Plug-In-Vehicle Battery Second Life: the Effect of Post-Vehicle, Distributed-Grid-Energy-Storage Value on Battery-Lease Payments

Brett Williams, PhD (corresponding author, 510-326-6429; bdw@berkeley.edu)

University of California, Berkeley
Transportation Sustainability Research Center (TSRC)
2150 Allston Way #280
Berkeley CA 94704
Fax: 510-665-2128

Submitted: 07/28/2011, resubmitted with edits 11/08/2011.

Word count: 5,727; Table/figure count: 6; Total "word" count: 7,227

ABSTRACT

This research analyzes the potential reduction in plug-in-vehicle (PEV) battery-lease payments that incorporation of value from post-vehicle, stationary provision of grid services might provide in California. PEV batteries repurposed into distributed electrical storage appliances (DESAs) might provide valuable services to electricity customers, utilities, and regional grid operators alike, improving grid operation, helping to defer costly upgrades, and supporting the penetration and profitability of intermittent renewable energy.

The research advances methods for analyzing combined vehicular and post-vehicular value and uses new and increasingly sophisticated inputs, including specific PEV characterizations and value for 19 grid applications. It finds positive but sometimes-modest potential benefits. Bounding scenarios all show battery-lease payment reductions. For the "Chevy Volt"-based 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 might need downward adjustment to account for uncertainty, possibly negating second-life benefit.

The analysis indicates that, if valuable regulation revenues are hotly contested and provide limited impetus to DESA commercialization, value from multiple applications will be necessary to support profitability. This makes the artful combination of services a critical uncertainty. One previously identified multi-application combination related to servicing local A/C loads was examined as the base case and might be attractive. Another important uncertainty is the cost of power-conditioning requirements, which must also be optimized with specific combined load profiles and/or reduced, e.g., through coupling DESAs with local photovoltaics.

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

1. INTRODUCTION

The core problem motivating this analysis is that battery upfront costs present a major barrier to the widespread commercialization of plug-in vehicles (PEVs) and electric-fuel (e-fuel). This analysis overhauls and expands previous preliminary research (*1*) investigating the potential reduction in plug-in-hybrid battery-lease payments that incorporation of value from post-vehicle, stationary provision of distributed energy-storage services in California might provide. PEV batteries repurposed into distributed electrical storage appliances (DESAs) might provide valuable services to electricity customers, utilities, and regional grid operators alike, improving utility operation, helping to defer costly grid upgrades, and supporting the profitability and penetration of intermittent renewable energy.

Many 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 lay foundations for further evaluation. A 2002 Sandia National Laboratory study (*2*) focused on nickel-metal-hydride batteries, but suggested that many of the process-oriented results are broadly applicable to other chemistries. A 2010 study for Sandia (*3*), provides a thorough, high-level examination of energy-storage applications independent of technology or product type. This analysis incorporates and builds upon those studies and a growing body of knowledge about PEVs, opportunities for distributed energy storage, and the potential use of repurposed plug-in-vehicle batteries in particular. It evaluates not only over a dozen new applications, but uses a wide range of characterizations of commercial and near-commercial PEVs, including battery-electric vehicles.

Scope limitations

This work is an estimate and optimization of value. It is not a competitive analysis, which would place the value of the DESA 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. smart charging) and 2) a variety of technologies competing within each product definition (e.g., flow batteries vs. compressed-air storage). It 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 structured and accessed. To use an analogy, the estimate of DESA values developed here 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.

Further, as this project progressed, several related activities exploring battery second-use with hardware demonstrations 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, Solar City with Tesla and UC Berkeley, EnerDel with Itochu, DTE with A123, and Nissan with Sumitomo (*4-7*). These efforts will provide an increasingly clearer understanding of the technical challenges and expectations of various second-life contexts.

If determined to provide sufficient value, repurposing vehicle batteries for second-life use might improve the commercialization prospects of PEVs—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 better understand, let alone realize, the potential of such strategies.

2. FIRST LIFE: PLUG-IN ELECTRIC VEHICLE BATTERIES

Production-Vehicle Approximations, Battery Cost, and Lease Payments

This analysis is based on a database of over 30 production or near-production PEVs. Three such vehicle approximations form the basis of discussion: the Toyota Prius PHV, the Chevy Volt, and the Nissan LEAF. Table 2-1 roughly characterizes those vehicles based on public information. 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 (*8, 9*) and with the USABC end-of-life criteria for electric vehicles (*10*). The implications of this "80% at 8 years" starting-point assumption, including testing a wide range of assumptions using Monte Carlo analysis, are explored in Section 5.

Table 2-1 also 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 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 per *available* kilowatt-hour ($825/kWh)—the midpoint of "current" cost estimates in a recent U.S. DOE study (*11*)—scaled by ratios reflective of cost differences between chemistries (*12*). All dollars are U.S. dollars circa 2010, unless stated otherwise. Because of greater access to published data characterizing iron-phosphate (LFP) batteries, various characteristics, including cost, are normalized to the iron-phosphate value (e.g., the cost-scaling factor for LFP/graphite is 1 and for manganese-oxide or LMO/graphite is 0.71). Additionally, $100/kWh plus $1,000 is added to capture the costs of the minimal management system and thermal and electrical interfaces accompanying the battery into second life. Rather than doubling the cell cost as is reasonable for today's systems with full balance-of-plant, this starting-point assumption for minimal module-management-system costs produces a 20–30% contribution. It should be refined and is examined in the sensitivity analysis.

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 2-1 also presents battery-lease estimates, the monthly payment to lease the battery (only), fully depreciating it over "first life." The lease is structured analogously to a car lease, but for the battery only, assuming: $0 first-life residual value, a 6.99% APR, a lease fee proportional to the battery cost (e.g., $266 for the Volt battery), and 9.75% sales tax.

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 Section 4, and the costs of repurposing the battery are explored in Section 3.

3. REPURPOSING: DISTRIBUTED ENERGY-STORAGE APPLIANCE COSTS

The costs associated with repurposing PEV batteries into DESAs can be divided into two categories. The first, "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 added to the second category, "ESA cost," which consists of those cost components common to all energy-storage appliances of a given type, including power-conditioning, assembly, distribution, installation, and maintenance.

Maximum Allowable Repurposing Cost: New-Battery Costs

For DESAs 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. For example, assuming rapid initial battery-cost decreases as volume ramps up to meet initial plug-in-vehicle offerings—e.g., using a 82% "experience curve" approach (18% cost reduction with each doubling of production, occurring at decreasing intervals), new battery costs may be roughly half today's costs by the time a battery is removed from the vehicle in year 8. Thus, for comparison in the next subsection, the fully-burdened repurposed Volt battery could cost the DESA no more than roughly $4,100 to possibly be competitive with a new battery. 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 (*18*), a 15% used-product discount would lower this maximum allowable cost to roughly $3,500.

Repurposing Cost

Cready *et al*. (*2*) 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 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). Repurposing costs are summarized in Table 3-1 along with common "ESA costs," described next. (Acknowledging precision and certainty limitations, most tables present rounded results—e.g., to 3 significant figures.) In the Volt case, repurposing costs are less than 30% of expected new-Volt-battery costs as described above, considerably lower than the allowable limit. However, this does not fully take into account the decreased health 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.

Distributed Energy-Storage Cost

The rest of the cost components summarized in Table 3-1 falls under the second category—those costs common to DESA production. The power capabilities (kilowatts) of the DESAs have been capped at twice the energy-storage capacity (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 Section 4). Further, because this ratio represents a reasonable dis/charge rate limit (2C) and is potentially mild when compared to several-C vehicular life (e.g., 6C over 10 minutes for fast charging all-battery EVs), it helps 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-DESA). 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.

In order to allow for the exploration of fully capable DESAs, the highest costs for power conditioning, controls, and interfaces from Cready *et al.* were used in the second row of Table 3-1. For the next two rows, more modest costs were assumed to apply to DESAs than bulk-storage facilities. However, because Cready *et al*.'s modest "residential load following" estimates may not be fully adequate, the next cheapest estimates (those derived from a facility in Chino, California), were used to be conservative.

4. SECOND LIFE: DISTRIBUTED GRID ENERGY STORAGE

DESA-Sized Distributed Energy-Storage Benefits

A taxonomy of the gross benefit provided by grid energy storage by Eyer and Corey (*3*) includes 19 applications grouped into five categories: Electric Supply, Ancillary Services, the Grid System, End User/Utility Customer, and Renewables Integration. Eyer and Corey characterize each application with a range of discharge durations and application-specific benefits. Using average values from that report and an assumed 96% average discharge efficiency, Table 4-1 presents a menu of single-application, system-wide benefit values that might accrue in California to PEV-based DESAs. Each value is the net-present-value of 10 years of application. As described in Section 3, the assumed DESA power capabilities have been capped to avoid disproportionate benefit estimation and to minimize potential battery-degradation effects by confining the batteries to more modest dis/charge rates than designed for in the car.

Further refinement is of course necessary to make the estimates in Table 4-1 increasingly meaningful and accurate for a given context. However, Corey and Eyer explicitly intended their framework to be used as a high-level, system-perspective tool, and accordingly several lessons for subsequent analysis can be drawn. For example, the estimates give an indication of the maximum DESA costs that could be supported in each individual application (net benefit is discussed in Section 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 area regulation, an ancillary grid market created to help improve the match between the supply of and demand for power on the grid, thereby maintaining grid parameters (e.g., frequency) within acceptable ranges. This is expected and consistent with precursor analysis (*1, 19-21*), and thus warrants further discussion. First, it is important to note that both the Eyer and Corey framework (*3*), and precursor work with similar regulation-valuation findings (*21*) use regulation prices (up+down) from several years ago: 2006 (*3*) and 2006–2008 (*21*). Compiling recent values (*22*), 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-DESA regulation benefit from \$23,250 to less than \$9,300, a significant reduction.

Future price levels are unclear, however, as the economy recovers and electricity use increases, and in the context of a 33% Renewable Portfolio Standard (RPS). Additionally, in February 2011, the California Independent System Operator (CAISO) approved a "regulation energy management" (REM) tool that "permits energy-storage and demand-response resources with 15-minute capability to begin bidding in the CAISO market" (*23*). As described above, the DESA dis/charge rates have been capped here at 2C; 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 DESA gross regulation benefit. Regardless, it should be noted that control and aggregation of DESA-sized units into the one-half-megawatt size necessary for participation in REM markets might be challenging and costly (see below).

Regulation Competition and Market Potential

The potentially high value of providing regulation services is also consistent with the active market development for bulk-energy-storage provision by Beacon Power and others. Regulation will be hotly contested by those looking through various product lenses and using alternative technology options. Thus, the market pull for DESAs could be limited. Even without competition, it would only take about 44,000 Volt-DESAs to amount to the 2006–2008 average CAISO regulation (up+down) requirement of 732 MW per year. 44,000 batteries, each making \$3,500/year would theoretically "earn" more than \$150 million/year, though revenues will not remain constant as markets saturate.

Further, GM hopes to sell 45,000 Volts in the U.S. in 2012 alone. On the other hand, only a fraction of those Volt 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 DESAs using four repurposing centers as described in Section 3.

Meanwhile, the requirements for flexible capacity in California are likely to rise to support of the 33% RPS, though the extent required remains unclear. Meanwhile, CAISO's over 20,000 megawatts of regulation-certified capacity may be sufficient to provide—if not in the optimally efficient manner—California's near-to-mid-term regulation needs (*24*).

Thus, though the potential regulation value per DESA in California is large, the overall potential of the market to sustain high value and/or many DESAs may be limited. For this reason, various multi-application value propositions are explored.

Multi-Application Value Propositions

Comparing Table 4-1 to Table 3-1—and given the limitations of, and competition for, regulation—no single application benefit appears likely to sustain the DESA value proposition. Multiple-application value propositions are therefore needed. Eyer and Corey provide some insight into which applications are compatible, and four of their proposed multi-application combinations are summarized in Table 4-2. Further, single-application estimates for the Volt-based DESA are combined in three ways for illustration. The first is a simple sum that implies the (probably impossible) theoretical-maximum use of a single device to fully serve all of the applications in the combination, 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 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 the need to aggregate the benefits of distributed devices. These blunt percentage parameters are explored further in Section 5.

Table 4-2 indicates that a promising use of DESAs might be to prioritize electric-service power quality in the context of serving small air-conditioning loads.

5. INTEGRATING RESULTS, UNCERTAINTY & SENSITIVITIES, AND ALTERNATIVE SCENARIOS

Table 5-1 integrates the results and shows the net impact that value from the "small A/C load" multi-application combination has on the battery-lease payment. It also calculates the simple net-present-value (NPV) of the second-life value, bringing it forward from year 8 to year 1 using a 10% discount rate. Recall that both measures of 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 may be shared by those parties necessary to implement the value proposition whose interests have not been explicitly or sufficiently accounted for here—possibly including the DESA consumer and the automaker (for any extra efforts necessary to facilitate second-life use). (Parties whose requirements have been explicitly, though not necessarily fully or accurately, covered include the DESA service aggregator, the DESA producer, and the battery manufacturer.)

The NPV of second life presented in Table 5-1 ranges from a-few-hundred to a-few-thousand dollars and the reductions in lease payments range 11–24%. 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 on the parameters listed in Table 5-2 using Oracle's Crystal Ball software. The "best-guess" point estimates discussed so far are in bold and have been bounded by ranges defined by "minimum" and "maximum" estimates based on a combination of the literature used to produce the corresponding point estimate and author judgment. All but two ranges have been characterized with triangle probability distributions defined by linearly decreasing probability from the point estimate to the minimum and maximum estimates. Additionally, two parameters for which it was thought particularly little was known about the appropriate probably distribution were assigned uniform distributions throughout their range of potential values.

In contrast to the point-estimate of $95/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 last column in Table 5-2 gives the contribution to the variance produced by each parameter.

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 2) the parameter characterizing the per-kilowatt cost of DESA power conditioning, controls, and interfaces. Clearly, the artful combination of value in multi-application combinations is critical to Volt-based DESA profitability: if the DESA 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 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 DESA 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).

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 DESA 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 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 increasing it and possibly investing in additional batteries (to make up for increased degradation).

Battery Replacements and Shortened Initial Deployment

Though difficult to justify for the purpose of allowing increased power ratings, battery replacement is worth considering 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 Section 4. Several conservatisms have been discussed and employed in this analysis, and it is reasonable to suspect that many second-life applications will be less demanding and taxing than the rigorous vehicle environment for which the batteries are originally designed. But clearly this is all dependent on the specific load profiles experienced by the battery serving various combinations of purposes, a complex and interesting area for further research.

Should a used-battery replacement be needed halfway through second life, however, the following simplistic example illustrates the effect: leasing two Volt-type batteries up-front would cost $244 per month. Judging the operation-and-maintenance description in Cready *et al*. to be adequate to cover one year-5 module swap, one DESA required to bear battery repurposing costs in second-life years 1 and 5 would still reduce the lease payment, to $223 per month.

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

Bounding Estimates

Two bounding scenarios were also developed. Combining all of the unfavorable assumptions for the Volt-DESA results in modest movement in the battery lease: from $145/month to $143/month. Combining the favorable assumptions produces a roughly 32% reduction: from $104/month to $71/month.

6. CONCLUSIONS, DISCUSSION, AND DIRECTIONS FOR FUTURE WORK

This analysis finds positive potential benefits from repurposing PEV batteries into energy-storage devices sized in accordance with their degraded vehicle capacity. Bounding estimates for the Volt-based DESA, which exhibited a roughly 22% reduction in battery-lease payments 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 DESA 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 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/or granting DESA or similar units access to several existing and future markets, via aggregation (nominally accounted for here) or otherwise. Initial policy steps already identified and underway would allow or improve the strategies like those described here (*25*), but many more would ultimately be needed.

It is unclear if the potential benefits characterized above would provide sufficient impetus to create the policies, business channels, and other elements necessary to establish markets for used-battery DESAs, let alone drive the commercialization of PEVs to any great extent, at least initially. Of course, PEVs—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, 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.

To the extent that efforts to improve energy-storage prospects in general are successful (e.g., California's AB2514), they will lift the tide for repurposed plug-in-vehicle batteries—whose fully burdened costs have not been shown the weak link in the overall value proposition and are estimated to be several times cheaper than the allowable limit defined by new-battery costs (see Section 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 carefully" 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.

Directions for Future Work

This analysis indicates that, if potentially valuable grid-regulation revenues are to be hotly contested and provide limited impetus to DESA commercialization, value from multiple applications is necessary to support DESA profitability, making the artful combination of services (and thus load profiles) a critical uncertainty. This should be explored in detail using increasingly specific characterizations of the individual applications and their artful combination.

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 DESAs 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.

Several other potential values have not yet been quantified here. Potential sources of additional value include, but are not limited to, Eyer and Corey's incidental benefits (*3*), other aspects of renewables firming and carbon reduction (particularly in future contexts), as well as DESA participation in demand-response programs and other nearer-term market manifestations of the grid-services explored more conceptually here. Further, the potential synergies between local PV and distributed energy storage appear particularly intriguing.

More generally, parallels can be drawn between 1) the traditional grid with just-in-time delivery of power to unscheduled loads and 2) 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 various, increasingly multi-directional and networked purposes appear to allow several more degrees of design freedom than do 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.

ACKNOWLEDGEMENTS

Foremost thanks go to Timothy Lipman, the PI of the project that produced this research and co-author on related work. This project was funded by the CEC PIER Program. We are appreciative of their timely support. We particularly thank Philip Misemer and Erik Stokes of PIER for their guidance and assistance and Tom Turrentine and Dahlia Garas of the UCD PH&EV Center for their management and oversight. Others providing provocative thoughts and insights include Jeremy Neubauer, Mike Ferry, John Holmes, Andy Burke, and Omo Velev. We also thank the approximately 30 participants in the "Plug-In-Vehicle Battery-Second-Life Workshop" held in Berkeley on 7 March 2011. Dana Goin of UCB was instrumental to the organization and execution of the workshop and supported TSRC in several important ways throughout the project period. Rémi Habfast of UCB also contributed to the research effort. Of course, the author is responsible for the contents of this paper.

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TABLE 2-1 PEV characterizations

Characteristic	**PHV**	**Volt**	**LEAF**
Battery (rated)	5.2 kWh (*13*)	16 kWh (*14*)	24 kWh (*15*)
Initial capacity available to driving	75% (3.9 kWh)	65% (10.4 kWh) (*14*)	85% (20.4 kWh)
Charge depleting fuel economy	36 kWh/100mi (*16*)	36 kWh/100mi (*16*)	34 kWh/100mi (*15*)
Charge depleting (electric) range	13 mi	35 mi (*16*)	73 mi (*15*)
Rated capacity at end of first life (80%)	4.2 kWh	12.8 kWh	19.2 kWh
Chemistry	Panasonic NCM/graphite (*17*)	LG Chem LMO/graphite	AESC (NEC) LMO/graphite
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

TABLE 3-1 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[a]
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 DESA cost	**$6,120**	**$15,400**	**$30,000**

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

TABLE 4-1 Menu of Potential Second-Life Energy-Storage Gross Benefits[a] Per DESA (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[b]	$2,790	$7,430	$14,580
T&D Upgrade Deferral 90th percentile[b]	$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

[a] lifecycle benefit over 10 years, with 2.5% escalation and 10% discount rate

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

TABLE 4-2 Ten-Year Value Proposition Benefit: Volt Estimate (Rounded)

Eyer&Corey'10 Value Proposition (*3*)	**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) [a] + 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) [a] + 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

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

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 8 years)	$64	$122	$225
10-year 2nd-life value	$6,970	$18,600	$36,500
DESA 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

TABLE 5-2 Contributions of Key Parameters to the Variance in the Volt-DESA Battery Lease

Parameter	**Minimum**	**Likely**	**Maximum**	**Contribution to variance**
"% of rest" (non-priority grid-service values)	0%	Uniform	**50%**	-54%
Per-kW 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%