Final Draft

Public Interest Energy Research (PIER) Program

FINAL PROJECT REPORT

Analysis of the Combined Vehicle- and Post-Vehicle-Use Value of Lithium-Ion Plug-In-Vehicle Propulsion Batteries

Task 3, Second Life Applications and Value of 'Traction' Lithium Batteries

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Of course, the authors are responsible for the contents of this paper.

PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- Renewable Energy Technologies
- Transportation

Analysis of the Combined Vehicle- and Post-Vehicle-Use Value of Lithium-Ion Plug-In-Vehicle Propulsion Batteries is the final report for Task 3 of the Second Life Applications and Value of 'Traction' Lithium Batteries project (contract number 500 - 02 - 004, work authorization number [insert #] or grant number [insert #]) conducted by UC Berkeley's Transportation Sustainability Research Center. The information from this project contributes to PIER's Transportation Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

Advances in electric-drive technology, including lithium-ion batteries, as well as the development of strong policy drivers such as California's Global Warming Solutions Act, now contribute to a more promising market environment for the widespread introduction of plug-in vehicles in California. Nevertheless, battery costs remain high and uncertain, presenting significant hurdles to commercialization.

This report builds upon previous research (CEC-500-2009-091) investigating the potential reduction in plug-in-hybrid battery lease payments that incorporation of value from post-vehicle provision of grid energy storage services in California might provide. That work discussed the potential to lower battery lease payments by repurposing used vehicle batteries for stationary use as grid-support, distributed electrical storage devices. Such devices, if realized as home energy storage appliances (HESAs), might not only provide valuable services needed by existing statewide grid-support markets, but could also provide customer-side-of-the-meter benefits, improve utility operation, help defer costly grid upgrades, and potentially support the profitability and penetration of intermittent renewable energy.

This report advances methods for analyzing combined vehicular and post-vehicular value using specific plug-in electric vehicle examples, incorporates new and more sophisticated inputs based on a growing body of knowledge, and describes lessons learned about testing and repurposing vehicle batteries for post-vehicle use. It analyzes offsetting plug-in-vehicle battery costs with value derived from post-vehicle stationary use, quantifying the possible effect the net-present-value of several of these benefits might have on battery lease payments.

This analysis finds positive but modest potential benefits from repurposing batteries into energy-storage devices sized in accordance with their degraded vehicle capacity. Bounding scenarios all show battery lease payment reductions. For the "Chevy Volt"-based HESA example, which exhibited a 22% reduction in the base case, the bounding scenarios ranged from 1% to 32%. Monte Carlo analysis indicates the point estimates developed throughout might need upwards adjustment to account for uncertainty, possibly negating second-life benefit in the base case.

The analysis indicates that, if valuable grid-regulation revenues are hotly contested and provide limited impetus to HESA commercialization, value from multiple applications is necessary to support HESA profitability. This makes the artful combination of services (and thus duty cycles/load profiles) a critical uncertainty. One previously identified combined value proposition related to servicing local air conditioning loads was examined as the base case and might be particularly attractive. Another important uncertainty is the level of cost associated with power-conditioning requirements, which must also be optimized with increasingly specific combined load profiles in mind and/or reduced, e.g., through coupling HESAs with local photovoltaic systems.

Keywords: plug-in hybrid, PHEV, electric fuel, electric vehicle, EV, plug-in electric vehicle, PEV, battery cost, battery lease, energy storage, repurposing, secondary use, ancillary services, grid storage, area regulation, second life, distributed energy storage, grid services, lithium-ion batteries

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EXECUTIVE SUMMARY

Introduction

The core problem motivating the analysis is that battery first costs present a major barrier to the widespread commercialization of plug-in, electric-fuel (e-fuel) vehicles. This report builds upon previous research (CEC-500-2009-091) investigating the potential reduction in plug-in-hybrid battery lease payments that incorporation of value from post-vehicle provision of distributed grid energy storage services in California might provide. Such devices, if realized as home energy storage appliances (HESAs), might not only provide valuable services needed by existing statewide grid-support markets, but could also provide customer-side-of-the-meter benefits, improve utility operation, help defer costly grid upgrades, and potentially support the profitability and penetration of intermittent renewable energy.

Many other potential application values were not quantified in that previous work, and thus it was not only a preliminary but also a partial picture. This report advances methods for analyzing combined vehicular and post-vehicular value using specific vehicle examples, incorporates new and more sophisticated inputs based on a growing body of knowledge, and describes lessons learned about testing and repurposing vehicle batteries for post-vehicle use.

Scope

This work supplements Task 1 and 2 efforts (under separate CEC contract with the California Center for Sustainable Energy or CCSE), which focus more on the utility perspective on using Community Energy Storage (CES) in existing market structures. This Task 3 effort focuses more on system-level cost and benefits, and on the home energy storage appliance, per the project's initial Request For Proposals language. It is important to note that Task 3 is an estimate and optimization of value. It is not a competitive analysis, which would place the value of the HESA in context relative to: 1) a spectrum of other product lenses through which energy storage opportunities might be viewed (e.g., traditional generation resources vs. bulk energy storage vs. industrial, commercial, and residential distributed energy storage vs. smart charging vs. vehicle-to-grid power) and 2) a variety of technologies competing within each product definition (e.g., lithium-ion batteries vs. flow batteries vs. compressed-air storage). Task 3 is also not a specific business-case analysis, which would shed more light on who incurs the costs, who receives the benefits, and how the markets are and might be structured and accessed.

First life: plug-in electric vehicle energy storage

This analysis is based on a spreadsheet model that uses a drop-down menu of "vehicles" to select a set of relevant values or vehicle characteristics. Three such vehicle approximations form the basis of discussion and are generally detailed throughout the report: the Toyota Prius PHV, the Chevy Volt, and the Nissan LEAF. As a starting point, it is further assumed that all vehicle batteries will have approximately 80% of their capacity after approximately 8 years, on average—consistent with the warranty periods for the Volt and LEAF [1, 2], and with the USABC end-of-life criteria for electric vehicles [3]. The implications of this "80% at 8 years" starting-point assumption, including testing a wide range of percentage and other assumptions using Monte Carlo analysis, are explored in greater detail in Chapter 5.

Battery cost and lease payments

Table E-1 summarizes estimates for battery costs and equivalent lease payments. "Battery" is defined here to mean only the modules, a minimal management system (e.g., for voltage, temperature, and other monitoring, balancing, and protection), and integral structure/interfaces that will be removed from the vehicle and repurposed for use in second life, i.e., integrated modules. This does not include the supporting balance-of-pack components that will remain behind in the vehicle (e.g., the vehicle-integrated thermal management components, AC charger, DC-DC converter, crash sensors, power conditioning, vehicle-level pack management systems, etc.).

Table E-1: Battery-cost and lease-estimate summary

	PHV	Volt	LEAF
Cost per available kWh	$732	$585	$585
Cost of balance of module system carried into 2nd life	~$1,390	~$2,040	~$3,040
Total battery cost	~$4,240	~$8,130	~$15,000
Battery lease payment (per month over 8 years)	$64	$122	$225

These lease payments are still a significant premium to pay on top of the vehicle financing for a vehicle with recharge capability. How might this situation be further improved? The potential value that might be derivable from a battery's second life is explored in Chapter 4, and the process of repurposing the battery for second life is explored in Chapter 3.

Repurposing

Used plug-in vehicle batteries intended for second-life use will need to be tested, sorted, and certified as part of the repurposing process. Given the expected variation in battery degradation at the module level (with underlying variation at the cell level), there is a spectrum of potential battery repurposing strategies that could be considered. These include different levels of intrusion into the battery and associated processing costs. Building on previous work (e.g., [4, 5]) Chapter 3 develops four repurposing scenarios and focuses on Scenario 1 "low repurposing cost":

<u>Scenario 1: Low repurposing cost (HESA base case)</u>

- receive used batteries at repurposing facility
- visually examine battery modules for physical damage, leaks, and signs of abuse
- examine data from battery/module management system (BMS) health meter or "cloud based" data storage, if any
- conduct initial voltage and resistance measurements to identify failing or failed modules
- remove failed modules for possible refurbishment, cell reconditioning (see Strategy 3), or recycling
- replace removed modules with suitable ones sorted by capacity, power capability limits, and calendar age
- repackage modules for use in HESA units with existing balance of battery systems
- conduct additional testing of apparently "good" HESA battery systems to verify condition

Battery testing recommendations have been developed by Cready *et al*. for Sandia National Laboratory in 2002 [4] as well as more recently by Cessna and Velev at AeroVironment, Inc. for Task 1 and 2 of this project [5].

The "certified, pre-owned" batteries would need to be tested and certified as safe stationary energy storage according to the relevant standards organizations. Key certifications that will be required of HESA and other grid-connected storage devices include the IEEE 1547, suite of standards for distributed resource interconnection, a related and harmonized Underwriters Laboratories (UL) 1741 standard, and the ANSI/IEEE 62.41 standard for surge withstand testing.

Home energy storage appliance costs

Cready *et al*. [4] estimated the costs for a repurposing facility covering one of California's four major metropolitan areas and capable of repurposing roughly 2,880 battery packs per year, including collection (truck and driver), testing, materials handling, facilities costs, various forms of overhead, etc. Batteries from each of the vehicles analyzed are burdened with these costs (inflated to Year 2010 dollars), as well as $500 per battery to cover the cost of dismounting the battery from the vehicle (e.g., at the dealership during a major tune-up). Using the Volt case as an example, these repurposing costs amount to less than 30% of expected new-Volt-battery costs in a scenario of rapidly declining new-battery costs. The repurposing costs are summarized in Table E-2 along with the rest of the cost components required for assembly, installation, and operation & maintenance of HESAs based on the three vehicle batteries analyzed.

Table E-2: Energy storage appliance cost estimates (rounded)

ESA cost component	Basis	PHV 3kWh/6kW	Volt 8kWh/16kW	LEAF 16kWh/32kW
Battery (modules+mgt. system)	Repurposing cost	$744	$1,150	$1,780
Power conditioning, controls, interfaces	Inflated $442/kW=CreadyEtAl'02 max. for fully-capable bulk storage	$3,310	$8,830	$17,300[1]
Accessories, facilities, shipping, catch-all	Inflated $117/kWh=CreadyEtAl'02 for load leveling, arbitrage, and transmission deferral facility at Chino	$442	$1,170	$2,290
10-year operation and maintenance	NPV($18/kW-y)=Chino facility. Compare to $102/y for residential load following	$828	$2,210	$4,330
Installation, residential circuitry	EVSE-style installation costs (sans charger), based on max. power	$800	$2,000	$4,300
	Total HESA cost	**$6,120**	**$15,400**	**$30,000**

[1] Compare to a $20,500 31 March 2011 quote on energybay.org for a 30-kW, 480V SatCon PVS-30 inverter.

Second life: distributed grid energy storage

One taxonomy of the gross benefit provided by grid energy storage is presented in a 2010 report for Sandia National Laboratories by Eyer and Corey [6] and is grouped into five categories: Electric Supply, Ancillary Services, the Grid System, End User / Utility Customer, and Renewables Integration. Building on this framework, Table E-3 presents a menu of single-application, system-wide benefit values that would accrue in California were HESA devices using repurposed batteries from various plug-in-vehicle batteries used in each of the applications. Each value is the net-present-value of 10 years of application. The assumed HESA power capabilities have been capped to avoid disproportionate benefit estimation and to minimize potential associated battery degradation effects by confining the batteries to more modest dis/charge rates than designed for in the car.

Table E-3: Menu of potential second-life energy storage gross benefits* per HESA (rounded)

Application	PHV	Volt	LEAF
Electric Energy Time-shift	$330	$880	$1,720
Electric Supply Capacity	$320	$850	$1,670
Load Following	$800	$2,130	$4,180
Area Regulation	$8,720	$23,250	$45,610
Electric Supply Reserve Capacity	$280	$750	$1,470
Voltage Support	$2,870	$7,670	$15,040
Transmission Support	$1,200	$3,190	$6,270
Transmission Congestion Relief	$60	$150	$300
T&D Upgrade Deferral 50th percentile†	$2,790	$7,430	$14,580
T&D Upgrade Deferral 90th percentile†	$4,390	$11,690	$22,940
Substation On-site Power	$600	$1,600	$3,130
Time-of-use Energy Cost Management	$730	$1,960	$3,840
Demand Charge Management	$220	$580	$1,140
Electric Service Reliability	$3,700	$9,860	$19,340
Electric Service Power Quality	$4,170	$11,120	$21,820
Renewables Energy Time-shift	$230	$620	$1,220
Renewables Capacity Firming	$810	$2,160	$4,240
Wind Generation Grid Integration, Short Duration	$4,680	$12,480	$24,480
Wind Generation Grid Integration, Long Duration	$380	$1,000	$1,970

* lifecycle benefit over 10 years, with 2.5% escalation and 10% discount rate
† converted here to approximate 10 years of benefit to be comparable to other applications, but this is not likely at a single location

The single application with the largest potential benefit per device is, in each case, area regulation, which is discussed in detail in Chapter 4. Though the potential regulation value per HESA in California appears compelling, the competition for regulation revenues may be high and the overall potential of the market to sustain high value and/or a large number of Volt-based HESAs may be limited. For this reason, various multi-application value propositions are explored in Chapter 4. One potentially valuable combination is summarized in Table E-4 using the Volt-based HESA example.

Table E-4: Value proposition benefit: Volt estimate summary (rounded)

Eyer&Corey'10 Value Proposition	Sum (double counting)	Total: 90% of biggest, 50% of rest	Total -10% aggregation fee
storage to service small A/C loads = voltage support + e-supply reserve capacity + load following + transmission congestion relief + e- service reliability + e- service power quality + renewables energy time-shift	$32,400	$20,700	$18,600

Table E-4 indicates that a promising use of HESAs might be to prioritize electric service power quality in the context of serving small air-conditioning loads. A related opportunity for highly-distributed energy storage, currently under development in a project lead by Solar City using Tesla batteries would firm the output of local photovoltaic installations. If done at the household meter level, this might be particularly appropriate for a home energy storage device and would presumably spread many of the HESA costs (e.g., power conditioning) over both PV and energy-storage applications.

Integrating results, uncertainty & sensitivities, and alternative scenarios

Table E-5 combines the results and shows the impact the net residual value from the "small A/C load" multi-application value proposition has on the battery lease payment. It also calculates the simple net-present value (NPV) of the second-life residual value, bringing it forward from year 8 to year 1 using a 10% discount rate. Recall that both the effect on the battery lease payment and the NPV of the second-life net value are used as indicators of total-system net benefit, not specific business models. As such, any decrease in the lease amount will not necessarily pass solely to the vehicle purchaser, but rather will be shared by those parties necessary to implement the value proposition whose interests have not been explicitly or sufficiently[2] accounted for here—notably both the vehicle and HESA consumers, but possibly also the automaker (for any extra efforts that may be necessary to facilitate second-life use).

[2] Parties whose requirements have been explicitly, though not necessarily fully or accurately, covered include at a minimum the HESA service aggregator, the HESA producer, and the battery manufacturer.

Table E-5: Net residual value summary (rounded)

	PHV	Volt	LEAF
Total battery cost	$4,240	$8,130	$15,000
Battery lease payment (per month over 8 years)	$64	$122	$225
10-year 2nd-life value	$6,970	$18,600	$36,500
HESA cost	$6,120	$15,400	$30,000
Net benefit = residual value	$850	$3,230	$6,450
8-year battery lease payment with 10-year 2nd-life residual value	$57	$95	$172
NPV (residual value, 10% discount rate)	$397	$1,510	$3,010

The values presented in Table E-5 are positive but some are modest, particularly when comparing the battery lease payments with and without second-life net benefit. However, many of the inputs are uncertain.

Uncertainties and sensitivities

To explore the importance of various input assumptions on the battery lease payment, a Monte Carlo simulation of 50,000 trials was run using Oracle's Crystal Ball software. In contrast to the point-estimate of $95 per month for the Volt battery lease payment, the simulation produced a relatively symmetrical beta distribution with a mean of $132 and a 95% confidence interval ranging from $74 to $193. This suggests that the lease-payment values may be somewhat higher than the point estimates indicate.

The two dominant uncertainties, accounting for over three-fourths of the variation in the simulation, were 1) the "% of rest" parameter characterizing the amount of value captured from the non-priority application in the multi-application value proposition, and 3) the parameter characterizing the variable cost of HESA power conditioning, controls, and interfaces. Clearly, the artful combination of value in multi-application value propositions is critical to Volt-based HESA profitability: if the HESA were able to only capture the benefit from the single-most valuable application in the group, the costs would outweight the benefits, causing the battery lease payment to rise, not fall.

The cost of replacing the HESA batteries mid-deployment warrants further investigation. As a simplistic starting point, leasing two Volt-type batteries up-front would cost $244 per month. That is reduced to $223 per month using one HESA required to bear battery repurposing costs in second-life years 1 and 5.

On the other hand, shortening the initial deployment of the battery in the vehicle does not appear to be helpful: the benefit increase due to making more battery capacity available to second life is outweighed by the increase in costs from shortening the first-life battery lease term.

Two bounding scenarios were also developed. Combining all of the unfavorable assumptions for the Volt-HESA case results in a scenario with very modest movement in the battery lease: from $145/month to $140/month. Combining all of the favorable assumptions produces a scenario with a roughly 32% reduction: from $104/month to $71/month.

Conclusions

This analysis finds positive but somewhat modest potential benefits from repurposing batteries into energy-storage devices sized in accordance with their degraded vehicle capacity. Bounding estimates for the Volt-based HESA, which exhibited a roughly 22% reduction in battery lease with the addition of second-life benefit as residual value, all show battery lease payment reductions, ranging from roughly 1% to 32%. On the other hand, Monte Carlo analysis indicates the base-case point estimates of lease payment developed might need upwards adjustment to account for the effects of uncertainty, possibly negating the benefit from repurposing.

It is unclear if the potential benefits characterized above will ultimately provide sufficient impetus to create the policies, business channels, and other elements necessary to establish markets for used-battery HESAs, let alone drive the commercialization of plug-in vehicles to any great extent, at least initially[3].

To the extent that efforts to improve the prospects for energy storage in general are successful, they will raise the tide for repurposed plug-in-vehicle batteries, whose fully burdened costs have not been shown to be a weak link in the overall value proposition and are estimated to be several times cheaper than the maximum allowable limit defined by new-battery costs (see Chapter 3). Thus, possibly even if requiring replacement to match the longevity of new batteries with similar capacity, the use of used batteries may still be a viable alternative for whatever overall value propositions develop into profitability. This coupled with the continuing need to find appropriate and valuable uses for plug-in-vehicle batteries at the end of their vehicle life motivates further investigation. "Proceed, but proceed with caution" may be one appropriate take-home conclusion. Further, the analysis thus far pre-supposes a reasonable but specific context that may be subject to considerable change in the future as the transportation and energy industries slowly collide. The continuing development of unprecedented and major policy drivers in California and the evolution of socio-political contexts will have important implications for energy and climate policy, innovations, and business development. With this in mind, and informed by the dynamics laid out above, future work should also ask, "How might things look differently?" in order to explore how alternative policy futures could impact the battery second-use value proposition.

Several directions for future work are discussed at the end of Chapter 5.

[3] *NB*: Of course, plug-in vehicles—like hybrids before them, which are by most accounts commercially successful but have yet to exceed 10% of sales even in California—face a long, possibly multi-staged road to widespread commercialization. Even if not capable of assisting with initial introduction, second-life value has the opportunity to lower costs in subsequent scale-up stages.

CHAPTER 1: Introduction

Problem statement & project background

The core problem motivating the analysis is that battery first costs present a major barrier to the widespread commercialization of plug-in, electric-fuel (e-fuel) vehicles. Faced with battery cost and design challenges, the extent to which e-fuel vehicles can be commercialized to the masses remains uncertain.

As described in precursor work to this project [7], several strategies working in concert could be employed to alter the commercialization picture for e-fuel vehicles in California. Like the vehicles they help, these strategies straddle automotive and electrical-energy worlds, embracing their convergence. They include: optimized battery sizing, standardization, leasing, potentially shortened initial vehicle deployment, and repurposing/down-cycling into stationary use for building and grid-support services. Leasing and third-party or other non-conventional battery ownership arrangements—e.g., utility rate basing—might not only align incentives for battery improvements and full and responsible use, but may allow the net-present-value of battery services to be accounted for in the initial vehicle transaction, lowering costs, and easing initial design and commercialization expectations.

Many other potential application values were not quantified in that previous work, and thus it was not only a preliminary but also a partial picture. Previous studies [4, 6, 8] lay foundations for evaluating dozens of these potential applications. A 2002 Sandia National Laboratory study [4] focused on nickel-metal-hydride (NiMH) batteries, but suggested that some of the results are likely to be broadly applicable to other chemistries. A 2010 study for Sandia National Labs [6], provides a thorough, high-level examination of energy storage applications independent of energy storage technology or product type. This report further incorporates and builds upon those studies and a growing body of knowledge surrounding opportunities of distributed energy storage in general, and the potential use of repurposed plug-in-vehicle batteries in particular.

Additionally, many types of related value (~207 in total) not addressed here are discussed using a different framework in *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size* [8], presenting an ever broadening vision of the opportunities ahead that remained to be explored. Further, as this project progressed, several related activities exploring battery second-use with real-world demonstration and R&D efforts were announced and/or underway. Many of these activities could not be accessed or incorporated fully into this effort, but they include those by GM and ABB for used Chevy Volt batteries, Solar City with Tesla and the University of California at Berkeley, EnerDel with Itochu, DTE with A123, and Nissan with Sumitomo in an effort called 4R Energy [9-12]. These efforts will provide an increasingly clearer understanding of the technical challenges and performance levels expected from batteries in various second-life contexts.

Of course, the realization of these many potential benefits is predicated upon several assumptions and pre-conditions, requiring coordination, standardization, code and safety-procedure development, and granting such units access to several existing and future markets. Initial policy steps already identified and underway would allow or improve the strategies like those described here, including: modifying certificating procedures to include battery storage devices as CAISO generating units, further rewarding fast-response units in proportion to their operational and other benefits, and providing investment incentives [13].

If determined to provide sufficient value, repurposing vehicle batteries for stationary use (including infrastructure) might improve the commercialization prospects of plug-in vehicles, strengthening the ever-tightening connections between transportation and stationary energy and might help to launch a new era of electric-fuel technologies. However, much work remains to be done to better understand, let alone realize, the potential of such strategies.

Overall project goals

In addition to the challenges addressed by Tasks 1 and 2 of the overall project "Second Life Applications and Value of 'Traction' Lithium Batteries," Task 3 aims to provide better understanding of both the potential requirements for and the potential benefits of repurposing vehicular propulsion batteries for post-vehicle use as home energy storage appliances (HESAs). It incorporates and advances a growing body of knowledge into an economic analysis of battery repurposing and combined vehicular and post-vehicular use.

Scope limitations

This work supplements Task 1 and 2 efforts (under separate CEC contract with the California Center for Sustainable Energy or CCSE), which focus more on the utility perspective on using Community Energy Storage (CES) in existing market structures. Task 3 focuses more on system-level cost and benefits, and on the HESA, per the project's initial Request For Proposals language.

Many important questions and lines of inquiry are outside of the scope of Task 3 analysis. Their description here not only helps clarify Task 3 activities, but suggest important steps for desired subsequent work. When considering the work presented in this report, please consider the following caveats and points of clarification.

First, Task 3 is an estimate and optimization of value. It is not a competitive analysis, which would place the value of the HESA in context relative to: 1) a spectrum of other product lenses through which energy storage opportunities might be viewed (e.g., traditional generation resources vs. bulk energy storage vs. industrial, commercial, and residential distributed energy storage vs. smart charging vs. vehicle-to-grid power) and 2) a variety of technologies competing within each product definition (e.g., lithium-ion batteries vs. flow batteries vs. compressed-air storage). Second, Task 3 is not a specific business-case analysis, which would shed more light on who incurs the costs, who receives the benefits, and how the markets are and might be structured and accessed. Thus, Task 3 stops short of being a full implementation analysis describing how the HESA business case might be realized through policy and/or business development.

To use an analogy, the estimate of HESA and related values developed here and elsewhere provide a sense of the overall pressure or voltage available to drive California towards realization of these opportunities, but does not describe the network of pipes or circuits through which the current must flow. Much work remains.

Glossary and explanation of terms: energy storage & secondary use

To increase the effectiveness of and coordination between the two project teams and two project management teams, it was proposed to adopt the use of the glossary found in Eyer and Corey (2010) [6], along with the following additions, modifications, and clarifications:

Application – "A specific way or ways that energy storage is used to satisfy a specific need; how/for what energy storage is used," (p. xxv). "In general terms, an *application* is a *use*, whereas a *benefit* connotes a *value*," (p. 2). Specifically, energy storage applications include [6]:

- electric supply applications: electric energy time-shift and electric supply capacity;
- ancillary services applications: load following, area regulation, electric supply reserve capacity, and voltage support;

- grid system applications: transmission support, transmission congestion relief, transmission and distribution upgrade deferral, and substation on-site power;
- end-user/utility-customer applications: time-of-use energy cost management, demand-charge management, electric service reliability, and electric service power quality; and
- renewables integration applications: renewables energy time-shift, renewables capacity firming, and wind generation grid integration.

Product – Defined here as the specific real or theoretical manifestation of an energy storage device—the means by which an application is served—as characterized by such factors as:

- ***technology*** (e.g., battery, flywheel, compressed-air);
- relative position in the electric-system from generator to load, i.e., ***distributed*** (positioned "nearer" or in greater accordance with individual loads) or ***aggregated*** (positioned "further" from individual loads, serving multiple loads, or in greater accordance with traditional generation);
- beneficiary: load ***sector*** (residential, commercial, industrial) and/or ***grid entity*** (utility and system operator) served (not mutually exclusive); and
- other descriptors of context.

Thus products are specific means by which to create value serving various applications. A home energy storage appliance (HESA) is a type of highly distributed battery storage designed to serve one residence, the utility, and the grid operator. Other product lenses through which to view electric-system- or grid-support applications include (from highly distributed to aggregated): vehicle-to-grid power, smart charging, distributed energy storage (residential, commercial, and industrial), bulk energy storage (e.g., Beacon Power flywheel facility), and traditional generation.

Note that multiple streams of value—typically monetized as financial benefit (e.g., revenues) for comparison with costs—can in principle be created in each application. Eyer and Corey handle this by 1) narrowly defining each application for suitable characterization using a single benefit, and 2) supplementing this one-to-one correspondence between applications and benefits with an additional set of "incidental" benefits [6]:

- increased asset utilization, avoided transmission and distribution energy losses, avoided transmission access charges, reduced transmission and distribution investment risk, dynamic operating benefits, power factor correction, reduced generation fossil fuel use, reduced air emissions from generation, flexibility, and incidental energy.

Further, their analysis of benefits is relatively technology-neutral, thereby ignoring certain product- and context-specific value, and they acknowledge that benefits that are not "utility-related," are not addressed explicitly. Many additional types of relevant value—both utility-related and not, incidental and otherwise (~207 in total)—are discussed using a different framework in *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size* [8] and can be drawn upon if desired to supplement the primary use of, and focus on, the Eyer and Corey work.

Secondary use – Use in addition to the primary use. Secondary uses for plug-in vehicle batteries, for which propulsion is the primary use, include not only second-life uses (see next), but also secondary uses in first life, collectively termed elsewhere "mobile electricity" [14, 15]: vehicle-to-grid power; mobile power for tools, emergencies, office-on-wheels; etc..

Second-life use (a subset of secondary uses) – Post-repurposing use, including both subsequent use in another vehicle as well as post-vehicle stationary use.

CHAPTER 2: First life: plug-in electric vehicle energy storage

Production-vehicle approximations

This analysis is based on a spreadsheet model that uses a drop-down menu of "vehicles" to select a set of relevant values or vehicle characteristics. As further detailed in the appendices, over 20 production or near-production plug-in vehicles are characterized in the model to varying degrees of fidelity. Three form the basis of discussion and are generally detailed throughout the report: the Toyota Prius PHV, the Chevy Volt, and the Nissan LEAF. Tables 2-1 through 2-3 characterize rough approximations of those three production vehicles based on available public information.

As a starting point, it is further assumed that all vehicle batteries will have approximately 80% of their capacity at the end of their average life in the car, consistent with the USABC end-of-life criteria for electric vehicles [3]. However, based on informal indications of the current status of several major-manufacturer plug-in vehicles, it is assumed that 80% capacity can reasonably be assumed to be reached after approximately 8 years, on average. This is irrespective of whether or not the OEM "design life" is longer (i.e., lower percentages—e.g., 70%—may be accommodated and other variations in approach will undoubtedly exist).

Perhaps coincidentally, 8 years is also the U.S. warranty period for both the LEAF and Volt battery packs [1, 2], providing reasonable assurance that retirement earlier than 8 years will be largely unnecessary (assuming the costs of supporting those warranties is to remain reasonable). The implications of this "80% at 8 years" starting-point assumption, including testing a wide range of percentage and other assumptions using Monte Carlo analysis, are explored in greater detail in Chapter 5.

Table 2-1: Approximation of the Toyota Prius PHV

Characteristic	PHV	Basis
Battery (rated)	5.2 kWh	[16]
Initial capacity available to driving	75% (3.9 kWh)	
Charge depleting fuel economy	36 kWh/100mi	Volt EPA rating [17]
Charge depleting (electric) range	13 mi	Assumes 82% charging efficiency
Available capacity per electric mile	0.30 kWh/mi	CD range calculation
First life	8 years	Volt and LEAF warranties [1, 2]
Rated capacity at end of design life	4.2 kWh	80%, EOL definition by USABC
Chemistry	Panasonic NCM/graphite	[18]

Table 2-2: Approximation of the Chevy Volt

Characteristic	Volt	Basis
Battery (rated)	16 kWh	[19]
Initial capacity available to driving	65% (10.4 kWh)	[19]
Charge depleting fuel economy	36 kWh/100mi	EPA rating [17]
Charge depleting (electric) range	35 mi	EPA rating [17]
Available capacity per electric mile	0.30 kWh/mi	CD range calculation
First life	8 years	Volt and LEAF warranties [1, 2]
Rated capacity at end of design life	12.8 kWh	80%, EOL definition by USABC
Chemistry	LG Chem LMO/graphite	

Table 2-3: Approximation of the Nissan LEAF

Characteristic	LEAF	Basis
Battery (rated)	24 kWh	[20]
Initial capacity available to driving	85% (20.4 kWh)	
Charge depleting fuel economy	34 kWh/100mi	EPA rating [20]
Charge depleting (electric) range	73 mi	EPA rating [20]
Available capacity per electric mile	0.28 kWh/mi	CD range calculation
First life	8 years	Volt and LEAF warranties [1, 2]
Rated capacity at end of design life	19.2 kWh	80%, EOL definition by USABC
Chemistry	AESC (NEC) LMO/graphite	

Note that the vehicles characterized above are not assumed to have constant electric range capability throughout their entire vehicle life. Unless the battery is sufficiently oversized initially (and thus costly) relative to vehicle performance requirements, if constant electric range is maintained by utilizing a constant absolute amount of battery capacity, accelerated battery degradation can be expected as the required depth of discharge happens at lower and lower levels of thermodynamic state-of-charge[4] [3]. In order to protect batteries from this accelerated

[4] Thermodynamic state-of-charge (t-SOC) is a dynamic measure indicative of the then-current state of the battery, i.e., not simply the SOC as defined by the initial rated capacity.

degradation, a dynamic control strategy can be used to adjust the "available capacity" dynamically to be, e.g., a constant *percentage* of a decreasing capacity. The latter approach, assumed here, would perhaps be less noticeable in a plug-in-hybrid, where the computer can minimize fuel-economy decreases or other effects by optimizing the combined combustion and electric systems.

Battery cost and lease payments

Table 2-4 summarizes estimates for battery costs and equivalent lease payments. "Battery" is defined here to mean only the modules, a minimal management system (e.g., for voltage, temperature, and other monitoring, balancing, and protection), and integral structure/interfaces that will be removed from the vehicle and repurposed for use in second life, i.e., integrated modules. This does not include the supporting balance-of-pack components that will remain behind in the vehicle (e.g., the vehicle-integrated thermal management components, AC charger, DC-DC converter, crash sensors, power conditioning, vehicle-level pack management systems, etc.).

The cost estimates assume a base module cost of 825 dollars[5] per *available* kilowatt-hour[6] [21] ($825/kWh), scaled by ratios reflective of cost differences between chemistries [22]. Because of greater access to various forms of published data characterizing iron-phosphate (LFP) batteries, LFP/graphite is the chemistry combination used as the default chemistry, and various associated characteristics, including cost, are normalized to the value for the iron-phosphate chemistry (e.g., the cost scaling factor for LFP/graphite is 1 and for manganese oxide or LMO/graphite is 0.71). Additionally, $100 per kWh plus $1,000 is added to capture the costs of the minimal management system and thermal and electrical interfaces that stay with the battery into second life.

Table 2-4: Battery cost and lease estimates

	PHV	Volt	LEAF
Cost per available kWh	$732	$585	$585
Cost of balance of module system carried into 2nd life	~$1,390	~$2,040	~$3,040
Total battery cost	~$4,240	~$8,130	~$15,000
Battery lease payment (per month over 8 years)	$64	$122	$225
Different than: battery contribution to a 3-year *car* lease payment (per month over 3 years, straight-line depreciation)	$72	$139	$255

Even at these costs, a significant upfront cost hurdle remains. A battery lease could help spread those costs over the operational life of the battery. Table 2-4 also presents two battery lease estimates. The first is the monthly payment to lease the battery (only), fully depreciating it over the "first life" period as defined by the vehicle choice in the model (see previous tables). The lease is structured analogously to a car lease, but for the battery only, assuming: $0 ultimate residual value, a 6.99% APR, a lease fee proportional to the battery cost (e.g., $266 for the Volt

[5] All dollars are U.S. dollars circa 2010, unless stated otherwise.

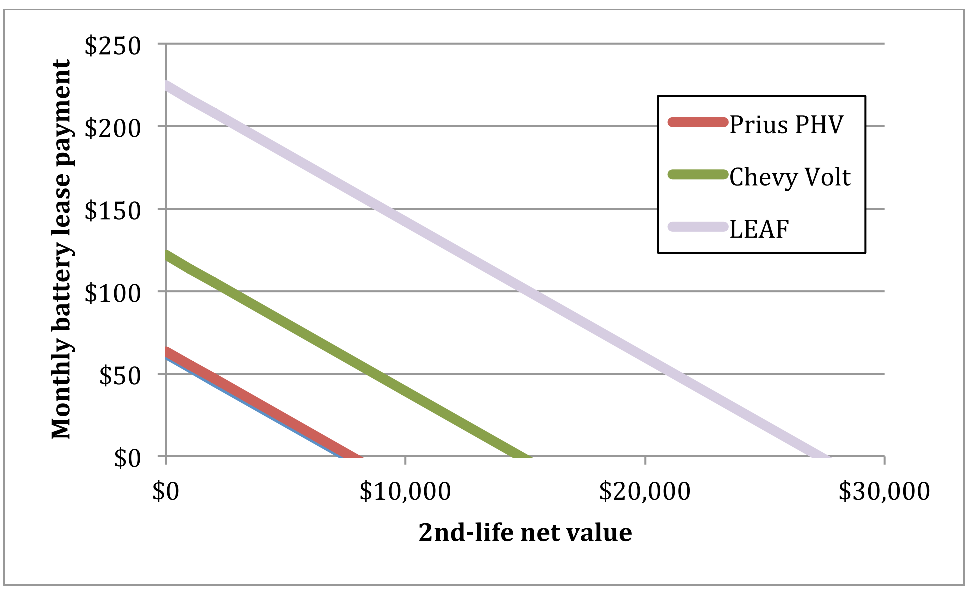
[6] $850/kWh is the midpoint in "current status" cost estimates from the recent U.S. DOE EERE program status update cited. Compare to the Deutsche Bank's $450/kWh: Sankey, P.; Clark, D. T.; Micheloto, S. The End of the Oil Age: 2011 and beyond: a reality check; 1223fm-05; Deutsche Bank: 22 Dec, 2010.

battery), and 9.75% sales tax. In contrast (for reference only and not used in subsequent analysis), the second lease payment in Table 2-4 is the amount that the battery might contribute to a 3-year *car* lease payment, assuming straight-line depreciation (i.e., significant residual value remains at year 3 not covered by this lease payment, as with a traditional car lease). These lease payments are still a significant premium to pay on top of the vehicle financing for a vehicle with recharge capability. How might this situation be further improved?

In the plug-in-vehicle commercialization scenario described above, the large-format propulsion battery, a young innovation, is forced to compete in its infancy as a commodity in a competitive automotive supply market. Even with the help of some type of lease, which could align incentives in a such a way as to shift battery design, manufacture, provision, use, and take-back somewhat towards a more lifecycle-oriented electric-fuel-service enabler, the financing picture remains challenging, driven by high initial costs and long and demanding life requirements. Further, because suitability for automotive application is defined so rigorously, including the desire to specify for an end-of-design-life capacity, a relatively high-value and capable asset emerges at the end of the financing period. What second-life residual value might remain, and, if brought forward into the initial purchase decision, to what degree might it help ameliorate the battery lease payment?

Figure 2-1 illustrates the effect that various levels of second-life net value, acting as battery lease residual value, might have on the battery lease payment. The potential value that might be derivable from a battery's second life is explored in Chapter 4, and the process of repurposing the battery for second life is explored next, in Chapter 3.

Figure 2-1: The effect of second-life net value on the battery lease



CHAPTER 3: Repurposing

Re-defining the battery lifecycle

Several opportunities for creating secondary value from propulsion batteries exist, both during its initial deployment onboard the vehicle—referred to here as supplemental value from secondary use in first life—as well as afterwards, in subsequent vehicular or stationary applications. Many opportunities would significantly complicate initial commercialization challenges. For example, secondary use during initial vehicle deployment in applications like vehicle-to-grid, emergency, or mobile power [15]—if used to a significantly large degree—might further tax immature battery durability and be difficult to anticipate and accommodate into the initial vehicle design requirements and consumer performance expectations. And "cascading" batteries from more demanding vehicular applications to less demanding ones—e.g., from a large, new-model, highly-capable, and possibly pricey OEM plug-in hybrid to a smaller, lower-expectation, possibly cheaper used-hybrid conversion, and then to non-highway vehicle niches, etc.—might increase standardization challenges and/or require complex, customized refurbishing and refitting. Nevertheless, these opportunities should be investigated given the potentially long useful lifetimes of some of the latest battery technologies.

One secondary application that might present somewhat lower and simpler initial-performance, design, standardization, and other challenges might be the one-time repurposing of plug-in vehicle batteries into stationary electricity appliances. Such devices could be used—distributed in household garages/basements or aggregated into power centers—as power- and energy-storage devices providing various services to the grid, the utility, and the neighborhood electrical distribution system, as well as the building in which they were located, with benefits on both sides of the electrical meter. No longer facing the portability, environmental survivability, and high-performance requirements of vehicle life, re-rated and repurposed batteries may effectively provide valuable services years after "retirement" from plug-in-hybrid application.

Repurposing the battery for stationary use

Used plug-in vehicle batteries intended for second-life use will need to be tested, sorted, and certified as part of the repurposing process. This is necessary to identify battery modules that appear to have sufficient capability left to perform well in a second-life product such as the HESA. After several years of use, some battery cells and modules can be expected to have degraded more than others, with degradation following some level of statistical "scatter" depending in turn (at least partially) on the level of manufacturing consistency or "tightness of tolerances" in the battery manufacturing process.

Repurposing Scenarios

Given this expected variation in battery degradation at the module level (with underlying variation at the cell level), there is a spectrum of potential battery repurposing strategies that could be considered. These include different levels of intrusion into the battery and associated processing costs. Building upon [4], we focus here on Scenario 1 "low repurposing cost" outlined below, but also consider the implications of Scenario 2 "moderate repurposing cost." Further extremes along the spectrum are discussed below as Scenario 0 "minimal repurposing cost" and Scenario 3 "full repurposing cost."

<u>Scenario 1: Low repurposing cost (HESA base case)</u>

- receive used batteries at repurposing facility
- visually examine battery modules for physical damage, leaks, and signs of abuse

- examine data from battery/module management system (BMS) health meter or "cloud based" data storage, if any
- conduct initial voltage and resistance measurements to identify failing or failed modules
- remove failed modules for possible refurbishment, cell reconditioning (see Strategy 3), or recycling
- replace removed modules with suitable ones sorted by capacity, power capability limits, and calendar age
- repackage modules for use in HESA units with existing balance of battery systems
- conduct additional testing of apparently "good" HESA battery systems to verify condition

<u>Scenario 2: Moderate repurposing cost (some customization for 2^{nd} use application)</u>
- receive used battery packs at repurposing facility
- visually examine battery modules for physical damage, leaks, and signs of abuse
- examine data from BMS health meter or "cloud based" data storage, if any
- conduct initial voltage and resistance measurements to identify failing or failed modules
- remove failed modules for possible refurbishment, cell reconditioning, or recycling
- sort modules by capacity, power capability, and calendar age
- conduct additional testing of apparently "good" modules to verify condition
- repackage modules into appropriately sized packs for second use application, with adaptation of existing or inclusion of newly-designed balance-of-plant systems (potentially including modified thermal management)[7]

Compared with Scenario 1 and 2, Scenario 3 "full repurposing cost" reflects the possible widespread need to go a few steps further and dismantle battery modules into component cells, conduct individual cell testing, possibly "reconditioning" bad cells if possible[8] (e.g. by restoring lithium to the battery cathodes, washing accumulated lithium from the anodes, etc.), and then to recompose the selected and/or reconditioned cells into refurbished battery modules. While this is possible, it would entail significant additional costs that appear difficult to support on a widespread (vs. reject-only) basis based on the estimates of second-life application values estimated in Chapter 4. Thus, we consider strategies that involve dismantling the actual battery modules only if significant extra value could be gained from rejected modules that would otherwise be recycled.

On the other extreme, in Scenario 0 "minimal repurposing cost," used batteries would be used more or less "as is" with minimal practical disturbance to the unit received after undergoing testing to determine acceptance or rejection. However, this is likely to be undesirable for two

[7] The extent of thermal management needed in second-life applications could vary from passive or active air ventilation systems to liquid cooling (for batteries liquid cooled in first life that cannot accommodate air cooling in second-life). The requirements may vary depending on dis/charge rates and load profile, as well as local ambient temperatures. In this study, the batteries are constrained to relatively modest dis/charge rates, as described below in the repurposing costs section, making reasonable the assumption that active air cooling in the HESA will be adequate. But this is an area in need of further technical assessment.

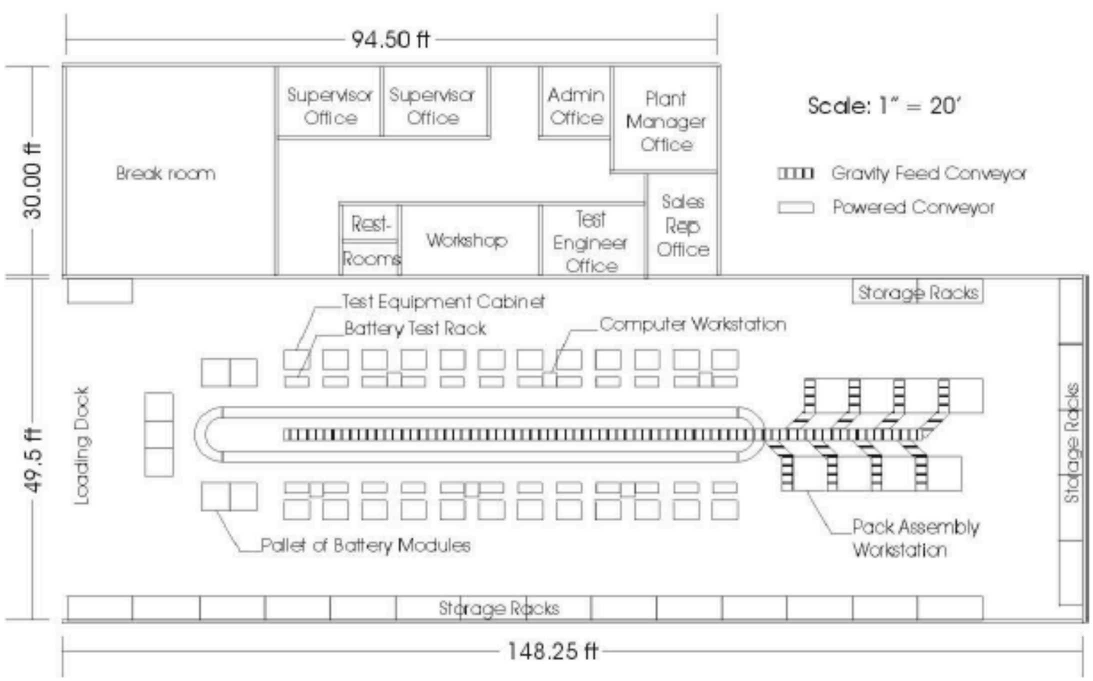
[8] *cf.*, for example, GM's application for a patent on a "Method and apparatus for rejuvenation of degraded pouch-type lithium ion battery cells" (Patent Pub No. US 2010/0124691 A1).

key reasons. First, as noted above, modules are not expected to age in completely uniform ways, and thus some sorting of modules is likely to be advantageous to cull the weaker modules and repackage the batteries into more uniform units after several years of use (with care taken to minimize removal and replacement of module interconnections). Second, further optimization of increasingly specific second-life use scenarios may find the increased costs from greater reconfiguration (e.g., as described in Scenario 2) offset by optimal sizing benefits. Thus it may be determined that certain energy-storage products and applications require different battery configurations than those represented by typical degraded vehicle packs, the *de facto* and default standard assumed here and in Scenario 1 to minimize repurposing costs. Thus some reconfiguration of the packs (especially aggregation for larger-scale products and/or applications but possibly sub-division for smaller-scale products and/or applications) is likely to be desirable in at least some optimizations.

In our base case for this report, however, focusing on the HESA application and in order to maintain relatively low repurposing costs as in Strategy 1, we assume that HESA products are developed based upon the highest-volume vehicle packs (e.g., LEAF, Volt, and PHV) with minimal practical reconfiguration cost. This is reasonable as the battery pack sizes in these vehicles span what is expected to be useful at the HESA or electricity grid distribution level, especially once battery degradation after first use is considered and the batteries have lost some power and capacity.

Figure 3-1 is a schematic layout of a potential battery repurposing facility [4] capable of carrying out the steps described above for Scenarios 0–2, with the exception of cell reconditioning and recycling (which may be beneficially co-located). The facility includes space for battery storage and testing, conveyor belts, workshops, offices, a break room, and restrooms. The facility is designed to process approximately 8 battery packs or 200 battery modules per day (assuming 25 modules per pack) and occupies about 11,000 square feet. It forms the basis of, and is further described in, the section on repurposing cost estimates at the end of this chapter.

Figure 3-1: Cready *et al.* illustrative battery repurposing facility layout [4]



Battery monitoring and pre-testing triage

To facilitate battery repurposing—as well as other secondary and second-life use (e.g., vehicle cascading, various forms of repurposing, down-cycling, and recycling), it would be useful for each battery to have integrated in its management system a "health meter" that would track a few key battery history parameters. Such a system could be relatively unsophisticated and still be useful. It might include tracking of: total battery throughput (e.g., kWh); total cycles; depth-of-discharge distribution; average, maximum, and minimum battery operating temperature; percentage of life spent at high temperature and full charge (e.g., >90% state-of-charge), and calendar age.

Additionally, vehicle OEMs have indicated they will use sophisticated monitoring systems integrated with cloud-computing centers (e.g., via the OnStar system) to carefully monitor and track battery operation over the life of the vehicles. Such systems can monitor vehicle performance on the sub-second level with dozens of data streams available, though not necessarily permanently stored. Access to these data in place of or in conjunction with some basic battery-integrated data would provide time-series data for differential diagnosis of various degradation mechanisms that might be difficult to identify cost effectively if the batteries were delivered without history to the repurposing center loading dock.

Furthermore, there is discussion of requiring on-board diagnostics (OBD) systems to measure plug-in-vehicle battery performance, as is currently done for hybrid vehicle batteries under the OBD-II regulations. For example, OBD diagnostic trouble code P0A7F is used to determine if the hybrid vehicle battery has exceeded an established level of internal resistance (expected to increase as the battery ages) or if another malfunction has occurred. The California Air Resources Board has implemented hybrid vehicle requirements for the current OBD-II program in the California Code of Regulations Section 1968.2 as follows:

> (15.1.1) Except as provided in sections (e)(15.1.3), (e)(15.1.4), and (e)(16), the OBD II system shall monitor for malfunction any electronic powertrain component/system not otherwise described in sections (e)(1) through (e)(14) that either provides input to (directly or indirectly) or receives commands from the on-board computer(s), and: (1) can affect emissions during any reasonable in-use driving condition, or (2) is used as part of the diagnostic strategy for any other monitored system or component.
>
> (15.1.5) For hybrids, manufacturers shall submit a plan to the Executive Officer for approval of the hybrid components determined by the manufacturer to be subject to monitoring in section (e)(15.1.1). In general, the Executive Officer shall approve the plan if it includes monitoring of all components/systems used as part of the diagnostic strategy for any other monitored system or component, monitoring of all energy input devices to the electrical propulsion system, monitoring of battery and charging system performance, monitoring of electric motor performance, and monitoring of regenerative braking performance.

It is thus up to hybrid vehicle manufacturers to develop and present plans for vehicle compliance with OBD-II that include appropriate monitoring and diagnostic trouble code generation where appropriate. Similarly, OBD data could be useful to assess the state of battery health at the end of first life, particularly if some performance history is included along with present battery condition. For plug-in hybrids at least, requiring this type of OBD monitoring may be justified because the performance of the battery is potentially important to the emissions performance of the vehicles.

In any event, even limited information from first life would increase the potential sophistication and/or effectiveness of battery triage at the repurposing center. For example, some battery packs may be sufficiently degraded based on various criteria (e.g., cycle life, calendar life, and/or operating temperatures) to not warrant further testing (i.e., triage "red" and divert to reconditioning or "black" and divert to recycling streams), where others are sorted as clearly promising (triage "green" for low-cost repurposing) and others as marginal (triage "yellow") and in need of careful inspection and testing.

Battery testing

Battery testing recommendations have been developed by Cready *et al*. for Sandia National Laboratory in 2002 [4] as well as more recently (2010) by Cessna and Velev at AeroVironment, Inc. for Task 1 and 2 of this project [5]. These are briefly summarized below, with additional details available through the respective citations.

The test regime outlined by Cready *et al*. is based on the USABC Reference Performance Test 2 sequence and conversations with electric-vehicle battery manufacturers. It includes (p. 26):

1. "Establishing the module capacity via four charge-discharge cycles, charging per the manufacturer's recommended profile, and discharging at C/3 (based on manufacturer's original rating) to 100% of capacity.
2. Establishing the power capability by recharging, discharging at C/3 to 50% DOD, and determining the sustained (30 sec) power capability at 2/3 of the module's open circuit voltage."

AeroVironment has developed a lithium battery evaluation test and procedure plan as part of Tasks 1 & 2 of this project. The test plan includes both general and "application specific" tests that are intended to reveal key capabilities of the battery for specific applications. Key elements of this plan include the following:

1. Initial inspection
2. Constant current performance test
3. Pulse power test
4. Constant power performance test
5. Self-discharge test
6. Application specific test: energy use shift
7. Application specific test: frequency regulation
8. Application specific test: load leveling

The above two protocols were developed with (reasonably priced) battery repurposing explicitly in mind. Additional, related battery test procedures are available to supplement those procedures as needed, particularly in more elaborate repurposing scenarios. For example, there is also an extensive set of battery testing protocols established for new hybrid batteries by the Idaho National Laboratory [23]. This test manual outlines sets of procedures for: 1) assessing the readiness of battery cells for large-scale production for use in hybrid battery packs; and 2) demonstrating that overall battery packs meet their life targets (e.g., 15-year, 150,000-mile life at a 90% confidence level). The procedures identify test-matrices for assessing both cycle and calendar life, varying temperature, state-of-charge (SOC) level, throughput rate, and pulse power level. Based on the outcomes of these tests, employment of a "phenomenological model" is used to predict expected battery lives.

The test procedure includes a Monte Carlo modeling element to simulate cell-to-cell variations. In addition to estimating these variations for new batteries in a prospective manner, statistical data from used battery tests might be incorporated to provide a sense of the expected future variation in battery performance and life.

Among the steps described in the manual for establishing baseline cell/battery performance are (p. 32):

- mapping cell open-circuit voltage vs. SOC;
- estimating the means and standard deviations of cell capacity, various measures of impedance, self-discharge rates, and cold-cranking power;
- ranking and assigning cells to core and supplemental life test matrices;
- examining electrochemical impedance spectra (EIS) for anomalous characteristics; and
- assessing the variability in the cell population to estimate the magnitudes of noise in the impedance data from cell-to-cell manufacturing variations and measurement errors.

These results are then combined with the those from the supplemental test matrices provided in the manual that further explore the impacts of the key "stress factors" (temperature, state of charge, throughput rate, and discharge/charge pulses) to estimate the potential life of a certain battery technology.

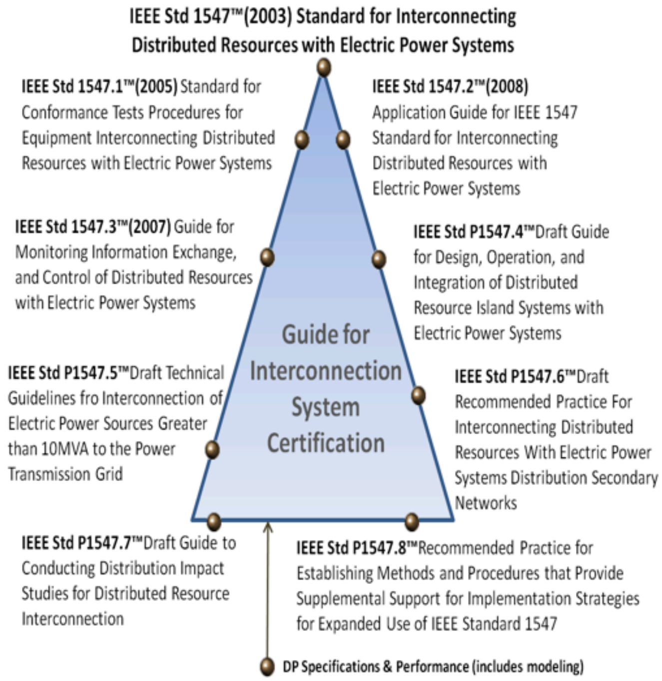
There are clearly a number of battery-testing approaches that can be used. The AeroVironment test procedure is a modern and thorough procedure developed with second-life applications in mind. However, variations on this procedure, potentially drawing on the extensive Idaho National Laboratory procedures for new battery life verification, could be adopted based on the equipment and resources available.

Certification

In addition to any local permitting required to operate battery-repurposing facilities, the "certified, pre-owned" batteries themselves would need to be tested and certified as safe stationary energy storage according to the relevant standards organizations. These entail significant product testing and associated administrative costs that could vary considerably depending on the jurisdiction of the repurposing plant, its scale, and any unforeseen design issues that may arise during the testing/certification procedure.

Key certifications that will be required of HESA and other grid-connected storage devices include the IEEE 1547, suite of standards for distributed resource interconnection, a related and harmonized Underwriters Laboratories (UL) 1741 standard titled "The Standard For Inverters, Converters and Controllers For Use In Independent Power Production Systems," and the ANSI/IEEE 62.41 standard for surge withstand testing (e.g., in the event of lightning strikes). Figure 3-2 presents the set of IEEE 1547 standards that have formed the core set of specifications and procedures for safe interconnection of small- and medium-scale power devices to utility grids around the world.

Figure 3-2: IEEE 1547 Suite of Distributed Energy Resource Interconnection Standards [24]



The standards for safe interconnection of distributed energy resources to utility grids have undergone much improvement over the past 10 years, and many devices from solar PV inverters to switchgear for larger distributed resources systems (such as microturbines and stationary fuel cells) have now been developed to meet these standards. Similar power electronics and switchgear could be adapted for HESA units and other ESA products, reducing initial engineering costs and overall costs of system development.

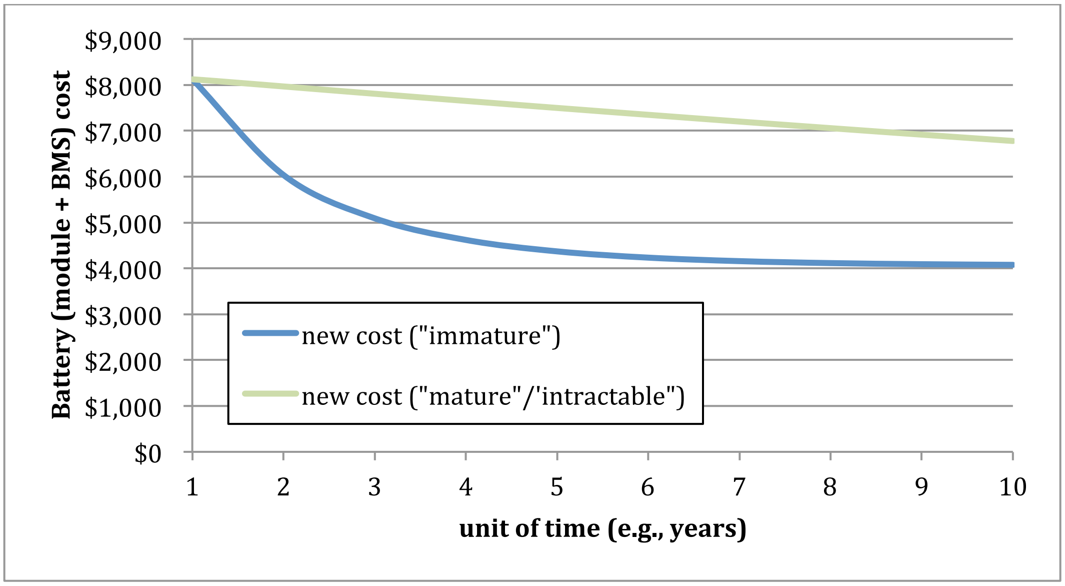
Home energy storage appliance costs

The costs associated with repurposing plug-in vehicle batteries into home energy storage appliances can be divided into two major categories. The first category, "repurposing cost," consists of those cost components unique to the use of used, plug-in-vehicle batteries—rather than new, single-purpose batteries—and includes paying off any remaining first-life residual value, dismounting, collecting, sorting, and testing the used batteries. The cost of the battery, whether new or repurposed, is in turn a component of the second category, "ESA cost," which consists of those cost components common to all energy-storage appliances of a given type and includes assembly, distribution, and installation.

Maximum allowable repurposing cost: new-battery costs and the used-product discount

For HESAs with repurposed batteries to be viable, the cost of the used battery, fully burdened with repurposing costs, must be significantly lower than the cost of a new battery. As new battery costs decline over time, they thus set a declining maximum allowable repurposing cost. Figure 3-3 illustrates this declining ceiling for a Volt-type battery as a function of time (e.g., years), given two types of new-battery declining cost functions. The first type, meant to reflect "immature market" conditions (the lower line), is consistent with, but slightly more conservative than, several estimates of rapid initial battery cost decreases as volume ramps up to meet initial plug-in vehicle offerings. It was constructed using an 82% "experience curve" approach (18% cost reduction with each doubling of production, taken here to occur at decreasing intervals. The second type, meant to reflect the more gradually declining costs of either a more mature market or a more intractable or volume-insensitive cost function is depicted by the upper line and constructed using a simple, 2%-per-year decline.

Figure 3-3: New-battery cost as maximum allowable repurposing cost: Volt illustrative example



Thus for a battery being taken out of the vehicle at year 8, the fully-burdened repurposed battery could cost the HESA no more than roughly $4,100 to have a chance of being competitive with a new battery produced in year 8, assuming costs fall rapidly to roughly half their initial costs in that period of time (immature scenario). Further, even if it were possible to certify a used battery to near equivalency to a new battery for a given set of specifications, the market is unlikely to be willing to pay full, new-battery prices for used batteries. Following Neubauer and Pesaran [25], a 15% used-product discount would lower this maximum allowable cost to roughly $3,500. As seen below in Table 3-1, the cost of repurposing is anticipated to be considerably lower than this price ceiling, which does not factor into the rest of the analysis. However, this does not take into account the decreased performance of the used battery (discussed elsewhere and a subject of future work), which along with a significantly larger used-product discount may result in a binding ceiling—e.g., if the combined effect were more than a 70% reduction.

Repurposing cost

Cready *et al.* [4] estimated the costs for a repurposing facility covering one of California's four major metropolitan areas and capable of repurposing roughly 2,880 battery packs per year, including collection (truck and driver), testing, materials handling, facilities costs, various forms of overhead, etc. Though the study was conducted with NiMH batteries in mind, they indicate that the repurposing expenses cited here would likely be applicable to Li-ion chemistries. Further, their analysis formed the basis of the repurposing scenarios described above and should be sufficient to cover most of the activities described in Scenarios 0 and 1, if not 2 (we do not assume cost reductions from recycling or other salvage revenues.) Their Figure 7 (p. 45) summarizes their cost findings for reconfigured EV batteries on a dollars per kilowatt-hour basis: $9.92/kWh for packaging materials, $3.14/kWh for testing equipment, $19.34/kWh for labor, $1.58/kWh for rent, $3.43/kWh for insurance, $18.28/kWh for general and administrative, $4.57/kWh for warranty, $3.01/kWh for capital recovery, earnings, and taxes, and $2.00/kWh for all other expenses. They also incorporate battery "buy-down" costs (used-battery purchase price), which are excluded here because the allowable buy-down costs are explored in this analysis using the systemic battery lease payment as an index (see Chapter 5).

Table 3-1 summarizes the repurposing cost for batteries from various vehicle types by assigning the costs described above, multiplied by 1.2 to inflate Year 2002 to 2010 dollars, and including an additional $500 per battery to cover the cost of dismounting the battery from the vehicle (e.g., at the dealership during a major tune-up). Though these estimates are clearly uncertain, comparing the Volt estimate in Table 3-1 to the illustrative example of maximum allowable repurposing cost described above indicates the cost as estimated for Table 3-1 might be considerably lower than the allowable limit.

Table 3-1: Repurposing cost estimates (rounded[9])

PHV	Volt	LEAF
$744	$1,150	$1,780

Energy storage appliance (ESA) cost

The rest of the cost components analyzed here falls under the second category—those costs common to HESA production. Table 3-2 summarizes the ESA cost components and total HESA cost for home appliances based on various vehicle batteries. The power capabilities in kilowatts of the HESAs analyzed have been capped at twice the energy storage capacity in kilowatt-hours. This ratio is consistent with the provision of grid-services contracts no shorter than one half-hour, thereby acting as a conservatism to avoid inflated estimates of application value for applications with short discharge durations (see Chapter 4). Further, because this ratio represents a reasonable dis/charge rate limit (2C) and is potentially mild when compared to several-C vehicular life[10], it acts as a conservatism to help minimize degradation in second life. Also, recall that the relative percentage of depth-of-discharge allowed in first life is used in second life (e.g., 65% of 16 kWh in first life for the Volt and 65% of 12.8 kWh in second life for the Volt-HESA). For plug-in-hybrid batteries in particular, second life may well be optimized using a wider swing, making this an additional conservative assumption that should also foster long life for those vehicles (the LEAF-based HESA is allowed to use 85% in second life as in first life).

Though full details are not presented in the report, the Cready *et al.* estimates for residential load following do not appear to be adequate for use in Table 3-2 because 1) in that report, some of the costs (e.g., for power conditioning capability) were assumed to be covered by the distributed generation unit to which the energy-storage device was assumed to be coupled, and 2) a wider range of energy-storage applications are explored for the HESAs in Chapter 4.

Thus, in order to allow for the exploration of fully capable HESAs, the highest costs for power conditioning, controls, and interfaces from Cready *et al.* were used in Table 3-2. For the next two rows in the Table 3-2 (which include facilities costs and operation and maintenance), more modest costs were assumed to apply to HESAs than large-scale, bulk-storage facilities. However, because the modest "residential load following" estimates may not be fully adequate,

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[9] Acknowledging the limitations to the precision and certainty of speculative analyses like this one, most tables present rounded results (e.g., to 3 significant figures) to reduce the unwarranted appearance of excessive numbers of significant figures.

[10] Further, compare to 6C over 10 minutes for fast charging of all-battery EVs.

the next cheapest estimates (those derived from a facility in Chino, California), were used in order to be conservative.

Table 3-2: Energy storage appliance cost estimates (rounded)

ESA cost component	Basis	PHV 3kWh/6kW	Volt 8kWh/16kW	LEAF 16kWh/32kW
Battery (modules+mgt. system)	Repurposing cost	$744	$1,150	$1,780
Power conditioning, controls, interfaces	Inflated $442/kW=CreadyEtAl'02 max. for fully-capable bulk storage	$3,310	$8,830	$17,300[11]
Accessories, facilities, shipping, catch-all	Inflated $117/kWh=CreadyEtAl'02 for load leveling, arbitrage, and transmission deferral facility at Chino	$442	$1,170	$2,290
10-year operation and maintenance	NPV($18/kW-y)=Chino facility. Compare to $102/y for residential load following	$828	$2,210	$4,330
Installation, residential circuitry	EVSE-style installation costs (sans charger), based on max. power	$800	$2,000	$4,300
	Total HESA cost	**$6,120**	**$15,400**	**$30,000**

[11] Compare to a $20,500 31 March 2011 quote on energybay.org for a 30-kW, 480V SatCon PVS-30 inverter.

CHAPTER 4: Second life: distributed grid energy storage

Once repurposed, situated, and grid-connected for stationary use, the HESA battery and its electrical storage/generation capability could provide several services, including regional grid support; avoided generation, transmission, and distribution upgrades for utilities; avoided energy and demand charges for buildings; and emergency power. Several of the many potential value streams are discussed and analyzed to various degrees below.

HESA-sized distributed energy storage benefits

One taxonomy of the gross benefit provided by grid energy storage is presented in a 2010 report for Sandia National Laboratories by Eyer and Corey [6]. Table 4-1 reproduces the key characteristics of 19 energy storage applications that have been grouped into five categories. The first two relate to Electric Supply, the next four Ancillary Services, the next five the Grid System, the next four the End User / Utility Customer, and the last four Renewables Integration. Table 4-1 characterizes each application with a range of discharge durations that would be required of the energy storage device, as well as a range of application-specific, lifecycle benefits from its use in California. Except for the benefit from transmission and distribution upgrade deferral, which are for one year, the benefits presented in Table 4-1 are the present value of 10 years of benefit, assuming a 10% discount rate and 2.5% cost escalation.

Additionally, Eyer and Corey identified several "incidental benefits" not listed in Table 4-1 and for which they do not attempt quantification. These are: 1) increased asset utilization, 2) avoided transmission and distribution energy losses, 3) avoided transmission access charges, 4) reduced transmission and distribution investment risk, 5) dynamic operating benefits, 6) power factor correction, 7) reduced generation fossil fuel use, 8) reduced air emissions from generation, and 9) "flexibility."

Table 4-1: Eyer & Corey (2010) energy storage applications, discharge duration, and benefit [6]

Application	Discharge Duration, Low (h)	Discharge Duration, High (h)	Benefit, Low ($/kW)*	Benefit, High ($/kW)*
Electric Energy Time-shift	2	8	$400	$700
Electric Supply Capacity	4	6	$359	$710
Load Following	2	4	$600	$1,000
Area Regulation	0.25	0.5	$785	$2,010
Electric Supply Reserve Capacity	1	2	$57	$225
Voltage Support	0.25	1	$400	$800
Transmission Support	0.00056	0.0014	$192	$192
Transmission Congestion Relief	3	6	$31	$141
T&D Upgrade Deferral 50th percentile**	3	6	$481	$687
T&D Upgrade Deferral 90th percentile**	3	6	$759	$1,079
Substation On-site Power	8	16	$1,800	$3,000
Time-of-use Energy Cost Management	4	6	$1,226	$1,226
Demand Charge Management	5	11	$582	$582
Electric Service Reliability	0.083	1	$359	$978
Electric Service Power Quality	0.0028	0.017	$359	$978
Renewables Energy Time-shift	3	5	$233	$389
Renewables Capacity Firming	2	4	$709	$915
Wind Generation Grid Integration, Short Duration	0.0028	0.25	$500	$1,000
Wind Generation Grid Integration, Long Duration	1	6	$100	$782

* lifecycle benefit over 10 years, with 2.5% escalation and 10% discount rate
** benefit for one year. However, storage could be used at more than one location at different times for similar benefits.

Using average discharge-duration and benefit values from Table 4-1 and an assumed 96% average discharge efficiency, Table 4-2 presents a menu of single-application, system-wide benefit values that would accrue in California were HESA devices using repurposed batteries from various plug-in-vehicle batteries used in each of the applications characterized by Eyer and Corey. However, as also described in Chapter 2, the power capabilities in kilowatts of the HESAs analyzed have been capped at twice the energy storage capacity in kilowatt-hours. This ratio effectively limits the discharge duration expectations in Table 4-1 to a minimum of 30 minutes, thereby reducing the total number of kilowatts the device could provide while maintaining the ability to fulfill grid-services contracts no shorter than one half hour. This avoids inflated estimates of application value for applications with the shortest discharge durations seen in Table 4-1. Further, this ratio represents a reasonable dis/charge rate limit (2C)—potentially modest when compared to several-C discharges that typically occur during vehicular life[12]. This assumption thus acts in a conservative way to help minimize high-dis/charge-rate driven degradation effects in second life, which is implied by the framework discussed here to be 10 years. Additionally, the percentage (of degraded, re-rated capacity) allowed to be used in second life is assumed to be the same percentage (of new rated capacity) used in first life—a possibly conservative and HESA-life-fostering assumption for plug-in-hybrid-based HESAs with narrow allowable percentage swings. The extent to which high dis/charge rates and large allowable depth-of-discharge swings exacerbate degradation varies by battery chemistry and is a key area for further research, including for larger-scale, transmission-level ESA applications.

[12] Further, compare to 6C over 10 minutes for fast charging of all-battery EVs.

Table 4-2: Menu of potential second-life energy storage gross benefits* (rounded)

Application	PHV	Volt	LEAF
Electric Energy Time-shift	$330	$880	$1,720
Electric Supply Capacity	$320	$850	$1,670
Load Following	$800	$2,130	$4,180
Area Regulation	$8,720	$23,250	$45,610
Electric Supply Reserve Capacity	$280	$750	$1,470
Voltage Support	$2,870	$7,670	$15,040
Transmission Support	$1,200	$3,190	$6,270
Transmission Congestion Relief	$60	$150	$300
T&D Upgrade Deferral 50th percentile†	$2,790	$7,430	$14,580
T&D Upgrade Deferral 90th percentile†	$4,390	$11,690	$22,940
Substation On-site Power	$600	$1,600	$3,130
Time-of-use Energy Cost Management	$730	$1,960	$3,840
Demand Charge Management	$220	$580	$1,140
Electric Service Reliability	$3,700	$9,860	$19,340
Electric Service Power Quality	$4,170	$11,120	$21,820
Renewables Energy Time-shift	$230	$620	$1,220
Renewables Capacity Firming	$810	$2,160	$4,240
Wind Generation Grid Integration, Short Duration	$4,680	$12,480	$24,480
Wind Generation Grid Integration, Long Duration	$380	$1,000	$1,970

* lifecycle benefit over 10 years, with 2.5% escalation and 10% discount rate
† converted here to approximate 10 years of benefit to be comparable to other applications, but this is not likely at a single location

Further refinement is of course necessary to make the estimates in Table 4-2 increasingly meaningful and accurate for a given region. However, Corey and Eyer explicitly intended their framework to be used as a high-level, system-perspective tool, and accordingly several lessons and guidance for subsequent analysis can be drawn from the estimates based on it in Table 4-2. For example, the order of magnitude of the estimates give an indication of the maximum HESA costs that could be supported in each individual application (net benefit is discussed in Chapter 5), and the relative values help prioritize applications for refinement and testing.

Area regulation

The single application with the largest potential benefit per device is, in each case, area regulation. This is expected and consistent with precursor analysis [7, 26], and thus warrants further description and discussion.

At the super-utility level, a regional grid operator—in California, the Independent System Operator (CAISO)—is charged with the nearly statewide, larger-scale balance of electricity supply and demand, in order to maintain the availability and quality (e.g., frequency) of the electricity being bought by consumers [27]. To meet these demands, various "behind-the-scenes" markets for ancillary grid services have been created, requiring increasingly rapid response. They are relatively costly to serve with large power plants and might be better served by relatively small, agile generators and/or storage devices scattered about the electrical landscape. Peak-power markets only pay participants for the energy actually supplied. In contrast, ancillary-service (e.g., spinning-reserve and regulation) markets also pay generation for being on-call and available, based on the power capacity promised over a given contract period. Thus an important determinant of revenues for a device selling services in ancillary-service markets is the number of hours it is assumed to be grid-connected, available, and on-call each day.

Adapting and building upon previous research [15, 28, 29], that explored the case of vehicle-to-grid (V2G) ancillary-service provision for supplemental value, precursor work [7, 26] explored stationary battery electrical storage/power provision, or "battery-to-grid" (B2G) services. Key features of an assessment following that methodology [7, 26] are presented next using the Volt-based-HESA case for rough comparison with those estimated based on the Eyer and Corey framework.

Cost of Regulation Energy (Volt-HESA example): With 8.3 kWh per battery available after 8 years in automotive application (as described above), the repurposed battery could fulfill up to a 16.6-kW, half-hour regulation call. Providing regulation energy with such a device is estimated to cost about $1,600 per year, assuming the stationary battery is: 1) available 7,060 hours per year (20 useful hours per day, with one unavailable day per month); 2) called upon an average of one-tenth of the time available; and 3) able to "generate" at $0.13/kWh (by buying electricity at an average price of $0.115/kWh and storing it with 85% round-trip efficiency).

Regulation Revenues (Volt-HESA example): Regulation revenues include energy and capacity payments. Selling regulation energy at the same average price ($0.115/kWh) yields approximately $1,400 per year in energy payments. On the capacity front, batteries could sell both regulation-up (capacity to produce power) and regulation-down (capacity to consume power, which can be used to charge the battery). Using the CAISO's 2006–2008 regulation capacity price (regulation up plus regulation down)—which averages to $0.033 per kilowatt capacity made available per hour contract ($0.033/kW-h)—a 16.6-kW device could earn up to an additional $3,800 per year in regulation capacity payments. This brings regulation revenue to a total of $5,200 per year, or $3,600 per year net of energy costs.

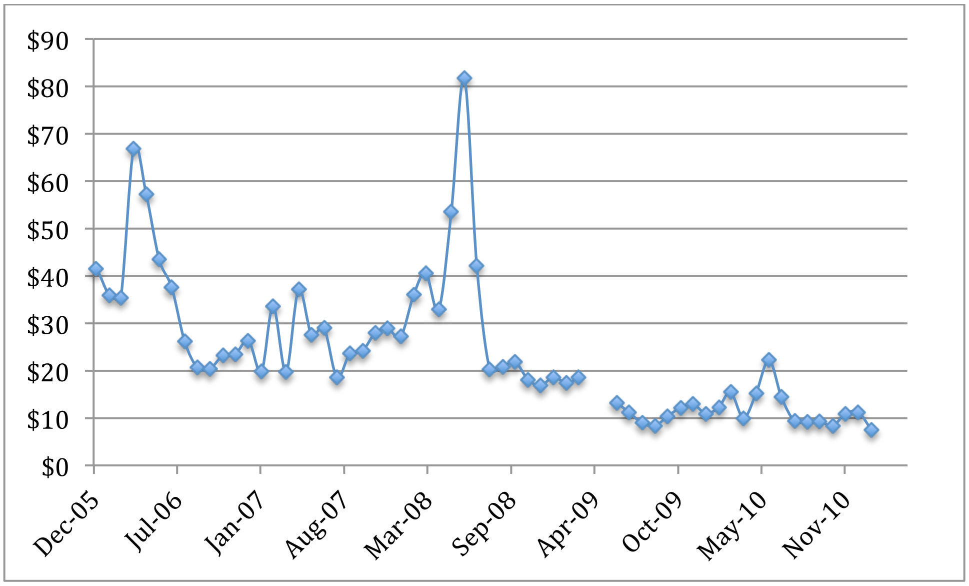
With a 10% discount rate, the net-present-value of regulation revenues would amount to up to about $22,000 over 10 years. This is roughly similar to the $23,250 produced using the Eyer and Corey framework for the Volt-based HESA using escalation as seen in Table 4-2.

Recent regulation market developments

It is important to note, however, that both frameworks use regulation prices (up+down) from several years ago: 2006 (Eyer and Corey) and 2006–2008 (Williams and Lipman). As seen in Figure 4-1, regulation prices have been near or below the $20-per-MW level since August 2008. The average from August 2008 through February 2011 (two months in spring 2009 are unavailable) is $13.66/MW per hour contract. Using that average price reduces the Volt-HESA regulation benefit seen in Table 4-2 from $23,250 to less than $9,300, a significant reduction.

Future price levels are unclear, however, for example as the economy recovers and electricity use increases, and in the context of a 33% Renewable Portfolio Standard. Additionally, on February 3, 2011, the California Independent System Operator (CAISO) Board of Governors approved a "regulation energy management" tool that permits energy storage and demand response resources with 15-minute capability to begin bidding in the CAISO market" [30]. As described above, the HESA dis/charge rates have been capped at 2C to help assure sufficient durability and avoid overestimation of benefit. However, were the devices found to be capable of providing up to 4C capability over 10 years of second-life use, this might double the potential HESA gross regulation benefit. Regardless, it should be noted that control and aggregation of HESA-sized units into the one-half megawatt size necessary for participation in Regulation Energy Management markets might be challenging and costly (see Chapters 3 and 5).

Figure 4-1: CASIO regulation prices (up+down in $/MW) (compiled from [31])



Competition in regulation markets and overall market potential

The potentially high value of providing regulation services is also consistent with the active market development for bulk energy storage provision of regulation by Beacon Power and others. Regulation will therefore be a hotly contested application by those looking through various product lenses (e.g., bulk energy storage, smart charging, etc.) and using alternative technology options (e.g., flywheels, compressed air, flow batteries, etc.). Thus, the total market potential for HESAs providing regulation could be limited. Even without competition, it would only take about 44,000 Volt-HESA batteries to amount to the 2006–2008 average CAISO regulation (up and down) requirement of 732 MW per year. For a sense of scale, 44,000 batteries, each making $3,500 per year would "earn" more than $150 million per year, though revenues are unlikely to remain constant as markets begin to saturate and the value of regulation services starts to fall.

Further, GM hopes to produce and sell 45,000 Volts in the U.S. in 2012 alone. On the other hand, only a fraction of those Volts batteries would presumably be top candidates for repurposing in California, and it would take 3–4 years to process 44,000 top-candidate batteries into HESAs using four repurposing centers in each of California's major metropolitan centers as described in Chapter 3. Meanwhile, the requirements for flexible capacity in California are likely to rise in order to support the 33% Renewable Portfolio Standard, though the extent to which remains unclear. In the meantime, CAISO's over 20,000 MWs of regulation-certified capacity may be sufficient to provide, even if not in the optimally efficient manner, California's near-to-mid-term regulation needs: "The combination of the inventory of regulation capacity and ramp rates, the record of sustained regulation procurement at up to 600 MW of regulation up and regulation down, and the empirical analysis of on-line regulation ramp capability suggest that the ISO can meet the higher regulation requirements forecast for 20 percent renewable energy," (p. 23) [32]. Thus, though the potential regulation value per HESA in California is not small, the overall potential of the market to sustain high value and/or a large number of Volt-based HESAs appears to be limited.

Multi-application value propositions

Comparing the menu of potential second-life values in Table 4-2 to the illustrative HESA costs in Table 3-2, and given the limitations of, and competition for, area regulation, it would appear that no single application benefit is likely to sustain the HESA value proposition. Multiple-application value-propositions are therefore needed. Eyer and Corey provide some insight as to which applications are compatible with others, and four of their proposed multi-application value propositions are summarized in Table 4-3. Further, single-application estimates for the Volt-based HESA are combined in various ways for illustration. The first is a simple sum that implies the unlikely (probably impossible), theoretical-maximum use of a single device to provide the full value of all of the applications in the value proposition, thereby double counting the device's time where simultaneous service provision would be required. The second combination illustrates the total value were the device tasked with prioritizing the most profitable application in the value proposition and able to capture the equivalent of 90% of its value as well as half of the value of the other applications. This total is then reduced by 10% in the final estimate to reflect some level of loss due to the need to aggregate the benefits of distributed energy storage. These blunt percentage parameters are explored further in Chapter 5.

Table 4-3: Ten-year value proposition benefit: Volt estimate (rounded)

Eyer&Corey'10 Value Proposition [6]	Sum (double counting)	Total: 90% of biggest, 50% of rest	Total -10% aggregation fee
e- energy time-shift + T&D upgrade deferral (10 years of value)† + e- supply reserve capacity	$13,400	$11,400	$10,300
TOU energy cost management + demand charge mgt	$2,540	$2,050	$1,850
T&D upgrade deferral (10 years of value)† + e- service power quality + e- service reliability (equivalent here to Eyer&Corey's "distributed storage for bilateral contracts with wind generators" proposition)	$32,700	$20,800	$18,700
storage to service small A/C loads = voltage support + e- supply reserve capacity + load following + transmission congestion relief + e- service reliability + e- service power quality + renewables energy time-shift	$32,400	$20,700	$18,600

† converted here to approximate 10 years of benefit to be comparable to other applications, but this is not likely at a single location

Table 4-3 indicates that a promising use of HESAs might be to prioritize electric service power quality in the context of serving small air-conditioning loads. A related opportunity for highly-distributed energy storage, currently under development in a project led by Solar City using Tesla batteries would firm the output of local photovoltaic installations. If done at the household meter level, this might be particularly appropriate for a home energy storage device and would presumably spread many of the HESA costs (e.g., power conditioning) over both PV and energy-storage applications.

CHAPTER 5: Integrating results, uncertainty & sensitivities, and alternative scenarios

Integrating results: net-value summary and the battery lease

Table 5-1 combines the results from the previous chapters and shows the impact the net residual value from the "small A/C load" multi-application value proposition has on the battery lease payment. It also calculates the simple net-present value (NPV) of the second-life residual value, bringing it forward from year 8 to year 1 using a 10% discount rate. (For further comparison, the summary of a calculation that re-creates the methodology used in preliminary previous work [7, 26], but using inputs similar to those summarized in Table 5-1, is presented in the appendices.)

Recall that both the effect on the battery lease payment and the NPV of the second-life net value are used as indicators of total-system net benefit, not specific business models. As such, any decrease in the lease amount will not necessarily pass solely to the vehicle purchaser, but rather will be shared by those parties necessary to implement the value proposition whose interests have not been explicitly or sufficiently[13] accounted for here—notably both the vehicle and HESA consumers, but possibly also the automaker (for any extra efforts that may be necessary to facilitate second-life use).

Table 5-1: Net residual value summary (rounded)

	PHV	Volt	LEAF
Total battery cost	$4,240	$8,130	$15,000
Battery lease payment (per month over entire car life)	$64	$122	$225
10-year 2nd-life value	$6,970	$18,600	$36,500
HESA cost	$6,120	$15,400	$30,000
Net benefit = residual value	$850	$3,230	$6,450
Battery lease payment per month w/2nd life (8+10y)	$57	$95	$172
NPV (residual value, 10% discount rate)	$397	$1,510	$3,010

Would the benefits shown above be enough to incentivize repurposing of plug-in vehicle batteries? The values presented in Table 5-1 are positive but modest, particularly when comparing the battery lease payments with and without second-life net benefit. However, many of the inputs are uncertain and some will have significantly different values depending on the future context in which repurposing endeavors might be conducted. As such, a sensitivity analysis is conducted and instructive alternative scenarios are constructed and explored.

[13] Recall that parties whose requirements have been explicitly, though not necessarily fully or accurately, covered include at a minimum the HESA service aggregator, the HESA producer, and the battery supplier.

Uncertainty and sensitivities

To explore the importance of various input assumptions on the battery lease payment, a Monte Carlo simulation of 50,000 trials was run using Oracle's Crystal Ball software on the parameters listed in Table 5-2 for the Volt-HESA case. All parameters but two were characterized using triangle probability distributions defined by the minimum, likely, and maximum values shown. The two exceptions were characterized using a uniform distribution between the minima and maxima shown. The point estimates used in the analysis thus far are in bold.

The last column in Table 5-2 summarizes the contribution to the variance by each parameter produced by the simulation. In contrast to the point-estimate of $95 per month for the Volt battery lease payment, the simulation produced a relatively symmetrical beta distribution with a mean of $132 and a 95% confidence interval ranging from $74 to $193. In other words, using the Table 5-2 characterizations of inputs, the point estimates appear to be in the lower portion of a range constructed by incorporating uncertainty about the inputs. This suggests that the lease-payment values may be higher than shown in Table 5-1.

Table 5-2: Contributions of key parameters to the variance in the Volt-HESA battery lease

Parameter	Minimum	Likely	Maximum	Contribution to variance
"% of rest" (non-priority grid-service values)	0%	Uniform	**50%**	-54%
Variable cost of power conditioning, controls, interfaces	$200/kW	Uniform	**$442/kW**	29%
Aggregation fee	0%	**10%**	20%	4.4%
Battery cost base	$700/kWh	**$825/kWh**	$950/kWh	3.5%
Ratio of kW to kWh cap	1	**2**	6	2.7%
Balance of battery (module MS) variable cost component	$50/kWh	**$100/kWh**	$150/kWh	2.7%
% of largest (priority grid service value)	80%	**90%**	100%	-2.2%
Variable cost of accessories, facilities, shipping, catch-all	$0/kWh	**$117/kWh**	$200/kWh	1.2%
Discount rate	4%	**10%**	12%	-0.5%
APR	5.99%	**6.99%**	7.99%	0.2%
O&M rate	$16/kW-y	**$18/kW-y**	$20/kW-y	0.2%
Battery swap cost	$250	**$500**	$1,000	0.1%
Rated % at end of car life	50%	**80%**	90%	-0.1%
Sales tax	8.75%	**9.75%**	10.75%	~0%
Repurposing burden	$65/kWh	**$78/kWh**	$100/kWh	~0%
Used-product discount	10%	**15%**	20%	0%

Dominant uncertainties: multi-application value and power-conditioning-related costs

Though the results in Table 5-2 are dependent on the ranges input and could be narrowed with increasing confidence than embodied in ranges used, they give an idea of the order of importance of each parameter, and thus which parts of the model need most refinement in subsequent analyses. It should be noted that for precise interpretation of the Crystal Ball results, the parameters modeled should also be independent. Though this appears to be largely true for the parameters examined here, exceptions exist. For example, the relationship between the two percentages of applicaton value (i.e., “percent of largest” and “percent of rest”) captured by the HESA are likely correlated, focusing scrutiny on them. However, the contribution of “percent of largest” is relatively small, making its correlation with “percent of rest” less important. Further, the dominant contribution to the variation of “percent of rest” also draws attention to it as the priority for refinement in its own right.

Clearly, the artful combination of value propositions is critical to Volt-based HESA profitability (as characterized here). If the HESA were able to only capture the benefit from the single-most valuable application in the group (“the largest” = electric service power quality, one of the most valuable non-regulation applications according to the Eyer and Corey framework), the lease would actually *rise* from $122 to $157 per month due to high estimated HESA costs, meaning the whole concept would be unsupportable. The principal contribution to those costs comes from power conditioning, controls, and interfaces, which is also the next largest contributor to the variance of lease-payment estimation seen in the simulation. Indeed, these costs should be examined as a priority.

The next tier of parameter importance includes parameters related to battery costs as well the level of second-life gross-profitability leakage necessary to facilitate aggregation of HESA services. However, it should be noted that initial battery costs are important as a determinant to the lease setup fee; the “cost base” and “balance of battery” parameters are not important in a similar simulation done directly on the NPV of the residual value, which exhibits a similar structure (but into which the the APR and sales tax also do not factor).

Capacity, power available for second life, and battery replacements

Surprisingly, the percentage of battery capacity remaining at the end of first life is of relatively low importance in the current model structure, contributing only 0.1% to the variance observed. This is despite a relatively wide range simulated, from 50% to 90%.

Unsurprisingly, however, the cap imposed on the rate at which the HESA would be allowed to discharge, partly a conservatism to minimize the degradation of the used battery in second life, is also an important factor. The battery will likely be subject to greater discharge rates in first life, and the economics of intentionally degrading the battery at a greater rate for greater value should be further examined. Interestingly, however, the benefits of increasing the kW-to-kWh ratio upwards from 2 in the current model structure are overcome by the associated costs that scale with power, so there is no incentive within that structure to consider investing in additional batteries (to make up for increased degradation) for this purpose.

Though difficult to justify for the purpose of allowing increased power ratings, battery replacement is worth considering in isolation for its own sake due to the possibility that degradation or calendar-life constraints will prevent the battery from capturing the full second-life value described in Chapter 4. Several conservatisms, such as capping the dis/charge rate and allowing limited depth-of-discharge swings, have been employed in this analysis to assure that the benefits estimated are not overly disproportionate to the HESA’s ability to capture them, and it is reasonable to suspect that many second-life applications will be less demanding and taxing on the batteries than the rigorous vehicle environment for which it is originally designed. For example, certain application load profiles might utilize lower average rates, depths, and frequencies of discharge, etc. If true, this has the potential to dramatically increase cycle life. An example based on NiMH battery analysis is instructive: if consistently cycling at 30% DOD, a battery might get on the order of 30,000 cycles, the equivalent energy throughput of 9,000 80% DOD cycles (= 3 times the 3,000-cycle life at 80% DOD) [33]. Similarly, the USABC goal for hybrid-like charge-sustaining operation is 300,000 cycles, but for charge depleting operation the goal is 5,000 cycles [34]. But clearly this is all very dependent on the specific load profiles experienced by the battery serving various combinations of purposes, a complex and interesting area for further research. Clearly, much work remains to be done to begin to piece together an understanding of battery degradation in specific second life contexts. Should a used battery replacement be needed halfway through second life, however, the following simplistic example illustrates the effect and is summarized in Table 5-3. Leasing two Volt-type batteries up-front would cost $244 per month. Judging the operation and maintenance description in Cready *et al*. to be roughly adequate to cover one module swap at year 5, using one HESA required to bear battery repurposing costs in second-life years 1 and 5 would reduce the battery lease to $223 per month.

Table 5-3: Net residual value summary: Volt-HESA with battery replacement (rounded)

Number of batteries needed:	1	2
Battery capital costs	$8,130	$16,300
Battery lease payment (per month over entire car life)	$122	$244
10-year 2nd-life value	$18,600	$18,600
HESA cost (+ NPV of replacement in year 5 if needed)	$15,400	$16,100
Net benefit = residual value	$3,230	$2,520
Battery lease payment per month w/2nd life (8+10y)	$95	$223

Shortening initial deployment

Consider the Volt batteries characterized in Chapter 2, initially sized based on an expected 20% or so degradation in capacity over their eight-year automotive first life. What if they are repurposed after just five years of high-capacity service in a rigorous vehicle environment and re-rated at 13.9 kWh with a 65% allowed depth of discharge for 9.0 kWh of capacity available for stationary use? As the cost of the battery-swap and lease-setup fees are included in the analysis, this offers the potential for both monthly savings in addition to the opportunity to upgrade the vehicle's electric-drive performance every five years with a newer, presumably more capacious and powerful or otherwise improving battery. Table 5-4 summarizes the impact. Although the HESA does capture additional benefit from increased capacity, it is not enough to offset the increase in the lease costs due to the shorter term.

Table 5-4: Net residual value summary: 8 vs. 5 years in car (rounded)

Years in car:	8	5
Total battery cost	$8,130	$8,130
Battery lease payment (per month over entire car life)	$122	$179
Capacity available for HESA (kWh)	8.3	9.0
10-year 2nd-life value	$18,600	$20,200
HESA cost	$15,400	$16,500
Net benefit = residual value	$3,230	$3,730
Battery lease payment per month w/2nd life (8 or 5 + 10y)	$95	$123
NPV(residual value, 10% discount rate)	$1,510	$1,740

Transformer-protecting cap

At 16 and 32 kW, respectively, the Volt-HESA and LEAF-HESA represent larger resources than typical household peak loads. Thus they may challenge the abilities of existing local transformers sized to accommodate groups of residences based on pre-HESA load expectations. Table 5-5 summarizes the effect of capping the output of the Volt- and LEAF-based HESAs at 10 kW. As expected, the reduction in power capability reduces the second-life benefit when using the Eyer and Corey framework. Further, the savings on power electronics is not enough to offset this loss. Compared to Table 5-1, the integrated lease payments have increased by 13% for the Volt-HESA and 24% for the LEAF-HESA. Note, however, that the devices in Table 5-5 will have slightly different characteristics than those described previously, due for example to even lower C-rate dis/charging limits (presumably reducing degradation further) and potentially "underutilized" energy capacity (i.e., second-life benefit may increase in certain circumstances for devices with the same power output but greater energy capacity).

Table 5-5: The effect of capping Volt- and LEAF-HESA output at 10 kW (e.g., to protect local transformers) (rounded)

	Volt	LEAF
Total battery cost	$8,130	$15,000
Battery lease payment (per month over entire car life)	$122	$225
10-year 2nd-life value	$12,800	$14,400
HESA cost	$11,000	$12,700
Net benefit = residual value	$1,860	$1,740
Battery lease payment per month w/2nd life (8+10y)	$107	$210
NPV (residual value, 10% discount rate)	$869	$811

Bounding cases

To provide further context for the point estimates described throughout the report, Table 5-6 bounds the results presented in Table 5-1 with two additional point-estimate cases: a "worse" case consisting of all of the unfavorable input assumption values described in Table 5-2, and a "better" case with the favorable assumptions. The "worse" case produces several hundred dollars of residual value for the battery, which move the lease payment very little, whereas the "better" case estimates several thousand dollars more residual value, generating a roughly 32% reduction in the lease payment.

Table 5-6: Illustrative bounding cases: Volt-HESA example (rounded)

	"Worse"	"Estimate"	"Better"
Total battery cost	$10,100	$8,130	$6,690
Battery lease payment (per month over entire car life)	$145	$122	$104
10-year 2nd-life value	$8,900	$18,600	$21,800
HESA cost	$6,540	$15,400	$17,500
Net benefit = residual value	$580	$3,230	$4,300
Battery lease payment per month w/2nd life (8+10y)	$143	$95	$71
NPV (residual value, 10% discount rate)	$269	$1,510	$1,990

CHAPTER 6: Conclusions, discussion, and directions for future work

Conclusions

As seen in Tables 5-1 and 5-6, this analysis finds positive but modest potential benefits from repurposing batteries into energy-storage devices sized in accordance with their degraded vehicle capacity. Bounding estimates for the Volt-based HESA, which exhibited a roughly 22% reduction in battery lease with the addition of second-life benefit as residual value, all show battery lease payment reductions, ranging from roughly 1% to 32%. The overall net economic benefit of battery second use in the Volt-based HESA example ranges from a few hundred dollars with conservative assumptions to a couple thousand dollars with more optimistic assumptions. On the other hand, Monte Carlo analysis indicates the base-case point estimates of lease payment developed might need upwards adjustment to account for the effects of uncertainty, possibly negating the benefit from repurposing.

Of course, the realization of *any* benefits is predicated upon several assumptions and pre-conditions, which in implementation will require coordination, standardization, code and safety-procedure development, and granting HESA or similar units access to several existing and future markets, via aggregation (nominally accounted for here) or otherwise. We caution that it is unclear if the potential benefits characterized above will provide sufficient impetus to create such policies, business channels, and other elements necessary to establish markets for used-battery HESAs, let alone drive the commercialization of plug-in vehicles to any great extent, at least initially[14].

Nevertheless, several related efforts are underway to improve the prospects for grid energy storage in general, and initial policy steps already being taken include: modifying certificating procedures to include battery storage devices as CAISO generating units, further rewarding fast-response units in proportion to their operational and other benefits, and providing investment incentives [13]. To the extent that these and related efforts are successful, they raise the tide for repurposed plug-in-vehicle batteries, whose fully burdened costs have not yet been shown to be a weak link in the overall value proposition and are estimated to be considerably cheaper than the maximum allowable limit defined by new-battery costs (see Chapter 3).

Thus, possibly even if requiring replacement to match the longevity of new batteries with similar capacity, used batteries may still be a viable alternative for whatever overall value propositions develop into profitability. This, coupled with the continuing need to find appropriate and valuable uses for plug-in-vehicle batteries at the end of their vehicle life, motivates further investigation. “Proceed, but proceed with caution” may be one appropriate take-home conclusion. Further, the analysis thus far pre-supposes a reasonable but specific context that may be subject to considerable change in the future. This can be expected as the transportation and energy industries slowly collide amidst the continuing development of unprecedented and major policy drivers in California and the evolution of socio-political contexts. These factors will have important implications for energy and climate policy, innovations, and business development. With this in mind, and informed by the dynamics laid out above, future work should also ask, “How might things look differently?” in order to

[14] *NB*: Of course, plug-in vehicles—like hybrids before them, which are by most accounts commercially successful but have yet to exceed 10% of sales even in California—face a long, possibly multi-staged road to widespread commercialization. Even if not capable of assisting with initial introduction, second-life value has the opportunity to lower costs in subsequent scale-up stages.

explore how future policy and market scenarios could impact the battery second-use value proposition.

Directions for future work

Addressing critical uncertainties

This analysis indicates that, if potentially valuable grid-regulation revenues are to be hotly contested and provide limited impetus to HESA commercialization, value from multiple applications is necessary to support HESA profitability, making the artful combination of services (and thus load profiles) a critical uncertainty. One previously identified combined value proposition related to servicing local A/C loads was examined and might be particularly attractive. It formed the basis of the net-benefit calculations summarized at the beginning of this chapter. The single most important source of variation in the analysis was a blunt parameter used to characterize the degree to which the value from each of the individual applications could be captured while presumably prioritizing the most valuable one. This should be explored in detail using increasingly specific characterizations of the individual applications and their artful combination, ultimately (if warranted) by subjecting used vehicle batteries to a an integrated load profile representing concordant multi-application use. As a first step in this direction, initial conversations have begun with Energy and Environmental Economics, Inc. (E3)—whose energy-storage model supported EPRI's development of a similar but alternative framework to the Eyer and Corey framework described here [35]—about characterizing second-life multi-application value in a more specific and integrated way.

The next most important uncertainty is the level of cost associated with energy-storage appliance power-conditioning requirements, which should also be optimized with increasingly specific combined load profiles in mind and/or reduced, e.g., through coupling HESAs with local photovoltaic systems. As the two largest sources of uncertainty-based variation are characterized in an increasingly sophisticated way, additional Monte Carlo simulations should be run to verify or adjust the remaining, presumably more prominent and re-balanced sources of variation (e.g., the aggregation-fee parameter and the underlying process it represents, etc.).

Though determined to be a lower priority (and arguably unnecessary until a more thoroughly compelling revenue and cost structure are developed), additional related work might model battery degradation explicitly with the following sequence in mind: 1) a per-mile and throughput-based, rather than per-year, characterization of first life, 2) a per-year characterization of second life, and 3) with increasing load-profile specificity and battery-chemistry-specific data availability, a throughput-based characterization of second-life use.

Other un-quantified values, scale comparisons

Several other potential values have not yet been quantified here. Previous studies (e.g., [8]) lay foundations for evaluating dozens of these potential values, and some of the analysis remains pertinent today. Potential sources of additional value include, but are not limited to, Eyer and Corey's incidental benefits (listed in Chapter 4) [6], other aspects of renewables firming and carbon reduction (particularly in future contexts), as well as HESA participation in demand-response programs and other nearer-term market manifestations of the grid-services explored more generally here. Further, as mentioned in Chapter 4, the potential synergies between local PV and distributed energy storage appear particularly intriguing.

Competitive analyses and the future context

Finally, although beyond the scope of Task 3, a few comments are in order about potential future work related to competing products and a changing future context. These issues are particularly intricate as the market context for small-scale energy storage is evolving rapidly in response to increasing use of intermittent power sources such as wind and solar, driven by policy requirements for renewable generation.

First, further analysis should explicitly compare the benefits of implementing household/building ESAs (in both the current context and the context of the coming "smart grid" wherein household device control may be implemented for other reasons anyway, see below) versus spatially aggregating vehicle-based energy-storage units into bulk energy storage units. On the one hand, these larger systems should have economies of capital, operational, and transactional scale, avoid concerns about safety in home-use devices, and possibly simplify other challenges. On the other, they may not offer some of the more localized benefits to "feeder level" power distribution systems, they may require more expensive and complicated approval, siting and permitting procedures and grid-connect infrastructure, may be less accordant with the de facto standards resulting from high-volume plug-in vehicle manufacture, and may benefit less from economies of production scale as modular power conditioning and related components are developed for a variety of small-scale uses.

Second, it is important to consider another hotly developing "competitor" for grid-services value that takes advantage of the "slack" present in the thermostatic control of various thermal-storage facilities and end-use appliances such as refrigerators and air-conditioning units. Increasingly smart control of these thermal loads form the basis of existing and evolving demand-response (DR) programs, and, along with smart control of plug-in vehicle charging offer highly-distributed grid services without the explicit cost of energy storage itself.

"Demand response" is thus a broad concept that currently confounds product, technology, and market elements. On the one hand, thermostatic control spans product and technology definitions and can be considered a supply-system solution. On the other, DR is a near-term market structure in which energy storage units (with or without their own meta-DR capabilities) could presumably participate if allowed. Tradeoffs therefore exist and must be examined between the cost of energy storage (at all levels of distribution with concordant control at the building or grid-facility level) and the costs of controlling down to the individual end-use appliance at the sub-building level. Important components of these cost tradeoffs are not purely financial and must also be considered within a broad context. Might, for example, the financial cost of energy storage be partially offset by shielding concerned consumers of various types from the greater intrusion implied by centralized control of individual smart appliances, while nevertheless giving a smart grid valuable automated control on short time scales? Further, interesting opportunities to couple energy storage—both "certified pre-owned" and "dedicated"—with the other product lenses and alternative technologies should be explored.

Within reasonable limits, parallels can be drawn between the traditional grid with just-in-time delivery of power to unscheduled loads and conventional vehicle drivetrains with just-in-time production and delivery of torque. Doing so highlights the possible benefits of "hybridizing" both systems in various ways with energy-storage buffers. Indeed, the opportunities to populate the electric landscape with energy storage at many levels and in many locations serving many, increasingly multi-directional and networked purposes appear to allow several more degrees of design freedom than vehicle drivetrains.

This creates a world of both confusion and possibilities for analyses like this one and the many more related studies that can be derived and otherwise imagined. In that sense, an important part of what this effort and others attempt to contribute is not solely based on whether or not "right" or "wrong" answers have been found to questions about opportunities for which it is too early and arguably inappropriate to judge as "good" or "bad." Important, too, is learning how to think about opportunities like this one (and others unthought-of) that will arise from the rapid tectonic collision of the electric and transportation industries. It is hoped that this work has, at a minimum, contributed to the development of interesting frameworks that will facilitate that heuristic learning—even while the future context that will ultimately determine the attractiveness of such opportunities unfolds.

APPENDIX A: Vehicle approximations

Table A-1 is an illustrative portion of the model characterizing production and near-production plug-in vehicles to varying degrees of fidelity. Colors indicate the level of confidence (red = unknown/default value used, yellow = uncertain, but some reasonable basis, green = news or other source used).

Table A-1: Illustrative vehicle approximations (partial)

Plug-in vehicle	Manufact.	Rated kWh	Avail %	Avail kWh	Battery Supplier	Neg elect.	Chemistry	Cost factor
Baseline	(BDW)	5.2	65%	3.4	Hypothetical	C	LFP	1.00
Prius PHV	Toyota	5.2	75%	3.9	Panasonic EV Energy	C	NCM	0.89
Accord PHV	Honda	6.0	65%	3.9	Blue Energy Co.	C		#N/A
Escape PHEV	Ford	10	65%	6.5	JCS (Johnson Controls-Saft)	C	NCA	0.87
F3DM	BYD	13.2	65%	8.6	BYD	C	LFP	1.00
Chevy Volt	GM	16	65%	10.4	LG Chem Power	C	LMO	0.71
i	Mitsubishi	16	80%	12.8	Lithium Energy Japan	C		#N/A
smart fortwo ed	Daimler	16.5	85%	14.0	Tesla	C	NCA	0.87
F6DM	BYD	20	65%	13.0	BYD	C	LFP	1.00
500EV	Chrysler-Fiat	22	80%	17.6	SB LiMotive	C	LMO	0.71
Karma	Fisker	22.5	65%	14.6	A123	C	LFP	1.00
Focus Electric	Ford	23	80%	18.4	LG Chem Power	C	LMO	0.71
City	Th!nk	23	80%	18.4	EnerDel	C	LMO	0.71
LEAF	Nissan	24	85%	20.4	AESC (NEC/Nissan)	C	LMO	0.71
Transit Connect Electric	Azure/Ford	28	80%	22.4	JCS (Johnson Controls-Saft)	C	NCA	0.87
ActiveE	BMW	32	80%	25.6	SB LiMotive	C	NCM	0.89
Coda Sedan	Coda	34	80%	27.2	Lio Energy Systems (Lishen)	C	LFP	1.00
Cooper MINI-E	BMW	35	80%	28	SB LiMotive	C	NCM	0.89
SUT	Phoenix	35	80%	28.0	Altairnano	LTO	LMO	1.05
RAV4EV	Toyota	35	80%	28.0	Tesla (Panasonic 18650?)	C	NCA	0.87
Edison Panel Van	Smith EV	36	80%	28.8	Valence	C	LFP	1.00
Model S	Tesla	42	80%	33.6	Panasonic	C	NCA	0.87
Roadster	Tesla	53	86%	45.6	Panasonic	C	NCA	0.87
e6	BYD	72	80%	57.6	BYD	C	LFP	1.00

APPENDIX B: 7 March 2011 workshop

Plug-In Vehicle Battery "Second Life" Workshop
7 March 2011, University of California at Berkeley

List of Attendees

Name	Affiliation
Bodnar, Guillermo	KnGrid
Bomberg, Matthew	UC Berkeley
Burke, Andrew	UC Davis
Cowart, Daniel	UC Berkeley
Crosby, Matthew	CPUC
Cun, David	Honda
Davis, Stephen	KnGrid
Dempster, Peter	BMW
Ferry, Mike	CA Center for Sustainable Energy
Garas, Dahlia	UC Davis
Goh, Ian	UC Berkeley
Goin, Dana	UC Berkeley
Gruendling, Paula	Mills College
Habfast, Remi	UC Berkeley
Holmes, John	Sempra Energy
Jungers, Bryan	UC Davis
Kamath, Haresh	Electric Power Research Institute
Kostecki, Robert	Lawrence Berkeley National Laboratory
Kwong, Anthony	UC Berkeley
Lipman, Timothy	UC Berkeley
Marnay, Chris	Lawrence Berkeley National Laboratory
Misemer, Philip	California Energy Commission
Neubauer, Jeremy	National Renewable Energy Laboratory
Richardson, David	Vision Ridge
Schewel, Laura	UC Berkeley
Stokes, Erik	California Energy Commission
Suh, John	General Motors
Turrentine, Tom	UC Davis
Velev, Omourtag	AeroVironment
Williams, Brett	UC Berkeley
Witt, Maggie	UC Berkeley

APPENDIX C: CEFIS-methodology calculation

For comparison of preliminary work to the current analysis, the following summarizes a calculation made for the Volt using the previous methodology. Compare to Table 5-1.

- Starting with a 16 kWh, $10.6k battery
  - Degraded over 8y in car to ~12 kWh
  - Can post-vehicle use cover, say, $18k in repurposed HESA costs?
- NPV(mostly regulation net revenues) ~ $4.7k in battery "residual value"
- Lowers $204/month battery lease requiring full depreciation over 8y (car-only scenario) to:
- $115/month, 8y lease (car-and-repurposing scenario)
  - Several unexplored revenue streams

Acronyms

$	U.S. dollar(s)
/	as in $100/kWh = per
A	ampere
Battery	"Battery" is generally defined here to mean only the modules, a minimal management system (e.g., for voltage and other monitoring, balancing), and integral structure/interfaces that will be removed from the vehicle and repurposed for use in second life.
C	LiC_6, graphite, a negative electrode material
CAISO	California Independent System Operator
CES	Community Energy Storage
CD	charge depleting
CS	charge sustaining
DR	demand response
e-fuel	electric fuel (electricity used as a transportation fuel)
EV	electric vehicle (i.e., electrically powered; when used alone it is usually in reference to an all-battery electric vehicle)
EPRI	Electric Power Research Institute
HESA	household electricity storage appliance (a home-based, distributed energy storage device)
INL	Idaho National Laboratory
LCO	lithium colbalt oxide, $LiCoO_2$
LFP	lithium iron phosphate, $LiFePO_4$
LMO	lithium manganese oxide, spinel, $LiMn_2O_4$
LTO	lithium titanate, $Li_4Ti_5O_{12}$
km	kilometer(s)
mi	mile(s)
MW	megawatt(s)
NCA	nickel/cobalt/aluminum oxide, $LiNi_xCo_yAl_zO_2$
NCM	nickel/cobalt/manganese oxide (=NMC), $Li(Li_aNi_xCo_yMn_z)O_2$
NMC	nickel/cobalt/manganese oxide (=NCM), $Li(Li_aNi_xCo_yMn_z)O_2$
NiMH	nickel metal hydride
OBD	on-board diagnostics
RFP	Request for Proposals
SDGE	San Diego Gas & Electric
SNL	Sandia National Laboratory
SOC	state of charge
TSRC	UC Berkeley's Transportation Sustainability Research Center
UC	University of California
V	volt(s)
y	year(s)

References

1. "General Motors announces 8-year/100,000-mile warranty for Chevy Volt battery." autoblog.com. 14 Jul 2010. http://www.autoblog.com/2010/07/14/general-motors-announces-8-year-100-000-mile-warranty-for-volt-b/
2. "Nissan LEAF Electric Car - Answers - Warranty - What kind of warranty will this car have?" Nissan. 2011. http://www.nissanusa.com/leaf-electric-car/faq/view/52 - /leaf-electric-car/faq/view/52
3. Wood, E.; Alexander, M.; Bradley, T. H. "Investigation of Battery End-of-Life Conditions for Plug-in Hybrid Electric Vehicles." *Journal of Power Sources* **2011,** 196, (11), 5147-5154.
4. Cready, E.; Lippert, J.; Pihl, J.; Weinstock, I.; Symons, P.; Jungst, R. G. *Technical and Economic Feasibility of Applying Used EV Batteries in Stationary Applications: A Study for the DOE Energy Storage Systems Program*; SAND2002-4084; Sandia National Laboratories: Albuquerque, NM, March, 2002.
5. Cessna, D.; Velev, O. *Second Life Applications of Lithium Batteries: Evaluation Test Plan and Procedures*; 17037-06002_1X; AeroVironment, Inc.: Morovia CA, 10 Dec, 2010.
6. Eyer, J.; Corey, G. *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*; SAND2010-0815; Sandia National Laboratories: Feb, 2010. http://prod.sandia.gov/techlib/access-control.cgi/2010/100815.pdf
7. Williams, B. D.; Lipman, T. E. *Strategies for Transportation Electric Fuel Implementation in California: Overcoming Battery First-Cost Hurdles*; CEC-500-2009-091; California Energy Commission Public Interest Energy Research (PIER) Transportation Program: Sacramento, 2009. http://www.energy.ca.gov/2009publications/CEC-500-2009-091/CEC-500-2009-091.PDF
8. Lovins, A. B.; Datta, K. E.; Thomas, F.; Rabago, K. R.; Swisher, J. N.; Lehmann, A.; Wicker, K. *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size*; Rocky Mountain Institute: Snowmass CO, 2002.
9. "Duke Energy and ITOCHU to Develop Strategies for Reusing Vehicle Batteries." Duke Energy. 2010. http://www.duke-energy.com/news/releases/2010112301.asp
10. "Nissan and Sumitomo Establish Joint Research Company for Promotion of '4R Energy' Business." Nissan. 2010. http://www.nissan-global.com/EN/NEWS/2010/_STORY/100915-02-e.html
11. "ABB and GM to collaborate on electric car battery research." ABB. 2010. http://www02.abb.com/global/seitp/seitp202.nsf/0/28a86dd17b3be7a4c12577a50047ccd7/$file/10_36_battery+project.pdf
12. "SolarCity, Tesla, and UC Berkeley to Collaborate on Solar Storage Technologies." SolarCity. 20 Sep 2010. http://www.solarcity.com/pressreleases/70/SolarCity-Tesla-and-UC-Berkeley-to-Collaborate-on-Solar-Storage Technologies.aspx
13. Hawkins, D., DRAFT Frequently Asked Questions about markets for energy storage. In California Independent System Operator (CAISO): 2008.
14. Williams, B. D. "Commercializing Light-Duty Plug-In/Plug-Out Hydrogen-Fuel-Cell Vehicles: "Mobile Electricity" Technologies, Early California Household Markets, and Innovation Management." PhD Dissertation, University of California at Davis, Davis CA, 2007.
15. Williams, B. D.; Kurani, K. S. "Commercializing light-duty plug-in/plug-out hydrogen-fuel-cell vehicles: "Mobile Electricity" technologies and opportunities." *Journal of Power Sources* **2007,** 166, (2), 549-566.
16. Abuelsamid, S., "Toyota officially launches plug-in Prius program, retail sales in 2011." autobloggreen.com. 14 Jul 2009. http://green.autoblog.com/2009/12/14/toyota-officially-launches-plug-in-prius-program-retail-sales-i/
17. Murph, D., "2011 Chevy Volt gets stickered: 93MPG on battery, 37MPB on gasoline." engadget.com. 2010. http://www.engadget.com/2010/11/26/2011-chevy-volt-gets-stickered-93mpg-on-battery-37mpg-on-gasol/

18. "Rockwood Holdings, Inc. - FORM 8-K - EX-99.1 - May 12, 2010." faqs.org. 2010. http://www.faqs.org/sec-filings/100512/Rockwood-Holdings-Inc_8-K/a10-9955_1ex99d1.htm
19. Lyle, "Chevrolet Volt Will Utilize 10.4 KWH of Battery to Achieve EV Range." gm-volt.com. 2010. http://gm-volt.com/2010/10/26/chevrolet-volt-will-utilize-10-4-kwh-of-battery-to-achieve-ev-range/
20. "Nissan Leaf snags 99 mpg rating on official EPA sticker." autoblog.com. 22 Nov 2010. http://www.autoblog.com/2010/11/22/nissan-leaf-snags-99-mpg-rating-on-official-epa-sticker/
21. Howell, D. In *Vehicle Technologies Program*, Annual Merit Review, Energy Storage R&D and ARRA Overview, Washington DC, 8 June, 2010; U.S. DOE EERE: Washington DC, 2010.
22. Choi, D.; Wang, W.; Viswanathan, V. V.; Yang, G. Z. In *Low Cost, Long Cycle Life, Li-ion Batteries for Stationary Applications*, DOE EERE Energy Storage Program Annual Update 2010, Washington, DC, 2 Nov, 2010; PNNL: Washington, DC, 2010.
23. Haskins, H.; Battaglia, V.; Christophersen, J.; Bloom, I.; Hunt, G.; Thomas, E. *Battery Technology Life Verification Test Manual*; INEEL/EXT-04-01986; Idaho National Laboratory (INL): Idaho Falls, ID, Feb, 2005.
24. "1547 Series of Interconnection Standards." IEEE. 28 Dec 2010. http://grouper.ieee.org/groups/scc21/dr_shared/
25. Neubauer, J.; Pesaran, A. *NREL's PHEV/EV Li-ion Battery Secondary-Use Project*; NREL/CP-540-48042; National Renewable Energy Laboratory (NREL): Golden, 21 May, 2010. http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/48042.pdf
26. Williams, B. D.; Lipman, T. E. In *A Strategy for Overcoming Plug-In-Hybrid Battery Cost Hurdles in California: Integrating Post-Vehicle Secondary Use Values*, Transportation Research Board Annual Meeting, Washington DC, 2010; Transportation Research Board: Washington DC, 2010.
27. Kempton, W.; Tomic, J.; Letendre, S.; Brooks, A.; Lipman, T. E. *Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California*; UCD-ITS-RR-01-03; University of California at Davis: Davis CA, June, 2001. http://www.its.ucdavis.edu/publications/2001/RR-01-03.pdf
28. Kempton, W.; Tomic, J. "Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy." *Journal of Power Sources* **2005,** 144, (1), 280-294.
29. Kempton, W.; Tomic, J. "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue." *Journal of Power Sources* **2005,** 144, (1), 268-279.
30. "California Energy Regulatory Update." Wilson Sonsini Goodrick & Rosati. 7 Feb 2011. http://www.wsgr.com/cleantech/alerts/alert18.asp
31. "Monthly Market Performance Reports Archive." CAISO. 2011. http://www.caiso.com/17ed/17ed90c231ac0.html
32. CAISO *Integration of Renewable Resources: Operational Requirements and Generation Fleet Capability at 20% RPS*; 2804d036401f0; CAISO: 31 August, 2010. http://www.caiso.com/2804/2804d036401f0.pdf
33. Kalhammer, F. R.; Kopf, B. M.; Swan, D. H.; Roan, V. P.; Walsh, M. P. C. *Status and Prospects for Zero Emissions Vehicle Technology: Report of the ARB Independent Expert Panel 2007*; California Air Resources Board: Sacramento, 13 April, 2007. http://www.arb.ca.gov/msprog/zevprog/zevreview/zev_panel_report.pdf
34. Francfort, J. E. In *U.S. Department of Energy - Vehicle Technologies Program*, Power UP 2008 Summit, Wenatchee, Washington, May, 2008; Idaho National Laboratory: Wenatchee, Washington, 2008.
35. *Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs and Benefits*; 1020676; Electric Power Research Institute (EPRI): Palo Alto, CA, Dec, 2010.