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NREL's PHEV/EV Li-ion Battery Secondary-Use Project

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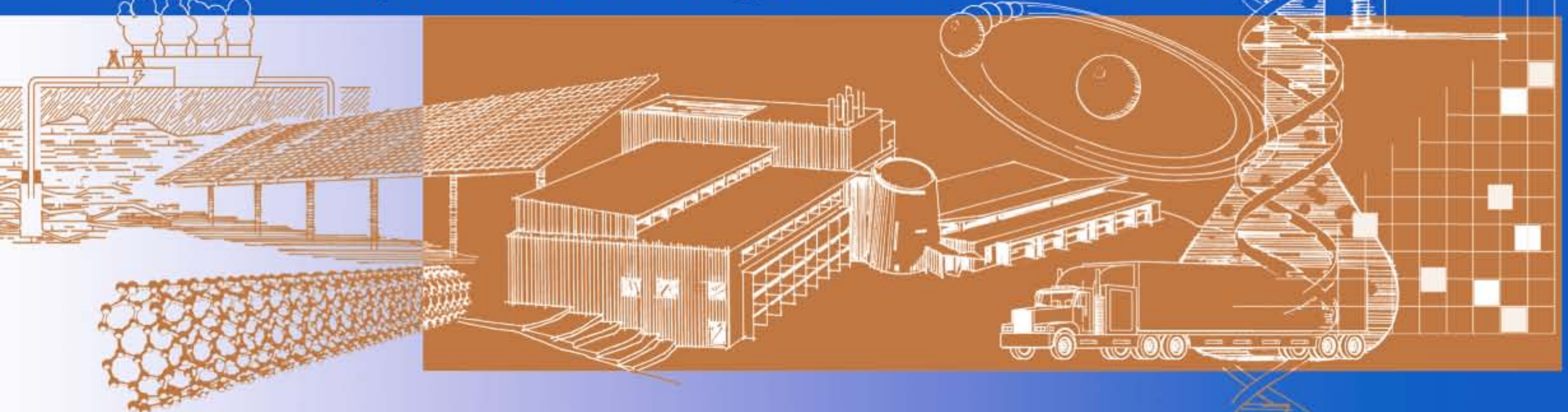

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NREL's PHEV/EV Li-Ion Battery Secondary-Use Project

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Accelerated development and market penetration of plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) is restricted at present by the high cost of lithium-ion (Li-ion) batteries. One way to address this problem is to recover a fraction of the battery's cost via reuse in other applications after it is retired from service in the vehicle, when the battery may still have sufficient performance to meet the requirements of other energy storage applications.

In several current and emerging applications, the secondary use of PHEV and EV batteries may be beneficial. For example, the use of renewable solar and wind technologies to produce electricity is growing, and their increased market penetration requires energy storage to mitigate the intermittency of wind and solar energy. New trends in utility peak load reduction, energy efficiency, and load management also need energy storage. Smart grid, grid stabilization, low-energy buildings, and utility reliability require energy storage as well. However, neither the full scope of possible opportunities nor the feasibility or profitability of such secondary-use battery opportunities have been accurately quantified.

With support from the Energy Storage activity of the U.S. Department of Energy's Vehicle Technologies Program,, researchers at the National Renewable Energy Laboratory (NREL) are addressing this matter because of their extensive expertise and capabilities in energy storage for transportation and in distributed grids, advanced vehicles, utilities, solar energy, wind energy, and grid interfaces, as well as their understanding of the dynamics of the stakeholders. This paper and poster introduces the motivation, objective, and plans of NREL's PHEV/EV Li-ion Battery Secondary-Use project.

Motivation

NREL's mission includes developing technologies and practices to address the nation's energy and environmental goals, and in particular, reducing the nation's dependence on foreign oil and emissions of greenhouse gases. Increased market share of PHEVs and EVs addresses both of these goals by improving the overall fuel efficiency and reducing the emissions 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 Li-ion traction batteries. It has been estimated that a reduction of ~50% in battery costs is necessary to equalize the current economics of owning PHEVs and conventionally fueled vehicles [1].

Several strategies are currently being pursued to address high Li-ion battery costs, such as the development of Li-ion chemistries based on less costly materials, more cost-efficient cell and battery designs and manufacturing techniques, etc. Many of these approaches are unlikely to yield a near-term cost reduction to the consumer sufficient to encourage increased PHEV/EV market share, though. For example, the often-discussed cost savings achievable via efficiencies of scale in mass production requires first an increased PHEV/EVs market share.

The idea of reusing PHEV/EV traction batteries in secondary-use applications following the end of their automotive service life could reduce the initial cost of these batteries today. The life cycle of a battery utilized in such a manner is illustrated in Figure 1. By extracting additional services and revenue from the battery in a post-vehicle application, we can increase the total lifetime value of the battery. This subject has been studied in the past in reference primarily to the nickel metal hydride batteries powering some hybrids [2, 3] and has recently seen renewed interest spurred by the coming generation of Li-ion-based hybrids and EVs.

Most readily, the direct benefit of secondary use to the automotive customer is quantified as a battery resale value once the battery is no longer sufficient for automotive use. This approach may have only a minor impact on new car buyers, given the uncertainty of the batteries' future resale value. However, via ownership of the battery by the automotive manufacturer or a third party willing to assume the risk inherent in such an endeavor, the battery's automotive salvage value can be transformed into a substantial reduction in initial purchase price, and thus significantly impact current PHEV/EV adoption rates.

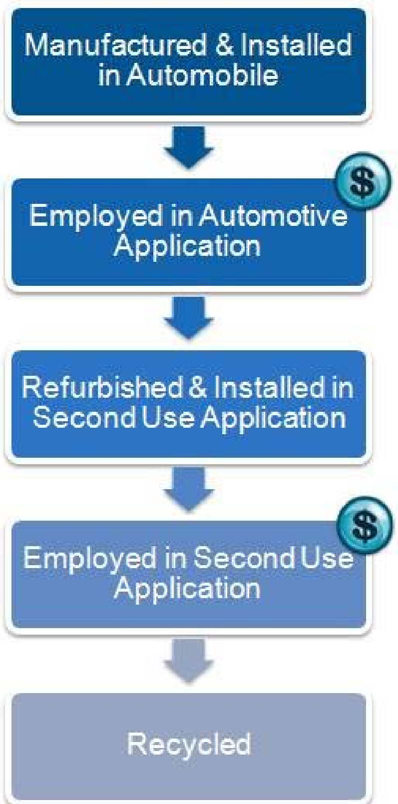

Figure 1: Lifetime of a PHEV/EV battery when second-use applications are considered to increase its total lifetime value

How much of a break in the current battery price is possible from secondary-use applications? This precise calculation will be a major focus of NREL's study, requiring detailed knowledge of the operating requirements of the selected secondary-use application, financial data for revenues and operating costs, battery refurbishment and distribution costs, etc. Nonetheless, a reasonable upper bound to the initial price reduction can be made based upon anticipated future Li-ion prices when the following assumptions are made:

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

Under those 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, refurbishing, and certifying the used battery, and a "used" product discount factor. One means of capturing this relation is given in Equation 1:

$$V_{salvage} = K_h *(1 - K_r - K_u)\, C_{new} \qquad Eq\ (1)$$

where

$V_{salvage}$ = *future salvage value of used battery, $*
C_{new} = *forecasted future new battery cost, $*
K_h = *forecasted battery health, %*
K_r = *relative cost of refurbishment, %*
K_u = *used product discount, %.*

The net present value (NPV) of the salvaged battery, which can be applied to the initial purchase price reduction, can then be readily calculated by Equation 2:

$$NPV_{salvage} = V_{salvage} *(1-r)^n \qquad Eq\ (2)$$

where

$NP\ V_{salvage}$ = *NPV of used battery, $*
r = *annual discount rate, %*
n = *automotive service life, years.*

Note that this approach requires two not-so-easily-attained bits of information: the future cost of Li-ion batteries and the state of health of the used battery at the time of automotive service retirement. However, reasonable estimates for these values (in the context of creating a best case salvage value estimate) can be had by combining conservative forecasts of battery cost as a function of production quantity [4] and PHEV sales forecast [5] with a simple model for battery degradation defining end of automotive service at 10 years and 70% of initial battery health. Then, assuming K_r=15%, K_u=15%, and r=2.5%, a best case initial battery price reduction of 28% can be calculated, per Figure 2.

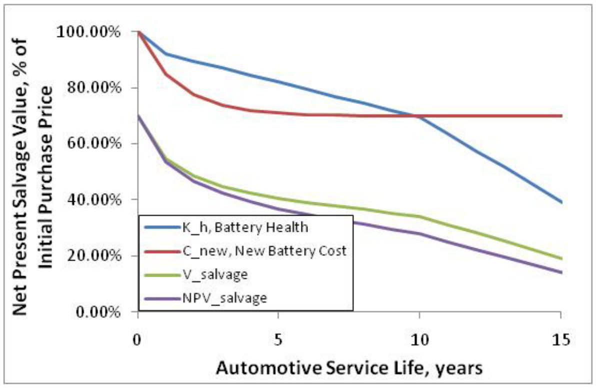

Figure 2: Best case estimate of the net present salvage value of PHEV/EV Li-ion batteries retired from automotive service

Regardless of the specific values applied to these equations, two worthwhile generalizations can be made to help guide more detailed secondary-use studies:

- Decreasing C_{new} in the future (as well as general improvements in battery performance) will negatively affect future battery salvage values and thus reduce the initial price discount achievable today.
- Replacing an automotive battery will always come with an increased cost to the vehicle owner (C_{new} is always greater than $V_{salvage}$). Combined with exponential decay rates for C_{new} and battery health, annualized automotive costs are minimized at maximum possible n, despite the fact that $V_{salvage}$ decreases with time.

Objective

Given that secondary use appears to have the potential to significantly impact the initial battery cost, and thus the adoption rate, of PHEV/EVs, NREL's objective for this project is, broadly, to identify, assess, and verify favorable secondary-use applications and strategies for PHEV/EV Li-ion traction batteries. Here "favorable applications and strategies" are defined as those that—

- Maximize the total lifetime value of the battery and thus imply the largest initial cost reduction
- Have a scale of implementation well matched to the size of the PHEV/EV market and thus a high capacity to affect PHEV/EV market share
- Have a high feasibility of implementation with respect to assumed risks, regulatory hurdles, technical hurdles, etc.

Plans

NREL is implementing a three-phase plan to achieve this objective: (1) assess the merit of secondary-use applications and strategies, (2) verify performance and economic projections, and (3) facilitate the implementation of secondary-use programs.

In the first phase, a broad set of secondary-use applications will be compiled and briefly assessed, from which four to five of the most promising applications will be down-selected. These applications will then go through a more rigorous analysis, in which all aspects of a battery's life cycle will be addressed in search of an optimal use strategy. Completing this task will require detailed economic data for not only the secondary-use application but also for battery maintenance and refurbishment activities. Forecasting battery performance throughout the entirety of its automotive and secondary-use service will also be critical.

In phase two, the most favorable applications and use strategies identified in phase one will be verified in long term tests. These tests will ideally utilize field-aged, mass production PHEV/EV battery designs subjected to representative second-use application conditions in a controlled environment.

Finally, phase three will address facilitating the implementation of the identified and verified secondary-use applications and strategies. NREL will go beyond merely disseminating study findings to providing validated tools and data to industry, as well as developing PHEV/EV battery design and manufacturing standards and proposing the necessary regulatory changes to encourage secondary battery use.

Moving Forward

As of April 2010, NREL is seeking organizations from industry and academia to help evaluate secondary-use applications for PHEV and EV Li-ion batteries. A Request for Proposal was planned for release to co-fund such subcontractors to analyze potential secondary-use battery applications, secure aged Li-ion traction batteries from PHEVs and/or EVs, and perform representative long-term secondary-use testing on the batteries to verify predicted performance.

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[1] Brooker, A., et al., "Technology Improvement Pathways to Cost-Effective Vehicle Electrification," *presented at the SAE 2010 World Congress*, Detroit, MI, April 2010.

[2] *Market Feasibility for Nickel Metal Hydride and Other Advanced Electric Vehicle Batteries in Selected Stationary Applications*, EPRI, Palo Alto, CA, and SMUD, Sacramento, CA: 2000.

[3] *Technical and Economic Feasibility of Applying Used EV Batteries in Stationary Applications*, Sandia National Laboratories, Albuquerque, NM: 2002.

[4] Kamath, H., "Lithium Ion Batteries in Utility Applications," *Proceedings of the 27th International Battery Seminar and Exhibit,* Ft. Lauderdale, FL, March 2010.

[5] *PHEV Market Introduction Study Final Report*, Oak Ridge National Laboratory, Oak Ridge, TN: 2010.

Figure 4: A broad range of secondary-use applications will be considered with respect to value, PHEV/EV market share impact, and feasibility

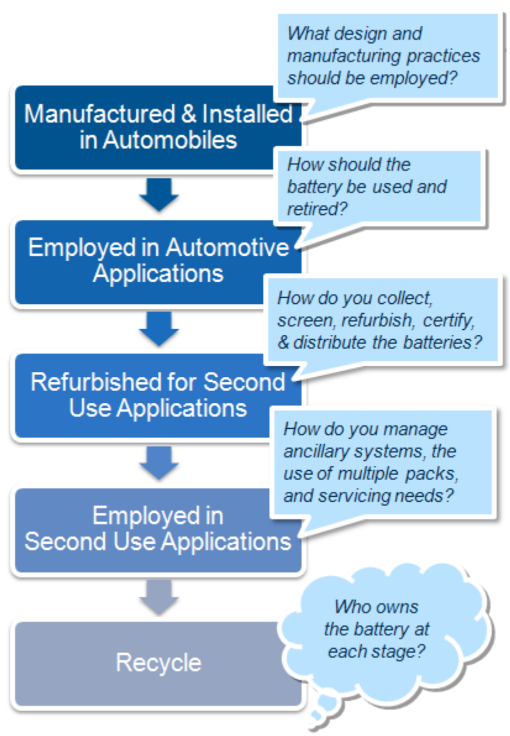

Figure 5: All aspects of a battery's full life cycle will be addressed when optimizing use strategies

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