Journal of Power Sources 196 (2011) 10351–10358

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

The ability of battery second use strategies to impact plug-in electric vehicle prices and serve utility energy storage applications

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ARTICLE INFO

Article history:
Received 19 April 2011
Received in revised form 14 June 2011
Accepted 15 June 2011
Available online 22 June 2011

Keywords:
Lithium ion
Battery
Second use
Energy storage
Plug-in hybrid vehicle
Electric vehicle

ABSTRACT

The high cost of lithium ion batteries is a major impediment to the increased market share of plug-in hybrid electric vehicles (PHEVs) and full electric vehicles (EVs). The reuse of PHEV/EV propulsion batteries in second use applications following the end of their automotive service life may have the potential to offset the high initial cost of these batteries today. Accurately assessing the value of such a strategy is exceedingly complex and entails many uncertainties. This paper takes a first step toward such an assessment by estimating the impact of battery second use on the initial cost of PHEV/EV batteries to automotive consumers and exploring the potential for grid-based energy storage applications to serve as a market for used PHEV/EV batteries. It is found that although battery second use is not expected to significantly affect today's PHEV/EV prices, it has the potential to become a common component of future automotive battery life cycles and potentially to transform markets in need of cost-effective energy storage. Based on these findings, the authors advise further investigation focused on forecasting long-term battery degradation and analyzing second-use applications in more detail.

1. Introduction

Increased market share of plug-in hybrid electric vehicles (PHEVs) and full electric vehicles (EVs) is one major strategy to address reducing the nation's dependence on foreign oil and emissions of greenhouse gases by improving the overall fuel efficiency and cleanliness of light vehicles in the United States. Perhaps the largest impediment to the proliferation of such vehicles, however, is the prohibitively high cost of their lithium ion (Li-ion) propulsion batteries. It has been estimated that an approximate 50% reduction in battery costs is necessary to equalize the current economics of owning PHEVs and conventionally fueled vehicles [1,2].

Several strategies are presently being pursued to address high Li-ion battery costs, such as developing Li-ion chemistries based on less costly materials, more cost-efficient cell and battery designs and manufacturing techniques and building high-volume production battery plants [3]. However, many of these approaches are unlikely to yield a near-term cost reduction to the consumer sufficient to encourage increased PHEV/EV market share.

The reuse of PHEV/EV propulsion batteries in second-use applications following the end of their automotive service life may have the potential to offset the high initial cost of these batteries today. The life cycle of a battery utilized in such a manner is illustrated in Fig. 1. By extracting additional services and revenue from the battery in a post-vehicle application, the total lifetime value of the battery is increased. This subject has been studied in the past in reference primarily to the nickel metal hydride batteries planned to power EVs at the time [4–6] and has recently seen renewed interest spurred by the coming generation of Li-ion based hybrids and EVs [7–10].

There are several current and emerging grid-related applications where the second use of PHEV/EV batteries may be beneficial. For example, the use of renewable solar and wind technologies to produce electricity is growing, but achieving high levels of market penetration may require energy storage to mitigate the effects of their intermittency. Other utility needs such as area regulation, peak load reduction, and transmission upgrade deferral can also be served by energy storage. Alternatively, energy storage may provide similarly valued services on the customer side of the meter in industrial, commercial, and/or residential settings.

To date, however, the full scope of possible second use opportunities, the feasibility, and profitability of such opportunities have not been accurately quantified. Furthermore, no one has yet estimated the ability of second use strategies to impact the cost of PHEV/EV batteries. Accordingly, our primary objective in this paper is to take that first step to estimate the expected impact of battery second use on the initial cost of PHEV/EV batteries to automotive consumers. In addition, we will take an initial look at the potential for grid-based energy storage applications to serve as a market for used PHEV/EV batteries.

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doi:10.1016/j.jpowsour.2011.06.053

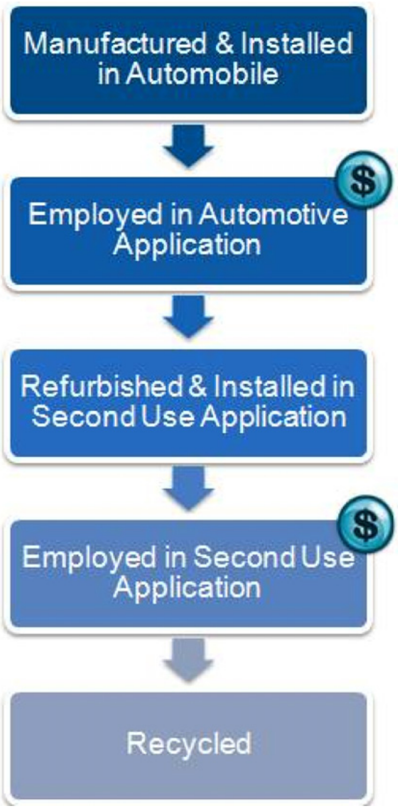

Fig. 1. Lifetime of a PHEV/EV battery when second use applications are considered to increase its total lifetime value.

In this paper we describe a framework capable of estimating the effect of battery second use on PHEV/EV battery prices and apply it to calculate the maximum possible value of second use to current and future battery-powered vehicles. In doing so, we address the identification of optimal automotive battery retirement points as well as the effect of vehicle type (PHEV or EV) on second use value. In addition, we evaluate the potential value of common utility applications for energy storage in the context of second use. After selecting three suitable high-value applications, an allocation analysis is performed to investigate the effects of the anticipated availability of second use batteries and the demand of the selected utility applications.

2. Analysis

2.1. *A framework for estimating the possible value of battery second use strategies*

Battery second use strategies may have the potential to reduce the cost of PHEV/EVs to advanced vehicle consumers, which is at present a major barrier to advanced vehicle adoption. Accurately quantifying the precise value thereof is complex, necessitating detailed knowledge of the operating requirements of the selected second use application, financial data for revenues and operating costs, battery refurbishment and distribution costs, etc. However, it is possible to identify an upper bound to the initial battery cost reduction based upon anticipated future battery costs when the following assumptions are made:

- Profitable and willing secondary use applications will be available at the time of the battery's automotive service retirement.
- The principal competitor for second use PHEV/EV batteries in the selected second use application is newly produced PHEV/EV batteries.

Under these assumptions, the premise that demand will exist for used PHEV/EV batteries priced less than equally capable new PHEV/EV batteries is valid. Accordingly, it is reasonable to assume that the future salvage value of a used PHEV/EV battery will be proportional to the cost of an equally capable new battery, taking into consideration the health of the used battery; the cost of collecting, repurposing, and certifying the used battery; a used product discount factor equal to the ratio of what a customer is willing to pay for a used product to what that same customer is willing to pay for an equally capable new product; and the alternative value of recycling. One means of capturing this relation is given in Eq. (1):

$$S = \max(K_u K_h C_n - C_{rp}, C_{rc}) \tag{1}$$

where S is the salvage value; K_h is the health factor; K_u is the used product discount factor; C_n is the cost of new battery; C_{rp} is the cost to repurpose; C_{rpc} is the recycling revenue.

Note that the maximum operator is applied to represent the decision between allocating a used battery for second use versus recycling, based on the desire to maximize revenue (or alternatively, minimize cost).

Both the health factor and the cost of new batteries are major sensitivity factors that vary with time and thus merit further discussion.

The health factor, K_h, is defined as the fraction of remaining battery throughput in kWh relative to total battery throughput at beginning of life. This is selected to best indicate the remaining value in the battery, as the revenue generated by many potential second use applications is proportional to energy throughput. Further, work in Peterson et al. [11] has shown that a constant throughput model is appropriate for some Li-ion chemistries. Assuming that the daily cycling regime of a PHEV/EV battery is approximately constant, Eq. (2) is then a reasonable definition for K_h.

$$K_h = 1 - \mu t \tag{2}$$

where u is the battery degradation coefficient; t is the time of ownership.

Note that the alternative definition of K_h on recoverable capacity (or energy) at the time of retirement can be misleading. For example, it is generally speculated that EV batteries will be retired from use when they have degraded to 70–80% of their initial capacity. Although it is tempting to employ these values for K_h, they do not give a direct indication of relative value as there is no remaining cycle life data attached. Clearly, a battery retired with 70% of its initial capacity remaining is not worth 70% of its initial cost (nor 70% of the cost of a new battery) if it only has 10% of its initial cycle life remaining. Utilization of a definition tied to throughput avoids this oversight.

The cost of new batteries as a function of time can be approximated based on today's battery cost, an expected future minimum cost, and an exponential decay factor to connect these two values as shown in Eq. (3).

$$C_n = C_{n,\infty} + (C_{n,0} - C_{n,\infty})e^{-\phi t} \tag{3}$$

where $C_{n,0}$ is the today's battery cost; $C_{n,\infty}$ is the future minimum battery cost; ϕ is the future battery cost time factor.

Eq. (3) does not explicitly include the effects of inflation. As long as the cost-depressing effects of manufacturing scale-up and technology improvements outweigh inflationary effects, thus preventing the cost of batteries from increasing during the period of interest (the time from initial purchase to automotive battery retirement), the parameters of Eq. (3) may be selected such that inflation is implicitly accounted for. If it is anticipated that batteries will increase in cost due to inflationary or other factors, Eq. (3) must be modified accordingly; however, such conditions are not treated in this paper.

The maximum discount available to the advanced vehicle consumer at the time of the initial purchase made possible by second use, D, can now be estimated via a simple present value calculation (Eq. (4)).

$$D = Se^{-\alpha t} \tag{4}$$

where D is the initial battery discount; α is the discount rate.

2.2. Financially based battery retirement from automotive service

When decreasing future battery costs are expected, all of the factors in Eq. (4) work to decrease the initial second use discount, D, the longer the battery is kept in the car. Thus, one might pose the question: when is it financially optimal to sell a PHEV/EV battery into a second use market? This can be answered by first computing the driver's levelized cost per mile to operate the battery in the automobile, L, as a function of the time of ownership, t, then differentiating that value with respect to t. Negative dL/dt implies that continued ownership effectively reduces the per-mile battery cost of each mile driven to date and is thusly financially advisable. On the other hand, positive dL/dt suggests the collective per-mile battery cost is increasing and it would be financially advisable to sell the battery into a second use market. Identifying the dL/dt zero crossing from negative to positive therefore identifies where the total levelized battery cost is minimized, corresponding to when the battery should be sold into second use for financial reasons.

To perform these calculations, the initial discount equation (Eq. (4)) is simplified to that of Eq. (5). It can be shown that such an approximation is accurate for α greater than 0.03. This is reasonable based upon discount rates (0.05–0.15) commonly employed for similar analyses [2,12].

$$D \cong (K_u C_{n,0} - C_{rp})e^{-\lambda t} \tag{5}$$

where λ is the calculated equivalent rate factor.

Now, assuming that total miles driven is proportional to time via the constant m, the levelized cost per mile of the battery considering the second use discount is given by Eq. (6), and its time derivative by Eq. (7).

$$L = \frac{C_{n,0} - (K_u C_{n,0} - C_{rp})e^{-\lambda t}}{mt} \tag{6}$$

$$\frac{d}{dt}(L) = \frac{(K_u C_{n,0} - C_{rp})\lambda e^{-\lambda t}}{mt} - \frac{C_{n,0} - (K_u C_{n,0} - C_{rp})e^{-\lambda t}}{mt^2} \tag{7}$$

where L is the levelized cost per mile; m is the miles per year.

Analysis of Eq. (7) shows that as long as $K_u C_{n,0} - C_{rp} < C_{n,0}$, dL/dt will be negative. Given that $K_u < 1$ and $C_{rp} > 0$, dL/dt must always be negative. Therefore, under these assumptions, PHEV/EV batteries will never be retired from automotive use to serve a secondary market while they are still capable of meeting all automotive performance requirements.

2.3. Performance-based battery retirement from automotive service

Although the analysis above has eliminated from consideration the notion of financially motivated battery retirement, it still leaves the question of performance-based retirement timing and remaining throughput thereafter. It may be reasonable to estimate the timing of automotive retirement from the warranties provided by major original equipment manufacturers (OEMs), or emission requirements in the case of certain PHEVs, but that does not provide information regarding remaining throughput.

Adopting a constant throughput degradation model as described in Peterson et al. [11] is convenient for approaching this problem. Equipped only with the knowledge that capacity fade is proportional to to-date throughput, of the retained capacity at which the battery no longer meets its automotive requirements, and of the minimal retained capacity required for safe and useful operation in a second use application, K_h at automotive retirement can be calculated using Eq. (8).

$$K_{h,AR} = \frac{Cap_{AR} - Cap_{EOL}}{1 - Cap_{EOL}} \tag{8}$$

where $K_{h,AR}$ is the health factor at the time of automotive retirement; Cap_{AR} is the battery capacity at the time of automotive retirement; Cap_{EOL} is the allow able battery capacity at the end of a second life.

Cap_{EOL} is assumed to occur at the "knee" in the life curve for a Li-ion battery. After this point, accelerated degradation minimizes the utility of additional throughput, and it may be unsafe to operate beyond this point as well due to the anode becoming the limiting element [13]. In this discussion, we assume the knee occurs at 50% retained capacity, recognizing that there is considerable uncertainty in this election due to differences in chemistry, history, etc.

For EVs, Cap_{AR} is indicative of the reduction in vehicle range tolerable to the driver. In this discussion, it is assumed to be 75% based upon what is commonly reported in the media for the point of automotive battery retirement [16].

For PHEVs, Cap_{AR} may be dependent on the OEM selected depth-of-discharge (DOD), driver-tolerable all-electric range reduction, emissions regulations, or a combination of these factors. For example, consider the Chevrolet Volt PHEV, which reportedly operates at a DOD of 65% [14]. For the vehicle to be sold as an advanced technology partial zero emissions vehicle (AT-PZEV) in California (to receive the state $6500 tax credit), the battery must come with a 10-year/150,000-mile warranty [15]. Although not explicitly stated, this may be read to imply that the vehicle is required to maintain its beginning-of-life emissions performance over the life of the warranty. Ignoring the impacts of battery resistance and efficiency, this means that at automotive retirement, the battery will have a Cap_{AR} of 65%, allowing the vehicle to achieve its beginning-of-life all-electric range and thereby maintain constant emissions performance.

On the other hand, if the emissions requirement is replaced by the driver's tolerance for range reduction, it may be the case that the battery is retired from automotive service when only 75% of the beginning-of-life DOD is achievable. Thus, Cap_{AR} could be as low as 49%, meaning that our 50% Cap_{EOL} would be achieved in the car, leaving no remaining throughput for a second use.

This creates a broad range of potential $K_{h,AR}$ values. The EV example yields a $K_{h,AR}$ of 50%, while the emissions-driven PHEV retirement example yields $K_{h,AR} = 30\%$, and the range-driven PHEV retirement example yields $K_{h,AR} = 0\%$. The first two cases may be of interest to second use applications as they leave a not insignificant amount of throughput for post-automotive use. The third case of the PHEV retired on customer range requirements leaves no post-automotive throughput, and thus it is not of interest for second use consideration. However, it is worth pointing out that this may be the case in which the total lifetime value of the battery is maximized by extracting all of the battery's usable throughput in the vehicle.

Table 1
Values for impact assessment.

Parameter	2011 EV	2011 PHEV	Future EV	Future PHEV
K_h	50%	30%	50%	30%
K_u	50%	50%	75%	75%
$C_{n,0}$	\$24k	\$16k	\$12k	\$8.0k
$C_{n,AR}$	\$7.2k	\$4.8k	\$8.4k	\$5.6k
C_{rp}	\$1k	\$1k	\$250	\$250
C_{rc}	\$100	\$100	\$100	\$100
t_{AR}	8 yrs	8 yrs	15 yrs	15 yrs
S	\$800	\$100	\$2.9k	\$1.0k

2.4. Calculating second use impact on EV and PHEV consumers

Here we evaluate the potential impact of battery second use on initial battery cost for four distinct scenarios: a model year 2011 and a future EV retired on range requirements, and a model year 2011 and a future PHEV retired on emissions requirements.

For the model year 2011 scenarios, the above calculated $K_{h,Ar}$ values of 50% and 30% for the EV and PHEV, respectively, will be employed. For each vehicle type, an eight-year automotive service life is assumed based on today's offered warranties for such vehicles [16]. This implies that used batteries will first become available in quantity around 2019, by which time the U.S. Department of Energy expects that the increased production rate of Li-ion batteries will have reduced battery costs by approximately 70% or more from today's assumed cost of approximately \$1000 per kWh [17]. For example, for 24-kWh EV and 16-kWh PHEV batteries, this corresponds to $C_{n,0} = \$24{,}000$ and $C_{n,t=AR} = \$7200$ EV battery costs and $C_{n,0} = \$16{,}000$ and $C_{n,t=AR} = \$4800$ PHEV battery costs.

Considering that these first-generation EVs and PHEVs are not explicitly designed for repurposing and that their 2019 battery resale will be the first of its kind, it can be expected that repurposing costs are relatively high ($C_{rp} = \$1000$) and used discount factors relatively low ($K_u = 50\%$).

Using these assumptions (summarized in Table 1), the initial purchase discount, D, is calculated and displayed as a percent of the initial battery cost for discount rates varying from 5% to 15% in Fig. 2. These results span the range of a largely negligible 0.2% for the PHEV battery with a high 15% discount rate to a marginal 2.2% for the EV battery with a low 5% discount rate.

One of the major factors driving down the impact of second use under these assumptions is the large anticipated reduction in future battery costs (70%). With the planned efforts to ramp up automotive battery production between 2010 and 2015 [18], it is reasonable to assume that *future* batteries will be a relatively mature product and that the majority of the benefits owed to economies of scale will have been achieved, allowing the following:

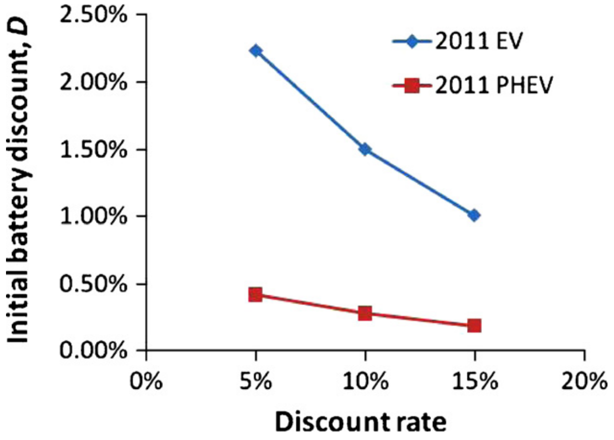

Fig. 2. Possible discounts from second use for model year 2011 EV and PHEV scenarios.

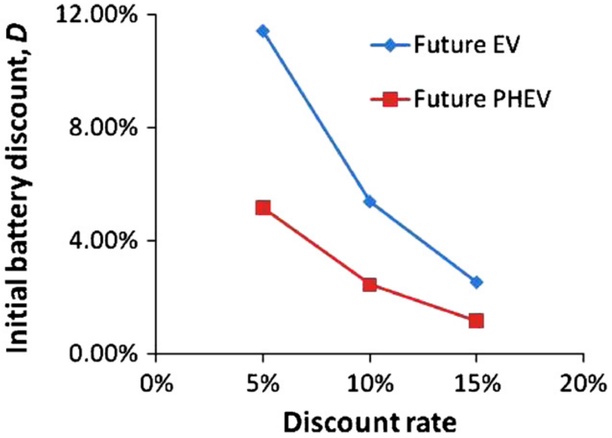

Fig. 3. Possible discounts from second use for future EV and PHEV scenarios.

- Initial battery costs fall to \$500 per kWh or less.
- Battery life is improved such that 15 years of in-vehicle life is common.
- Battery cost reduction across the battery life is relatively small (30%).
- Batteries are treated as a commodity, reducing the effect of used product discount factors (75%).
- Anticipating the value of second use and leveraging advances in battery health monitoring, automotive battery repurposing costs are minimized ($C_{rp} = \$250$).

The K_h values were not changed relative to the 2011 model year cases because neither the assumption of a constant throughput battery degradation model nor the PHEV's assumed 65% DOD was changed.

Under these revised assumptions (also summarized in Table 1), the impact of second use on initial automotive battery costs circa 2015 and later increases to up to 11%, as shown in Fig. 3.

Given that it is estimated that more than a 50% reduction in battery costs is necessary to equalize the current economics of owning PHEVs and conventionally fueled vehicles 2, the cost reductions provided by second use of batteries in the model year 2011 scenarios are not expected to accelerate early EV or PHEV adoption. The possible impacts of battery second use on the economics of more mature EVs and PHEVs are significantly larger and have the potential to make second use strategies a standard component of an automotive battery life cycle. However, this analysis has so far assumed that sufficient demand for used automotive batteries will exist. If this is not the case, the initial battery discount will be further eroded, possibly to the point where recycling automotive batteries is an economically superior option to employing them in a second use.

2.5. Utility applications for used automotive batteries

Utility-based applications are often considered for reusing automotive propulsion batteries. This is due in part to the required energy of individual installations (larger than or equal to the size of EV batteries), the large perceived scale of the market (even though very little energy storage is currently installed on the grid), and the expectation of less-demanding electrical requirements (such that the full performance of a new Li-ion battery is not required). Such markets are very immature and are only recently seeing pilot plant demonstrations [19]. Accordingly, the profitability and allowable systems costs of utility energy storage has been a significant unknown.

Recently, however, Eyer and Corey performed an in-depth analysis on the value of utility-based energy storage applications [12]. For each application with the exception of the two transmission and distribution (T&D) upgrade deferral applications, the present value of the total revenues (benefit) accruable over a 10-year period is computed, assuming a 2.5% annual inflation rate and a 10% annual discount rate. Where the efficiency of the energy storage system had significant impact on these calculations, a round-trip efficiency of 75–80% was assumed. Note that plant operation labor, maintenance, and replacement costs, as well as decommissioning and disposal costs, have explicitly been excluded.

For the two T&D upgrade deferral applications, benefits were calculated as described above but only for a single year of operation rather than the 10 years assumed for all other applications. Therefore, in our calculations the reported single-year revenue for the T&D upgrade deferral applications has been multiplied by a factor of 7.17 to account for 10 years of benefit under the assumptions of a 2.5% annual revenue escalation rate and a 10% annual discount rate, as was already included for the remaining applications.

It is important to highlight that for this approach to be valid, a given T&D upgrade deferral energy storage system can only serve a specific location for one year. This is because the total energy storage installed at a given location would need to be incremented by the initially installed amount in each subsequent year to continue deferring the T&D upgrade investment (under constant load growth conditions). Because the cost of the actual T&D upgrade does not change appreciably over this time, the benefit per kW (and per kWh) falls dramatically as the amount of energy storage increases. Thus, the energy storage solutions to serve this application must be portable (and service ten different specific locations over its assumed ten year service life) to yield the benefits calculated herein.

The benefit described in dollars per MW is not alone sufficient to identify which applications will offer the largest return on investment for a Li-ion battery. To do so, an energy storage system must be sized to each application based on the required discharge durations and the restrictions of the selected energy storage technology. In this analysis, the discharge duration, d, is combined with a maximum allowable power-to-energy (P/E) ratio of 4 and an energy-referenced DOD range of 20–80%, generally indicative of the limitations of today's Li-ion technology. Under these assumptions, the range of the P/E ratio of the energy storage system required by each application can be calculated as follows (note that d must be defined in hours):

$$\left(\frac{P}{E}\right)_{\min} = \min\left(\frac{0.2}{d_{\max}}, 4\right) \tag{9}$$

$$\left(\frac{P}{E}\right)_{\max} = \min\left(\frac{0.8}{d_{\min}}, 4\right) \tag{10}$$

The DOD range implies the battery is sized to operate at no less than 20% DOD and no more than 80% DOD when energy, not power, drives the sizing. This allows for the energy storage system designer to trade initial battery size for extended life. For example, for a certain application it may prove advantageous to operate the battery at 40% DOD, which in comparison to operation at 80% DOD sacrifices battery size and initial cost but may increase cycle life and could result in lower overall costs. Of course, this trade must be performed for each application and battery chemistry independently to accurately ascertain battery size and cost, but for now these maximum and minimum values will be employed to support an initial application down selection.

Next, the maximum and minimum 10-year revenues in dollars per MWh can be calculated in Eqs. (11) and (12) by combining the P/E ratio of the application (in h^{-1}) with the benefit (in dollars per MW) from Table 1.

$$\text{Revenue}_{\min} = \left(\frac{P}{E}\right)_{\min} * \text{Benefit}_{\min} \tag{11}$$

$$\text{Revenue}_{\max} = \left(\frac{P}{E}\right)_{\max} * \text{Benefit}_{\max} \tag{12}$$

Multiplying by 10^3 gives revenue in the more familiar dollars per kWh units. Applying these calculations to each application in Eyer and Corey and averaging the minimum and maximum revenue values yields Fig. 4. The error bars span Revenue$_{\min}$ and Revenue$_{\max}$.

These data predict that only one application's revenue (electric service power quality) exceeds today's generally assumed cost of Li-ion batteries at ~\$1000 per kWh [17] under the worst-case revenue assumptions, although six additional applications (area regulation, short duration wind generation grid integration, electric service reliability, 90th and 50th percentile T&D upgrade deferrals, and voltage support) have the potential to exceed that cost under more favorable assumptions. At \$500 per kWh, only two more applications (transmission support and long duration wind generation) are

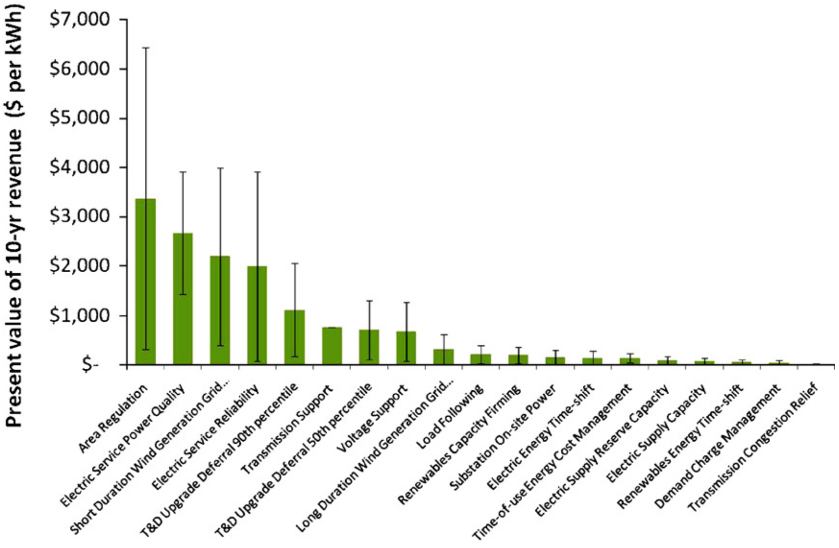

Fig. 4. Ten-year average revenue of Li-ion batteries serving various utility applications.

included. Note however that this revenue must not only cover the upfront cost of the battery, but also all addition capital (e.g., power electronics, facilities, etc.), installation, operating, replacement, disposal, etc., costs over the 10-year life of the system discounted back to present value terms.

It is worthwhile to highlight the source of considerable uncertainty (error bars) in the preceding analysis. There are three contributing factors: the range of benefit values and discharge durations reported in Eyer and Corey [12] and the range of assumed allowable DODs. The dependence on benefit value is obvious; for the latter two factors, utilization of the minimum discharge duration and maximum DOD gives a higher revenue (via increasing the *P*/*E* ratio).

Accordingly, a more precise approach must be taken to assess the profitability of Li-ion batteries serving these utility applications. Specifically, more precise elections of discharge duration and allowable battery DOD and rate must be employed. This is done for the three most promising applications to fall out of the above analysis: area regulation, electric service power quality and reliability (ESPQ&R), and 50th percentile T&D upgrade deferral. These three applications were down-selected from the top nine applications above as follows:

- *Long and short duration wind generation grid integration* were omitted because their values were computed as an aggregate of other listed applications [12]. In this analysis, application aggregations are treated separately.
- *90th percentile T&D upgrade deferral* was omitted as it is effectively covered by the larger market 50th percentile T&D upgrade deferral. As will be seen in the following analysis, market size has a large effect on the viability of second use strategies.
- *Transmission support* was omitted because consideration of the cost of power electronics at $0.20 per watt or higher makes the total revenue negative.
- *Voltage support* was omitted because consideration of the cost of power electronics at $0.20 per watt or higher reduces total revenue by 50% or more.
- *Electric service power quality and electric service reliability* were combined on the basis that they are well suited to aggregation (see below) and that likely customers would desire both services.

For the top three applications, the values listed in Table 2 are employed for the subsequent analysis. Benefits and discharge durations are selected as the average value of those reported in Eyer and Corey [12]. The battery *P*/*E* ratio was then selected to yield a 50% DOD. For the case of area regulation, this leaves margin for battery degradation over the 10-year period of performance where the battery may be cycled multiple times per day. For T&D upgrade deferral applications, this provides significant margin for errors in load forecasting and therefore required battery performance.

For the quality and reliability applications, the 50% DOD requirement is applied to the much longer duration quality application. Using a 50% DOD for these applications accounts for uncertainty in the frequency of reliability events and the long-term degradation expected from such operation. The two applications are then combined on the assumption that only one application is being performed at any given time, and that the peak power demanded by either application is identical in a given installation, thus determining the DOD for the quality application.

Table 2
Refined parameters for down-selected utility applications.

	Benefit	Discharge duration	*P*/*E*	DOD
Area regulation	$1.4 per MW	0.375 h	1.33	50%
ESPQ&R				
Quality	$0.67 per MW	0.01 h	0.92	0.9%
Reliability	$0.67 per MW	0.54 h	0.92	50%
50% T&D upgrade deferral	$4.2 per MW	4.50 h	0.11	50%

In addition to providing total revenue data and application specific discharge durations, forecasts of 10-year market potentials – described as the “potential for actual sale and installation of energy storage, estimated based on reasonable assumptions about technology and market readiness and trends, and about the persistence of existing institutional challenges,” – were also given in Eyer and Corey. Dividing the reported market potential in MW by the assumed *P*/*E* ratio gives a value in MWh.

Special consideration of the T&D upgrade deferral application market potentials must be made. Recall that earlier we adjusted the reported single-year benefit to account for an expected 10-year life for a given energy storage system, also assuming that said system only serves a specific location for one year to maintain the validity of the calculations. As the reported market potential for this application is the summation of the annual energy-storage-servable load growth, it would be a gross overestimation to treat this application the same as the others given that the new market potential in one year does not continue into the next. Rather, the energy storage employed to serve the first year of demand is reallocated to meet the demand in Year 2 along with some amount of new energy storage to account for larger load growth year to year.

Thus, the 10-year market potential is calculated herein based upon the largest annual load growth expected in a 10-year period, then taking the fraction of that number that corresponds to that which is in need of T&D upgrades and is servable by energy storage. Performing these calculations for the 50th percentile case using the same inputs and assumptions as Eyer and Corey yields a 10-year market potential of 626.9 MW, compared with the reported 4986 MW summation of annual need.

Observe that under the constraint of equal peak power for the quality and reliability applications, the market potentials of these two applications are equal in terms of MWh. Thus, we effectively assume herein that all customers of quality are also customers of reliability, and vice versa.

Fig. 5 presents both the revenue and market potential values calculated using the values from Table 2. Note that here the error bars on the revenue values are solely derived from the range of benefits reported in Eyer and Corey, and no longer incorporate uncertainty for DOD and *P*/*E* variations.

These results show reduced average values and error bars relative to the coarse initial approach discussed earlier. They also reveal a substantial range of market potentials across the applications, generally inversely related to application value.

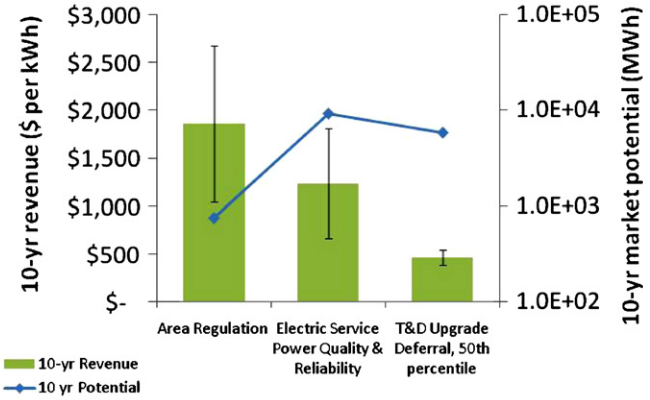

Fig. 5. Refined revenue and market potential forecasts for three down-selected applications.

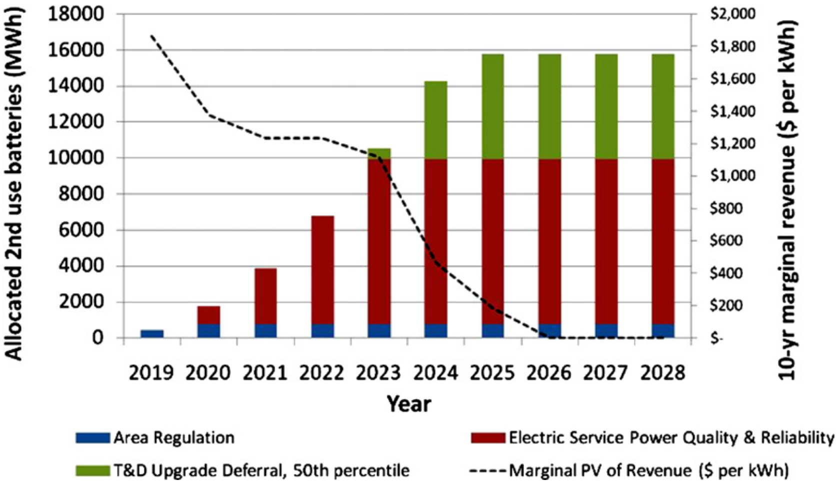

Fig. 6. Allocation analysis of second use batteries.

2.6. Supply and demand

To put these numbers into the context of automotive battery second use, an allocation analysis is performed considering the anticipated availability of used automotive batteries. For simplicity, we only consider full EVs (not PHEVs) with 25-kWh batteries degraded to 75% of their initial energy (19 kWh) at the time of automotive retirement 8 years after their initial sale. It is assumed that 25,000 of these EVs are produced in 2011, linearly ramping to 200,000 per year by 2015. These values are an approximation of the U.S. domestic automotive battery production capability funded under the American Recovery & Reinvestment Act [18], but also closely resemble announced production plans for the Nissan LEAF [20]. These projections result in the deployment of 563,000 EVs by 2015, and 1.56 million EVs by 2020.

In this hypothetical scenario, used (approximately 19-kWh) automotive batteries first become available for second use in 2019. At this point they are allocated to one of the three down-selected utility applications discussed above. The highest value application – area regulation – receives batteries first. Once the total 10-year market potential of that application is saturated, the second highest value – ESPQ&R – begins receiving batteries, and so on.

The results of this analysis are presented in Fig. 6. Ten years of battery production out to 2020 is addressed, resulting in the allocation of used batteries from 2019 to 2028. Note that we assume that the market values and potentials predicted in Eyer and Corey for the time period 2010–2020 are the same for 2019–2029. Given the difficulty of forecasting the underlying market trends (including the development of competing energy storage technologies, deployment of renewable generation, changes in utility regulation, etc.), it is not possible to ascertain the error associated with this assumption, nor whether it is an optimistic or pessimistic one. Thus, these results are only meant to illustrate the possible interplay of automotive and utility market sizes and the resultant effect on value.

The general trends resulting from these calculations show a relatively rapid saturation of these three high-value application markets. The average revenue calculated over all used batteries sold to date declines from $1863 per kWh in the first year to $987 per kWh by the time all three markets have been saturated after the first 7 years of assumed EV production.

Notice that 10 years of demand for area regulation is met in less than 2 years with the retirement of approximately 40,000 EVs. The $1863 per kWh provided is enticing, but clearly the area regulation market is exceedingly small relative to the automotive market. As is done in this analysis, it is impractical to assume that 10 years of demand for batteries from area regulation will be served in less than 2 years. It is more likely that a smaller number of batteries would be allocated each year, both lowering the initial marginal revenue and slowing its decay. However, this would not significantly impact the average value of all retired EV batteries over the entire 10-year period ($592 per kWh). Further, given that new batteries [21] and other technologies [22,23] are beginning to compete for regulation markets today, it may be the case that the market is already saturated when used automotive batteries become available.

Ten years of ESPQ&R markets are saturated in 4 years after an additional approximately 490,000 EV batteries are retired. At $1234 per kWh, it has the potential to prove a profitable venture once all non-battery costs are considered. Note that at this price point the total market for ESPQ&R is approximately $11B under our current assumptions.

The 50th percentile T&D upgrade deferral, which offers a much lower $465 per kWh, saturates with the retirement of approximately 297,000 EV batteries. In this case, however, it may not be irrational to assume that the 10-year market demand can be met in such a short period. Based on the method of calculation, the demand in Year 1 is not much smaller than that of Year 10, which is in itself the total demand considered over the 10-year period.

3. Discussion

With respect to our primary objective of estimating the expected value of battery second use and its impact on the initial cost of EV and PHEV batteries, we have found that the likelihood for second use strategies to impact the cost of *today's* EVs and PHEVs batteries to be largely negligible. However, our example of a 2015 EV scenario showed the ability of second use to reduce the initial battery cost by up to ~11% assuming sufficient demand exists at the time of their automotive retirement. It was shown that this maximum is achieved with EV batteries, while PHEV batteries operating at restricted DODs ($\leq$65%) may only achieve discounts half as large.

The difference in second use value between current and future vehicles is driven strongly by future battery cost trends – where new battery costs decline steeply during the period of automotive service, the relative value of second use falls dramatically. Thus, it is possible to employ battery second use as a hedge to new battery costs. For example, automotive OEMs could sell EVs today discounted under the assumption of second use to accelerate early market share. If battery costs stay high, second use could offer the necessary value to cover the provided discounts. If battery costs decline, so will second use value, but it is likely that EV sales volumes will increase instead to cover the second use discounts.

The difference in second use value between EVs and PHEVs is the product of differences in how the battery is operated during and when retired from automotive service. Under our assumption that battery degradation is proportional to throughput, it has been shown here that retirement of an EV battery at 75% of the initial range requirement leaves a much larger portion of initial throughput capability available for second use applications. Restricted DOD operation such as that in the GM Volt PHEV [14] reduces the remaining throughput at the point of automotive retirement, thus reducing second use value. However, this may in fact increase the total lifetime value of the battery by maximizing the portion of throughput supplied to the presumably higher-value automotive application. Note that these conclusions may change, though, with the application of alternate higher fidelity battery models.

Our high-level analysis of the profitability of used automotive batteries servicing common utility energy storage needs identified area regulation, T&D upgrade deferral, and ESPQ&R as potential high-value applications. A more detailed allocation analysis of these three applications considering the scales of both the demand from these utility applications and anticipated supply of used automotive batteries showed that a relatively low-volume EV deployment would quickly saturate all three markets. The highest value utility market – area regulation – saturated in just over a year after the retirement of fewer than 40,000 EVs, while all three of the identified high-value applications were saturated in the first 7 years of EV retirements.

4. Conclusions and future work

Although it is not expected that battery second use will notably affect today's EV and PHEV prices given our assumed battery cost and degradation behavior, it has the potential to become a common component of future automotive battery life cycles. Furthermore, due to the number of used batteries that may become available, second use may have the potential to transform markets in need of cost-effective energy storage. Thus, further study into second use is merited. Of the major sensitivities uncovered here, perhaps the most influential factors that can benefit from additional consideration are (1) long-term battery degradation, and (2) detailed analyses of second use applications.

Predicting long-term battery performance is a major difficulty for second use analyses. Not only must the performance of the battery be assessed through as many as 10–15 years of second life service, but this must be done after 5–15 years of automotive service. Calculating the state of health at the time of automotive retirement alone is complicated by the variability between drivers and regions, as well as limited data and tools as noted above.

This study has assumed a constant throughput degradation model and that somewhat-arbitrarily selected DODs will support a 10-year lifetime, but given that Li-ion battery degradation is a complex process sensitive to a number of parameters, these assumptions may be inaccurate. Employing a model where degradation is nonlinearly sensitive to rate and DOD will impact health factor estimates. Adjustment of the battery DOD to achieve this life requirement will have a strong impact on value provided per kWh. The limited data and tools available to perform this analysis accurately are a concern. Accordingly, second use specific life testing and development of high-fidelity battery degradation modeling tools are strongly recommended.

Application revenues for this study rely on coarsely calculated estimates of the value of and market for grid storage, with minimal consideration of application aggregation strategies and no accounting for balance of plant and operating expenses of an energy storage system. The latter are major unknowns due to the relative immaturity of Li-ion technology in utility applications, but past work on other chemistries suggests that the share of such non-battery costs are both significant and highly variable [5,24]. The other factors have the potential to significantly increase the value of energy storage in specific cases when benefits from multiple applications are intelligently aggregated, but both the battery's limitations of performance and the intersecting market sizes must be carefully considered. For these reasons, a detailed analysis of each of the three high-value applications down-selected herein is called for, as well as at least a preliminary study on the omitted wind integration application aggregates.

The National Renewable Energy Laboratory is leading a project to address these concerns, which will consist of both a more detailed analysis of second use applications and substantial field testing of aged EV and PHEV batteries to validate findings and investigate actual battery degradation behavior. The industry and academia team includes the California Center for Sustainable Energy, UC Davis Plug-In Hybrid Electric Vehicle Research Center, the UC Berkeley Transportation Sustainability Research Center, UC San Diego Strategic Energy Initiatives, San Diego Gas & Electric, and AeroVironment. The results of these efforts will be the subject of a future paper.

Acknowledgements

This study was supported Dave Howell and Brian Cunningham of the Energy Storage, Vehicle Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

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