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Analysis of Current and Projected Battery Manufacturing Costs for Electric, Hybrid, and Plug-in Hybrid Electric Vehicles

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Abstract

There have been a number of recent reports of the current and projected costs of advanced batteries for electric, hybrid, and plug-in hybrid electric vehicles (PHEVs). These studies have focused on lithium-ion batteries as the most attractive option for future deployment in these vehicles. The reported costs have varied widely. The objective of this paper is to examine the basis of these assessments, taking particular note of the varying assumptions used regarding such important factors as power-to-energy ratio, battery chemistry, production scale, rated capacity vs. useable capacity, and beginning-of-life vs. end-of-life. A high-power battery at low production volume will have a drastically different cost per kWh compared with a high-energy battery at high-volume production. Furthermore, other factors that are, or are not, included in the costs as reported, such as marketing, warranty, and profit, can have a significant impact on reported costs; the manner in which these factors are treated can account for large differences between a manufacturer's production cost and the battery selling price.

Keywords: battery, lithium-ion batteries, EV (electric vehicle), PHEV (plug-in hybrid electric vehicle)

1 Introduction

This paper compares recent results developed at Argonne National Laboratory (ANL) [1] [2] for the projected costs of HEV, PHEV, and EV batteries with other recently reported studies or published estimates, including:

- TIAX cost modeling results for PHEV-20s [3] [4],
- MIT study [5] estimating the "built-out cost" of fuel cell and battery vehicles,
- Studies by the Boston Consulting Group [6] and Pike Research [7],
- Analyst reports by Deutsche Bank [8], Roland Berger [9], Deliotte [10], and IHS Global Insight [11],
- Reports from the Electrification Coalition [12], and
- National Academy of Sciences report on PHEVs [13].

Estimates of current costs vary considerably. Furthermore, projections for future cost reductions based on continued research and development, manufacturing learning, and production scale also vary widely.

Aside from the inherent uncertainty surrounding projections of this type, there are several factors that account for some of the differences in reported costs. Some examples include:

- While most studies report battery costs based on beginning-of-life power and energy, some studies report costs based on end-of-life energy and power leading to higher reported cost per kWh for the same batteries.
- Battery costs are sometimes reported based on nominal or nameplate capacity (100% discharge). However, PHEVs will only be able to use a portion of full capacity in order to meet power and life requirements. The NAS report assumes 50% is the best possible, while some battery manufacturers believe that up to 75-80% is more likely for some battery chemistries. These differences have led to very wide variations in reported battery costs.
- The cell capacity, and therefore the number of cells in a pack, has a bearing on the resulting battery manufacturing cost.
- The type of battery thermal management is important, with air-cooling considered to be less costly in general than liquid-cooled systems.
- Some studies estimate the manufacturing cost without profit, whereas other studies include a profit to determine the "factory gate" price to the OEM purchaser.

2 Electric Vehicle (EV) Batteries

Numerous estimates of both current and projected costs for EV batteries have been published. Many of these are based on unpublished quotes from various battery manufacturers, and vary widely. More detailed cost estimates have been published based on a careful analysis of materials costs and manufacturing requirements.

The estimated cost of EV battery packs from the various studies is shown in Table 1.

Table 1. EV Battery Cost Estimates

Source	Battery Cost ($/kWh)		
	2010	2015	2020
Argonne National Lab			150-200
Advanced Automotive Batteries		500-700	375-500
Boston Consulting	990-1220		360-440
Deutsche Bank	650		325
Electrification Coalition	600	550	225
Pike Research	940	470	

While there are some differences in absolute value of these cost estimates, the trends for future cost reductions are in fairly good agreement. The estimated costs for the year 2020 are expected show a 50% or more reduction in cost compared to the 2010 estimates.

3 Plug-in Hybrid Vehicle (PHEV) Batteries

Several estimates of the cost of PHEV batteries have recently been published. These estimates are shown in Table 2.

Table 2. PHEV Battery Cost Estimates

Source	Battery Cost ($/kWh, based on nominal capacity)		
	2010	2015	2020
Argonne National Lab			200-400
Deutsche Bank	900-1000	500-600	400-500
National Academies (NAS)	825-875		535-570
TIAX LLC			211-398

Independent cost modeling analyses conducted by Argonne National Laboratory (ANL) and TIAX LLC have produced results in fairly good agreement. The TIAX study [4] was conducted for a PHEV20 battery, whereas the ANL study was carried out for various PHEV ranges from 10 to 40 miles [2].

The TIAX study indicated PHEV20 battery costs of $265/kWh useable (10-90% SOC and no fade) to $710/kWh useable (10-90% SOC, 30% fade) or $211-$398 based on nominal capacity, for a variety of battery chemistries and two different levels of allowance for battery degradation over vehicle lifetime. For a PHEV20, the Argonne model yielded costs of $200-272/kWh [2].

4 Factors Contributing to Cost Differences

Aside from the inherent uncertainty surrounding cost projections of this type, there are several factors that account for some of the differences in reported costs.

4.1 Power/Energy (P/E) Ratio

The NAS report suggests a very weak dependence on the battery power/energy ratio. The NAS report indicated that the PHEV10 battery actually costs less than a PHEV40 battery in terms of $/kWh, despite the much higher P/E ratio. The NAS study assumes that the PHEV10 battery has a useable capacity of 2 kWh and a power of 50 kW. The NAS study also assumes that the PHEV40 battery has a useable capacity of 8 kWh and a power of 100 kW. Thus, while the PHEV10 battery (P/E=25) has twice the power/energy ratio compared with the PHEV40 battery (P/E=12.5), the PHEV10 battery cost ($1650/kWh useable) is nonetheless less than the PHEV40 battery cost ($1750/kWh useable).

In contrast, the ANL [14] and EPRI analyses [15] suggest a very strong dependence on the battery power/energy ratio. From the ANL EVS-24 paper, one can compare a PHEV10 (40 kW, 4.29 kWh nominal) and a PHEV40 with power similar to the NAS PHEV40, approximated by combining two PHEV20 battery packs, (80 kW, 17.14 kWh nominal). In this case, the cost for the PHEV10 battery is $1513 (or $353/kWh nominal) and the cost for the PHEV40 battery is $4240 (or $247/kWh), based on nameplate capacity. Thus, the PHEV40 battery, with half the P/E ratio, costs 30% less on a $/kWh basis, than the PHEV10 battery.

4.2 Production Scale

The ANL 2009 study [1] showed that an increase in production level from 10,000 batteries/year to a production level of 100,000 batteries/year would result in a 37-44% reduction in battery cost. This level of cost reduction is consistent with publicly presented material by Ford Motor Company [16], which indicated a cost reduction of 20-40%. The ANL 2010 study [2] indicated that a further increase in production level, from 100,000 to 500,000 batteries per year, would achieve and additional 25-30% cost reduction.

4.3 Thermal Management Systems

Thermal management is recognized as an essential system element for maintaining battery temperatures in an acceptable range in order to achieve the required battery lifetime. Different battery manufacturers and vehicle developers has adopted different strategies for thermal management. Some have elected to employ air cooling for their battery systems, while others are using liquid cooling systems. While these difference are expected to have some impact on battery system cost, there appears to be little or no published information on the relative costs of these systems. It is generally believed that the simpler air-cooled systems will be somewhat lower in cost than liquid cooling. Future studies at ANL are planned to develop quantitative estimates of the costs for each cooling system, and thereby assess the overall importance from a cost perspective.

5 Conclusions

Numerous estimates of both current and projected costs for EV and PHEV batteries have been published. Many of these are based on unpublished quotes from various battery manufacturers, and vary widely. Despite the differences in estimates of current costs, the expectations for future cost reductions are more consistent, with costs expected to drop by 50 per cent or more between 2010 and 2020. Independent cost modeling studies, based on materials inputs and manufacturing requirements, yield cost estimates that are in fairly good agreement for PHEV battery costs.

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