# Second Life for Plug-In Vehicle Batteries

## Effect of Grid Energy Storage Value on Battery Lease Payments

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**This research analyzes the potential reduction in battery lease payments for plug-in electric vehicles (PEVs) in California that incorporate the value from postvehicle, stationary provision of grid services. PEV batteries repurposed into distributed electrical storage appliances (DESAs) might provide valuable services to electricity customers, utilities, and regional grid operators alike, with improved grid operation, deferred costly upgrades, and support for the penetration and profitability of intermittent renewable energy. This research advances methods for analyzing combined vehicular and postvehicular value and uses new and increasingly sophisticated inputs, including specific PEV characterizations and value for 19 grid applications. The results showed positive but sometimes modest potential benefits. Bounding scenarios all showed reductions in battery lease payments. 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 indicated that the point estimates that were developed might need downward adjustment to account for uncertainty, a situation that would possibly negate second-life benefit. The analysis indicated that if valuable regulation revenues were hotly contested and provided limited impetus to DESA commercialization, value from multiple applications would be necessary to support profitability. This possibility makes the artful combination of services a critical uncertainty. One previously identified combination of multiapplications related to servicing local air-conditioning loads was examined as the base case and was found to be attractive. Another important uncertainty is the cost of power-conditioning requirements, which must also be optimized or reduced with specific combined-load profiles, for example, through coupling DESAs with local photovoltaics.**

The core problem motivating this analysis is that battery upfront costs present a major barrier to the widespread commercialization of plug-in electric vehicles (PEVs) and electric fuel. This analysis overhauls and expands previous preliminary research, investigating the potential reduction in battery lease payments for plug-in hybrids that incorporation of value from postvehicle, stationary provision of distributed-energy storage services in California might provide (*1*). 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 that research provided not only a preliminary but also a partial picture. Previous studies laid foundations for further evaluation. A 2002 Sandia National Laboratory study focused on nickel–metal hydride batteries but suggested that many of the process-oriented results are broadly applicable to other chemistries (*2*). A 2010 study for Sandia provides a thorough, high-level examination of energy storage applications independent of technology or product type (*3*). 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 batteries from plug-in vehicles in particular. It evaluates not only more than 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 DESAs in context relative to (*a*) a spectrum of other product lenses through which energy storage opportunities might be viewed (e.g., traditional-generation resources versus bulk energy storage versus smart charging) and (*b*) a variety of technologies competing within each product definition (e.g., flow batteries versus 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. For an analogy, the estimate of DESA values developed here provides a sense of the overall pressure or voltage available to drive California toward 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, under way, or both. Many of these activities could not be accessed or incorporated fully into this effort, but they include those by General Motors (GM) and ABB; Solar City with Tesla and the University of California, Berkeley; EnerDel with Itochu; DTE Energy with A123 Systems, 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 it is determined to provide sufficient value, repurposing of vehicle batteries for second-life use might improve the commercialization prospects of PEVs—strengthening the ever-tightening con-

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nections 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.

## FIRST LIFE: PEV BATTERIES

This analysis is based on a database of more than 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 1 data roughly characterize those vehicles on the basis of public information. As a starting point, all vehicle batteries are assumed to still have approximately 80% of their capacity after approximately 8 years, on average—consistent with both the warranties for the Volt and the Leaf (*13, 14*) and the U.S. Advanced Battery Consortium end-of-life criteria for electric vehicles (*15*). The implications of this starting-point assumption of 80% at 8 years, including testing of a wide range of assumptions with Monte Carlo analysis, are explored in the section on integrating results.

Table 1 is also a summary of 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 a second life (i.e., integrated modules). This definition does not include the supporting balance-of-pack components that will remain in the vehicle (e.g., the vehicle-integrated thermal-management components, alternating-current charger, direct-current–direct current converter, crash sensors, power conditioning, vehicle-level pack-management systems).

The cost estimates assume a base module cost of $825 per available kilowatt-hour ($825/kW-h)—the midpoint of current cost estimates in a recent U.S. Department of Energy study (*16*)—scaled by ratios reflective of cost differences between chemistries (*17*). (All dollar figures are U.S. dollars circa 2010, unless stated otherwise.) Because of greater access to published data on iron phosphate batteries, various characteristics, including cost, are normalized to the iron phosphate value (e.g., the cost-scaling factor for iron phosphate–graphite is 1 and for manganese oxide–graphite is 0.71). Furthermore, $100/kW-h 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 the minimal costs of a module-management system produces a 20% to 30% contribution. This assumption should be refined and is examined in the sensitivity analysis.

Even at these costs, a significant up-front cost hurdle remains. A battery lease could help spread those costs over the operational life of the battery. Table 1 also shows battery lease estimates, the monthly payment to lease the battery (only), fully depreciating it over its 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% annual percentage rate, 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 in addition to the 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 the section on that topic, and the costs of repurposing the battery are explored in the next section.

## REPURPOSING: DESA 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 employment of used PEV batteries—rather than new, single-purpose batteries—and includes paying off any remaining first-life residual value, dismounting, collecting, sorting, and testing of the used batteries. The cost of the battery, whether new or repurposed, is in turn added to the second category, ESA (energy storage appliance) cost, which consists of those 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

**TABLE 1 PEV Characterizations**

| Characteristic | PHV | Volt | Leaf |
|---|---|---|---|
| Battery (rated) (kW-h) | 5.2 (*8*) | 16 (*9*) | 24 (*10*) |
| Initial capacity available to driving [% (kW-h)] | 75 (3.9) | 65 (10.4) (*9*) | 85 (20.4) |
| Charge-depleting fuel economy (kW-h/100 mi) | 36 (*11*) | 36 (*11*) | 34 (*10*) |
| Charge-depleting (electric) range (mi) | 13 | 35 (*11*) | 73 (*10*) |
| Rated capacity at end of first life (80%) (kW-h) | 4.2 | 12.8 | 19.2 |
| Chemistry | Panasonic NCM and graphite (*12*) | LG LMO and graphite | AESC (NEC) LMO and graphite |
| Cost per available kW-h ($) | 732 | 585 | 585 |
| Cost of balance of module system carried into 2nd life ($) | ~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 |

NOTE: NCM = nickel, cobalt, and manganese; LG = LG Chem Ltd.; LMO = lithium manganese oxide; AESC = Automotive Energy Supply Corporation; NEC = NEC Corporation.

decline over time, they thus set a declining maximum allowable repurposing cost. For example, when one assumes rapid initial battery cost decreases as volume ramps up to meet initial PEV offerings [e.g., using the approach of an 82% experience curve (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 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, and the like. 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 2 along with common ESA costs, described next. (Acknowledging precision and certainty limitations, most tables present rounded results, for example, to three 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 cost 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 2 fall 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 1/2 h, thereby acting as a conservatism to avoid inflated estimates of value for applications with short discharge durations (discussed in the next section). Further, because this ratio represents a reasonable charge–discharge rate limit [2C (a 1C rate represents a 1-h complete charge or discharge)] and is potentially mild when compared with a several-C vehicular life (e.g., 6C over 10 min for fast-charging all-battery EVs), it helps minimize degradation in second life. In addition, the relative percentage of depth of discharge allowed in first life is used in the second life (e.g., 65% of 16 kW-h in first life for the Volt and 65% of 12.8 kW-h in second life for the Volt DESA). For plug-in hybrid batteries in particular, second life may well be optimized by using a wider swing, making this an additional conservative assumption that should also foster long life.

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 2 (*2*). For the next two rows, more modest costs than bulk-storage facilities were assumed to apply to DESAs. However, because the modest residential load-following estimates of Cready et al. may not be fully adequate, the next-cheapest estimates (those derived from a facility in Chino, California) were used to be conservative.

## SECOND LIFE: DISTRIBUTED-GRID ENERGY STORAGE

A taxonomy of the gross benefit provided by grid energy storage by Eyer and Corey (*3*) includes 19 applications in five categories: electric supply, ancillary services, the grid system, utility customer, and renewables integration. Eyer and Corey characterize each application with a range of discharge durations and application-specific benefits. With average values from that report and an assumed 96% average discharge efficiency, Table 3 shows a menu of single-application, systemwide 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 the preceding section, the assumed DESA power capabilities have been capped to avoid disproportionate benefit estimation and to minimize potential battery-degradation effects by

**TABLE 2 ESA Cost Estimates (Rounded)**

| ESA Cost Component | Basis | PHV[a] ($) | Volt[b] ($) | Leaf[c] ($) |
|---|---|---|---|---|
| Battery (modules + management system) | Repurposing cost | 744 | 1,150 | 1,780 |
| Power conditioning, controls, interfaces | Inflated $442/kW = maximum for fully capable bulk storage (*2*) | 3,310 | 8,830 | 17,300[d] |
| Accessories, facilities, shipping, catch all | Inflated $117/kW-h = load leveling, arbitrage, and transmission deferral facility at Chino (*2*) | 442 | 1,170 | 2,290 |
| 10-year operation and maintenance | Net present value ($18/kW per year) = Chino facility. Compare with $102/year for residential load following | 828 | 2,210 | 4,330 |
| Installation, residential circuitry | EVSE-style installation costs (sans charger), based on maximum power | 800 | 2,000 | 4,300 |
| Total DESA cost | | 6,120 | 15,400 | 30,000 |

NOTE: EVSE = electric vehicle supply equipment.

[a] 3 kW-h or 6 kW.

[b] 8 kW-h or 16 kW.

[c] 16 kW-h or 32 kW.

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

**TABLE 3 Menu of Potential Gross Benefits of Second-Life Energy Storage 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[a] | 2,790 | 7,430 | 14,580 |
| T&D upgrade deferral 90th percentile[a] | 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 |

NOTE: Life-cycle benefit over 10 years, with 2.5% escalation and 10% discount rate. T&D = transmission and distribution.

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

confining the batteries to more modest charge–discharge rates than those designed for the car.

Further refinement is of course necessary to make the estimates in Table 3 increasingly meaningful and accurate for a given context. However, Eyer and Corey explicitly intend their framework to be used as a high-level system-perspective tool, and accordingly several lessons for subsequent analysis can be drawn (*3*). For example, the estimates give an indication of the maximum DESA costs that could be supported in each application (net benefit is discussed in the following section), 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 situation is expected and consistent with precursor analysis (*1, 19–21*) and thus warrants further discussion. First, 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 to 2008 (*21*). In a compilation of recent values (*22*), regulation prices have been near or below the $20/MW level since August 2008. The average from August 2008 to February 2011 (2 months in spring 2009 are unavailable) is $13.66/MW per hour contract. Use of that average price drops the Volt DESA regulation benefit from $23,250 to less than $9,300, a significant reduction.

Future price levels are unclear, however, both as the economy recovers and electricity use increases and in the context of a standard requiring a portfolio that includes 33% renewable energy. Furthermore, in February 2011, the California Independent System Operator (CAISO) approved a “regulation energy management” instrument that “permits energy storage and demand-response resources with 15-min capability to begin bidding in the CAISO market” (*23*). As described earlier, the DESA charge–discharge 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, control and aggregation of DESA-sized units into the 1/2-MW size necessary for participation in regulation energy management markets might be challenging and costly (as discussed next).

## Regulation Competition and Market Potential

The potentially high value of providing regulation services is also consistent with the active market development for provision of bulk energy storage 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 to 2008 average CAISO regulation (up + down) requirement of 732 MW/year. That number of batteries, each making $3,500/year, would theoretically earn more than $150 million per year, though revenues will not remain constant as markets saturate.

Further, General Motors hopes to sell 45,000 Volts in the United States in 2012 alone. In contrast, only a fraction of those Volt batteries would presumably be top candidates for repurposing in California, and using four repurposing centers as described earlier, it would take 3 to 4 years to process 44,000 top-candidate batteries into DESAs. Meanwhile, the requirements for flexible capacity in California are likely to rise to support of the 33% renewal portfolio standard, though the extent required remains unclear. However, CAISO’s more than 20,000 MW of regulation-certified capacity may be sufficient to provide—if not in the optimally efficient manner—California’s near- to midterm regulation needs (*24*).

Thus, although the potential regulation value per DESA in California is large, the overall potential of the market to sustain high value, many DESAs, or both may be limited. For this reason, various multiapplication value propositions are explored.

## Propositions of Multiapplication Value

Comparing Table 3 with Table 2—and given the limitations of, and competition for, regulation—no single application benefit appears likely to sustain the DESA value proposition. Propositions of multiapplication value are therefore needed. Eyer and Corey provide some insight into which applications are compatible, and four of their proposed multiapplication combinations are summarized in Table 4 (*3*). Furthermore, 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 the applications in

**TABLE 4 10-Year Value Proposition Benefit: Volt Estimate (Rounded)**

| 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 |
| Time-of-use energy cost management + demand charge management | 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 and Corey's "distributed storage for bilateral contracts with wind generators" proposition (*3*)] | 32,700 | 20,800 | 18,700 |
| Storage to service small air-conditioning 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 to approximate 10 years of benefit to be comparable to other applications, but this is not likely at a single location.

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 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 the following section.

The data in Table 4 indicate that a promising use of DESAs might be to prioritize power quality in the context of serving small air-conditioning loads.

## INTEGRATION OF RESULTS, UNCERTAINTIES AND SENSITIVITIES, AND ALTERNATIVE SCENARIOS

Table 5 shows an integration of the results and shows the net impact the value from the multiapplication combination serving small air-conditioning loads has on the battery lease payment. The simple net present value of the second life, bringing it forward from Year 8 to Year 1 by using a 10% discount rate, is also shown. Both measures of value are used as indicators of total-system net benefit, not specific business models. Therefore, 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.)

**TABLE 5 Summary of Net Residual Values (Rounded)**

| Cost Component | 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 second-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 second-life residual value | 57 | 95 | 172 |
| Net present value (residual value, 10% discount rate) | 397 | 1,510 | 3,010 |

The net present value of second life presented in Table 5 ranges from a few hundred to a few thousand dollars, and the reductions in lease payments range from 11% to 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 6 by means of Oracle's Crystal Ball software. The best-guess point estimates discussed so far are in boldface type in the table and have been bounded by ranges defined by minimum and maximum estimates on the basis of 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. In addition, two parameters were assigned uniform distributions throughout their range of potential values, although particularly little was thought to be known about their appropriate probability distribution.

In contrast to the point estimate of $95/month for the Volt battery lease payment, a relatively symmetrical beta distribution with a mean of $132 and a 95% confidence interval ranging from $74 to $193 was produced by the simulation. This result suggests that the lease payment values may be somewhat higher than the point estimates indicate. The last column of Table 6 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 (*a*) the "% of rest" parameter characterizing the amount of value captured from the nonpriority application in the multiapplication value proposition and (*b*) the parameter characterizing the per kilowatt cost of DESA power conditioning, controls, and interfaces. Clearly, the artful combination of value in multiapplication combinations is critical to Volt-based DESA profitability: if the DESA were able to capture only the benefit from the single most-valuable application in the group, the costs would outweigh the benefits, causing the battery lease payment to rise, not fall.

**TABLE 6 Contributions of Key Parameters to Variance in Volt–DESA Battery Lease**

| Parameter | Minimum | Likely | Maximum | Contribution to Variance (%) |
|---|---|---|---|---|
| "% of rest" (nonpriority 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/kW-h | **825/kW-h** | 950/kW-h | 3.5 |
| Ratio of kW to kW-h cap | 1 | **2** | 6 | 2.7 |
| Balance of battery (module MS) variable cost component ($) | 50/kW-h | **100/kW-h** | 150/kW-h | 2.7 |
| % of largest (priority grid service value) | 80 | **90** | 100 | –2.2 |
| Variable cost of accessories, facilities, shipping, catch all ($) | 0/kW-h | **117/kW-h** | 200/kW-h | 1.2 |
| Discount rate (%) | 4 | **10** | 12 | –0.5 |
| Annual percentage rate | 5.99 | **6.99** | 7.99 | 0.2 |
| Operation and maintenance rate ($) | 16/kW year | **18/kW year** | 20/kW year | 0.2 |
| Battery swap cost ($) | 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/kW-h | **78/kW-h** | 100/kW-h | ~0 |
| Used-product discount (%) | 10 | **15** | 20 | 0 |

The next tier of parameter importance includes parameters related to battery costs as well the level of leakage in second-life gross profitability necessary to facilitate aggregation of DESA services. However, initial battery costs are important as a determinant to the lease setup fee; the parameters for battery cost base and balance of battery in Table 6 are not important in a similar simulation done directly on the net present value of the residual value, which exhibits a similar structure (but into which the annual percentage rate and sales tax also do not factor).

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 result is despite a relatively wide range simulated, from 50% to 90%.

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. However, the benefits of increasing the ratio of kilowatts to kilowatt-hours upward from 2 in the current model structure are overcome by the associated costs that scale with power, so no incentive exists within that structure to consider increasing it and possibly investing in additional batteries (to compensate for increased degradation).

### Battery Replacements and Shortened Initial Deployment

Although difficult to justify for the purpose of allowing increased power ratings, battery replacement is worth considering for its own sake because of the possibility that degradation or calendar-life constraints will prevent the battery from capturing the full second-life value described earlier. 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 suspicion 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/month. By judging the operation-and-maintenance description in Cready et al. (*2*) to be adequate to cover a one-module swap in Year 5, one DESA that is required to bear battery repurposing costs in second-life Years 1 and 5 would still reduce the lease payment, to $223/month.

In contrast, shortening the initial deployment of the battery in the vehicle does not appear to be helpful. Doing so might be thought desirable: as the cost of the battery-swap and lease-setup fees are included in the analysis, this shorter deployment offers the potential for both monthly savings and the opportunity to upgrade the vehicle's electric-drive performance every 5 years with a newer, presumably more-capacious and powerful or otherwise-improving battery. However, the benefit increase from 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 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.

## CONCLUSIONS AND DISCUSSION OF RESULTS

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 roughly a 22% reduction in battery lease payments with the addition of second-life benefit as residual value, all show reductions in battery lease payments, ranging from roughly 1% to 32%. On one hand, the overall net economic benefit of battery second use in the example of the Volt-based DESA 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 point estimates of the base case of lease payment might need an upward 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 preconditions, which in implementation will require some combination of coordination, standardization, code and safety-procedure development, and the granting of DESA or similar units access to several existing and future markets—via aggregation (nominally taken into account here) or otherwise. Initial policy steps already identified and under way 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, multistage 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 Assembly Bill 2514), they will lift the tide for repurposed PEV batteries—whose fully burdened costs have not been shown the weak link in the overall value proposition and are estimated to be several times lower than the allowable limit defined by new-battery costs (as discussed earlier). Thus, possibly even if they require 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 possibility, coupled with the continuing need to find appropriate and valuable uses for PEV batteries at the end of their vehicle life, motivates further investigation. "Proceed, but proceed carefully" may be one appropriate take-home conclusion. Furthermore, the analysis thus far presupposes 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 sociopolitical contexts will have important implications for energy and climate policy, innovations, and business development. With these issues in mind, and informed by the dynamics laid out earlier, future work should also ask, "How might things look differently?" so as to explore how alternative policy futures could affect the battery second-use value proposition.

## DIRECTIONS FOR FUTURE WORK

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

The next most-important uncertainty is the level of cost associated with power-conditioning requirements of the energy storage appliance, which should also be optimized (or reduced) with increasingly specific combined-load profiles in mind (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 rebalanced, sources of variation (e.g., the aggregation-fee parameter and the underlying process it represents).

Although it has been determined to be a lower priority (and arguably unnecessary until a more thoroughly compelling structure for revenue and cost is developed), additional related work might model battery degradation explicitly with the following sequence in mind: (*a*) a per mile and throughput-based (rather than per year) characterization of first life, (*b*) a per year characterization of second life, and (*c*) with increasing load-profile specificity and the availability of data on specific battery chemistry, 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 photovoltaic systems and distributed-energy storage appear particularly intriguing.

More generally, one can draw parallels between (*a*) the traditional grid with just-in-time delivery of power to unscheduled loads and (*b*) 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 multidirectional and networked purposes appear to allow several more degrees of design freedom than do vehicle drivetrains. These opportunities create 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.

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