous studies published on the use and wear of batteries in automotive applications; of the value, size, and operational requirements of grid applications for energy storage; and other related topics relevant to the B2U analyses herein. We forgo summarizing them for the sake of brevity, although we will refer to select studies subsequently to support our analyses as appropriate. These works aside, the authors have identified several significant gaps in the literature specific to B2U that are in need of consideration.[1]

Of primary import is the lack of high-fidelity analysis of battery degradation in both automotive and second use roles. Although numerous studies have identified the large impact that battery degradation plays in determining the viability of B2U strategies, very few go beyond making simple assumptions as to the number of years a battery will last in automotive service, the amount of capacity it retains when leaving automotive service, and the number of years it will last in second use service. The few studies that do go beyond this level of fidelity are often limited to simplified estimations of cycle life. For example, Keeli and Sharma apply a simple amp-hour accounting method to predict second use battery degradation, and thereby lifetime, in a commercial building energy shifting application [25]. This model ignores capacity losses due to

[1] Ignoring for the moment the work completed by the authors [10–15] and expanded upon in this report.

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calendar degradation and wholly forgoes the effects of temperature, which we know to be two major contributors to battery degradation in such applications. Also, it simply assumes values for battery state of health (SOH) following automotive service rather than actually attempting to predict it. Hein et al. also makes use of an amp-hour–throughput life model [26]. While it is applied to automotive degradation therein, it ignores sensitivity to depth of discharge (DOD), state of charge (SOC), temperature, and calendar effects. Wolfs discusses the importance of all of these factors, plus the impact of rate effects, and cites multiple sources of how these factors can be included in a degradation model [22]. However, the study only employs an amp-hour–throughput model for one condition, while noting that the resultant 20-year second use service life prediction may be cut short by calendar effects. Viswanathan and Kintner-Meyer employ a degradation model with both cycling and calendar components that is applied to both automotive and second use service, but the cycling component is a simple amp-hour–throughput model, the calendar fade is predetermined for one condition, and the two are arbitrarily combined to yield the total SOH [24]. Neither model considers sensitivity to DOD or SOC. Furthermore, all of these studies assume a simple capacity limit-based criterion for removal of batteries from automotive service, ignoring consideration of battery and vehicle economics by drivers, and none of them separately assesses impacts on battery capacity and resistance. In defense of these studies, accurate, high-fidelity battery degradation life models are not widely available, and neither is the experimental data necessary to build such models.

The cost of repurposing batteries is also an important aspect that often receives insufficient attention. The first report known by the authors to address repurposing costs predicted this cost to be approximately $60/kWh-nameplate [8], which is certainly high enough to merit further attention. This is also the only report that has performed a detailed, bottom-up analysis of repurposing costs, and this was for only one set of assumptions on NiMH chemistry. While Narula et al. also evaluate repurposing costs [18], they apply the repurposing facility model of Cready et al. [8] to a scenario in which the annual facility throughput is increased by 22 to 33 times over its original design value without adjusting the amount of labor, equipment, and floor space accounted for, thus reporting excessively low repurposing costs of less than $3.50/kWh-nameplate. In [19], an economic model for repurposing is also proposed; however, the model is significantly simpler than that of Cready et al. [8], many large assumptions are not justified in the report (e.g., a $30M repurposing facility is assumed capable of 5,000 16-kWh batteries per year without explicit consideration of the floor space or equipment requirements), and only one scenario is evaluated. Additional detailed analysis is therefore necessary to identify analysis sensitivities and means to reduce repurposing costs.

Finally, proper assessment of the future supply of retired PEV batteries and comparison to the market potential (i.e., demand) of likely second use applications are rarely treated with adequate detail. This is important to address, because 1) markets capable of purchasing repurposed batteries may be too small to justify repurposing efforts, squashing second use strategies entirely, or 2) the supply of retired automotive batteries may greatly exceed their demand, which will minimize the overall value of B2U strategies to original automotive owners. In both Standridge and Corneal [19] and Jaffe and Adamson [20], projections for the availability of second use batteries are made, but are not compared to markets for repurposed batteries. In Narula et al. [18] and Wolfs [22], similar projections for second use battery availability and assessments of demand are made. However, they are simplified and assumption-heavy assessments of demand based on the U.S. penetration of wind energy in 2020 and completely flattening Australia's

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South West Interconnected System load profile. There is no consideration for serious technical requirements or for economic viability of repurposed batteries in these specific roles. Thus, we find that all treatments of supply are burdened by coarse estimates of battery life, and the limited treatments of demand do not adequately consider technical requirements or economic viability.

1.5 Approach

Based on a preliminary high-level analysis of the second use value chain, findings from past B2U studies, and gaps in the B2U literature, the authors identified the following key high-level questions in need of answers to assess the value and viability of B2U strategies:

1. When will used automotive batteries become available, and how healthy will they be?
2. What is required to repurpose used automotive batteries, and how much will it cost?
3. How will repurposed automotive batteries be used, how long will they last, and what is their value?

Detailed techno-economic analyses of automotive battery use, battery repurposing, and likely second use applications were performed to answer these questions. To address existing gaps in the literature, regular use of a high-fidelity battery model to predict battery degradation in both automotive and second use service has been included; the repurposing facility model of Cready et al. [8] has been expanded and applied extensively to a broad range of scenarios; and best efforts at estimating the future supply of repurposed batteries and the market potential for individual second use applications have been made. These elements were compiled into a detailed techno-economic analysis of the complete PEV battery lifetime, including automotive use, repurposing, and secondary use, conducted to quantify the value and assess the viability of B2U. Figure 1 outlines the analysis process. Gray boxes represent steps in the life cycle not treated herein, as the original manufacture[2] and ultimate recycling will likely take place identically whether B2U strategies are implemented or not.

[2] If B2U strategies were to incentivize a change in the design of PEV battery hardware, then the original manufacturing step would need to be considered. However, while this study does find incentives to make minor software changes in PEV battery systems, incentives for hardware changes are found to be minimal.

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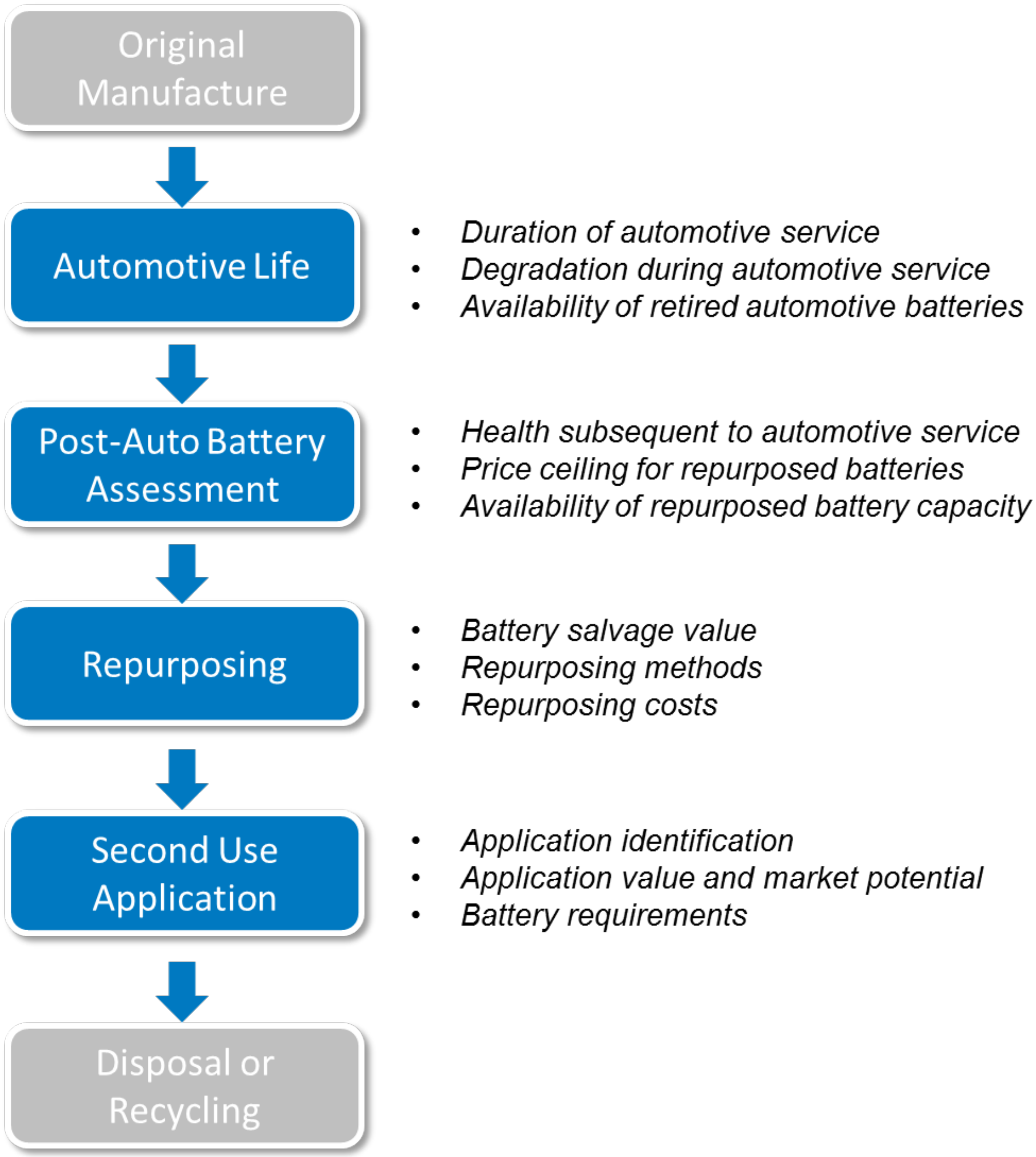

Figure 1. B2U life cycle and key analysis steps

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2 Automotive Life

Understanding the automotive life of a battery is critical to predicting when automotive batteries will become available for second use, as well as how healthy they will be. However, numerous factors complicate answering these questions. The following three factors are of critical importance and can be challenging to resolve:

1. Developing a method to predict battery degradation as a function of duty cycle, environment, and time
2. Understanding how PEV drivers will make automotive battery replacement decisions
3. Accounting for the breadth of duty cycles and environments PEV batteries will experience such that battery degradation prediction methods may be appropriately applied to automotive service.

These questions have not been well addressed in the literature to date, especially in the context of automotive B2U.

2.1 Predicting Battery Degradation

Quantification of the relative amount of remaining performance of a battery at any point in time requires an understanding of battery degradation. Prediction of battery degradation to arbitrary operating conditions is currently a working area of research in the battery community. Many models to do so are empirically based, interpolating between or extrapolating from different sets of measured battery capacity and resistance data sets [32–34]. These suffer from extensively large data needs and are often inadequate for extrapolating beyond the duration of the life test data upon which they are based. Alternatively, physics-based first-principles models have been proposed, but can be exceedingly complex and limited in scope to a narrow range of operating conditions [35–37].

NREL has developed a semi-empirical life model that attempts to bridge this gap, offering a combination of increased confidence in interpolations and projections while maintaining simplicity of implementation and a basis in actual laboratory data [38]. It separately accounts for both capacity and resistance effects induced by cycling-based and calendar-based mechanisms. Cycling-based mechanisms specifically address the effect of charging and discharging the battery, while calendar-based mechanism address degradation that occurs even in the absence of current flow. Nonlinear effects of time, temperature, DOD, and SOC are included. The specific model employed herein is fit to an extensive set of degradation data for a Li-ion cell with a nickel-cobalt-aluminum cathode and graphite anode. We apply this model within an assumed 15-year vehicle life, at which point approximately 67% of all vehicles have been removed from service [39].

2.2 Battery Replacement in Automotive Service

An understanding of the time and SOH of a PEV battery when it is removed from automotive service is also critical to calculating remaining battery performance. This requires knowledge of PEV battery replacement decisions, which can be made on multiple bases. In cases where the battery warranty ensures some minimum available performance criteria, the replacement decision may be straightforward. Vehicle leasing that entails similar performance guarantees

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would also be straightforward. At the time of writing, the 2014 Chevrolet Volt propulsion battery is warrantied to stay above 70% capacity during its 8-year / 100,000-mile term [40]. The 2014 Nissan LEAF battery is similarly warrantied over a 5-year / 60,000-mile term [41]. Nissan also offers a battery warranty extension for $100/month that can be extended for the total lifetime of the vehicle [42].

Where this is not the case and the vehicle is owned by its user, the majority of battery replacement decisions will be made by that user. The user's motivation for battery replacement may be 1) improved acceleration, 2) increased interior volume within the vehicle, 3) increased electric range of the vehicle, 4) decreased fuel costs, or 5) increased resale value. Our subsequent analyses suggest that vehicle acceleration is most likely limited by inverter and motor selection throughout the life of the vehicle, not the battery (even when degradation is considered). Motivations 1 and 2 thereby rely either on considerable modification to a vehicle beyond battery replacement, or that the original equipment manufacturer (OEM) has anticipated this future desire of the customer (e.g., oversizing of inverters and motors, expandable/retractable battery compartments). Thus motivations 1 and 2 are ruled out on the basis that these scenarios are expected to occur infrequently. Motivations 3, 4 and 5, on the other hand, are all viable, and all have quantifiable economic implications to the user (increased range leads to more miles driven on electricity rather than more expensive fossil fuels).

Thus, it is reasonable to assume that batteries will be replaced when either 1) a warranty (or similar) performance level is breached, or 2) there is an economic motivation for the user-owner to do so. Previous studies on battery degradation with NREL's Battery Ownership Model and Battery Lifetime Analysis and Simulation Tool for Vehicles (BLAST-V)—advanced techno-economic simulators for PEVs employing the aforementioned battery degradation model—have found it likely that 1) PEV batteries will retain more than 70% of their original performance over the first 8 years of operation, and 2) replacing batteries within the anticipated 15-year lifetime of a vehicle will not be economically justified [43–45]. While there will be exceptions for select high-wear cases (particularly for high-mileage drivers in hot climates), they are likely to be a small percentage of the total B2U supply stock.[3]

As such, the majority of B2U batteries should be expected to become available only at the end of a complete 15-year automotive service life,[4] and the subsequent analyses herein shall be restricted to these cases.[5]

[3] Where PEVs are leased rather than owned by their user, an additional opportunity for battery replacement (without lease terms that guarantee range) occurs after the lease and prior to resale of the vehicle. Here the original dealership will be faced with the decision to replace the installed battery, and thus the motivation will primarily concern vehicle resale value. It is challenging to predict consumer acceptance of used PEVs in future well-developed markets. While it is possible that consumers will demand new batteries be installed by the dealerships, resulting in relatively quick battery replacements 3 to 5 years after the original vehicle sale, it is also possible that such consumers will accept range-based warranties instead. This would result in the same 15-year lifetime that we expect to occur where PEVs are purchased rather than leased.

[4] Herein we omit consideration of replacements induced by premature battery failure, degradation beyond "normal wear and tear," and vehicle accidents for two reasons. First, such failures are expected to be infrequent if the PEV market is to be successful and thus will have a small impact on overall battery second use trends. Second, such batteries are expected to be unusable for second use applications as the cost of repurposing batteries where

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2.3 Battery Degradation in Automotive Service

NREL's BLAST-V was applied to compute the SOH of PEV batteries following 15 years of automotive service. This highly detailed PEV simulator includes consideration of driver patterns and aggression, climate, cabin thermal dynamics, infrastructure, and many other factors to compute the wear incurred by the battery and utility delivered to the driver. More detail on the functionality of this tool can be found in the BLAST-V documentation [46].

Recent BLAST-V studies have found that driver patterns and climate have the largest effect on battery degradation among many other factors, including driver aggression, vehicle and battery thermal management systems, available infrastructure [45, 47, 48]. Thus, BLAST-V is employed herein to predict battery degradation metrics for cold (Minneapolis, Minnesota), moderate (Los Angeles, California), and hot (Phoenix, Arizona) climates across a set of 91 year-long PEV-friendly drive patterns. These drive patterns are a subset of data recorded from the Puget Sound Regional Council's Traffic Choices Study [49], processed per Neubauer and Wood [45], that yield a year-one vehicle miles traveled ≥8,000 miles and a utility factor ≥80% when driven with a 75-mile battery electric vehicle (BEV),[6] as presented in Figure 2.

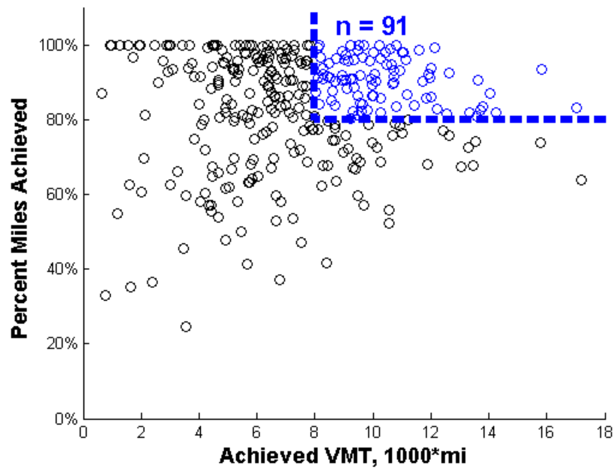

Figure 2. Utility factor vs. achieved vehicle miles traveled (VMT) for selected drive patterns

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significant amounts of technician time is needed (e.g., to replace individual cells within a module, replace a damaged housing, etc.) is anticipated to be prohibitively expensive (see Section 4.9).

[5] There are two possible scenarios that could result in shorter automotive service lifetimes on the large. First, battery degradation could prove to be much more severe than expected, inducing battery replacements under warranty or at cost to the automotive owner. This would presumably affect degradation in a second use application as well, making B2U overall less viable. Alternatively, new battery technology could advance significantly to the point where battery replacements become strongly incentivized to increase range and/or efficiency. The effect of this on B2U strategies is mixed, as it would provide healthier batteries at an earlier time, but they would compete in second use markets with more capable technology.

[6] The range of a BEV can vary greatly with operating conditions. Our definition of nameplate range for PEVs is calculated via simulation and weighting of the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Driving Schedule (HWFET) drive cycles per [50], which approximates the U.S. Environmental Protection Agency-rated range of a given vehicle. It is, however, common that our simulated PEVs achieve a greater than nameplate range as operating conditions allow.

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For these drivers and climates, two different PEVs are simulated: 1) a midsize sedan BEV with a 75-mile electric range (BEV75), and 2) a midsize sedan PHEV with a 20-mile electric range (PHEV20). The BEV is equipped with a 22.1-kWh battery that operates between 100% and 0% SOC. The PHEV is equipped with a 7.74-kWh battery that operates in charge depleting mode between 100% and 20% SOC, then switches to charge sustaining mode. To meet the high power demands of PHEV operation, the PHEV battery is assumed to have 50% lower cell resistance than the BEV battery. Each vehicle employs a heat-pump cabin heater, a conventional cabin air conditioner, and an active battery cooling system. Further details of the battery and thermal systems models can be found in Neubauer and Wood [45].

Road load energy consumption is based upon simulation of NREL's Drive-Cycle Rapid Investigation, Visualization, and Evaluation (DRIVE) cycle, scaled for normal-aggression drivers and the average speed of the specific trip being simulated [45]. Auxiliary loads—battery thermal management and cabin heating and cooling—are computed based on thermal simulations of the vehicle-battery system per Neubauer and Wood [45].

We assume that only at-home Level 2 charging (6.6 kW alternating current) is available, and that the battery cooling system actively cools the battery when at the charger. All vehicles are simulated for 15 years, our assumed end of automotive service. The vehicle simulation specifications are given in Table 1.

Table 1. Vehicle Simulation Specifications

Drivetrain	BEV75	PHEV20
Vehicle type	Midsize Sedan	Midsize Sedan
Battery size	22.1 kWh	7.74 kWh
Typical electric range @ BOL	75 miles	20 miles
Maximum SOC @ BOL	100%	100%
Minimum SOC @ BOL	0%	20%
Auxiliary equipment	Heat-pump cabin heater Conventional cabin air conditioner Active battery cooling	
Charging infrastructure	At-home Level 2 (6.6 kW alternating current, 93% efficiency) Battery cooling active at charger	

BOL = beginning of life

Resultant battery SOH data are presented in Figure 3, Figure 4, Figure 5, and Figure 6 for all drive patterns. Table 2 presents the median SOH values taken from all of the drive patterns.

These data show that for both BEVs and PHEVs, capacity loss is dominated by calendar effects (Q1), resulting in losses of 25% to 35% after 15 years of automotive life, depending on climate and driving pattern. The effect of climatic differences between Minneapolis and Los Angeles is significant, resulting in 4% more Q1 capacity loss in Los Angeles. The difference between Phoenix and Los Angeles is only 1%, however, presumably due to the presence of the active cooling system active above 20°C. Median Q1 capacity losses are approximately 4% higher in

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PHEVs than BEVs. While the cycling effect on capacity (Q2) is much greater (approximately 12%) in PHEVs than in BEVs due to the increased frequency of high DOD cycling, this has no immediate impact on battery performance or value, as the total capacity loss is determined by the greater of Q1 and Q2, not the summation.

Calendar effects on resistance (R1) are nearly identical for the BEVs and PHEVs. In all cases, the 25th to 75th percentile spread is extremely small. For the BEV, it is likely that the calendar effects on resistance are significantly larger than the cycling effect (R2); however, for the PHEV this trend is reversed: cycling effects (R2) are much more likely to dominate total resistance growth. As such, total resistance growth (the summation of R1 and R2) is much larger in the PHEV than the BEV. The observed effect of climate on resistance growth is similar to that of capacity fade: a significant difference exists between Minneapolis and Los Angeles, but a minimal difference exists between Los Angeles and Phoenix due to the set points of the active battery cooling system.

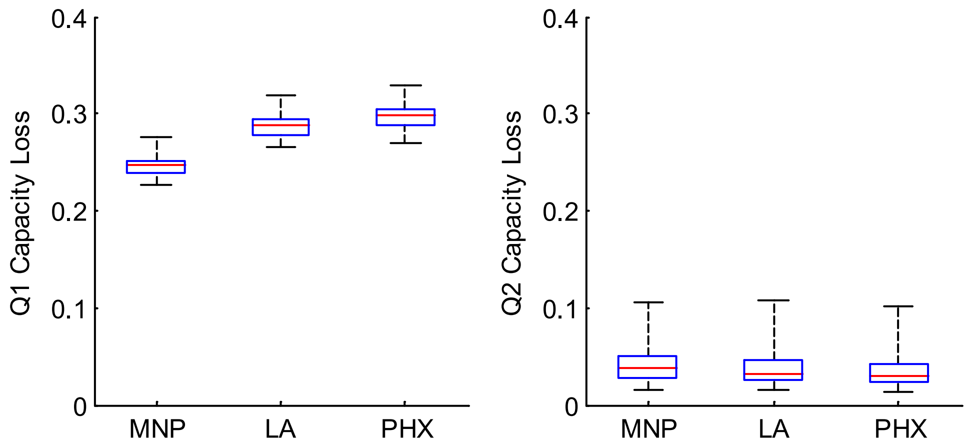

Figure 3. Box plot of BEV75 battery capacity loss due to calendar effects (Q1) and cycling effects (Q2).

Note that the total capacity fade is the greater of Q1 and Q2.

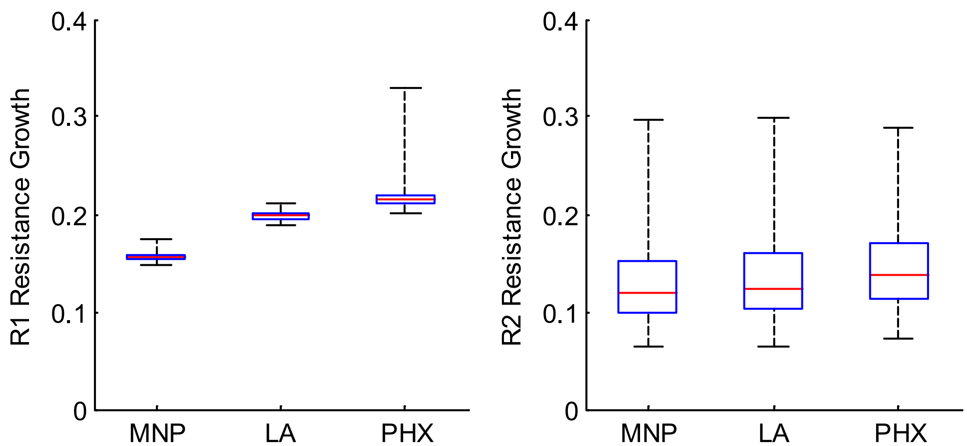

Figure 4. Box plot of BEV75 battery resistance growth due to calendar effects (R1) and cycling effects (R2).

Note that total resistance growth is the sum of R1 and R2.

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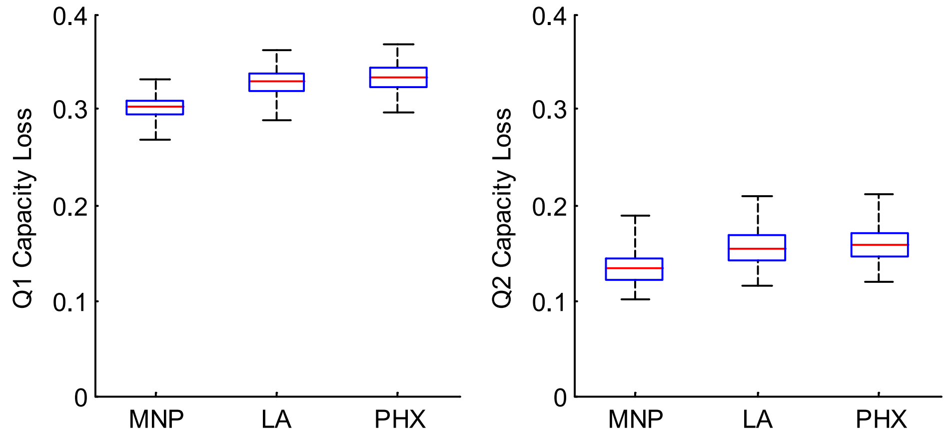

Figure 5. Box plot of PHEV20 battery capacity loss due to calendar effects (Q1) and cycling effects (Q2).
Note that the total capacity fade is the greater of Q1 and Q2.

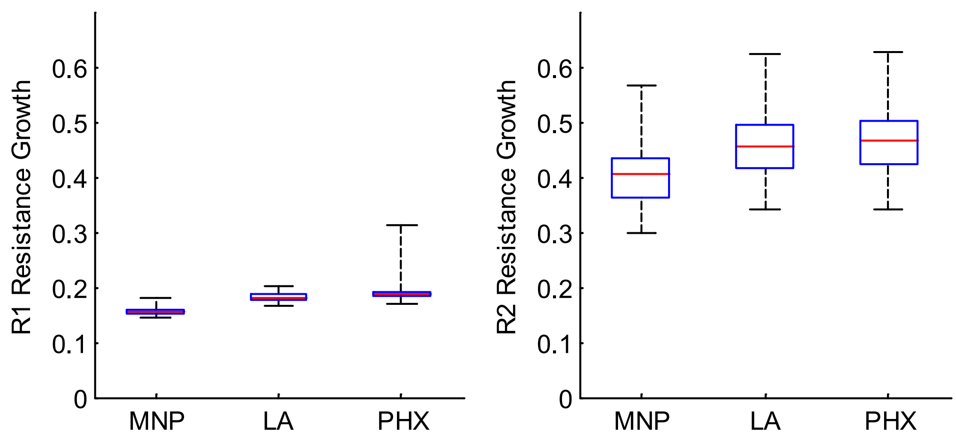

Figure 6. Box plot of PHEV20 battery resistance growth due to calendar effects (R1) and cycling effects (R2).
Note that total resistance growth is the sum of R1 and R2.

Table 2. Median Capacity Loss and Resistance Growth across Driving Patterns

SOH	Vehicle	Minneapolis, MN	Los Angeles, CA	Phoenix, CA
Capacity, Calendar (Q1)	BEV75	24.7%	28.8%	29.8%
	PHEV20	30.2%	32.9%	33.4%
Capacity, Cycling (Q2)	BEV75	3.7%	3.2%	2.9%
	PHEV20	13.3%	15.5%	15.9%
Resistance, Calendar (R1)	BEV75	15.5%	19.9%	21.4%
	PHEV20	15.5%	18.2%	18.7%
Resistance, Cycling (R2)	BEV75	12.0%	12.4%	13.8%
	PHEV20	40.6%	45.9%	46.7%

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2.4 Forecasting Availability of Retired PEV Batteries

Next, the potential supply of retired PEV batteries is assessed, starting with the comparison of multiple projections for PEV sales in the United States as shown in Figure 7 [51–53]. Note the difference in the two projections made circa 2010 with the more recent 2014 projections. Clearly, expectations for PEV sales have changed considerably over the last few years.

We elect to extrapolate the most conservative and recent projection [53] to create two PEV deployment scenarios for use in this study. In a less aggressive deployment scenario, we assume that Navigant's projected annual sales continues to grow at a rate of 45,000 vehicles per year until 2046, resulting in 1.6M PEV sales per year (approximately 10% of today's total annual vehicle sales). This value is then held constant for future years. In a more aggressive maximum deployment scenario, we apply a constant 16.3% annual sales growth rate to Navigant's 2014 sales prediction through 2040, at which point 6.7M PEVs are sold each year (approximately 45% of today's total annual vehicle sales). This value is then held constant for future years. Both scenarios are illustrated in Figure 8.

Note that we do not mean to imply that either of these scenarios is anticipated nor that our low and high scenarios bound our expectations for future PEV sales. These two scenarios are selected only to demonstrate the second-use implications of different levels of PEV sales.

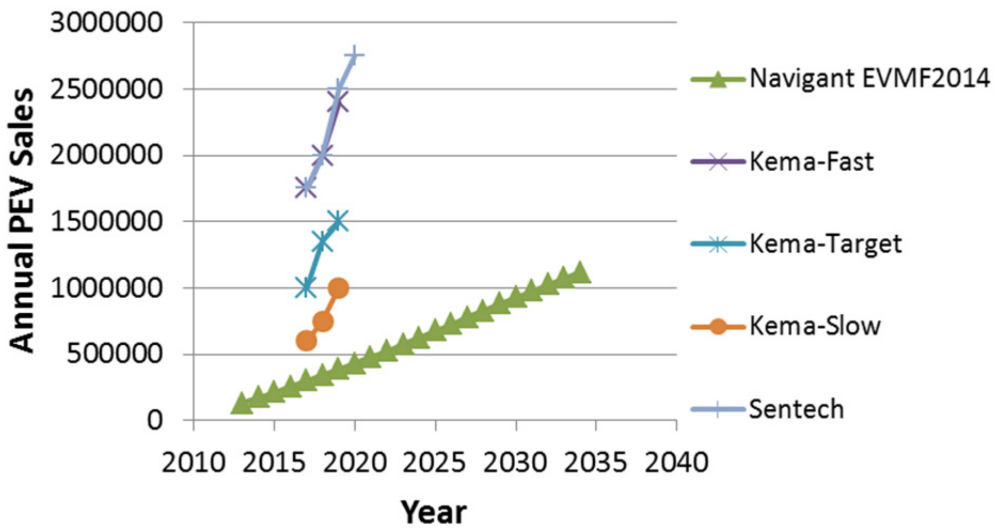

Figure 7. U.S. PEV sales projections

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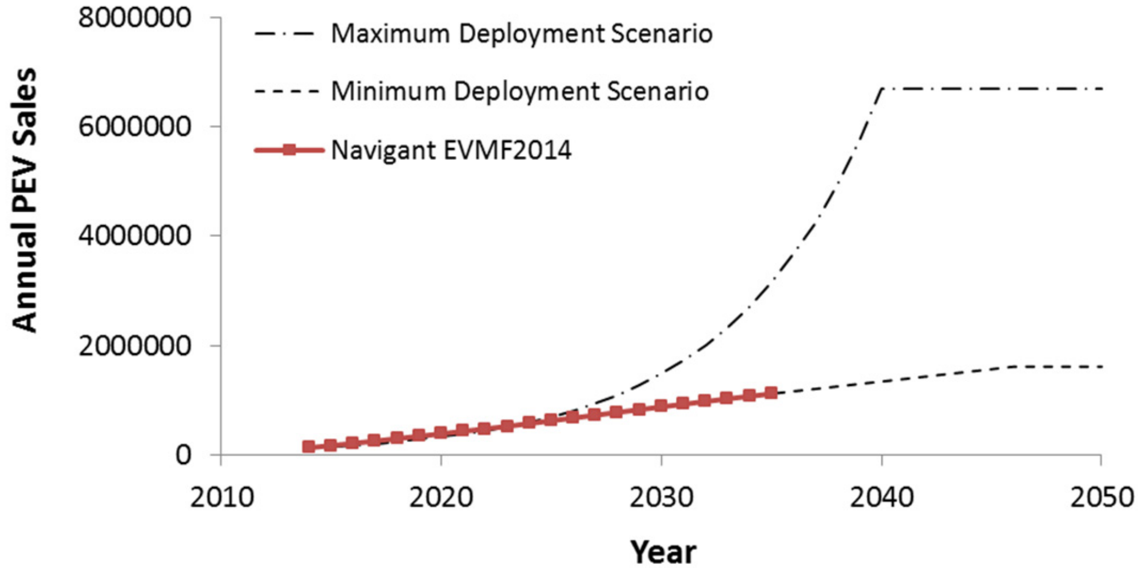

Figure 8. Employed maximum and minimum PEV sales projections

In addition to sales projections, we also need to know the typical installed battery size. A review of the data in Figure 9 for PEVs sold in California from December 2010 to June 2014 [54] shows that the average installed capacity is 22.3 kWh per vehicle. This number should be expected to change in the future as the PEV market evolves, which could change market preference towards vehicles with smaller or larger batteries. We assume that this could decrease by 25% to 16.7 kWh per vehicle on average if PHEV sales become dominant or increase to 27.8 kWh per vehicle if longer-range BEVs instead become dominant.

Figure 9. Average installed PEV capacity per vehicle sold in California

It is also necessary to know how many batteries are likely to survive to the vehicle end of life (assumed to be 15 years as discussed previously) without being irreparably damaged due to an accident or similar occurrence. Of the 135M passenger cars registered in 2009 [55], 83,613 were

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involved in rollover accidents, 15,333 were involved in fatal non-roll-over accidents, 1.45M were involved in non-rollover "injury crashes," and 3.66M were involved in "property damage only crashes" [56]. Unfortunately, it is not possible to ascertain with any certainty the fraction of these accidents that would result in batteries suitable for B2U. Assuming that 75% of fatal and roll-over crashes, 30% of non-rollover "injury crashes," and 10% of "property damage only crashes" result in irreparable battery damage, one would predict that 0.65% of PEV batteries in registered vehicles are removed from service each year and ineligible for repurposing due to accidents. Under this perhaps best case assumption, approximately 90% of the batteries originally deployed in PEVs will be eligible for repurposing after their 15-year automotive service life. Where all fatal and roll-over crashes, 70% of non-rollover "injury crashes," and 25% of "property damage only crashes" result in irreparable battery damage, only approximately 80% of the batteries originally deployed in PEVs will be eligible for repurposing after their 15-year automotive service life. We will apply these two estimates to bound our subsequent analyses.

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3 Post-Automotive Battery Assessment

3.1 Predicting Remaining Battery Performance

While BLAST-V provides predictions of battery capacity fade and resistance growth to the end of automotive service, these numbers alone are not wholly indicative of remaining battery performance. For example, the loss of 25% of initial capacity does not necessarily imply that 25% of the battery's value is lost: the battery could operate for only a few more cycles before becoming complete unusable, which would imply a much larger loss of value, or it may continue operate with minimal additional degradation for decades, which would imply a much smaller loss of value. As these examples illustrate, the remaining performance is also dependent on the number of remaining cycles and calendar time.

For the purposes of this study, where interest in remaining value is primarily economic, an economic approach to the calculation of remaining value is called for, such as Neubauer et al.'s Present Value of Throughput (PVT) method [12]. This method assumes that the battery's owner accumulates D dollars for every kilowatt-hour of throughput processed by the battery today, that D is expected to escalate at 2.5% per year, and that the owner's discount rate for future cash flows is 10% per year. Then, if the battery is operated with any arbitrary monthly throughput of x_i, for which it is known that the battery will last m months, the present value of the battery's remaining service life is given by Equation 1.

$$PVT = \sum_{i=1}^{m} \frac{(1+0.025)^{(i-0.5)/12}}{(1+0.10)^{(i-0.5)/12}} Dx_i \qquad \text{Eq. 1}$$

Definition of the health factor, k_H, in Equation 2 as the ratio of remaining PVT of a used automotive battery (PVT_U) to that of a new battery providing identical service (PVT_N) allows comparison of the value of a used battery relative to a new one. It is important to recognize that "identical service" means that the value of throughput (D) is the same (thus the value for D need not be specified). The number of months of service (m) and the annual throughput from the battery (x_i) are anticipated to be different for PVT_N and PVT_U. For example, one may find that PVT_N is optimized when a new battery is operated at a high annual throughput (implying a high DOD) over 10 years, while a used battery may be required to operate at lower annual throughput (restricted by available energy) and may only be capable of sustaining such operation for five years.

$$k_h = PVT_U / PVT_N \qquad \text{Eq. 2}$$

A simplified peak-shaving duty cycle consisting of a constant-power, two-hour discharge in the afternoon and a six-hour, constant-power, constant-voltage charge overnight, performed 252 days per year, was assumed to compute PVT_N. This is a reasonable duty cycle for a battery performing in a generic peak-shaving role, which, as will be seen in Section 5.2, is a reasonable expectation for a second use battery. An average temperature of 10°C above the U.S. national average ambient temperature of 11.16°C was assumed [57] to conservatively represent the combined effects of the battery container, heat generation during discharge, and solar irradiation if the battery is located outside. This effective temperature may also be representative of locating

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the battery inside a climate-controlled facility with moderate cooling. We select a maximum SOC of 100%.

These conditions were simulated for DODs of 40%, 50%, 60%, and 70%, and PVT_N was computed for each based on the resultant service life (m) to select a near optimal DOD. End of service life was defined as the point at which the battery could not sustain the defined duty cycle at or above the minimum allowed cell voltage and 0% SOC. Data for the BEV cells are shown in Figure 10, where PVT_N has been normalized to the best performer in this set. The use of a 50% DOD, yielding a 16.9-year lifetime, maximizes PVT_N. Simulation of the lower-resistance PHEV cell yielded similar results (not shown), but the battery lasts slightly longer (17.2 years at 50% DOD). Thus, a 50% DOD for each cell is employed as the optimal condition for the purpose of PVT_N.

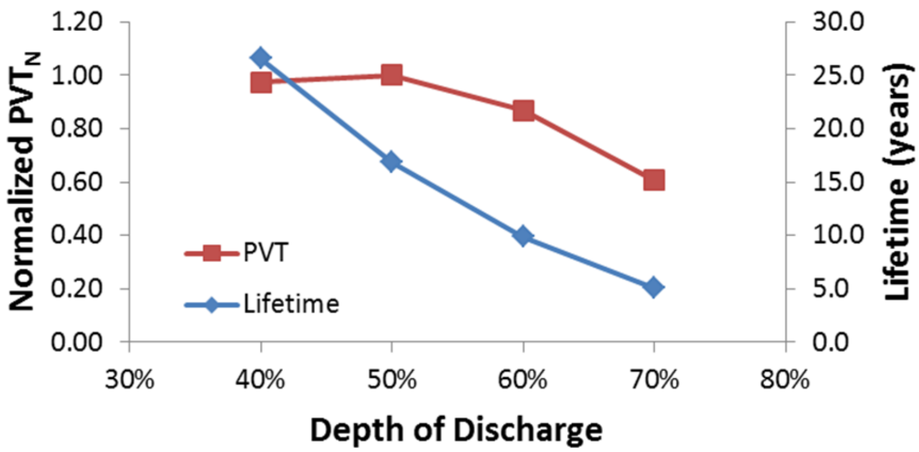

Figure 10. Lifetime and PVT_N for a new BEV battery operated at various DODs for a simplified peak-shaving duty cycle

Using the resultant lifetimes for the BEV and PHEV cells at 50% DOD, an equation for PVT_N as a function of D and beginning of life (BOL) capacity, Q_{BOL}, was derived in Equations 3 and 4, assuming 30.4 days per month:

$$PVT_{N,BEV} = \sum_{i=1}^{202} \frac{(1+0.025)^{(i-0.5)/12}}{(1+0.10)^{(i-0.5)/12}} Dx_i = 1797 DQ_{BOL} \qquad \text{Eq. 3}$$

$$PVT_{N,PHEV} = \sum_{i=1}^{206} \frac{(1+0.025)^{(i-0.5)/12}}{(1+0.10)^{(i-0.5)/12}} Dx_i = 1815 DQ_{BOL} \qquad \text{Eq. 4}$$

Next, batteries removed from automotive service were simulated to a similar peak shaving cycle employed for PVT_N to calculate the sustainable second use service life. DOD selection in second use was limited by two factors. First, large DODs were limited by capacity lost in automotive service. For example, a battery that has already lost 30% of its initial capacity cannot cycle at greater than a 70% DOD, as DOD is referenced to BOL battery capacity. Further, if this battery were cycled at 70% DOD, it would only be able to deliver this full cycle once as the battery continues to age. Second, it is unreasonable to employ excessively low DODs that result in

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extremely long battery lifetimes—these batteries will already have served 15 years in an automobile, and they are unlikely to have been designed to substantially exceed the vehicle's lifetime. Therefore, other mechanisms not accounted for in the battery degradation model (e.g., corrosion, failure of cell seals, fatigue of electrical connections, long-term electrochemical effects not yet witnessed in the underlying data) may become the primary pack failure mode if the second use lifetime becomes too large. For these reasons, investigations herein are limited to 50% and 60% DOD scenarios and a maximum 10-year second-use battery life.

After simulating the second use lifetime data, k_H was calculated. Because the duty cycle is the same as that employed for computing the reference PVT_N, Equations 1 through 4 can be combined and simplified to Equations 5 through 8.

$$k_{H,60\%,BEV75} = \frac{0.6*30.4}{1797}\sum_{i=1}^{m}\frac{(1+0.025)^{(i-0.5)/12}}{(1+0.10)^{(i-0.5)/12}} \qquad \text{Eq. 5}$$

$$k_{H,60\%,PHEV20} = \frac{0.6*30.4}{1815}\sum_{i=1}^{m}\frac{(1+0.025)^{(i-0.5)/12}}{(1+0.10)^{(i-0.5)/12}} \qquad \text{Eq. 6}$$

$$k_{H,50\%,BEV75} = \frac{0.5*30.4}{1797}\sum_{i=1}^{m}\frac{(1+0.025)^{(i-0.5)/12}}{(1+0.10)^{(i-0.5)/12}} \qquad \text{Eq. 7}$$

$$k_{H,50\%,PHEV20} = \frac{0.5*30.4}{1815}\sum_{i=1}^{m}\frac{(1+0.025)^{(i-0.5)/12}}{(1+0.10)^{(i-0.5)/12}} \qquad \text{Eq. 8}$$

The results of the second use lifetime simulations and health factor calculations for both vehicles and DODs are presented in Figure 11, Figure 12, Figure 13, and Figure 14. Median second use lifetimes and health factors across first use drive cycles are tabulated in Table 3. As with the automotive simulation results, the difference in predicted second use lifetimes and health factors between the batteries removed from service in Los Angeles and Phoenix was much smaller than the difference between the Los Angeles and Minneapolis batteries. Batteries from the PHEV20s were found to have considerably worse second use performance than those removed from BEV75s due to a combination of higher resistance growth and cycling-based capacity fade from automotive service. However, where the 10-year maximum B2U lifetime restriction comes into play (which occurs quite frequently for the 50% DOD cases), the impact of first-use climate is greatly reduced as most batteries are predicted to exceed the 10 year limit. Finally, the seemingly small difference in second use DOD (50% vs. 60%) was observed to have a large effect on second use lifetime and health factor: where the 50% DOD lifetime does not exceed our 10-year simulation limit, the lifetime and health factor of the 60% DOD case is approximately doubled.

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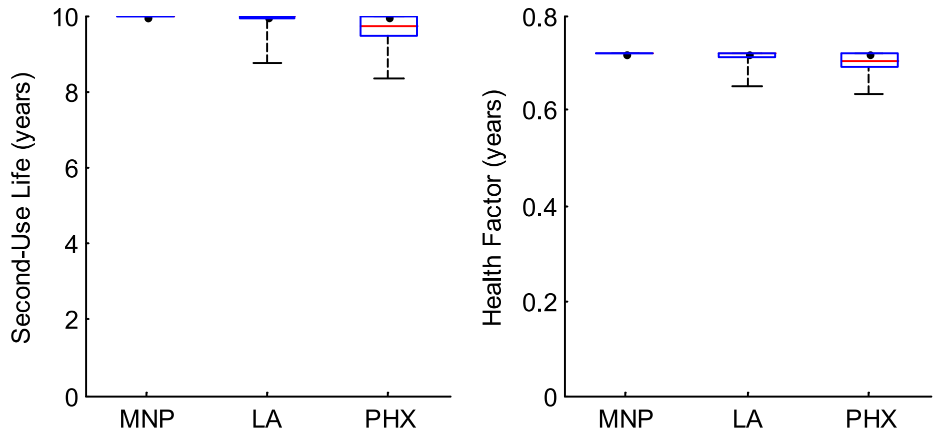

Figure 11. Predicted second use service life and health factor, 50% DOD, BEV75.
Many cases reached the 10-year simulation limit.

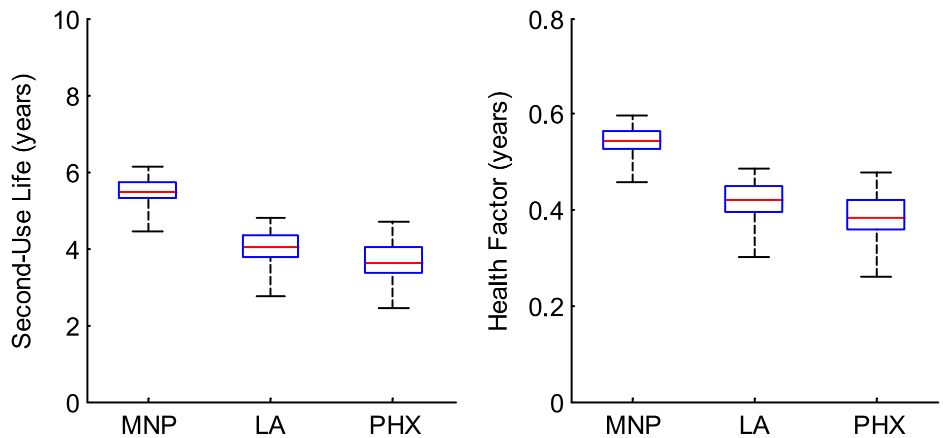

Figure 12. Predicted second use service life and health factor, 60% DOD, BEV75.
No cases reached the 10-year simulation limit.

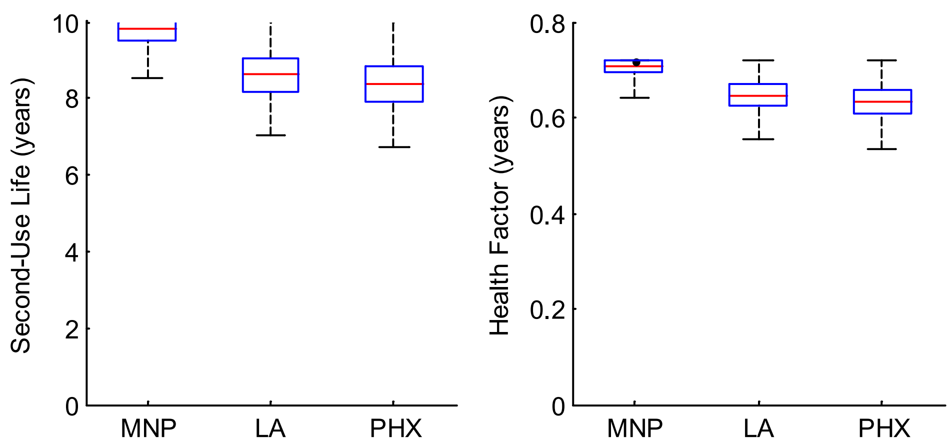

Figure 13. Predicted second use service life and health factor, 50% DOD, PHEV20.
Many Minneapolis cases reached the 10-year simulation limit. Few Los Angeles and Phoenix cases reached the 10-year simulation limit.

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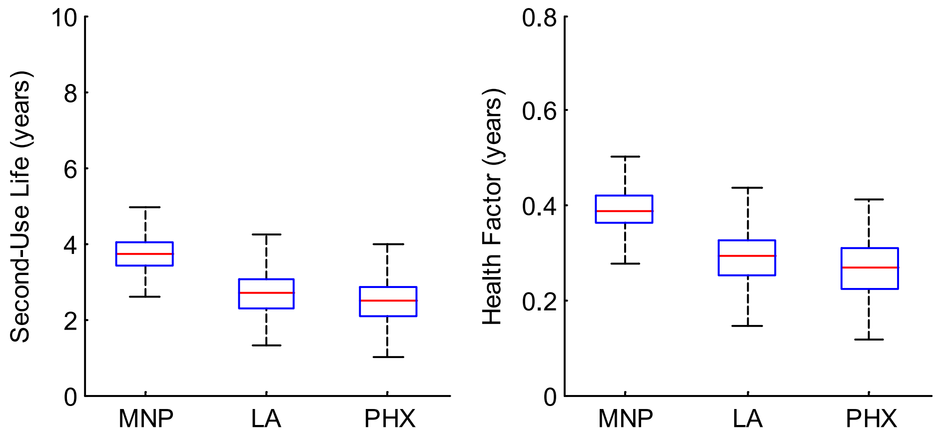

Figure 14. Predicted second use service life and health factor, 60% DOD, PHEV20.
No cases reached the 10 year simulation limit.

Table 3. Median Second Use Lifetimes and Health Factors for BEV75 and PHEV20

DOD	Parameter	Vehicle	Minneapolis, MN	Los Angeles, CA	Phoenix, AZ
50%	Second Use Lifetime (years)	BEV75	10[a]	10[a]	9.7[a]
		PHEV20	9.8[a]	8.6	8.4
	Health Factor, k_H	BEV75	0.72[a]	0.72[a]	0.70[a]
		PHEV20	0.71[a]	0.65	0.63
60%	Second Use Lifetime (years)	BEV75	5.5	4.0	3.6
		PHEV20	3.7	2.7	2.5
	Health Factor, k_H	BEV75	0.42	0.33	0.30
		PHEV20	0.39	0.29	0.27

[a] Values heavily affected by 10-year second use lifetime limit

Weighting the results from these vehicle platforms and climates to represent the second use performance of all PEV batteries from across the United States is challenging. Doing this properly entails not only forecasting the distribution for PEV deployments, but also forecasting the changing climate, which is beyond the scope of this study. Thus, on the simple basis that PEVs will be most successful in moderate climates, the predicted second use lifetimes and health factors from Los Angeles were employed for further evaluation. Both the 50% and 60% DOD cases will be retained for further study due to the significant differences in lifetime and value that result.

3.2 Repurposed Battery Price Ceiling

The maximum selling price of a repurposed automotive battery will be limited by that of an equally capable new battery. Fully appreciating the term "equally capable" is difficult, as this could take into account many factors, including energy density, specific energy, safety, communication and interfacing, form factor, etc., depending on the application. For the purposes

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of this B2U analysis, however, "equally capable" will focus on PVT as described previously while benchmarking against new Li-ion automotive batteries to ensure that other aspects are as similar as possible. Thus, the price ceiling for a repurposed automotive battery is the product of the health factor and the price of new automotive Li-ion batteries (P_N) per Equation 9.

$$P_{R,\,max} = k_H P_N \qquad \text{Eq. 9}$$

The expected health factor was provided by the analyses of the previous section. A survey of battery price forecasts used to define P_N is presented in Figure 15. The majority of reported prices are those paid to the battery manufacturer (e.g., Samsung, JCI) by large systems integrators (e.g., GM, ABB) for full battery packs in large quantities [58–63].The Roland Berger projection is for cell cost rather than pack costs [64]. Further note that the Nissan LEAF battery replacement cost is that presented to consumers and may be artificially low to encourage vehicle purchases and ensure customer satisfaction [65].

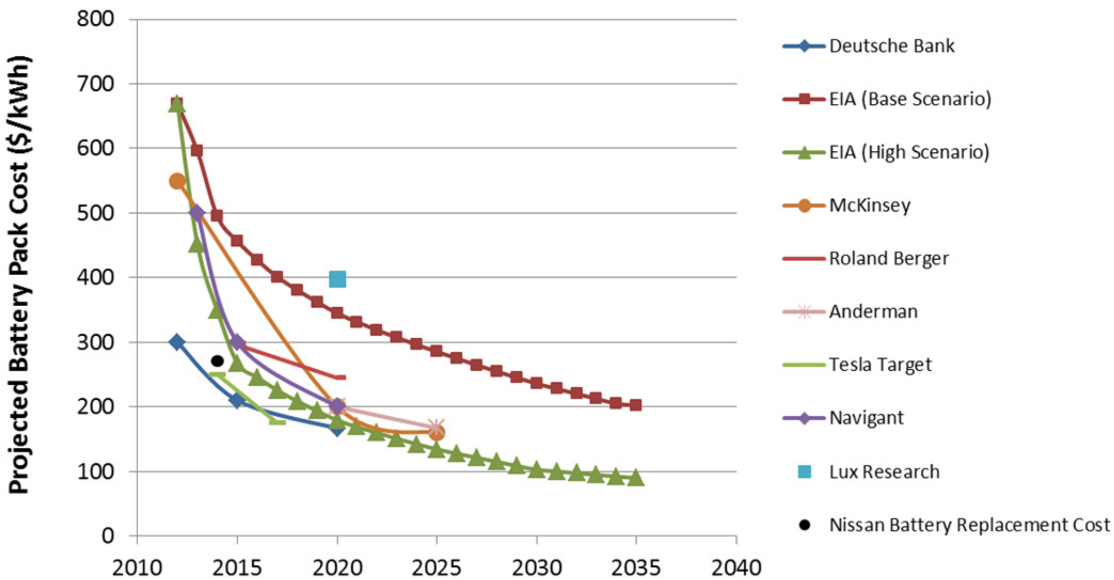

Figure 15. Future battery pack price projections

While these projections clearly show uncertainty in future battery prices, they do bound the problem. Exclusive of the U.S. Energy Information Administration (EIA) Base Scenario [59] and Lux Research's estimate [63], all of the projections suggest that automotive Li-ion battery pack prices will fall below $250/kWh by 2020. Though few projections extend further, the available data suggest that reaching $150/kWh by 2030 (where significant quantities of second use batteries are expected to become available based on vehicle sales projections and an anticipated 15-year automotive battery life) is not unreasonable.

To allow some investigation of the sensitivity of this parameter, both $250/kWh and $150/kWh future new battery price scenarios were explored. Table 4 details eight scenarios of new battery price, second use DOD, vehicle type, and their effect on the maximum repurposed battery selling price. Clearly, this illustrates a large sensitivity to both new battery price and second use DOD. The effect of vehicle type, in comparison, is small.

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Table 4. Maximum Repurposed Battery Selling Price as a Function of New Battery Price and Second Use DOD for BEV75 and PHEV20

New Battery Price	Second Use DOD	Vehicle	Health Factor	Max Repurposed Battery Selling Price
$250/kWh	60%	BEV75	0.33	$83/kWh
		PHEV20	0.29	$73/kWh
	50%	BEV75	0.72	$180/kWh
		PHEV20	0.65	$163/kWh
$150/kWh	60%	BEV75	0.33	$50/kWh
		PHEV20	0.29	$44/kWh
	50%	BEV75	0.72	$108/kWh
		PHEV20	0.65	$98/kWh

3.3 Forecasting Availability of Repurposed PEV Battery Capacity

Next, the amount of operational second-use battery capacity in play as a function of time was forecasted. For the most conservative scenario, where annual PEV sales only reach an approximate 10% market share, installed capacity averaged 16.7 kWh per vehicle, 80% of batteries survived 15 years of automotive service to become eligible for repurposing, a 50% DOD is employed for second use duty cycles, and second use batteries lasted only 3 years on average, the annual second use battery supply was projected to reach 10.8 GWh/year in 2061 and the total second use battery deployment to level off at approximately 32.3 GWh of available energy storage by 2063 (Figure 16). Using the more aggressive sales projection, where PEVs ultimately reached approximately 45% market share, installed capacity averaged 27.8 kWh per vehicle, 90% of batteries survived 15 years of automotive service to become eligible for repurposing, a 60% DOD is employed for second use duty cycles, and second use batteries lasted 10 years on average, the annual second use battery supply was projected to reach 101 GWh/year by 2055 and the total second use battery deployment to level off at approximately 1.01 terawatt-hours (TWh) of available energy storage by 2064 (Figure 17). Note that in both scenarios, vehicle sales prior to 2014 are ignored, and significant deployments of second use batteries did not begin until after 2030.

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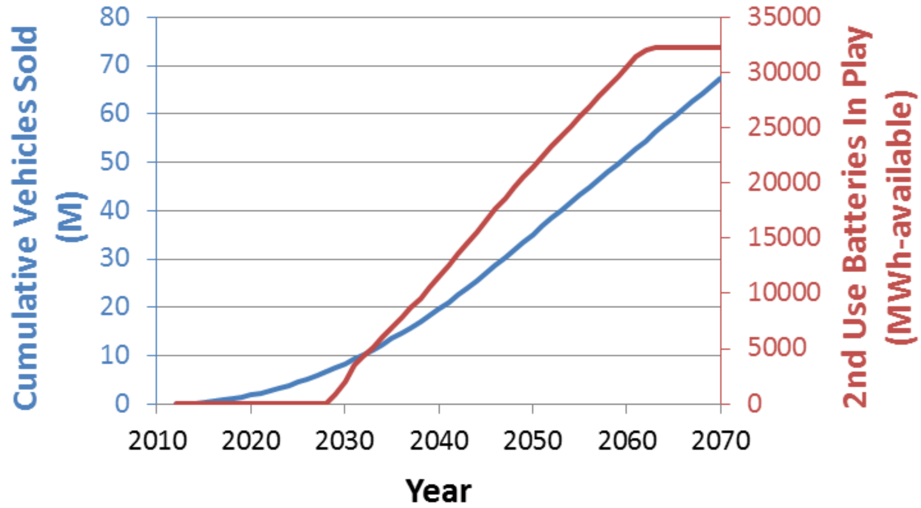

Figure 16. Available capacity from second use batteries, low scenario

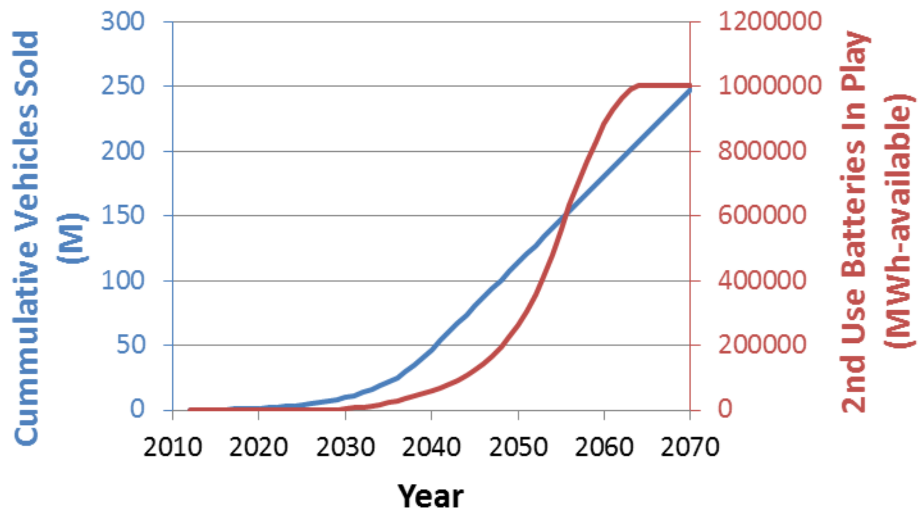

Figure 17. Available capacity from second use batteries, high scenario

Due to the high degree of uncertainty surrounding many of the parameters used to make these projections, they are intended only to highlight the potential amount of energy storage that could be provided and the large degree of variability inherent therein. Indeed, the primary finding of this exercise can be distilled to the following: while the variability and uncertainty in the future supply of retired automotive batteries are quite high, our lowest projection still predicts a large amount of storage can be provided by this resource.

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4 Repurposing Costs

The repurposed-battery selling price can be used to identify the used-battery buying price paid to the automotive battery owner (the salvage value) only if the costs involved in the processes between retiring a battery from automotive service and selling it to a secondary market (collection, testing, repackaging, warranty, etc.) are known. These costs are referred to as repurposing costs.

To quantify repurposing costs and their sensitivity to available vehicle-use data, facility size, module size, cell fault rates, required technician handling time, required testing time, and repurposed battery selling price, a bottom-up economic model of a facility was built, extending Neubauer et al.'s work [12] and Cready et al.'s original work [8]. This repurposing model assumes that battery modules (not packs or cells) are collected by the facility, and the same size battery modules are delivered by the facility (excluding pack assembly activities). Costs of extracting modules from automotive packs pre-repurposing are omitted in this section, as are the costs of integrating multiple modules into larger systems. In practice, it may prove advantageous for the repurposer to conduct one or both of these operations in-house. The separation of roles has been elected herein to simplify and decouple the math of these operations, maintaining flexibility within the scope of this analysis.

4.1 Identifying Remaining Battery Performance

The repurposer will need to identify the remaining battery performance of each battery it considers for purchase. The first question that arises is which SOH parameter is most important to identify. Figure 18 shows the predicted second use battery lifetimes of our previous simulations as a function of the battery SOH parameters at the end of automotive service. The lack of correlation between second use lifetime and R1, R2, and Q2 stands in stark contrast to the extremely consistent and linear correlation between second use lifetime and Q1 (capacity fade due primarily to calendar effects). We see the same correlation between second use lifetime and total capacity fade, as all of our automotive simulations resulted in dominant Q1 fade.

Thus, identifying Q1 appears to be crucially important to diagnosing the second use value of a retired automotive battery. This could be accomplished by three different means: 1) directly measuring battery capacity at the point of repurposing, 2) applying computational methods to duty cycles recorded near the end of a battery's automotive service life, or 3) by recording and reporting relevant metrics from automotive service that correlate strongly to Q1 capacity fade. The first method is well known and requires no additional capabilities be added to the vehicle; however, it requires specialized testing equipment and a relatively long testing duration. Thus it is viable for the repurposer to perform after a purchase has been made, but not before. The latter two are not well developed and do require some additional capabilities be added to the vehicle at BOL. These latter two methods are discussed briefly below.

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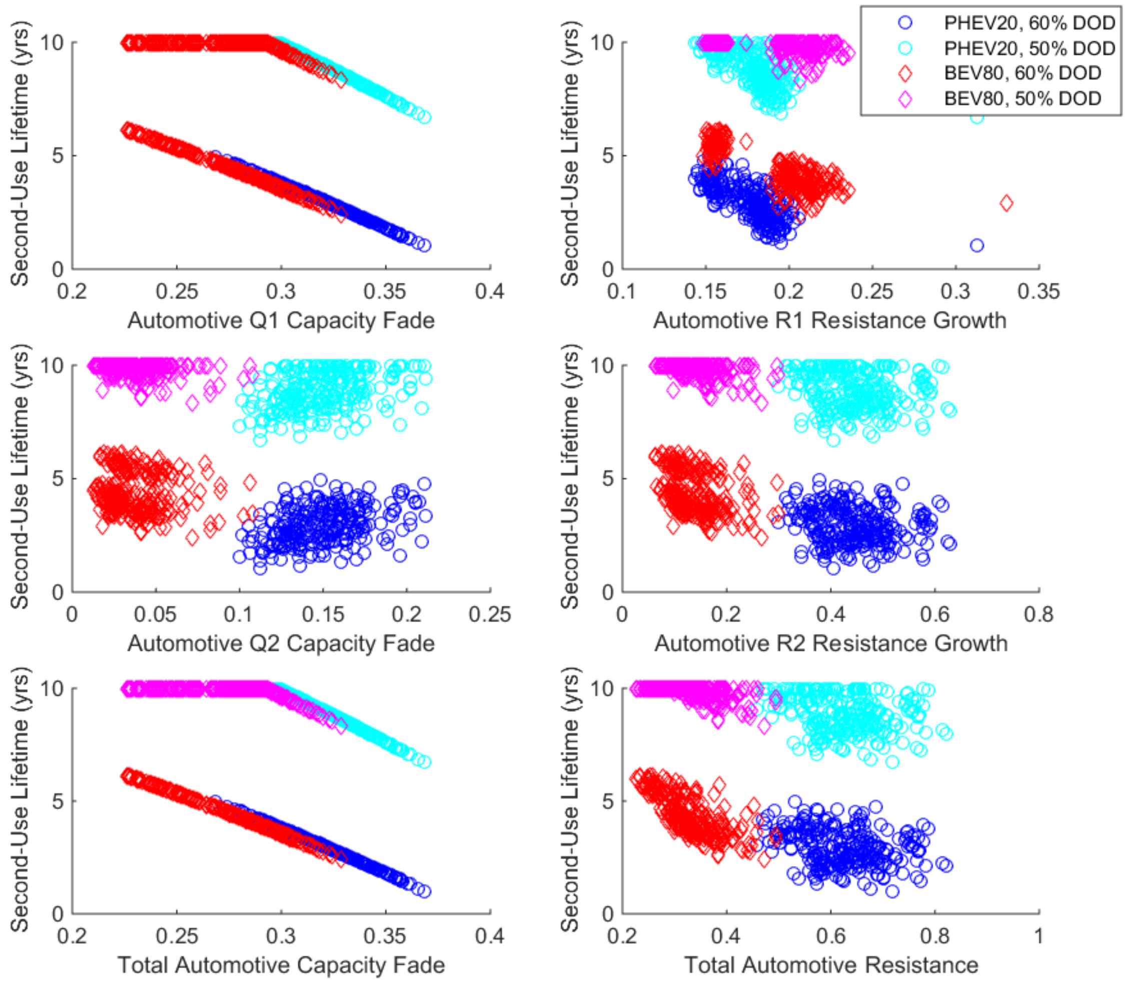

Figure 18. Comparison of second use lifetime to battery degradation at end of automotive service

4.1.1 In-Situ Analysis of Drive Cycles and Charge Events to Identify Q1 Capacity

As applied in this study, mathematical battery models can be used to predict the voltage, current, temperature, and SOC response of a battery to a specific duty cycle. However, this problem may also be inverted: knowledge of a battery's response to a duty cycle can be applied to create a model. While many of our battery models are created this way using purpose-designed duty cycles, it is also possible to build models using arbitrary duty cycles. Thus, if a sufficient set of parameters about battery response on-board a vehicle were monitored and recorded, a model of that battery could be built from regular field-use of the vehicle without the need for specialized equipment, visits to a service center, etc. Done properly, this model could extract the SOH parameters necessary to evaluate a battery for B2U. The data could be applied not only to second-use valuation, but also range estimation, vehicle-to-grid assessment, and other purposes throughout the battery's automotive life. It is likely that the benefits of these automotive life services—perhaps range estimation alone—are sufficient to motivate the inclusion of such technology by OEMs.

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NREL has developed and applied such algorithms on a limited basis to BEVs operating in the field. Battery duty cycles harvested from large datasets of in-use operation provide time series histories of pack and cell level current and voltage. These data are applied to a battery electrical model that considers zero-order equivalent circuit dynamics and a single-particle model of electrode concentration gradients (used to describe transient voltage relaxation). Modeled battery voltage is compared to the historical data and a constrained non-linear optimization algorithm is used to minimize the root mean square of model error (usually achieving root mean square error values of tens of millivolts per cell). Error is minimized by updating model parameters such as pack capacity, bulk resistance, initial thermodynamic state of charge, and multiple diffusion coefficients. An example comparison of modeled and measured battery response is shown in Figure 19.

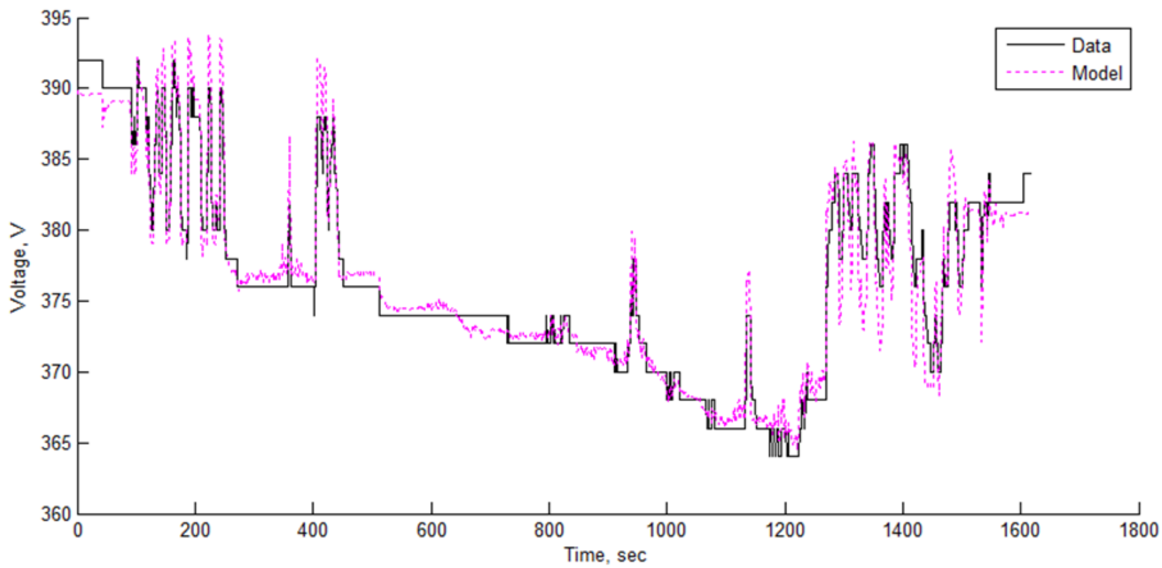

Figure 19. Example voltage fit of a pack-level battery model and data after optimization of battery capacity, resistance, and diffusion parameters

Following optimization of the model over each individual drive cycle, estimated parameters used to describe pack available energy and power are reported through time and compared to controlled performance tests conducted by NREL engineers in the field as available.

Figure 20 shows an example of fitting battery capacity and resistance for individual cells in six different BEVs over an approximate 2.5-year period. Applying these methods at the cell level offers the ability to identify individual cells with anomalous capacity or resistance parameters in addition to quantifying total pack performance.

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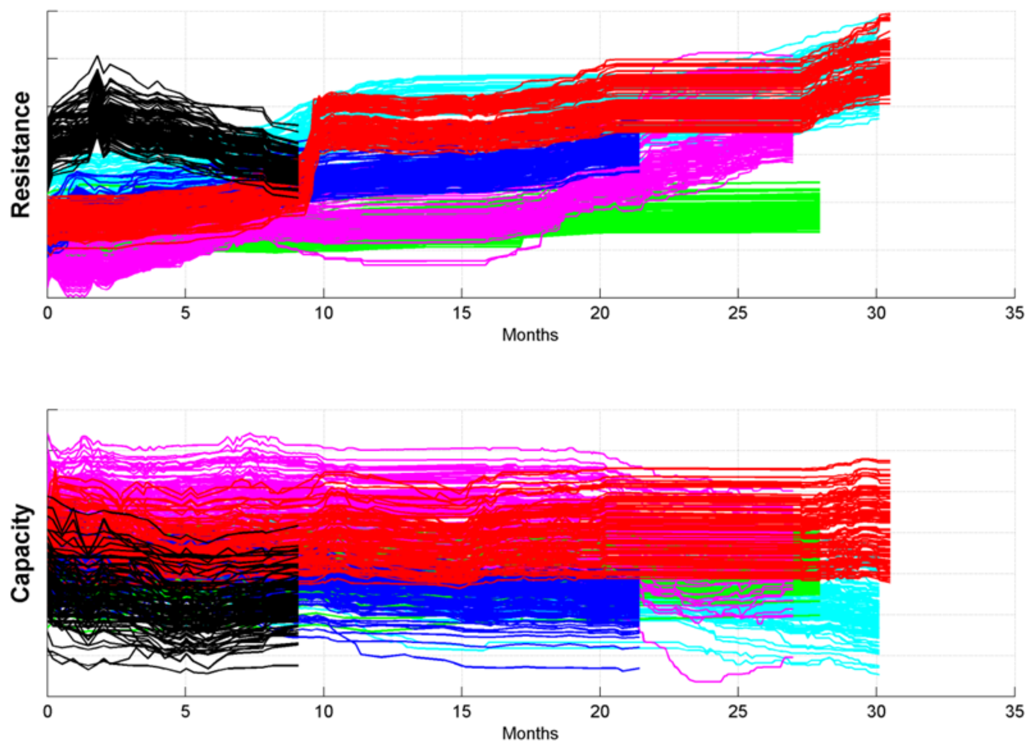

Figure 20. Example results of cell-level capacities and resistances calculated from field data from six BEVs

To date, this procedure has been applied to a small number of vehicle histories to develop and validate the technique. While the results of these methods have been encouraging, there is considerable room for improvement. Beyond advancing model fidelity and fitting algorithms, inclusion of battery response to charging events is expected to be both the easiest and most valuable addition to these methods (due to onboard hardware and software limitations, charging events were not available to NREL researchers in the work noted in these examples). Such low-rate, constant-current duty cycles, often terminated at a relatively precise final SOC and with considerable resting periods thereafter, will greatly improve the accuracy of capacity identification in particular—the critical component for second use battery valuation. Modifications to the charge protocol such as occasional charge interruptions to assess resistance or open-circuit voltage could also be implemented by the battery management system to further increase accuracy of SOH assessments.

The simplicity and potential for high accuracy of diagnostic methods relying on in-situ drive cycle and charge event analysis, combined with their value for improving onboard range estimation, could likely make them ubiquitous in PEVs of the near future. As these data could be used to great effect to support accurate resale value of a PEV, it may also become readily available to the vehicle owner. Thus, it would also likely be available to the repurposer to support valuation of packs prior to purchasing them.

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4.1.2 Use of Automotive Service Metrics to Identify Q1 Capacity

Comparison of simulated automotive service statistics to calculated Q1 capacity fade has uncovered an excellent correlation of lifetime average battery temperature to Q1 for the BEV75s simulated herein (Figure 21, $R^2 = 0.8686$). For the PHEV20s, this simple correlation between temperature and Q1 is significantly less compelling ($R^2 = 0.5169$); however, the weighted addition of lifetime average SOC to lifetime average battery temperature results in a notable improvement (Figure 22, $R^2 = 0.6910$).

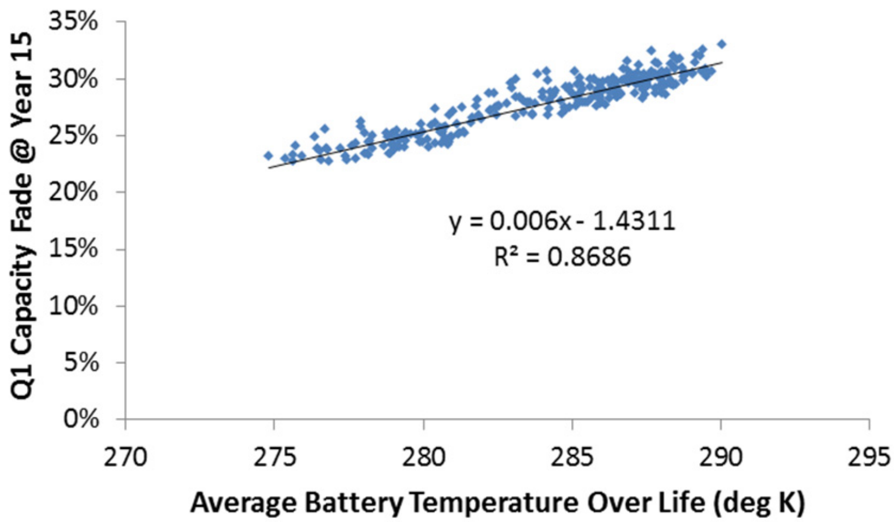

Figure 21. Correlation of Q1 capacity fade to average battery temperature for BEV75s

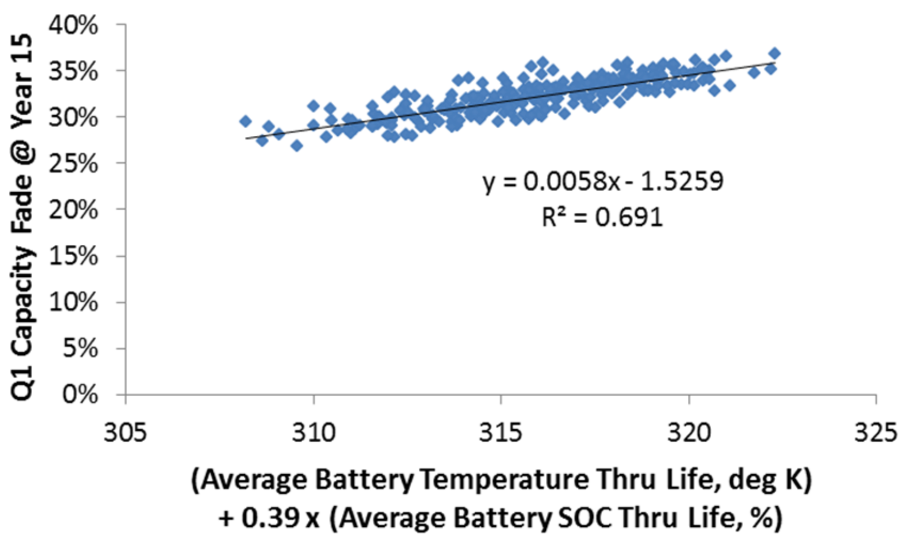

Figure 22. Correlation of Q1 capacity fade to average battery temperature and SOC for PHEV20s

Modern PEV batteries are equipped with the ability to record battery temperature and SOC. Compiling a lifetime average SOC would require minimal additions to on-board software if the vehicles do not already record and calculate such a metric. Compiling a lifetime average temperature metric, on the other hand, may require minor hardware additions. Temperature while

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parked is a large component of lifetime average temperature. While a battery's large thermal mass results in slow movement of battery temperatures and low required data logging rates, it is still necessary for the vehicle to "wake up" briefly and periodically during park events to measure and log new battery temperature data points.

The experience of the authors to date suggests that many PEVs do not record battery temperature data when the vehicle is in a key-off state and is not connected to a charger. Thus, software and possibly hardware changes would be required to implement these features. However, doing so would add a strong indicator of battery health and could be combined with the in-situ inverse modeling efforts described in the previous section for even more accurate estimates of battery SOH (possibly decoupling Q1, Q2, R1, and R2). As such, this feature too may be commonly included in PEVs in the coming years.

4.1.3 Recommended Identification Strategies

Taken together, the in-situ analysis of drive cycles and charging events along with recording of lifetime battery temperature and SOC metrics could provide an extremely high-confidence diagnostic for battery SOH. It may even prove capable of decoupling different wear mechanisms, such as the R1, R2, Q1, and Q2 terms employed herein. Combined with additional on-board vehicle data of cell-level metrics to identify cell-to-cell variability (e.g., identifying faulty individual cells), and prognostic methods to predict future SOH trends (e.g., a battery life model), repurposers could make low risk purchasing decisions that maximize yield and minimize required in-house testing. Given the minimal cost anticipated to add these capabilities to the vehicles and to share the data with repurposers, this path is strongly recommended.

However, given the long design cycle of new PEVs and the possibility that vehicle OEMs might not be willing to share such data, there may be a number of retired automotive batteries available without such information. Here, repurposing yields will certainly fall and increased in-house testing will be required. Thus, the effects of both cases (with and without advanced vehicle data) were analyzed in an attempt to quantify the value of adding these capabilities to PEVs.

4.2 Battery Module Collection

Much has been made of the classification of Li-ion batteries as a class 9 hazardous material [66] and its impact on shipping costs. Some have estimated this to be the dominant component of repurposing costs[7] [18]. The Code of Federal Regulations, Title 49, Part 173.185 requires that such batteries be shipped following certain guidelines (e.g., packaged in rigid containers and in a manner to effectively prevent short circuits or violent rupture), allowing for the repurposing facility to own and operate the vehicle used for transportation as well as for it to employ the driver. Therefore, bottom-up calculations of shipping costs are performed here, assuming the use of reusable, purpose-built shipping containers that meet the regulation. Containers designed to transport 10 kWh of battery modules are estimated to cost $500.

For shipping distances, we use three types of service areas: local, regional, and national. The local scenario assumes batteries are collected from one or more collection points in the same city

[7] Narula et al.'s estimate of transportation costs [18] was found to be based on a $3.85/pound charge for recycling reactive batteries by Recupyl, which presumably includes more than transportation costs (e.g., recycling costs, recycling profit margins) [12].

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as the repurposing facility is located, with low average travel speeds of 15 miles per hour. Note that this is intended to include the time needed to load and unload the truck as well. The regional scenario assumes a repurposing facility located just outside of Los Angeles, California, that collects batteries from Los Angeles, San Jose, and San Diego. Assuming equal trips to these three locations at an average speed of 40 miles per hour, the average round trip distance is approximately 320 miles and takes 8 hours. The national scenario assumes a repurposing facility located in Oklahoma City, Oklahoma. Assuming most battery collection points will be on either the east or west coast, we estimate an average round trip distance of 2,400 miles, taking 44 hours at an average speed of 55 mph. Note that both the regional and national scenarios may require considerable storage of used batteries prior to their being collected by the repurposer. Although not considered herein, this cost would effectively subtract from the salvage value provided to the automotive owner.

Table 5 defines the values employed for calculating the number of delivery vehicles and drivers for each scenario as a function of facility throughput.[8] Equations 10 and 11 define the number of trucks required in each facility. The required number of drivers is equal to the required number of trucks.

Table 5. Delivery Data

Scale	Truck Type	Truck Capacity	Truck Cost	Typical Round Trip Distance to Collection Points	Operating Cost	Typical Round Trip Time for Collection
Local	24-ft. box truck	339 kWh[a]	$62,000[b]	30 mi/load	$0.40/mi[c]	2 hr/load
Regional	Class 8 tractor with 53-ft. trailer	2,613 kWh[d]	$141,000[e]	320 mi/load	$0.50/mi[c]	8 hr/load
National	Class 8 tractor with 53-ft. trailer	2,613 kWh[d]	$141,000[e]	2,400 mi/load	$0.50/mi[c]	44 hr/load

[a] Assumes 2,950-kilogram cargo limit.

[b] A review of used box trucks available at Ebaymotors.com and trucker.com revealed a wide range of prices from approximately $6,000 to approximately $62,000. We elected to use the maximum observed price as a conservative estimate.

[c] Operating costs calculated assuming $4/gallon of diesel fuel and 10 miles per gallon for the box truck, 8 miles per gallon for the single-trailer semi, and 7 miles per gallon for the dual-trailer semi. Additional operation and maintenance costs are not included.

[d] Assumes 22,700-kilogram cargo limit.

[e] Review of prices on trucker.com suggested pricing of $17,000 for a 53-ft. x 102-in. trailer and up to $124,000 for a low-mileage 2013 model year semi-tractor.

[8] Throughput is defined as the quantity of batteries received for repurposing at a facility, measured either in units or energy. It is also representative of the quantity of batteries sold by the repurposer when a 100% yield is achieved.

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No. of Trips per Year = Annual Throughput / Truck Capacity Eq. 10

No. of Trucks = Ceiling [365 Days / (No. of Trips per Year × Typical Collection Time)] Eq. 11

4.3 Annual Throughput, Module Size, and Facility Size

First the amount of annual energy storage the desired facility will process and the size of individual modules to be processed in kilowatt-hours was defined. Facility size was then calculated using a parameterized, scalable floor plan. An example of such a floor plan is shown in Figure 23, but note that many dimensions, number of office, number of stations, etc. scale with the module size, annual facility throughput, and number and type of employees. Additional details on the specified floor plan can be found in [67].

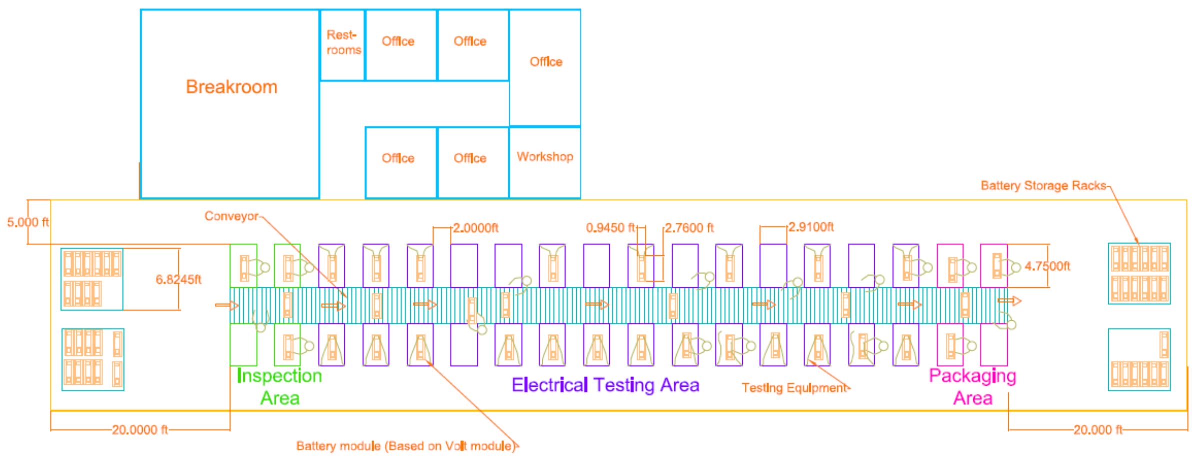

Figure 23. Example of parameterized scalable repurposing facility floor plan

The repurposing process was broken into three phases: initial inspection, electrical testing, and packaging. Equations 12, 13, and 14 were used to calculate the number of each type of station:

No. of Inspection Stations = ceiling [(no. modules / day) × (inspection time) / (24 hours/day)] Eq. 12

No. of Electrical Test Stations = ceiling [(no. modules / day) × (electrical connection, test, and disconnection time) / (24 hours/day)] Eq. 13

No. of Packing Stations = ceiling [(no. modules / day) × (inspection time) / (24 hours/day)] Eq. 14

These equations assume the facility operates 365 days per year, 24 hours per day. This was selected both to maximize the utilization of capital equipment (e.g., facility space, battery testers) and to simplify the scheduling of operations and correlations of amount of staff to equipment for the purpose of this analysis.

The size of each station is driven by the size of the modules to be repurposed, but is no smaller than 2 ft. by 3 ft. (to allow sufficient space for rack-mounted electrical test equipment underneath

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the stations and adequate room for a technician). Module volume and mass are determined based on a nameplate energy density of 150 watt-hours (Wh)/liter (L) and 115 Wh/kilogram, based on analysis of recent PEV battery modules from A2Mac1 [68] as shown in Figure 24 and Figure 25. Module dimensions were determined assuming that the height and width of each module were equal, and that the length was equal to twice the height.

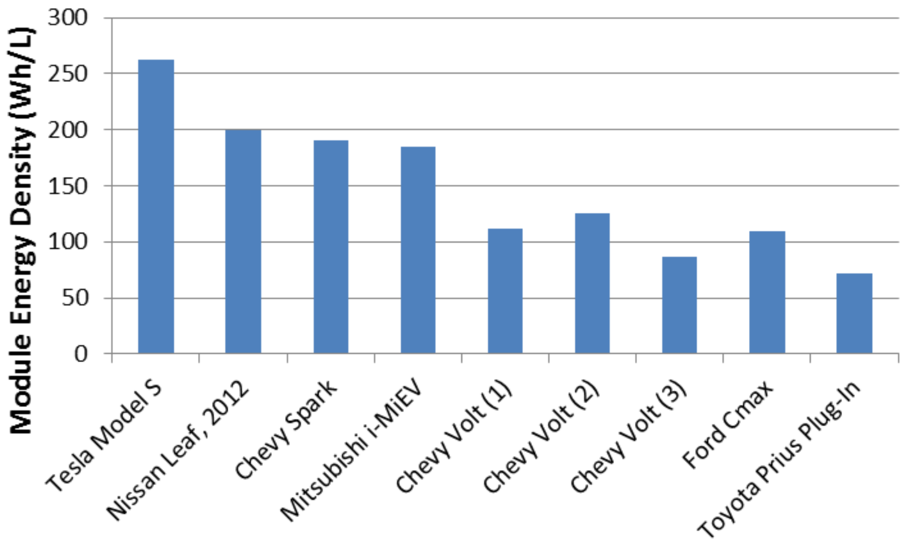

Figure 24. Energy density of battery modules from production PEVs

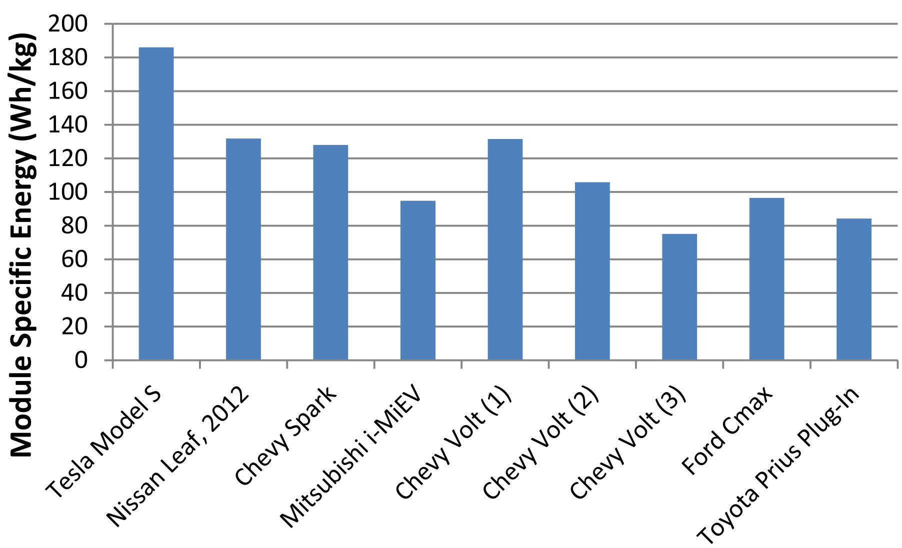

Figure 25. Specific energy of battery modules from production PEVs

Figure 26 presents data on module size from the same selection of commercially available PEVs. Clearly, the range of module sizes is considerable, from Nissan's approximately 500-Wh module in the LEAF to Chevy's approximately 6.2-kWh module in the Volt.

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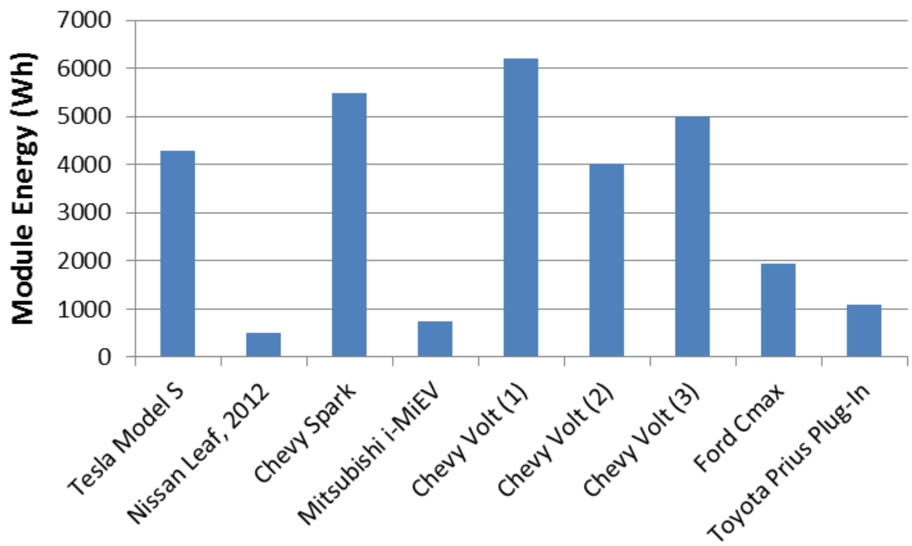

Figure 26. Nameplate energy of battery modules from production PEVs

Provisions to store one day's worth of incoming battery modules and one day's worth of outgoing modules are included based on standard pallet dimensions (approximately 3.3 ft. by 4 ft. by 0.5 ft.) and a 10-ft.-tall storage rack. Space for forklift maneuvering is also allotted. Space for offices, restrooms, a break room, and a workshop is also included, the quantity and size of which scale with the number of employees. Further details on all of the assumptions and equations for determining the size of the facility as a function of annual throughput and module energy can be found in [67].

4.4 Technicians and Technician Handling Time

Table 6 defines two different technician handling time allocations that represent best and worst case scenarios. The best case scenario applies to small simple modules, streamlined operation procedures, and purpose-built equipment for the modules being repurposed. The worst case scenario applies to large complex modules and suboptimal test equipment.

Table 6. Technician Handling Time Requirements

Operation	Minimum Time	Maximum Time
Receiving inspection & handling	10 minutes	60 minutes
Connection to and initiation of electrical test equipment	10 minutes	10 minutes
Disconnection from electrical test equipment	5 minutes	5 minutes
Final inspection and packaging	10 minutes	45 minutes
Total Time	35 minutes	3.0 hours

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The number of required technicians was then determined by Equations 15 and 16, which assume that each technician works 252 8-hour days per year:

Modules per Technician per Year = (252 days/year × 8 hours / day) / (handling time per module) Eq. 15

Total No. of Technicians = Modules per year / (Modules per Technician per Year) Eq. 16

4.5 Electrical Testing Time, Equipment, and Related Costs

Table 7 and Table 8 define two different electrical testing time allocations, again representing the best and worst case scenarios. In the short protocol, access to sophisticated onboard diagnostics data and an advanced electrochemical diagnostics model coupled with an efficient characterization protocol to accurately ascertain a module's health was assumed. This protocol does not assume that full cycles are completed to ascertain battery capacity, but rather that a specialized cycle is used to enable calculation of battery SOH through model identification techniques, complementing the onboard diagnostics data provided by the vehicle.

In the long protocol, the absence of both the vehicle's onboard diagnostics data and the electrochemical diagnostics model was assumed. In their place, a more traditional and time-consuming test protocol to directly measure module capacity, efficiency, resistance, and other parameters was required. This entails full discharge and charge events to identify capacity at a relatively low rate (approximately C/3), likely combined with higher power pulse patterns (up to approximately 2C) to determine resistance throughout the SOC range.

For both electrical testing scenarios, we assume that the battery cycling equipment must be capable of an approximate 2C discharge, e.g., a 1-kWh module will be tested on a 2-kW test channel. Equations 17 through 21 define the amount of hardware required for this approach. Note that we assume controller area network communications are required, which may only be true for larger modules. We also assume one computer is required per every four test channels.

Table 7. Electrical Testing Time Requirements—Short Protocol

Operation	Estimated Time
Connection to and initiation of electrical test equipment	10 minutes
Initial voltage set & balance	30 minutes
Advanced characterization	45 minutes
Disconnection from electrical test equipment	5 minutes
Total Time	1.5 hours

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Table 8. Electrical Testing Time Requirements—Long Protocol

Operation	Estimated Time
Connection to and Initiation of electrical test equipment	10 minutes
Initial charge & balance	50 minutes
Post-charge rest	15 minutes
Full discharge	180 minutes
Post-discharge rest	30 minutes
Full charge	210 minutes
Post-charge rest	10 minutes
Partial discharge	25 minutes
Disconnection from electrical test equipment	10 minutes
Total	8.0 hours

No. modules per year = Annual Throughput (kWh) / Module size (kWh) Eq. 17

No. modules per day = No. modules per year / 365 Eq. 18

No. of test channels required = Ceiling [No. modules per day × (Electrical Testing Time / 24 hr)] Eq. 19

No. of controller area network devices = No. of channels Eq. 20

No. of Computers = no. of channels / 4 Eq. 21

Electricity usage for testing is dominated by that used to run the electrical cyclers. We assume a worst case scenario where dissipative electrical cyclers are employed, e.g., they do not supply power back to the facility when batteries are discharging. We assume that 45 minutes of the short protocol is spent charging at an average rate of approximately 1C, and 260 minutes of the long protocol is spent charging at an average rate of approximately C/3. Assuming a charging efficiency of 85% for the cyclers, Equation 22 then provides the annual energy consumption of the facility due to battery testing.

Annual energy = (No. modules per year) × (Time Spent Charging x Average Charge Power) / 0.85 Eq. 22

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4.6 Labor and Additional Costs

Total labor costs are presented in Table 9. Individual labor rates were sourced from the U.S. Bureau of Labor Statistics (BLS) [69]. Additional non-labor costs are given in Table 10. Further detail used to calculate related values can be found in [67].

Table 9. Labor Costs

Description	Quantity	Annual Wage	Reference / Notes
Test Technician	Eq. 16	$37,860 ea.	BLS Occupation Code 51-9061
Supervisors	No. of test technicians / 10, rounded up	$58,150 ea.	BLS Occupation Code 51-1011
Forklift Driver	Based on anticipated forklift operating time	$32,660 ea.	BLS Occupation Code 53-7051
Truck Driver	Eq. 11	$33,490 ea.	BLS Occupation Code 53-3033
Administrative Assistant	Number of employees / 30, rounded up	$34,000 ea.	BLS Occupation Code 43-6014
Human Resources Manager	Number of employees / 30, rounded down	$100,800 ea.	BLS Occupation Code 11-3121
Electrical Engineer	Annual throughput / 100,000, kWh, rounded up	$93,380 ea.	BLS Occupation Code 17-2071
Sales / Logistics Rep.	Annual throughput / 100,000, kWh, rounded up	$85,610 ea.	BLS Occupation Code 11-2022
Operations Manager	1 if number of employees > 20	$116,090 ea	BLS Occupation Code 11-1021
Chief Executive	1	$178,400 ea	BLS Occupation Code 11-1011

Table 10. Module Repurposing Capital Equipment and Other Recurring Costs

Description	Quantity	Unit Cost	Reference / Notes
Initial battery purchases	Annual Throughput / 12	See note	Assume an upfront purchase of one month's worth of batteries. The unit cost is determined by the module energy and module buying price, the latter of which is calculated iteratively as discussed in Section 4.8.
Storage racks	Based on throughput	$100 ea.	Number of racks calculated to store one day's worth of incoming modules and one day's worth of outgoing modules
Forklift	1	$7,000 ea.	Review of used electric forklifts with <4,000 lb. lift capacity and 81-in. to 90-in. on Ebay.com revealed prices of approximately $4,000 to approximately $22,000 with a median near $7,000
Conveyers	Surface area dependent on floorplan	$50/ft^2	Review of internet pricing
Work stations	Eqs. 12-14	$500	Review of internet pricing
Battery test channel	Eq. 19	($2,000/kW) x (2 x Module kWh)	Although 1C average discharge and charge rates are assumed, 2C pulses may be needed for resistance characterization
Controller area network hardware	1 per battery test channel	$160 ea.	
Computer	1 per 4 test channels	$3,000	
Office and other equipment	1	$100,000 ea.	
Rent	Facility ft^2	$9.70/ft^2	
Test electricity	Eq. 22	$0.104/kWh	[71]
Other electricity	Facility ft^2	$2.27/ft^2	[72]
Taxes	39.3% of profits		[73]
Insurance	3% of direct costs		
General & administrative	5% of direct costs		
Warranty	5% of battery sales		
Research & development	3% of battery sales		
Non-wage labor	30.2% of labor costs		[74]
Misc.	2% of labor costs		

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4.7 Cell Fault Rates and Module Yield

Modern automotive Li-ion battery modules employ many assembly processes that impede the efficient replacement of faulty cells. For example, the electrical connections (tabs) on the cells are commonly welded to bus bars, adhesives are used to form structural connections, etc. If a repurposing facility were to attempt to replace faulty cells in modules, considerable technician time would be required as well as additional capital equipment to perform the necessary operations. As will be seen in Section 4.9, technician costs are a large component of total repurposing cost even when repurposing processes have minimal technician labor requirements. Thus, we do not anticipate that replacing faulty cells will be cost effective.

For these reasons, evaluation of scenarios in which faulty cells are replaced was omitted. Instead, when faulty cells within a module are identified, it was assumed that the entire module was discarded. Therefore, the facility's module yield was computed based on the likelihood that a bad cell was present within a module purchased by the repurposing facility. To do this, a cell fault rate representative of the chance that a purchased cell is bad was specified. To translate this to a module level yield, a common cell size of 74 Wh (approximately 20 amp-hours at 3.7 volts nominal) was employed and applied to Equation 23:

$$\text{Module Yield} = (\text{Cell Fault Rate})^{\text{Module Size}/74Wh} \qquad \text{Eq. 23}$$

Identifying appropriate cell fault rates to apply herein was not straightforward, as there was little to no data available on Li-ion cell mortality over 15 years of PEV applications. Thus, there was little justifiable basis for selecting cell fault rates. For the scenario in which advanced onboard diagnostics data are available from the vehicle before the repurposer's purchase, the cell fault rate was assumed to be a low 0.001%, or 1 in 100,000 cells, on the basis that faulty cells will be reasonably identifiable and repurposers will not purposefully purchase packs with bad cells. This implies that a repurposer exclusively buying 22-kWh batteries, each consisting of 297 cells, would find a faulty cell in 1 of every 337 packs they purchase. For the alternative scenario where no diagnostics data is available before the purchase of a retired batteries, higher cell fault rates of 0.01%, 0.1%, and 1.0% were applied. In the worst case scenario, every 22-kWh pack purchased would be expected to have three faulty cells, resulting in the disposal of one to three modules from the pack.

4.8 Computing Repurposing Cost and Battery Salvage Value

Battery salvage value—the price at which the repurposing facility purchases retired automotive batteries—was computed via iterative solution of Equation 24. This method effectively sets the buy price of used modules such that the facility will achieve a five-year payback period on the facility investment with an internal rate of return of 15%, given known repurposed battery selling prices and repurposing cost structures. Therein, capital costs and expenses were determined by the assumptions and equations laid out above, as well as the facility annual throughput and the battery salvage value (which was solved for). Revenues were computed based on the facility annual throughput and the repurposed battery selling price (estimated for multiple scenarios by the analysis in the preceding section based on retired battery health and new battery selling prices; see Table 4).

$$\sum(Capital\ Costs) = \sum_{i=1}^{5}(Revenues_i - Expenses_i)(1.15^{-i}) \qquad \text{Eq. 24}$$

The effective repurposing cost was then calculated by subtracting the computed salvage value (the facility's purchase price) from the repurposed battery selling price. Within this approach, scenarios that resulted in the highest battery salvage value and lowest effective repurposing cost are the most economically efficient.

4.9 Results

The sensitivity of repurposing costs to several variables, including facility reach (local, regional, national) and throughput, module size, cell fault rate, technician handling time, and electrical testing time was explored. Studies of each variable are presented below. For the facility reach and throughput, module size, and cell fault rate investigations, only two combinations of technician handling time and electrical testing time to bound best case and worst case scenarios were considered. Subsequently, a minimum repurposing cost scenario was investigated.

4.9.1 Baseline Scenario

For the baseline, the regional collection case with 600,000 kWh per year of battery throughput was selected. This corresponds to approximately 25,000 BEV batteries per year, not far off from the approximately 23,000 Nissan LEAFs sold in California in 2013 [74]. It was assumed that advanced battery data are available to make battery purchasing decisions, and thus used the short testing protocol and 0.001% cell fault rate. A 5-kWh module size, representative of the average energy of large modules seen in Figure 26, in conjunction with the long technician handling time scenario to account for the extra effort of inspecting and moving a larger module, was also employed.

Table 11 summarizes the results for eight different repurposed battery selling prices ranging from \$44/kWh to \$180/kWh. We note that for the conditions used, battery salvage value is always positive, indicating that the original battery owner will always be paid for his or her battery.

Table 11. Baseline Repurposing Cost Results

New Battery Price	Second Use DOD	Vehicle	Health Factor	Repurposed Battery Selling Price	Used Battery Salvage Value	Cost of Repurposing
\$250/kWh	60%	BEV75	0.33	\$83/kWh	\$51/kWh	\$32/kWh
		PHEV20	0.29	\$73/kWh	\$43/kWh	\$30/kWh
	50%	BEV75	0.72	\$180/kWh	\$131/kWh	\$49/kWh
		PHEV20	0.65	\$163/kWh	\$117/kWh	\$46/kWh
\$150/kWh	60%	BEV75	0.33	\$50/kWh	\$24/kWh	\$26/kWh
		PHEV20	0.29	\$44/kWh	\$19/kWh	\$25/kWh
	50%	BEV75	0.72	\$108/kWh	\$72/kWh	\$36/kWh
		PHEV20	0.65	\$98/kWh	\$64/kWh	\$34/kWh

Notice further that the salvage value and repurposing cost are highly sensitive to the selected repurposed battery selling price. Figure 27 shows that these relationships are highly linear. This

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is due to both our requirement to make an upfront purchase of one month of batteries as well as scaling several indirect costs (warranty, insurance, etc.) against variables that include the total cost of purchased or sold batteries.

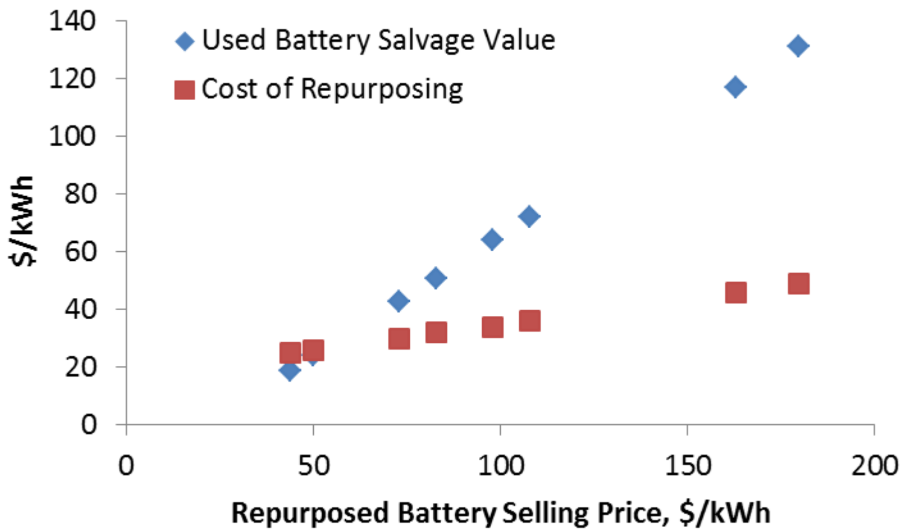

Figure 27. Relation of repurposing cost and salvage value to repurposed selling price

Figure 28 and Figure 29 show the breakdown of costs incurred by the repurposing facility for both the highest ($180/kWh) and lowest ($44/kWh) repurposed battery selling prices considered in our baseline scenario set. Several important points become immediately clear:

- Initial capital costs are dominated by the initial purchase of one month's worth of batteries. Therefore, this element varies strongly with the assumed selling price. Battery test channels are the next largest capital expenditure, but this is a significantly smaller cost. In total, capital costs are approximately 7% of annual operating expenses.
- Annual operating expenses are dominated heavily by the cost of purchasing used batteries. Where the cost of used batteries is high, this single cost component represents 76% of total annual costs. Where the cost is low, it still represents 45% of total annual costs.
- The second largest annual cost component is labor, which is dominated by the cost of technicians. At 60% of total labor costs, this represents a key area for cost reduction.

Key findings of this study are that the repurposed battery selling price is a primary driver of the repurposing cost and battery salvage value, and that the costs of purchasing used batteries can dwarf other costs components of a repurposing facility.

Subsequently, repurposing costs were investigated for additional scenarios where the battery selling price was restricted to its lowest value of $44/kWh. This is motivated by two factors. First, using the lowest value will reduce the impact of used battery purchases on repurposing economics, magnifying the effects of other factors. This serves the purpose of better identifying trends and avenues for improvement in repurposing economics. Second, supply and demand economics may suppress repurposed battery selling prices, making the use of the lower value more relevant to future second use economies. Results are discussed in the following sections.

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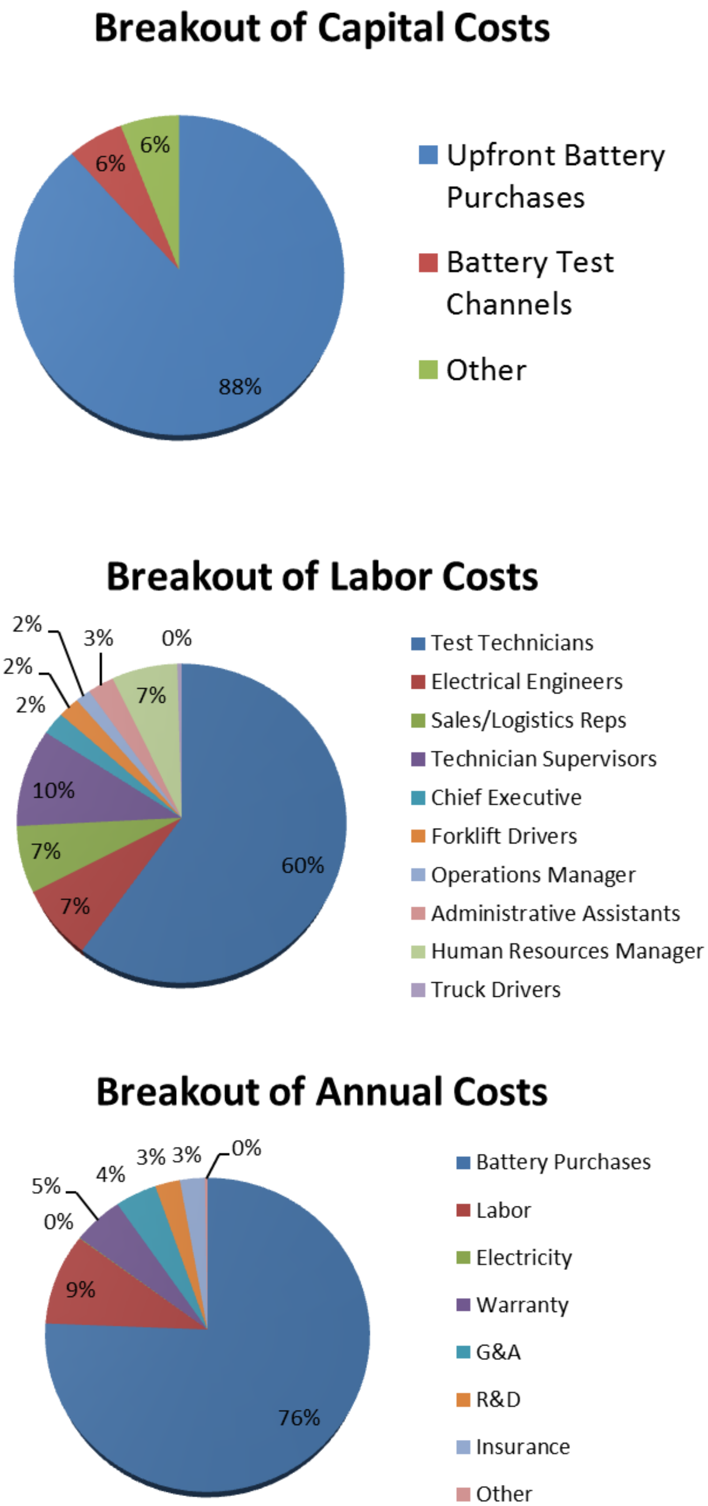

Figure 28. Breakout of capital, labor, and total annual costs for the baseline scenario where the repurposed battery selling price is $180/kWh

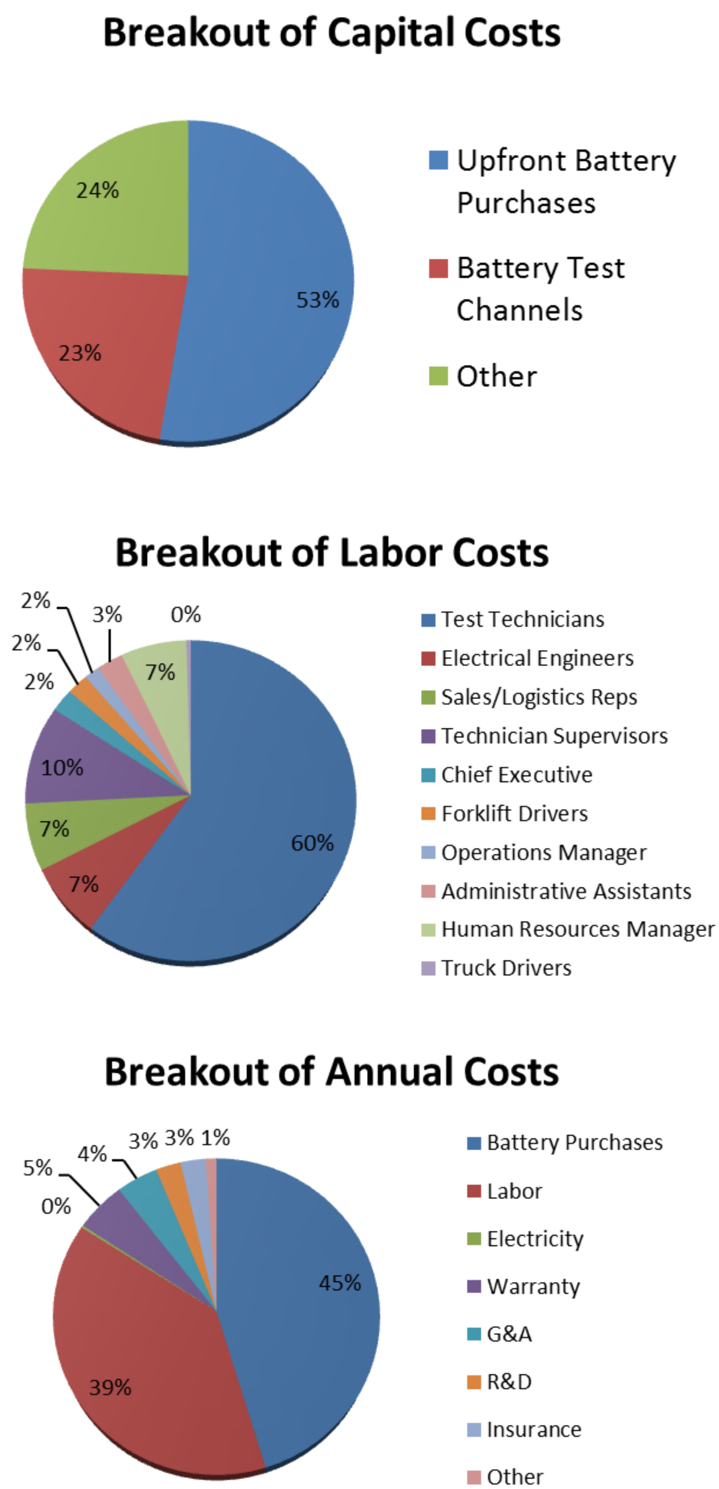

Figure 29. Breakout of capital, labor, and total annual costs for the baseline scenario where the repurposed battery selling price is $44/kWh

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4.9.2 Facility Reach and Throughput

The facility reach and throughput of our baseline scenario were varied per Table 12. Throughput bounds were advised by our projections of available second use batteries in Section 3.3. Note that the national maximum throughput corresponds to approximately 357,000 BEVs per year when equipped with 28-kWh batteries. Compare this to annual sales of the Toyota Camry at approximately 400,000 in 2012 and 2013 [75, 76]. A repurposed battery selling price of $44/kWh was employed; all other baseline scenario parameters are unchanged.

Table 12. Facility Reach and Throughput Variables

Facility Reach	Minimum Employed Throughput	Maximum Employed Throughput
Local	20,000 kWh/yr	200,000 kWh/yr
Regional	100,000 kWh/yr	2,000,000 kWh/yr
National	1,000,000 kWh/yr	10,000,000 kWh/yr

Figure 30 shows the results for the three facility reach scenarios and the range of throughputs in Table 12. As throughput increases, the facility becomes more economically efficient. This is critically important at throughputs less than 100,000 kWh per year. For annual throughputs less than 31,000 kWh per year, the repurposing cost exceeds the repurposed battery selling price, implying that the salvage value of the battery is negative: the automotive battery owner would be required to pay to have their battery repurposed. While this scenario is possible, our repurposing facility model is not designed to evaluate it.

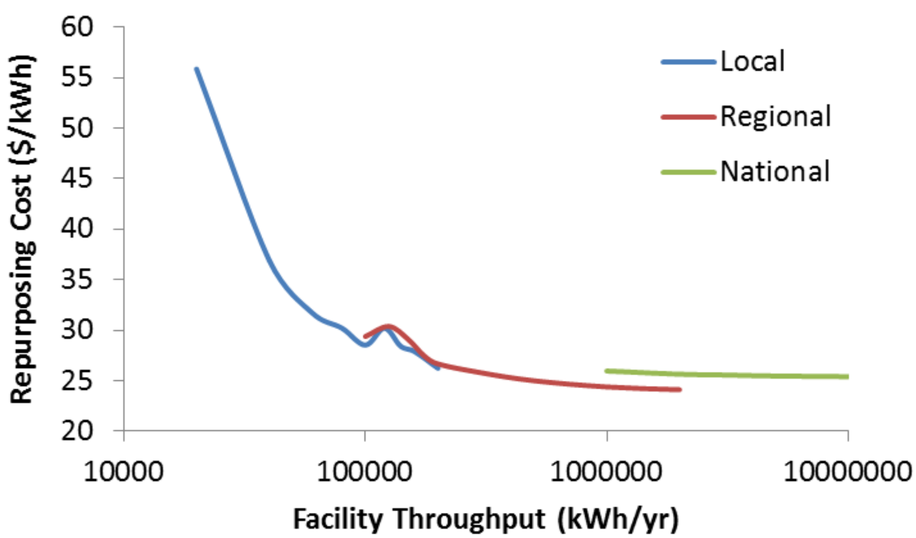

Figure 30. Repurposing cost as a function of facility throughput and reach, assuming a $44/kWh repurposed battery selling price

At the opposite extreme of large throughputs greater than 1,000,000 kWh per year, the benefits of scale are largely exhausted. Further, the switch from regional to national collection and the additional shipping costs it entails can make large nation-wide repurposing facilities less

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economic than smaller regional ones. At 1,000,000-kWh/yr throughput, the regional facility has reached a repurposing cost of $24.38/kWh. Doubling throughput only decreases repurposing cost by 1%. This level of throughput (approximately 3,750 BEV75 batteries per month) is aligned with the dedication of a single repurposing facility to a single model vehicle. In 2013, the Nissan LEAF averaged approximately 1,800 vehicles sold per month in California alone [74]. Where regions encompass multiple states and in future markets where monthly PEV sales are increased, it is likely such single model throughputs could be expected. This greatly simplifies the design and operation of repurposing facility, eliminating the need to simultaneously handle several models of batteries.

Given these points, subsequent analyses assume a facility with a regional reach processing 1,000,000 kWh of used automotive batteries per year.

4.9.3 Handling Time, Testing Time, and Module Size at Low Cell Fault Rates

Maintaining the assumption that advanced diagnostics data are available, and thus a low cell fault rate of 0.001% as well, the module size from 0.3 kWh (approximately four cells) to 40 kWh (a large pack, approximately 540 cells) was then varied. Two different handling times [35 minutes (short) and 3 hours (long) per Table 6], and two different testing times [1.5 hours (short) and 8 hours (long) per Table 7 and Table 8] were also employed. While in practice handling times and module size would be coupled (longer handling times being more applicable to larger modules), they were decoupled for these analyses.

Figure 31 presents the resulting repurposing costs for all scenarios, revealing that there are optimum module sizes for each handling and testing time scenario that result in minimum repurposing costs. For module sizes smaller than optimal, increasing module size increases the energy of batteries processed for the same amount of technician labor (a major cost component). As module size increases past the optimum, however, repurposing costs rise because the probability of finding a bad cell in a module increases with the module size. In the presence of the assumption that such modules must be disposed of, this drives down the yield (number of repurposed modules sold as a fraction of used modules purchased). Thus, the optimal repurposing size is driven by a trade in efficiency in handling labor, and yield is driven by the cell fault rate.

The data also illustrate the economic cost of repurposing small modules, as well as large amounts of hands-on time from technicians. Even when handling and testing times are short, excessive repurposing costs result for small modules: for economically attractive repurposing (where the cost of repurposing is less than the repurposed battery sale price, and battery salvage value is positive), modules must be larger than 0.5 kWh. When long handling times are assumed, this barrier increases to 2.0 kWh. For modules smaller than 10 kWh, there is a considerable cost penalty for the increased handling time; however, the long handling time assumed may not be applicable to the smallest modules.

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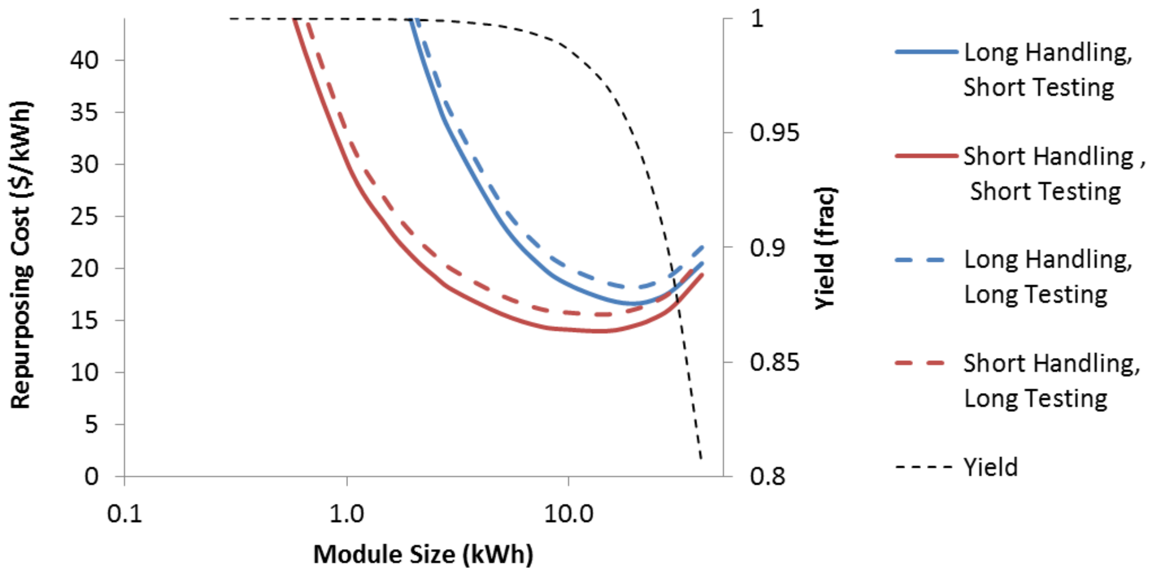

Figure 31. Repurposing cost as a function of handling time, testing time, and module size for a cell fault rate of 10^{-5} (one in every 100,000 cells is faulty)

While these results point towards an optimal module size of 10 to 20 kWh from the perspective of repurposing when cell fault rates are low, it is important to consider that the election of module size is not solely up to the repurposer, but also to the original pack designer. Considerations for the automotive life—such as packaging, repair and replacement of modules during automotive life, ability to share modules across vehicle platforms, etc.—may be a more powerful driver for module size than that of optimizing repurposing costs.

The lowest repurposing cost observed is $14/kWh when repurposing a 15-kWh module using short handling and testing time assumptions with an assumed cell fault rate of 0.001%. The use of a 0% cell fault rate at 40 kWh—indicative of approaching the lowest possible repurposing cost— reduces repurposing costs by 12% to $12.32/kWh.

4.9.4 Handling Time, Testing Time, and Module Size at High Cell Fault Rates

In this analysis, the cell fault rate was increased to 0.1%, effectively eliminating the assumption that advanced diagnostics data are available. As in the previous section, the module size was varied from 0.3 kWh (approximately four cells) to 40 kWh (a large pack, approximately 540 cells) and two different handling times [35 minutes (short) and 3 hours (long) per Table 6] and testing times [1.5 hours (short) and 8 hours (long) per Table 7 and Table 8] were applied.

The results are presented in Figure 32. Most notably, a drastically different yield curve was observed. Once module sizes reaches 10 kWh, the facility yield falls to less than 20%. This has a strong effect on driving up repurposing costs. The results may underestimate its impact as the costs of disposal of unusable modules have not been accounted for. The decreased yield amplifies the effect of handling time on repurposing costs. The effect of testing time, however, remains small.

Compared to the previous analysis where the cell fault rate was assumed to be two orders of magnitude lower, the optimum module size shifts to a considerably smaller level, and overall

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repurposing costs increase substantially. In this scenario, the optimum module size is 3 kWh where the short handling and testing time are assumed, resulting in a repurposing cost of $22.10/kWh.

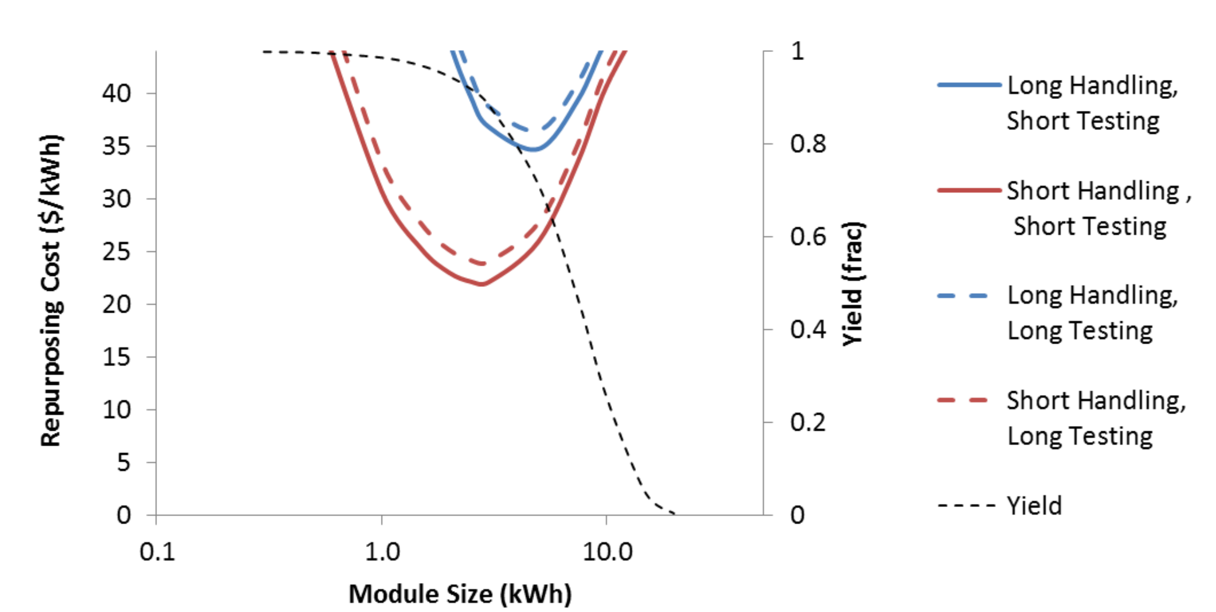

Figure 32. Repurposing cost as a function of handling time, testing time, and module size for a cell fault rate of 10^{-3} (one in every 1,000 cells is faulty)

4.10 Summary

The most important findings of this study on repurposing cost include:

- Selling price has a large impact on repurposing costs, as many of the costs scale with total sales or purchases. Similarly, the cost of purchasing used batteries is the largest expense of operating a repurposing facility. Initial start-up costs and other annual costs were often small relative to the amount spent to purchase one year's worth of used batteries.
- Regional repurposing facilities operating at a throughput of around 1,000,000 kWh/yr approach the minimum repurposing costs. This corresponds to approximately 3,800 22-kWh batteries per month. Thus, repurposing facilities will not be required to handle multiple types of batteries—the anticipated supply of used batteries from a single model of vehicle will likely be adequate to enable efficient operation.
- While testing time has little impact on overall repurposing costs, despite the increased requirement for capital equipment purchases, technician handling time has a strong impact. Technician labor was found to be the largest cost of operating a repurposing facility after used battery purchases. This may imply that replacing individual faulty cells will not be cost efficient. Further study into the amount of time, materials, and capital equipment required for individual cell replacement is necessary to confidently answer this question.
- Repurposing costs are highly sensitive to module size, a result of the opposing effects of technician labor efficiency and yield due to the presence of faulty cells. However,

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repurposing cost is not the only factor driving an OEM's selection of module size. For example, the economics of replacing modules during automotive service may encourage smaller modules to be employed, contrary to repurposing economics suggesting larger sizes. As battery reliability improves and OEMs gain more experience, this trend could diminish.

- The importance of cell fault rates should not be overlooked. Keeping fault rates below 0.001% has been shown to improve yield and enable the cost-effective repurposing of larger modules. Cell fault rates can be addressed in two ways: first, the batteries can be engineered to tighter tolerances and used more conservatively. This could significantly increase the original manufacturing cost, although it is unclear at present what level of cell fault rate today's PEV batteries will yield through the end of their automotive life and how much room for improvement exists. Second, retired automotive batteries can be screened more effectively prior to the repurposer's purchase.[9] The method discussed in Section 4.1.1 for identifying battery SOH using on-board diagnostics may be readily applied to this task as a cost-effective solution to both identifying faulty cells and quantifying overall module performance, which would then be applied to making a purchase decision and calculating a purchase price.

Based on these findings, the most important technical considerations OEMs can make to PEVs today to foster battery second use in the future are 1) proper selection of module sizes, 2) the inclusion of on-board diagnostic algorithms for determining the SOH of each individual cell (or groupings of parallel cells) within a battery pack, and 3) committing to making this data readily available to repurposers. This will enable repurposers to properly price used batteries and minimize repurposing costs, both directly by improving yields and indirectly by decreasing the sensitivity of their operations to the module size selected by the OEM.

Simple analysis suggests that the use of on-board diagnostic algorithms is economically justified. Consider a worst case scenario, where repurposed battery selling prices are at their lowest anticipated value ($44/kWh), making repurposing costs less sensitive to such improvements on an absolute scale. Further, consider BEV batteries coming from the Los Angeles climate, which have a comparably small spread in anticipated second use health factor of 12.6% across the 25th and 75th percentile cases (Figure 12). For a case where 5-kWh modules are employed, the value of the onboard diagnostics data ability to accurately price battery purchases and reduce test time (from our long to short assumption) and cell fault rate (from 0.1% to 0.001%) is estimated at $14.60/kWh. For a 22-kWh BEV, this corresponds to $321 of total value for second use functionality alone at the time of automotive retirement. Discounting that back to the point of sale 15 years prior with a discount rate of 10%/year reduces that amount to $77. Assuming 3,800 vehicles are sold per month over a three-year period, the total value of adding onboard diagnostics is $10.5M, which would appear to be more than sufficient to support the necessary upgrade.[10]

Where repurposed battery prices are higher than the $44/kWh minimum assumed here, the value of this capability will be increased. Further benefit provided by this capability during the

[9] Although this can greatly improve the repurposer's yield, it essentially shifts the liability of faulty cells back to the automotive owner.
[10] Assuming no change in hardware is required, which is likely the case using the method in Section 4.1.1.

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automotive life (e.g., improved range estimation, vehicle resale value, service need identification) could greatly increase the value of adding this capability from the perspective of the OEM.

The importance of optimizing module size once the use of onboard diagnostics data has reduced the cell fault rate (as observed by the repurposer) to 0.001% is best shown in Figure 33 and Figure 34. This shows that for a scenario where handling time is long and a low $44/kWh selling price is in effect, modules smaller than 2 kWh are not practical to repurpose.[11] Thus, to ensure the best chances for repurposing, OEMs are well advised to design and install modules sized at 2 kWh or greater. Figure 26 shows this appears to be the case for a significant number of modern PEVs, and, the industry may trend towards larger modules as reliability and experience increase. However, it is worth noting that this 2-kWh scenario effectively leaves no salvage value to the original automotive owner, which would be required at a minimum to cover the cost of extracting the battery from the vehicle.

The cost of extraction might conservatively be estimated at $20/kWh.[12] For a $44/kWh selling price, this can be achieved either by reducing handling time to our minimum value with 2-kWh modules or by increasing module size to 5 kWh where the longer handling time assumption is in effect. In such cases, proper selection of module size is an outright enabler of battery second use. At a minimum, the value of properly sizing modules is the deferred cost of battery extraction and disposal.

Where the selling price of repurposed batteries is high, there is more room for a broader range of module sizes. Modules down to 500 Wh can be effectively repurposed where the selling price is $180/kWh, even under the long handling time assumption. However, increasing the module size has a bigger effect on repurposing costs and salvage value. For example, when handling times are long, increasing module size from 2 kWh to 5 kWh will save $18.73/kWh in repurposing costs, while increasing from 5 kWh to 20 kWh can save an additional $10.12/kWh. These scenarios can result in considerable salvage value (greater than $100/kWh) for the automotive battery owner.

[11] Reporting in Figures 33 and 34 have been restricted to cases with positive salvage values, as the employed tools could not properly evaluate negative salvage value cases.

[12] Assuming 2.5 hours of time for two $100/hr technicians to remove a 24-kWh battery

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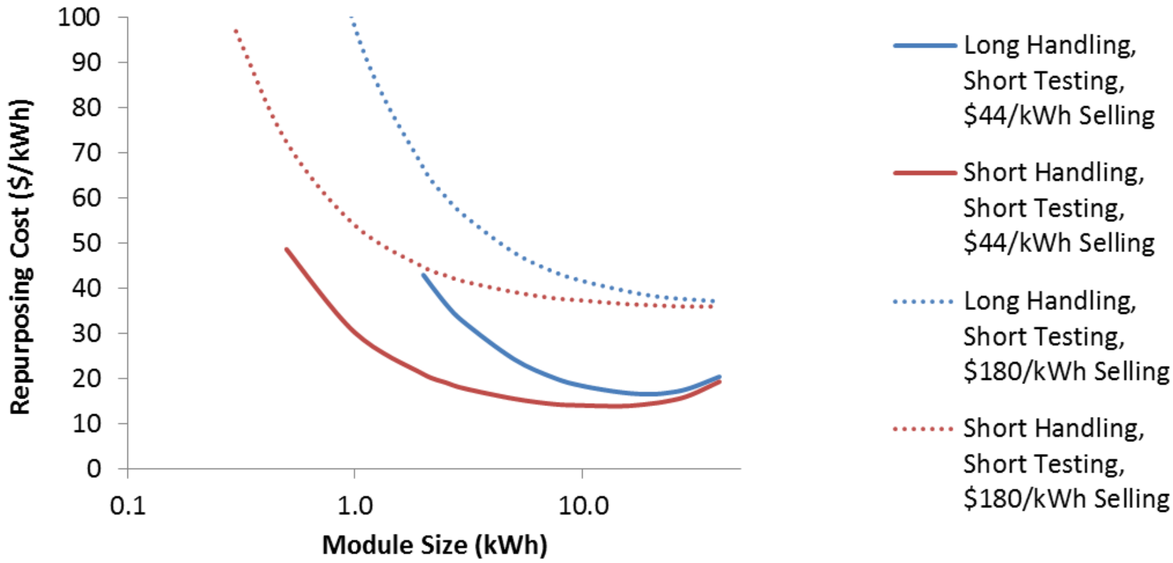

Figure 33. Repurposing costs as a function of module size, handling time, and repurposed battery selling price for a cell fault rate of 0.001%

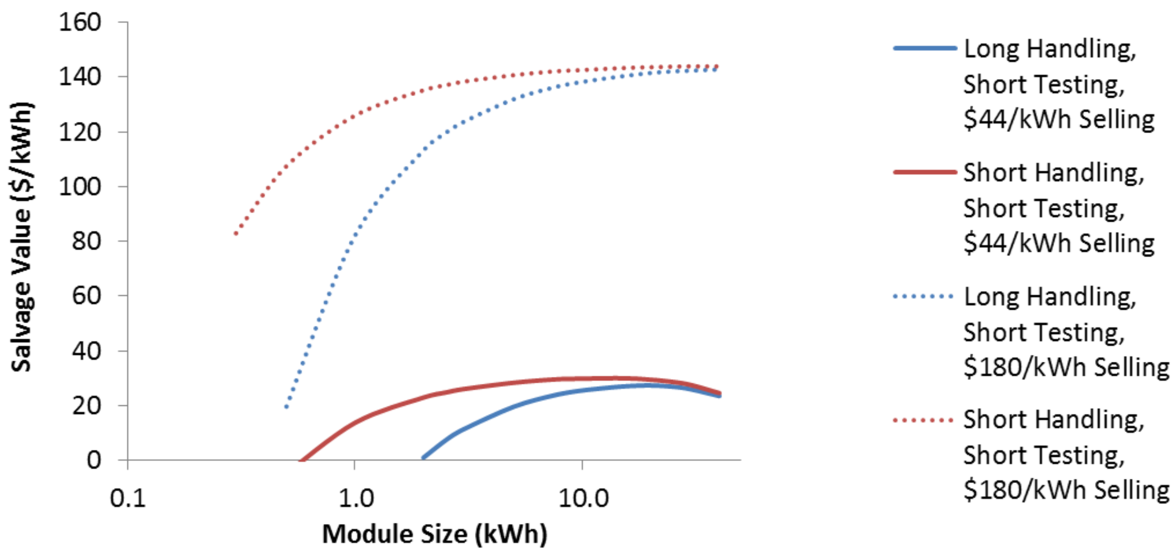

Figure 34. Salvage value as a function of module size, handling time, and repurposed battery selling price for a cell fault rate of 0.001%

Finally, the lowest feasible repurposed battery selling price was sought. A module size of 5 kWh was employed on the premise that larger modules make for more efficient repurposing, but that first-life constraints may prevent modules from growing much larger. Next, onboard diagnostics data were assumed to be available to reduce cell fault rates to 0.001% and enable the short testing protocol (Table 7). For handling time, the long and short handling times were averaged, setting both "initial inspection and handling" and "final inspection and packaging" times to 35 minutes each. Finally, a salvage value of $20/kWh-nameplate was enforced to provide enough value to the automotive owner to cover battery extraction costs. Thus, the automotive battery owner avoids any end of life costs (battery extraction, recycling, disposal, etc.), but does not receive any additional value for the battery being sold to a repurposer. Under these assumptions,

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a regional reach repurposing facility processing 1,000,000 kWh/yr of used automotive batteries could sell repurposed batteries at a price of $40/kWh-nameplate ($20/kWh-nameplate repurposing cost). This corresponds to $67/kWh-available when a 60% DOD is employed. The breakout of costs is shown in Figure 35.

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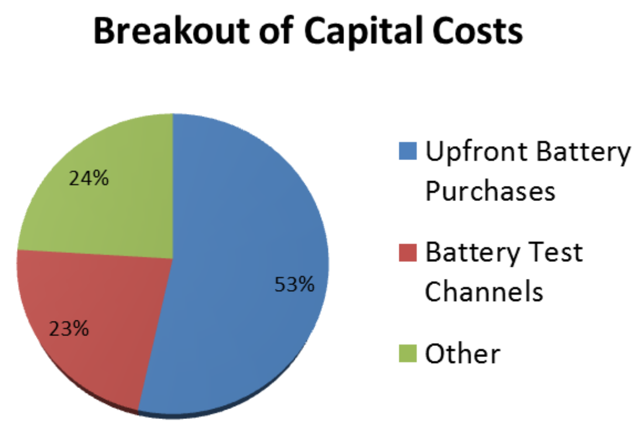

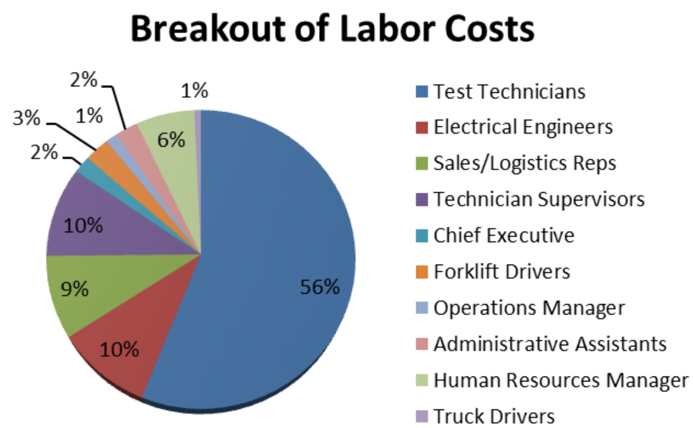

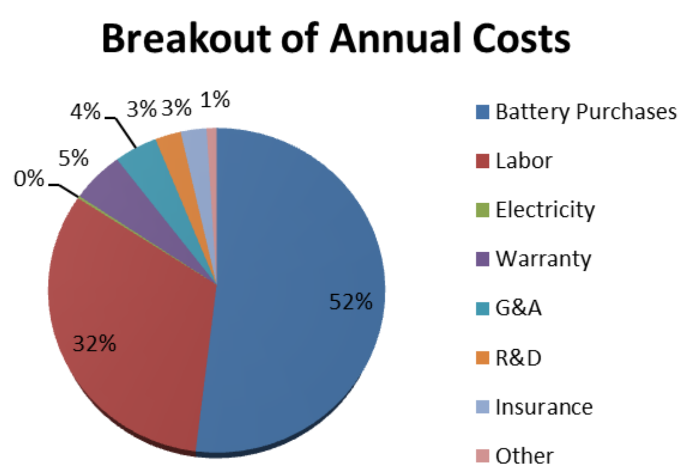

Figure 35. Breakout of capital, labor, and total annual costs for our minimum repurposed battery selling price scenario ($40/kWh-nameplate)

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5 Applications

The preceding analyses have revealed much of the likely metrics of second use batteries. These are summarized at the module level in Table 13. It is critical to recognize that the presentation of *available* energy accounts for the DOD planned for second life usage, e.g., a battery that was capable of storing a total of 1.0 kWh of energy but was planned to operate in its second life at only a 50% DOD would be listed as having 0.5 kWh of available energy. Note further that additional cost, mass, and volume will be required to assemble modules into packs, and packs into functional systems. However, these elements are likely to be application specific and are thus excluded from the present discussion.

Table 13. Anticipated Second Use Battery Metrics, Module Level

Metric	Value	Notes
Available energy per kilogram	75-90 Wh/kg	Assumes BOL specific energy of 115 Wh/kg [68] and 50%–60% energy availability in second use
Available energy per liter (module level)	58-69 Wh/L	Assumes BOL energy density of 150 Wh/L [68] and 50-60% energy availability in second use
Cost per available kWh (module level)	$67-360/kWh	Assumes $40–$180/kWh repurposed battery selling price based on BOL nameplate energy, translated to available energy in second use assuming 50%–60% DOD is employed
Cost per throughput kWh (module level)	$0.022-0.304/kWh	Applies median second use lifetime expectations for BEV75 and PHEV20 batteries originally operated in Los Angeles, then operated at either 50% or 60% DOD in their second life (Table 3), to cost per available kWh computed above.
Rolling supply of available energy	32.3 GWh to 1.01 TWh	See Section 3.3

Perhaps the most intriguing of these values is the rolling supply. At these levels, 10.8 to 101 GWh of newly available second use storage enters the market each year. This is an extremely large amount of storage in comparison to recent sale volumes of advanced batteries (24.6 GWh/year), as seen in Figure 36. This presents the challenge of finding markets large enough to consume the supply of second use batteries.

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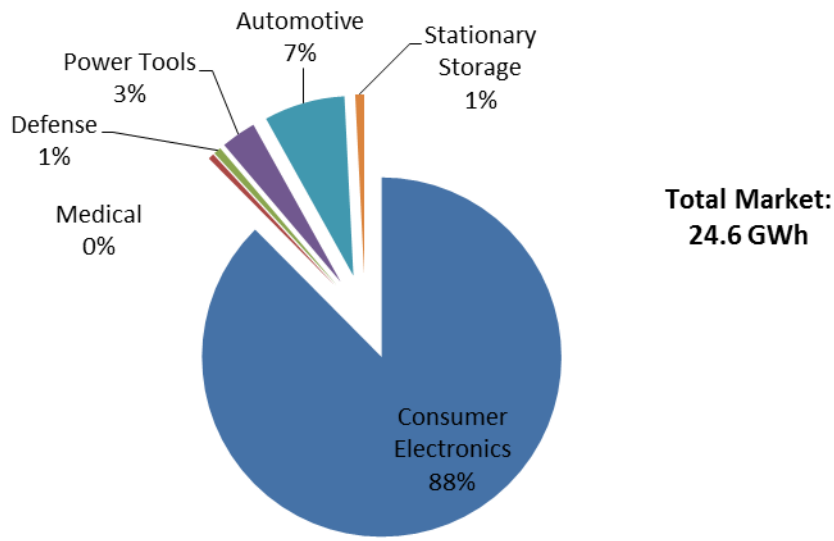

Figure 36. 2012 market for advanced batteries (24.6 GWh total)
Recreated from data in Jaffe [77]

Many potential markets for second use batteries can be ruled out quickly. The majority of today's advanced battery market—consumer electronics—is ill suited to the use of retired automotive batteries as they often require less energy than that provided by a single large-format automotive cell (not to mention the possibility of a multi-kilowatt-hour module or pack). Medical and power tool segments suffer similar constraints. Further, repurposed automotive batteries may not compete well in future advanced markets more generally due to their relatively poor performance: battery energy density, specific energy, specific power, etc. can be expected to advance considerably during a battery's anticipated 15-year automotive life span, and such metrics are often highly valued in advanced battery markets (e.g., PEVs).

Thus, repurposed PEV batteries must find their place competing in large markets for lower technology storage or in wholly new markets for storage. We propose two options: 1) competing with traditional lead acid batteries, and 2) entering the growing market for grid-connected storage.

5.1 Competing with Lead-Acid Batteries

Repurposed PEV batteries may serve as a general replacement for lead-acid batteries. Per Table 13, their improved energy per unit mass and volume, as well as their anticipated ability to sustain partial SOC cycling without excessive degradation, could make them superior to lead-acid batteries in many applications. Relevant markets for lead-acid batteries include automotive starting, lighting, and ignition; industrial trucks (e.g., forklifts); telecommunications backup power; and UPS.

The 2015 market for starting, lighting, and ignition batteries has been predicted at approximately $15B [78]. Assuming the price of new lead-acid batteries is $100 to $150/kWh, this market could consume 100 to 150 GWh of second use storage per year, encompassing the anticipated supply. The automotive market's move towards start-stop technology [79], which puts considerably greater cycling demands on the battery [80], could make Li-ion batteries even more

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relevant. However, the required energy for this application (≤1 kWh) is smaller than many PEV modules, and the high pulse power required for engine starting could present challenges for aged PEV batteries.

Cullen estimated the 2010 combined market for industrial truck, telecommunications backup, and UPS batteries (>25 amp-hours) to be nearly an order of magnitude smaller at $1.7B (Figure 37) [81]. Telecommunications and UPS applications will be treated in the next section as reliability applications. Industrial truck applications alone constituted a $786M annual market. Again assuming $100 to $150/kWh for new lead-acid batteries, this corresponds to 5.2 to 7.9 GWh of market potential. This is a significant fraction of the anticipated supply of the lower second use battery deployment scenario, but well less than that forecasted by the higher deployment scenario. While this application may merit further investigation, it is not addressed herein.

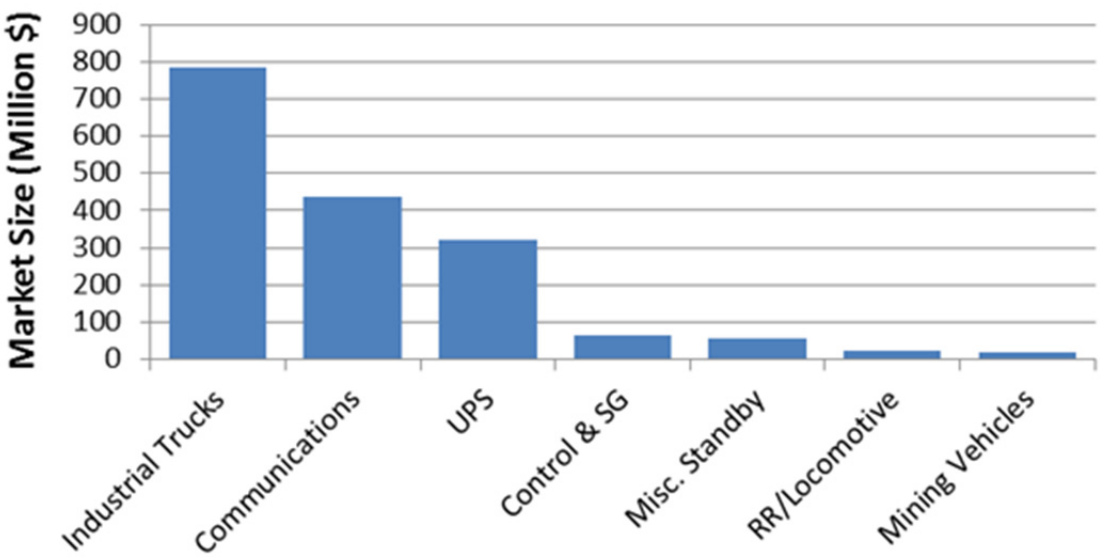

Figure 37. Estimated market for industrial batteries in North America, 2010
Recreated from data in Cullen [81]

5.2 Grid-Connected Storage

Over the past several years, as large energy storage technology has developed and growing trends in renewable energy and demand profiles have sparked concerns over new technical challenges, there has been considerable interest in the deployment of grid-connected energy storage. There are a plethora of functions energy storage can provide when connected to the grid, including control of frequency, peak shaving, relieving transmission congestion, etc.

However, the electricity industry is heavily regulated, and the regulations have generally not been written with energy storage in mind. This has made quantification of the value and market potential for storage in such applications difficult. A study by Sandia National Laboratories in 2010 made preliminary technology-agnostic estimates for many grid storage services [82]. Their data was applied to examine the specific values and market potentials of various grid storage applications when served by repurposed PEV batteries [11]. This included applying bounds for allowable DOD (25% to 65%), C-rate (±3), duration (referenced from Sandia [82]), and inverter

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and BOS costs ($300 to $700/kW) for each application. These same methods were applied to an EPRI study that made similar estimates of energy storage value [11, 83]. Figure 38 presents the results of this analysis as allowable battery budgets and market potentials per application.

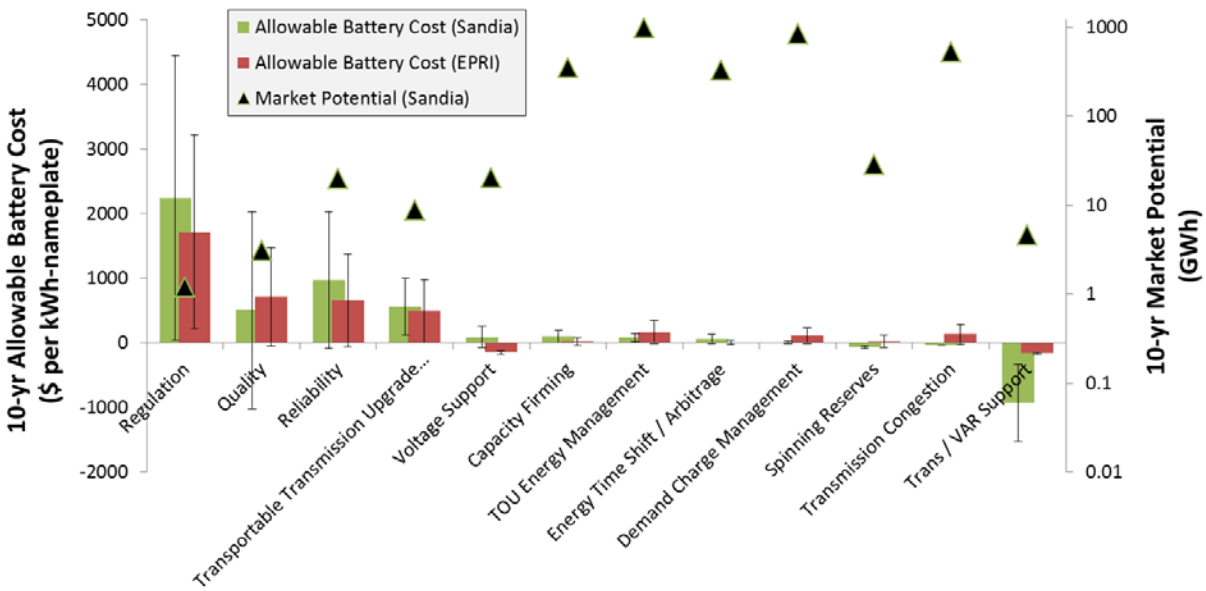

Figure 38. Allowable battery budget and market potential for grid-connected storage applications

There are three striking findings from these results. First, the error bars resulting from the range of assumptions are quite large. Even the highest-value applications have error bars that dip below zero. This implies the sensitivity of profitability to right-sizing the battery and minimizing the BOS cost is high. Second, not all applications are estimated to have positive value, but some positive values can be considerable. Regulation, for example, may be able to support batteries costing more than $2,000/kWh. Applications showing negative value imply that the BOS costs alone are greater than the revenue generated by the service, and thus wouldn't be profitable even with free batteries. Third, the highest-value applications have the smallest market potentials. Note that the 10-year market potential is defined in Eyer and Corey [82] as the total amount of storage that could be sold to a given application over a 10-year period. The highest-value applications—regulation, reliability,[13] and transportable transmission upgrade deferral—have a combined 10-year market potential of only 15.8 GWh. When compared to the estimated rolling supply of repurposed battery capacity of 32.3 GWh to 1.01 TWh, the mismatch in supply and demand is readily apparent. An allocation analysis of these applications for the minimum and maximum deployment scenarios (Figure 39 and Figure 40, respectively) reveals that all three could be saturated with the first 7 to 16 years of repurposed PEV battery production, assuming no competition from other technologies.

[13] Reliability is essentially the same market as UPS, discussed previously as an application in the discussion of lead-acid battery replacements.

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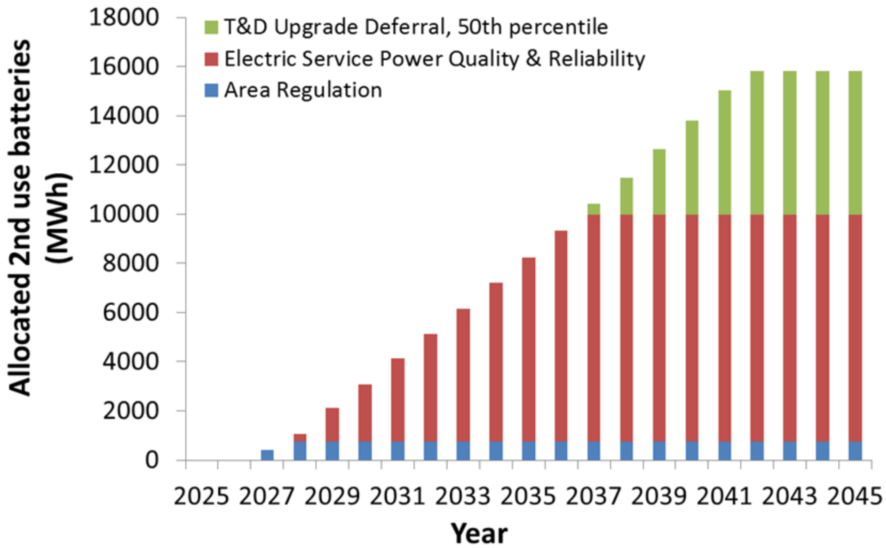

Figure 39. Allocation analysis for high-value grid storage applications in the minimum PEV deployment scenario

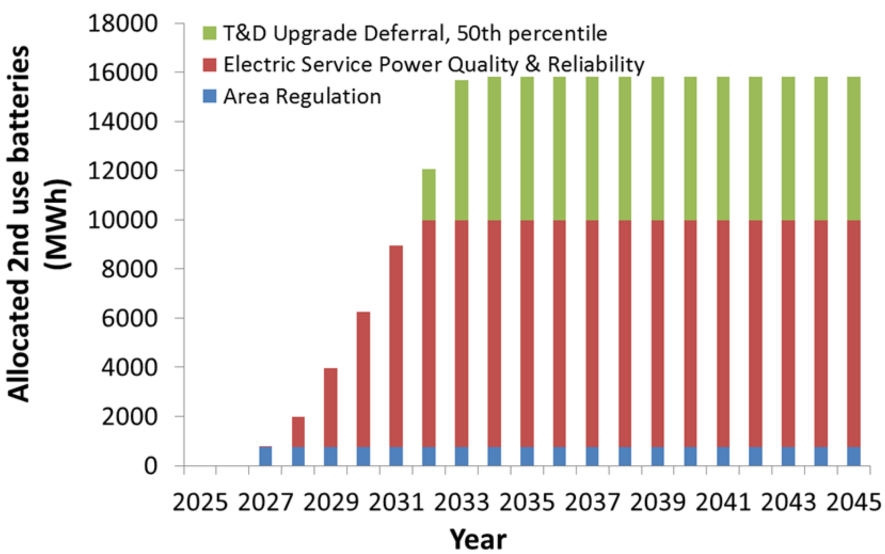

Figure 40. Allocation analysis for high-value grid storage applications in the maximum PEV deployment scenario

Given the high value associated with these applications, the long time span between the present and when substantial numbers of second use batteries are expected to enter the market, and the increasing trends of selling new batteries to these applications today, it is possible that these applications may be largely saturated with storage from other technologies (including demand response) by the time automotive second use batteries become widely available. While second use batteries may slowly replace these technologies if they prove to be more cost effective, the reduced rate of uptake may result in large unutilized oversupplies of retired PEV batteries.

This merits a shift in attention away from the most valuable applications to the largest ones: capacity firming (turning a variable generator such as a wind turbine into a constant power

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output generator), energy time shift, demand charge management, and time of use energy management.[14] These applications are all essentially peak-shaving services, where energy storage is employed to reduce the peak load for a demand profile. Capacity firming and demand charge management explicitly value the power reduction, whereas energy time shifting and time of use energy management both explicitly value the timing of energy delivery. Demand charge management and time of use energy management are both behind-the-meter (customer sited) applications, whereas capacity firming and energy shifting are both utility-side applications. While the benefits of power reduction are generally greater than those of time shifting energy usage, both the power and energy benefits can be reaped simultaneously without conflict, enabling increased value to the end user.

This motivated closer investigation of two grid-connected B2U use cases: 1) new installation of behind-the-meter storage employed primarily to reduce demand charges, and 2) replacement of a peaker plant used to provide firm capacity to the grid during periods of high demand.

5.2.1 Behind-the-Meter Storage

In addition to being charged for the amount of energy consumed, many commercial customers of electric utilities are subject to a rate structure that includes a demand charge—a fee proportional to peak power rather than total energy. In some instances, demand charges can constitute more than 50% of a commercial customer's monthly electricity cost. While installation of behind-the-meter solar power generation decreases energy costs, it is not always the case that the peak facility load aligns with peak solar power generation. Even when load and production do align, solar intermittency due to cloud cover may cause the peak load—and thereby demand charges—to remain unaffected. This then makes demand charges an even larger fraction of the remaining electricity costs. Adding controllable behind-the-meter energy storage, however, can more predictably manage building peak demand, in turn reducing electricity costs.

To better ascertain the value and market size of demand charge management, the relationship between peak demand reduction and the required amount of stored energy (i.e., the duration of the system) in typical facilities must be understood. The peak demand reduction achievable with an ESS depends heavily on the shape of a facility's load profile, so the optimal configuration is specific to both the customer and the amount of installed solar power capacity. To this end, NREL developed and employed the Battery Lifetime Analysis and Simulation Tool for Stationary applications (BLAST-S), with specific capability for assessing behind-the-meter scenarios [46].

Neubauer and Simpson used this tool to apply an optimal peak load reduction control algorithm to 98 real-world facilities with varying levels of installed solar power in search of cost-optimal energy storage configurations [84]. In an environment without incentives, they found the distribution of energy and power levels that yield minimal payback periods in a commercial facility demand charge management role are well suited to second use PEV batteries. The small recommended storage system size—largely less than 15.5 kWh and 30.5 kW—could readily be

[14] Transmission support is ignored on the basis that it is defined for energy storage with discharge durations on the orders of seconds, and is thereby unlikely to make sufficient use of a storage resource with hours of capacity in a profitable manner. Renewables integration is ignored on the basis that it is merely a combination of other included applications.

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met by a single repurposed PEV battery. This would largely negate the anticipated challenges of integrating large ESSs from several used PEV batteries of various SOHs, cell or module design, chemistry, etc., and therefore support the low BOS costs. With such configurations, they estimated a total U.S. market potential of 7.1 GWh available energy. Operating second use batteries at a 50% DOD translates to 14.2 GWh of nameplate potential. While this is a significant portion of our anticipated 32.3 GWh rolling supply in the low B2U deployment scenario, it is far from consuming the 1.01 TWh rolling supply of B2U batteries possible in the high deployment scenario.

Over the past few years, however, mandates and incentives for behind-the-meter energy storage have increased dramatically. For example, in 2010 the California legislature passed Assembly Bill 2514, which resulted in the California Public Utilities Commission releasing a procurement target for 1.325 GW of energy storage in the state by 2020 [3]. Approximately 15% of this allotment has been planned for customer-sited, behind-the-meter storage [4]. Customer-sited storage has been encouraged in California by the Self-Generation Incentive Program, which offers up to $1.62 per watt installed [5]. In New York, the utility ConEdison offers up to $2.10 per watt installed for advanced batteries through an enhanced load reduction program [85]. These substantial customer incentives often come with a required minimum duration for the storage system that, together, encourage the installation of a much larger system.

Where 2-hour system durations are required to collect the full incentive, the above predicted market potential for behind-the-meter demand charge management systems might quadruple to 56.8 GWh. While this surpasses the rolling supply of second use batteries expected in our low deployment scenario, it is far from that of the high deployment scenario. Further, as demand charge intensive rate structures and incentives for behind-the-meter storage are existent today, it is possible that significant competition from other storage technologies (e.g., new Li-ion batteries) will shrink the availability of this market for second use systems.

5.2.2 Utility Peaker Plant Replacement

Electricity on the grid is generated by a diverse portfolio of resources. Among these are base load plants, which run at a constant output targeting maximum utilization and efficiency; peaker plants, which run only when demand for electricity is its highest; and mid-merit plants, which provide a load following output to fill the space in between. Natural gas-powered combustion turbines are often the favored technology for peaker plant operation as they have lower capital costs and can ramp their power output up and down to meet changing demands more quickly than other options. However, due to their design and mode of operation, they are also among the least efficient power generators on the grid. Combined with their infrequent use, their levelized cost of energy delivered is high.

For ESSs to broadly replace combustion turbine peaker plants, the total cost of operating the combustion turbine peaker plant must be less than that of the battery, once the additional benefits of using a battery are considered. This relation is given by Eq. 25. The annualized capital cost and fixed operation and maintenance (O&M) costs of a peaker plant can be collected from multiple sources [86 - 88], suggesting a range of $77.9 to $105.6/kW-yr and $4.1 to $15.8/kW-yr, respectively.

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$$CapCost_{CT} + FixedO\&M_{CT} + VarO\&M_{CT} + ValueAdd_{ESS} \geq CapCost_{ESS} + FixedO\&M_{ESS} + VarO\&M_{ESS} \qquad \text{Eq. 25}$$

The variable O&M costs of a combustion turbine (primarily fuel) and ESS (primarily efficiency losses) may be considerably different. Further, an ESS may provide additional system-level benefits that provide additional value (e.g., energy arbitrage). These differences were collected and termed the incremental value, defined in Equation 26.

$$IncrValue = VarO\&M_{CT} - VarO\&M_{ESS} + ValueAdd_{ESS} \qquad \text{Eq. 26}$$

The incremental value of an ESS over a combustion turbine is difficult to assess as it requires detailed simulation of a large electricity grid to accurately quantify. Denholm et al. have, however, calculated that the incremental value of 8-hour storage systems in this role to range from approximately $60/kW-yr at low penetrations of storage to $15/kW-yr when penetration reaches approximately 23% of the combustion-based peaking capacity present in the baseline case [89]. As this study is interested in larger penetrations of storage due to the large expected supply of second use batteries, a range of $15/kW-yr to $30/kW-yr was employed herein.

Finally, the impacts of an ESS's limited storage capacity were accommodated. Because quantifying the exact impact of an ESS's duration is challenging, an array of values was selected advised by the results of Sioshani et al. [90], defined in Table 14. This was then applied to the above equations to create a criteria for the allowable annualized capital cost and fixed O&M of an ESS (Equation 27).

Table 14. ESS Duration Adjustments

Duration	x_{min}	x_{max}
2 hrs	0.35	0.76
3 hrs	0.39	0.88
4 hrs	0.42	0.99
5 hrs	0.52	1.00
6 hrs	0.61	1.00
7 hrs	0.71	1.00
8 hrs	0.80	1.00

$$CapCost_{ESS} + FixedO\&M_{ESS} \leq x(CapCost_{CT} + FixedO\&M_{CT} + IncrValue) \qquad \text{Eq. 27}$$

Application of the values above to Eq. 27 resulted in allowable annualized ESS capital and fixed O&M costs ranging from $35/kW-yr to $152/kW-yr, as shown in Figure 41. To attain the allowable battery cost for comparison with our estimated costs for repurposed automotive batteries, the fixed O&M and BOS costs must be subtracted from these values.

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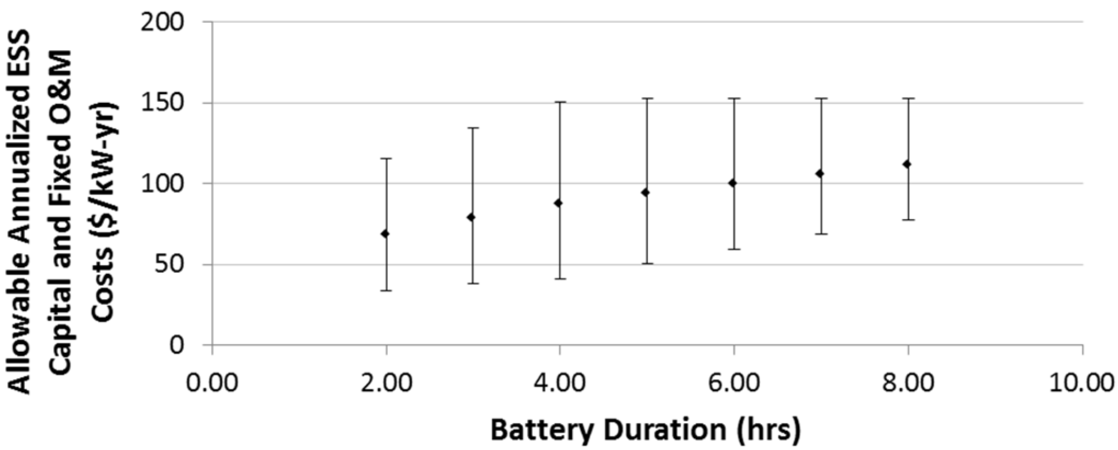

Figure 41. Allowable annualized ESS capital and fixed O&M costs

The current state of the large-scale grid-connect storage industry prevents accurate estimates of ESS fixed O&M costs. Thus, the only aspect of these costs considered here is that of battery replacement (with the understanding that repurposed battery lifetimes that may range from 5 to 15 years will not last the anticipated 30-year system life expected of a peaker plant). The cost of service to replace the batteries was estimated at $20/kWh-available[15] and discounted in time with a fixed charge rate, then converted to an annualized cost using the same fixed charge rate per Eq. 28:

$$FixedO\&M_{ESS} = r\sum_{i=1}^{N} \$20/kWh * d * (1+r)^{-y_i} \qquad \text{Eq. 28}$$

Where:

N = Total number of battery replacements over the 30-year system life

y_i = Year of the i^{th} battery replacement

r = Fixed charge rate

d = Duration of storage system at rated power, hr

Next, the annualized ESS capital cost was defined as a function of charge rate and upfront costs for the battery, inverter, BOS, and installation per Eq. 29. The DOE target for future inverter prices is $100/kW by 2020 [91]. The Committee on Climate Change forecasts a cost of £94/kW to £212/kW ($157/kW to $354/kW) in 2020 and £44/kW to £101/kW ($74/kW to $169/kW) in 2040 [92]. Note that these are cost targets and forecasts for unidirectional inverters; batteries will require bidirectional inverters to both charge and discharge. Based on these data, estimates of $150/kW to $200/kW were employed for inverter hardware. Akhil et al. [88] provide BOS and installation cost information for energy storage transmission and distribution support applications (the closest in scale to a peaker plant replacement application) based on quotes provided from ESS suppliers today (Table 15). On the assumption that mass deployment of B2U ESSs for

[15] This number was set identical to approximately half of the previously employed vehicle battery extraction cost, on the assumption that stationary B2U storage systems will be designed to simplify battery replacements.

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peaker plants could result in substantial benefits from production and installation at scale, we employ these values as a maximum estimate. Minimum estimates are created by reducing these values by 50%. The resultant range of BOS costs as a function of system duration, spanning \$444/kWh-available to \$79/kWh-available, is presented in Figure 42.

$$CapCost_{ESS} = r\left(Inverter + BOS_{\$/kW} + Install_{\$/kW} + d\left(Batteries_{\$/kWh} + BOS_{\$/kWh} + Install_{\$/kWh}\right)\right) \quad \text{Eq. 29}$$

Where:

$Inverter$ = Inverter cost, \$/kW

$BOS_{\$/kW}$ = BOS cost, \$/kW

$BOS_{\$/kWh}$ = BOS cost, \$/kWh

$Install_{\$/kW}$ = Installation cost, \$/kW

$Install_{\$/kWh}$ = Installation cost, \$/kWh

$Batteries_{\$/kWh}$ = Total cost of all repurposed batteries over 30-year system life, \$/kWh

d = Duration of storage system at rated power, hrs

r = Fixed charge rate

Table 15. BOS and Installation Costs

	Max [88]	Min
BOS equipment per kW	\$381/kW	\$191/kW
BOS equipment per kWh	\$12/kWh	\$ 6/kWh
Installation per kW	\$154/kW	\$ 77/kW
Installation per kWh	\$ 71/kWh	\$ 36/kWh

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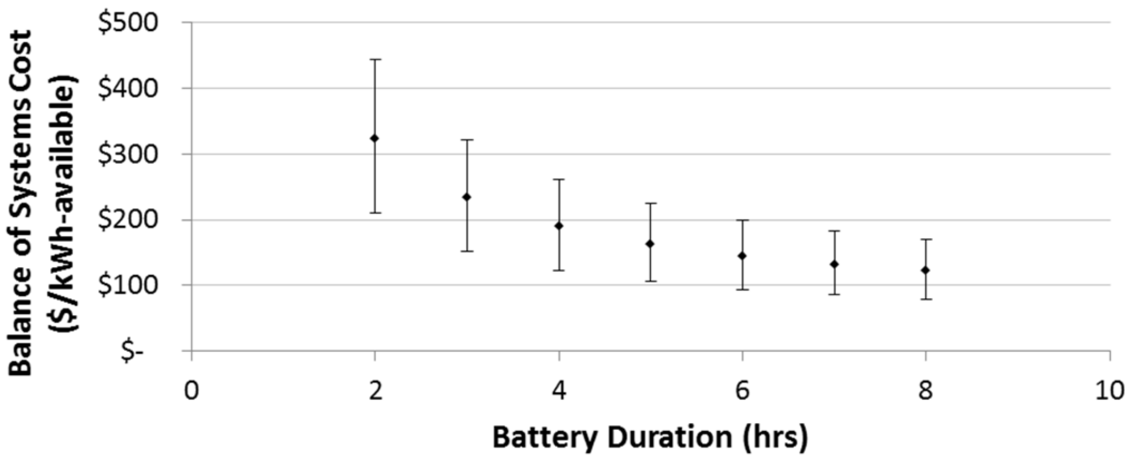

Figure 42. BOS costs as a function of system duration

Finally, the allowable price of a repurposed battery is computed, accounting for multiple replacements over the 30-year system life in Equation 30:

$$P_A = \frac{Batteries_{\$/kWh}}{\sum_{i=1}^{N}(1+r)^{-y_i}} \qquad \text{Eq. 30}$$

Where:

N = Total number of battery replacements over the 30-year system life

y_i = Year of the i^{th} battery replacement

r = Fixed charge rate

P_A = Maximum allowable cost of a single battery, $/kWh

Equations 27–30 are then combined and solved for the allowable repurposed battery price for various durations (2 to 8 hours), battery lifetimes (5 to 15 years) and fixed charge rates (9.8% to 13.9% [93-95]). Figures 43–45 show the calculated allowable repurposing prices for battery lifetimes of 5, 10, and 15 years, respectively, compared to the minimum repurposed battery selling price when used at a 50% DOD of $80/kWh, as computed in Section 4.10.

For the economics of repurposed batteries in this peaker plant replacement application to be viable, the allowable battery price must be greater than the minimum repurposed battery selling price. Where repurposed batteries last less than 5 years in this role, it can be seen that the maximum duration that can be deployed under our most favorable assumptions is approximately 4 hours. Where lifetime is increased, it becomes economically viable to increase the installed duration of the system and/or operate under less favorable assumptions. However, it is clear that repurposed batteries will not be economically viable as peaker plant replacements under all scenarios.

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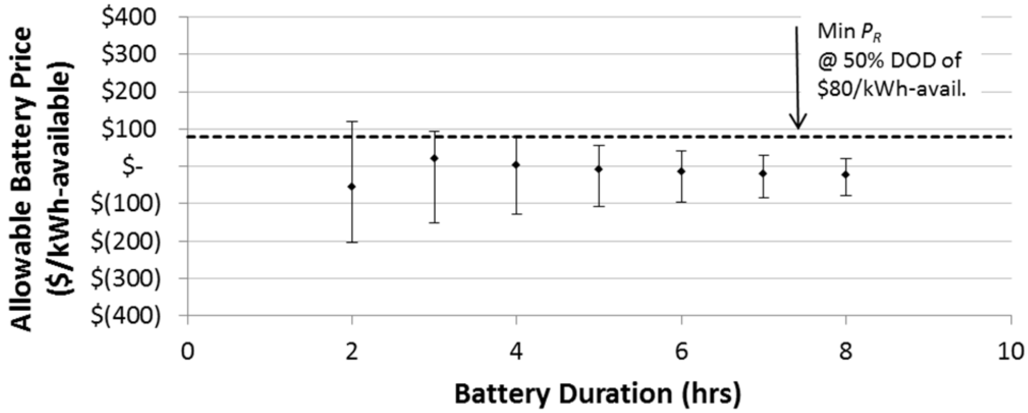

Figure 43. Allowable battery price for a 5-year battery lifetime

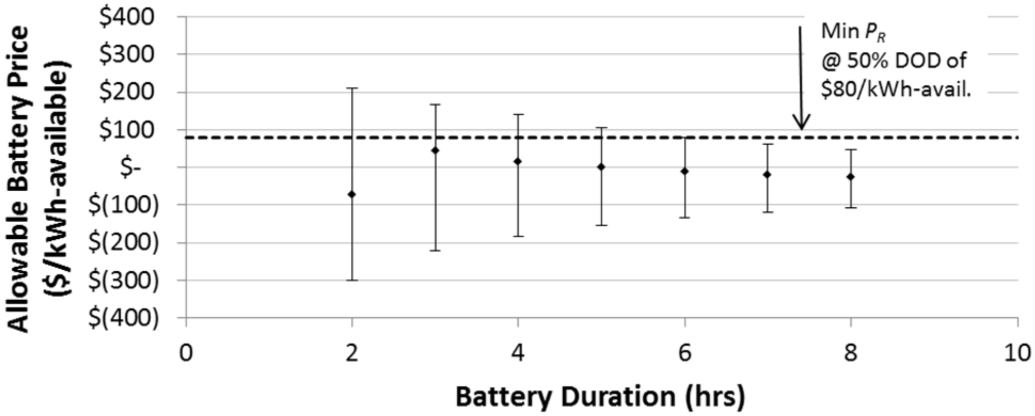

Figure 44. Allowable battery price for a 10-year battery lifetime

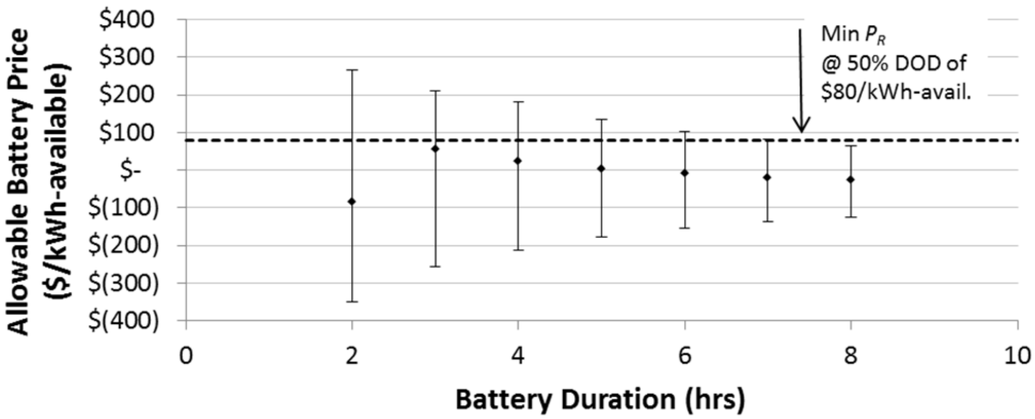

Figure 45. Allowable battery price for a 15-year battery lifetime

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Where B2U systems can economically replace combustion turbine peaker plants, they will provide significant reductions in emissions and consumption of fossil fuel, two items of national import. The reduction in carbon dioxide provided by batteries replacing peaker plants may match the carbon dioxide reductions provided by employing the battery to electrify transportation [28]. Additionally, the batteries offer increased flexibility in placement and use. When built as a battery, a 20-megawatt (MW) peaker plant could be deployed as a single 20-MW system or any number of smaller distributed units. Given their smaller size and silent, non-emitting operation, these units could be installed almost anywhere and address distribution-level issues in dense urban areas and areas of high renewable generation penetration that conventional combustion turbines are unable to address. Monetizing these aspects will make the deployment of second use batteries as peaker plant replacements more attractive and could expand the potential market.

Quantifying the market potential for these systems is not straightforward. EIA data show that 93.3 GW of combustion turbine capacity was added to the U.S. electricity grid in the last 20 years, and 101 GW in the last 30 years (Figure 46) [96]. The EIA also forecasts nearly linear growth in the online capacity of combustion turbine and diesel generators from 146 GW in 2020 to 220 GW in 2040 [97]. While the fraction thereof that will apply to constrained energy resources with continuously provided capacity limited to less than 8 hours is unknown, the high-deployment scenario would result in less than 10 GW of 5-hour storage systems by 2040, leveling out to 152 GW by 2063. Thus, it appears that the market for combustion turbine replacements would be large enough to consume the available supply of second use batteries.

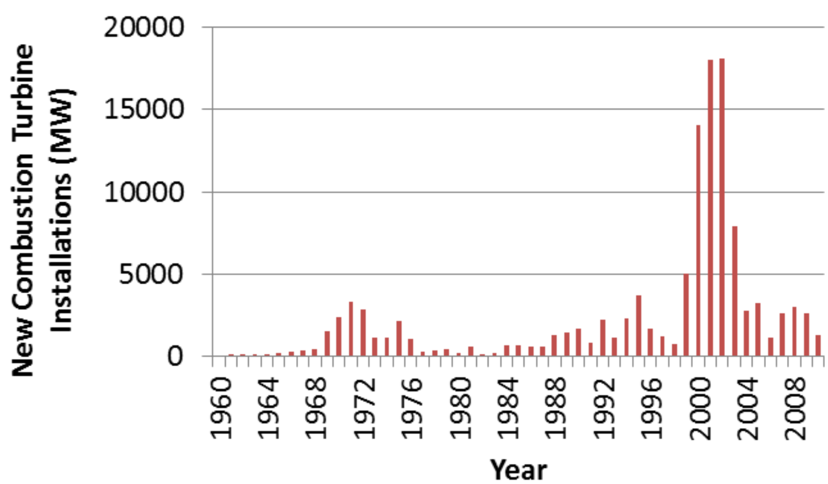

Figure 46. Newly installed combustion turbine capacity by year

While cost and supply align well, there are technical aspects that must be considered as well. First, peaker plants are megawatt-scale facilities. A 5 kWh-nameplate PEV module operated at 50% DOD to a 5-hour discharge would only output 500 W. Thus, approximately 2,000 of these modules must be interconnected to provide every 1 MW of plant output, which could entail significant additional cost. A second consideration is asset lifetime. Utilities have come to expect their assets to last 20 years or more. Even where second use batteries can achieve a 10-year service life, they fall well short of this expectation. Thus, for such a strategy to be successful, where a utility owns the peaker plant, it will need to either adapt to shorter asset lifetimes or purchase battery capacity as a service.

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6 Case Study

A simple case study was prepared to illustrate a potential future scenario for second use batteries. The findings from the previous investigations guided selections of assumptions throughout.

To forecast degradation in second use batteries, two assumptions of Section 2.1 were modified to better suit the expected duty cycle of a battery replacing a combustion turbine peaker plant. First, the battery performs a 5-hour constant power, 60% DOD (nameplate) discharge 104 days per year. This is intended to represent daily discharging in the summer where demand is generally at its highest. It corresponds to a 6% capacity factor, approximately equal to the average observed capacity factor of combustion turbines in recent years [98]. Second, to reduce degradation due to calendar effects, the battery is assumed to be stored between discharges in an end-of-discharge condition, waiting to begin recharging until 24 hours prior to the following discharge on the assumption that the activity of a peaker plant is reasonably predictable. Charging is done at constant power equal to that of the discharge, followed by a constant voltage charge to reach 100% SOC.

Simulating this scenario shows that repurposed BEV75 batteries from a moderate Los Angeles climate can regularly provide a full 10 years of second use peaker plant replacement service. In only three of the 91 simulated cases (corresponding to different automotive histories), the repurposed batteries did not last for 10 years, but none provided less than 9.1 years of second use service. Simulated repurposed PHEV20 batteries from the same climate provided a median second use peaker plant replacement service life of 8.5 years. Thirty-seven percent of cases exceeded 9 years of service, and 21% exceeded 10 years. Note that the reduced cycling (twice per week vs. once per day) and improved SOC management significantly improved second use service life relative to the 60% DOD results of Section 3.1, which predicted 4.0 and 2.7 year second use service lifetimes for repurposed BEV75 and PHEV20 batteries from Los Angeles, respectively.

For a 10-year life and 5-hour duration, Figure 44 reveals that the most favorable peaker plant replacement conditions yield an allowable battery cost of $106/kWh-available. This is the maximum value a peaker plant operator could pay up to purchase repurposed BEV75 batteries. The minimum-cost repurposing scenario in Section 4.10 for 5 kWh-nameplate modules, which included employing onboard diagnostic algorithms to quantify the remaining capacity and identify faulty cells at the end of automotive service, reported a repurposing cost of $20.71/kWh-nameplate. Combined, these values imply a maximum salvage value of $42.89/kWh-nameplate. For a 25-kWh BEV, selling its battery at the end of the automobile's life would then translate to a best-case total payment to the battery owner of $1,072.

To compare the supply of used batteries with the market potential for peaker plant replacements, maximum and minimum B2U battery deployment scenarios were created from the maximum and minimum PEV deployments of Section 2.4, assuming an average PEV battery size of 21 kWh-nameplate, and that 90% of PEV batteries are repurposed and deployed to second use service at a 60% DOD and last for 10 years. Available B2U energy was translated to peaker plant capacity by dividing by an anticipated 5 hour system duration. These forecasts for B2U peaker plant capacity were then compared to the EIA-forecasted deployment of combustion turbine and diesel generators [97], presented here in Figure 47.

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While the EIA forecast [97] for operational combustion turbines and diesel generators only extends to 2040, these findings imply that there is minimal risk of market saturation under any of these conditions. The EIA projects approximately 3.7 GW of new combustion turbine and diesel generator capacity will be installed annually from 2020 to 2040. In contrast, the minimum deployment scenario projects a maximum 5-hour B2U peaker plant capacity growth rate of only 1.14 GW per year in 2048. While our maximum deployment scenario predicts a much more rapid maximum growth rate 11.8 GW per year in 2055, battery capacity levels off at 152 GW in 2064, much lower than EIA's anticipated 220-GW market for combustion turbines and diesel generators in 2040.

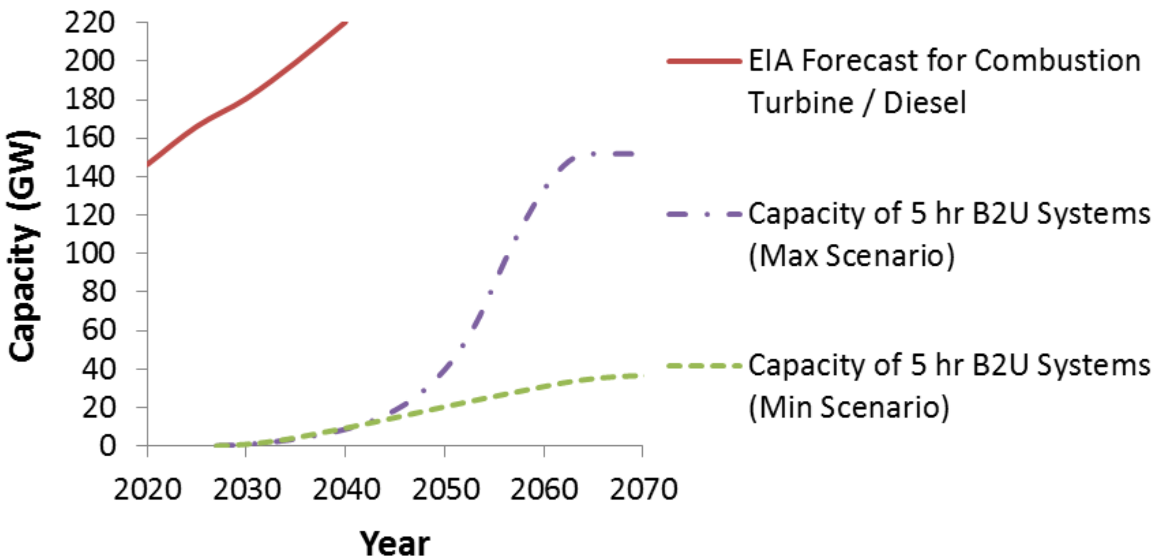

Figure 47. Comparison of forecasted market for combustion turbines and diesel generators with forecasted availability of 5-hour second-use ESS

Given that projected amount of B2U peaker plants is large in an absolute sense, but remains a relatively small fraction of total peaker plants, it is quite possible that the use of the highest allowable battery costs from Figure 44 is justifiable (e.g., BOS costs will be low, and batteries will only replace the most expensive combustion turbines). Thus, the results of this case study suggest that second use of automotive batteries as peaker plant replacements is viable. At the assumed 5-hour duration, the economics to the peaker plant operator and battery repurposer incentivize second use. The predicted salvage values also incentivize election of second use by the automotive battery owner where battery recycling and battery disposal options are economically less attractive. Further, the peaker plant market appears to be large enough to consume the supply of second use batteries under all assumed PEV deployment scenarios, although further investigation into required durations is necessary.

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7 Conclusions and Recommendations

Early in this second use study, three key high-level questions pertaining to the viability of second use were identified. The answers suggest that second use of PEV batteries is indeed viable and valuable. A number of sensitivities that could potentially change these conclusions were identified. These questions, answers, and sensitivities, are summarized below. Subsequently, recommendations are made to address the identified sensitivities in a manner that will foster the implementation of battery second use strategies in the future.

7.1 Questions Answered

1. **When will used automotive batteries become available, and how healthy will they be?**

   A detailed analysis was conducted of battery degradation in automotive service, of the economics of battery replacement in automotive service, and of battery degradation in a second use. The results show that there is little to no economic incentive to replace a PEV battery prior to the end of the original vehicle's service life. At the end of a 15-year vehicle service life, the battery will have approximately 70% of its initial capacity remaining when made available for a second use.

   However, quantifying the remaining *value* requires assessment of how long this battery will last in a second use application. Where battery cycling is diurnal, our studies showed this to be highly sensitive to the DOD. Climate, battery thermal management, and other factors can have a large impact as well. Answering this question of battery health is therefore quite complex, and the results can be highly variable. It is therefore necessary to know the operational requirements of the ultimate second use application.

   Optimizing remaining value for our anticipated peaker plant replacement application suggested that second use lifetimes could readily exceed 10 years when operated at a 60% DOD. At this point, it becomes necessary to consider other wear mechanisms beyond the electrochemical ones represented in the battery degradation model employed herein (e.g., corrosion of metallic cell interconnects, fracture of plastic housing components, failure of cell sealing).

2. **What is required to repurpose used automotive batteries, and how much will it cost?**

   Application of a battery repurposer business model illustrated the necessities of battery repurposing and the sensitivity of repurposing costs to several factors. A repurposing facility can likely be dedicated to batteries from a single model of PEV, avoiding the complexities of repurposing heterogeneous batteries. Operating such a facility on a regional level is sufficient to achieve the necessary economies of scale to minimize cost, while also avoiding the added costs of nationwide battery collection.

   Inside the facility, minimizing technician labor with streamlined processes and minimal battery handling and inspection is key to minimizing overall repurposing costs. Where it is economically impractical to replace faulty cells within modules, as the results herein suggest it will be, maintaining high yields is also important. This can be done by optimizing module size, but such a decision may not be up to the repurposer. Minimizing

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purchases of modules containing faulty cells by making use of available vehicle diagnostics data may therefore be critical to second use viability. Such data may also be applied to identifying overall module capacity, which is a good predictor of second use service life. Accordingly, one of the best things an automotive OEM can do today to support future second use is to include proper diagnostic tools with the battery management system, and to make that data available to repurposers in the future.

3. **How will repurposed automotive batteries be used, how long will they last, and what is their value?**

   To identify suitable applications for second use batteries, both economic (cost of repurposed batteries, value of service provided) and market size (supply of repurposed batteries, demand for service) factors have been addressed. It was found that the demand for storage in a given market (among those relevant to second use batteries) generally scales inversely with the price that it can bear, i.e., markets with large demand can only afford to buy very cheap storage, and vice versa. Further, the potential supply of second use batteries may be large enough to quickly saturate many markets for storage commonly discussed today.

   The most promising application identified for second use batteries is to replace grid-connected combustion turbine peaker plants and provide peak-shaving services. In comparison to automotive service, use in this application will entail relatively benign duty cycles, generally much less than one cycle per day with discharge durations of greater than one hour. Under these conditions, it is anticipated that second use battery lifetimes will be on the order of 10 years.

   The market appears large enough to consume the majority, if not all, of available second use batteries for the foreseeable future, while being valuable enough to support the cost of battery extraction and repurposing. While the value to the original automotive battery owner is restricted primarily to the elimination of end of service costs (battery extraction, disposal, recycling, etc.), the value to the broader community could be significant: reduction of greenhouse gas emissions and fossil fuel consumption, decreased cost and increased reliability of electricity service, and deferral of battery recycling.

7.2 Sensitivities

Together, the answers to these questions suggest that the second use of PEV batteries is both viable and valuable. However, the economic margins that make second use viable are often small, and thus several factors could affect this conclusion. Five primary factors could significantly affect our results, summarized below.

1. **Availability of Onboard Diagnostic Data**

   Applying vehicular use data to identify the presence of faulty cells and quantify the overall battery SOH can provide considerable value to repurposers with minimal cost to automotive OEMs. The availability of this data could be an outright enabler of second use; without it, the economics of PEV battery repurposing may prove too risky for many business ventures to undertake. It is not clear at present whether automotive OEMs are

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including adequate capability in this area or whether they will be willing to share the SOH estimates calculated by these systems with repurposers.

2. **Second Use Battery Lifetime**

   Battery degradation varies with many factors, not the least of which is chemistry. Our analysis herein has investigated only one type of Li-ion battery chemistry (nickel cobalt aluminum cathode, graphite anode), and thus it may prove that the degradation model does not provide accurate results for those chemistries that may dominate in future PEV deployments. This could strongly affect average battery lifetimes both in automotive and second life service, which will in turn impact economics.

3. **ESS BOS and Installation Costs**

   Under our assumed conditions, the cost of repurposed batteries for a 5-hour ESS constitutes only 24% of the total system cost. The inverter constitutes only 13%. Thus, 63% of costs are attributed to ESS BOS and installation costs. The early market data employed for quantifying these costs herein may be uncertain [88], and thus these values may change considerably as energy storage markets mature. With continued development and large-scale deployment of second use battery systems as peaker plant replacements, these values would likely fall, increasing margins and making it more likely second use batteries will be deployed in these applications. It is also possible that unaccounted for systems integration costs specific to repurposed batteries could increase these costs.

4. **Value and Market Size of Applications**

   Our forecasts of second use battery supply suggest that substantial numbers of repurposed batteries will not become available until 2030 or later. Between now and then, the markets for energy storage could change considerably. This could affect the demand, supportable price point, and operational requirements applied to second use batteries. Further, the cost of competing technologies (natural gas, battery technology, etc.) is highly uncertain and will affect the economic attractiveness of repurposed batteries.

7.3 Recommendations

Many of these sensitivities can be addressed before major investment into second use infrastructure is made. Below we list our recommendations by major stakeholder, noting that there may be considerable overlap in some areas (e.g., an automotive OEM may also elect to be the repurposer; the repurposer may also be the systems integrator).

- **Automotive and Battery OEMs**

  Automotive and battery OEMs should include onboard diagnostic capabilities that accurately track the capacity of individual cells (or parallel groups thereof) and pledge to share this data with repurposers. This will enable accurate identification of a battery's value and its viability for second use service. In addition, degradation and related statistics from automotive service should be quantified and shared.

- **Systems Integrators and Installers**

  Systems integrators and installers should work to develop large megawatt-scale ESS solutions for repurposed PEV batteries that minimize integration, BOS, and installation

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costs. These systems should monitor the health of individual modules and enable efficient replacement of individual faulty or end-of-life modules in the field.

- **Utilities and Regulators**

  Utilities and regulators should develop policies that encourage the use of ESS, particularly as peaker plant replacements, and that will support access to sufficiently large markets for repurposed batteries. Guidelines should be defined for minimum required system durations in these roles. Enabling the use of assets with durations as little as 1 hour would also be helpful. Demonstrating both new and repurposed batteries in these roles will be critical.

- **Laboratories, Universities, Future Repurposers, and other Third Parties**

  Battery degradation in both the automotive and second use environments is a critical uncertainty in the analysis of B2U strategies. Quantifying degradation of battery packs in first and second uses and developing tools to assess SOH and predict future battery degradation are therefore of great value to the field. Repurposing processed batteries should be demonstrated to confirm that a product of adequate reliability can be provided at low cost. Life cycle analyses that show the overall benefit to society of B2U strategies are important to demonstrate value that may not be captured in economic calculations.

7.4 Closing Thoughts

Significant B2U research and development obstacles remain to be overcome. Primary among these are the issues of accurately gauging battery health from automotive service data and forecasting battery performance and degradation in the second life, which will be critical to reducing the risks associated with B2U business ventures. Furthermore, balance of systems and installations costs for B2U ESSs must be minimized, and the market for using these systems as peaker plant replacements on the grid must be developed. This latter endeavor will likely be challenged by regulatory structures, and could require changes to how the electricity grid is operated in order to accommodate energy-limited devices not accustomed to such constraints

If these questions can be answered, it is quite possible that B2U could become an important part of both the automotive and electricity industries, however. While our analyses suggest that B2U has little ability to reduce the upfront cost of PEVs, it can eliminate end-of-service costs for the automotive battery owner and provide low- to zero-emission peaking services to electric utilities, reducing cost, use of fossil fuels, and greenhouse gas emissions. Thus, the overall benefit to society can be quite large. The authors are hopeful that government, industry, and academia will recognize these benefits and continue to push this important research area forward.

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