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# Large-Format Lithium-Ion Battery Costs Analysis

*Critical Review of Existing PHEV Lithium Ion Battery Cost Studies*

**1019923**



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Technical Update, December 2010

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# ABSTRACT

The high cost of lithium ion batteries poses a serious problem for the competitiveness of Plug-In Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs). The problem is complicated by the fact that the lithium ion battery cost projections developed by a number of apparently credible organizations over the past 5 years or so differ so much that different conclusions regarding the economic competitiveness of PHEVs (and even more so BEVs) have been stated. This situation creates confusion and disagreement regarding PHEV and BEV prospects. The objective of this study is to identify the key factors that drive lithium ion battery costs and to set a framework for the development of a model that will permit more transparent and confident cost estimates and projections for the various lithium ion batteries that are reasonable candidates for PHEV and BEV applications.

This report compares credible lithium ion battery cost studies in terms of their key assumptions, methodologies, and results. Seven recent studies of lithium ion battery cost were reviewed in some detail: three bottom-up cost models, two high-level models based on manufacturers' cost data, and two others that turned out to be of more limited scope and relevance.

The Argonne National Laboratory (ANL)'s ANL 2020 and the PHEV cost assessment by TIAX LLC are bottom-up models that clearly state their key assumptions and cost projection methodologies for batteries using a range of lithium ion chemistries. The lower end of the range of battery specific costs projected by TIAX (about $270/kWh for a 5.5kWh lithium ion battery) agrees with the upper end of the cost range of ANL which extends down to about $200/kWh for a comparable battery size. The California Air Resources Board Zero Emissions Vehicle (ARB ZEV) Panel study's lithium-ion cost projections are derived from a number of manufacturers' projections for batteries of different chemistries, cell sizes, and battery capacities. The Panel's range of specific cost projections is similar to the range projected by ANL, providing useful cross-validation of these very different approaches and their results. The ANL and ZEV Panel specific cost projections also yield similar conclusions for the dependence of specific cost on cell size and battery capacity for a given battery chemistry and design. These results make clear that direct comparison of lithium ion battery specific costs are meaningful only for batteries of the same cell sizes and capacities. This information should be stated as part of the comparisons.

These findings and conclusions led the authors to select the ANL 2020 model as the basis for continuing efforts to develop a lithium ion battery cost model with the flexibility to handle the full range of battery active materials, cell chemistries, cell and battery designs and sizes, mass production levels, and timeframes that can be foreseen for PHEV and EV applications. Collaboration with ANL will be sought in this effort and in the validation of key model features and projections with experts in the advanced battery and automotive industries.

### Keywords

Lithium ion batteries
Cost estimates
Electric vehicles
Plug-in hybrid vehicles (PHEVs)
Battery electric vehicles (BEVs)

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# 1
# INTRODUCTION

The high cost of lithium ion batteries poses a serious problem for the competitiveness of PHEVs and BEVs. The problem is complicated by significant uncertainty in battery costs. While lithium ion battery cost projections have been developed by a number of credible organizations over the past 5 years or so, the substantial differences among them have led to much confusion and disagreement over the expected future cost of these batteries and, consequently, over the prospective economic competitiveness of PHEVs and, even more so, BEVs.

In response, the overall goal of this continuing study is to improve the understanding of the factors that drive the costs of lithium ion batteries for PHEV and BEV applications and to develop more confident estimates and projections of the costs of such batteries. This goal is being pursued through development of a bottom-up cost model that (a) permits confident cost projections for lithium ion batteries with different chemistries, cell sizes, designs and manufacturing methods for battery designs and capacities of interest to automotive applications as produced at different rates in the near, intermediate and longer term; (b) takes advantage of established and advanced/developmental battery cost models and can accept the full range of parameters that drive battery materials, manufacturing, and customer (OEM) costs; and (c) is verified by experts in the battery and advanced electric automotive industries. The first step in this study is to better understand the status of lithium ion battery cost studies, including the differences between them and the issues they raise. The following sections report the approach taken to accomplishing this first step and the conclusions derived so far.

# 2
# CRITICAL REVIEW OF LITHIUM ION BATTERY COST STUDIES

This section presents an overview of lithium ion battery cost studies and projections that have been performed in the recent past, with emphasis on studies and projections of PHEV battery costs. From among a number of such studies, the following were selected because of their widespread citations:

- Argonne National Lab 2020 Lithium Ion Battery Cost Model: Authors: Paul Nelson and Kelvin Gallagher, ANL. [1]
- PHEV Battery Cost Assessment, TIAX LLC: Authors: Brian Barnet, *et al,* TIAX LLC. [2]
- Lithium Ion Battery Costs (2007 ZEV ARB Study): Authors: Fritz Kalhammer, *et al* [3]
- Lithium Ion Battery Costs (Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet): Authors: Mathew A. Kromer and John B. Heywood, MIT. [4]
- Assessment of Future Lithium Ion Battery Production Costs: Authors: Peter Mock, German Aerospace Center. [6]
- Tesla, Electric Vehicle, and Battery Update: Scale Alone Will Not Achieve Battery Cost Targets: Joshua Paradise, *et al*, Morgan Stanley Research. [7]
- Transitions to Alternative Transportation Technologies—Plug-in Hybrid Electric Vehicles: Authors: National Research Council of the National Academy of Sciences. [8]

These studies are reviewed below.

## Review of Lithium Ion Battery Cost Studies

### *A. Argonne National Lab 2020 Lithium Ion Battery Cost Model*

*Battery cost projection: $200-272/kWh (PHEV -20 battery of 7.1 kWh total, 100,000 packs per year)*

The Argonne cost model is a comprehensive bottoms-up cost model. It addresses several battery chemistries including graphite-based anodes combined with doped nickel oxide (NCA), nickel cobalt manganese (NCM), lithium manganese oxide (LMO), or lithium iron phosphate (LFP) cathodes as well as batteries with titanate anodes combined with LMO cathodes**.** The details of the model can be found in [1]. The model covers manufacturing investment costs (capital equipment, plant floor space, launch costs, and working capital), variable costs (material cost, direct labor, variable overheads), and fixed costs (general sales and administration costs, research and development costs, and depreciation). A key aspect of the model is its flexibility. which permits the user to vary key design and cost parameters.

Three different ways of specifying batteries are provided: by capacity, battery energy, or vehicle range. The model optimizes the cell size and other battery system parameters for the actual

battery size chosen, and it limits the electrode thickness to a preset value. For high power batteries, the model adjusts the cell design to increase area so that the maximum electrode thickness limit is maintained. The baseline manufacturing rate is 100,000 packs per year, but the desired manufacturing rate can be set by the user. The model provides reasonably consistent results for production rates between 30% and 300% of the baseline rate. The effect of production scale is modeled using the so-called "production learning curve" method in which the cost of a manufacturing plant with a desired capacity is estimated from the known cost of a plant of a given capacity by multiplying the cost of the known plant by the ratio of the two capacities raised to some power, usually about 0.6 to 0.7:

$$C_i = C_o(R_i/R_o)^p \qquad \text{Equation 2-1}$$

Where $C_o$ = capital cost of an installed equipment item designed for the baseline processing rate, $R_o$, p = the power factor relating the capital investment cost and the processing rate for the manufacturing step.

The results of a battery cost study performed using the Argonne model are documented in [1]. Some key results are presented here:

- At a particular battery power, battery size can be increased up to a certain point by increasing electrode thickness. Further increase in battery energy is possible by only increasing cell area, which in turn results in increased cell power. The cost of the battery is proportional to battery size for a given battery power, but this relationship changes somewhat when the cell area needs to be increased for the design of larger batteries that would have required an electrode thickness above the practical limit.
- For a given battery capacity, a small number of higher energy storage capacity cells are substantially less expensive to manufacture than a larger number of lower-capacity cells. The extra cost for the larger number of cells results from the larger number of cell hardware parts such as the state-of-charge management devices and the extra equipment, as well as labor required for formation cycling and cell testing.

### Comments

A key result of the ANL study is that battery cost is a nonlinear function of battery size (capacity). The underlying physical reason is that the balance of battery system cost does not scale linearly with battery capacity. This important finding is discussed in more detail in Chapter 4 of this report in the section titled "Cell and Battery Size".

## *B. PHEV Battery Cost Assessment (TIAX LLC)*

*Battery cost projection: $265-710/kWh (for PHEV-20 battery of 6.9kWh total, 5.5kWh practically used capacity produced at the 500,000 packs/year rate from small cells)*
*(Lower bound applies for high energy designs with low fade over the useful battery life and for low cost materials and equipment used at high throughput rates, upper bound are for high power designs with 30% fade, more expensive materials and equipment, and low throughput rates.)*

TIAX LLC is developing an assessment of PHEV battery costs for the Department of Energy (DoE) [2]. The TIAX model is a comprehensive bottom-up cost model. Its inputs include battery chemistries, state of charge (SOC) range, electrode loadings and cell format, required battery

energy, discharge and recharge power, nominal battery pack voltage, fade with aging, and annual manufacturing rate. Factors with significant impact on battery costs are isolated in this model.

The model addresses battery chemistries with NCA, NCM, LMO, LFP and layered-layered nickel manganese cobalt (LL-NMC) cathodes and with graphite-based as well as titanate anodes. Three cell designs are considered: two with wound cylindrical, and one with stacked prismatic cell form factors. Three different cathode loadings are considered, each for a 0% fade and a 30% fade scenario. The model typically assumes an 80% utilization of capacity in practical applications of the batteries. The cost model is based on a manufacturing process commonly used for mass manufacturing of standard 18650 cells. A manufacturing rate of 500,000 packs per year is assumed. This volume may be on the high side although new plants for HEV batteries now have capacities of 300,000-500,000 packs per year. The battery cost is projected for low, baseline, and high material cost scenarios.

Key findings of the TIAX cost study are:

- There is a significant overlap in battery costs among various battery chemistries. Battery cost is a strong function of electrode design. Accordingly, electrode design contributes to the model's wide variation in battery costs for a given battery chemistry.
- Batteries with titanate anodes are significantly more expensive than batteries using graphite-based anodes because of the lower voltage of titanate-based cells. As a result titanate-based packs require approximately 60% more cells to reach the typical 300Vbattery voltage specification. Another consequence of the lower cell voltage is that the volume of titanate-based packs is almost twice the volume of packs with graphite-based cells.
- Battery system cost depends strongly on the design of the electrode, with thicker and shorter electrodes resulting in lower costs**.** Increasing manufacturing speed factors (such as electrode production line speed) decreases battery costs appreciably, and manufacturing process speed and labor costs are important contributors to battery costs.
- Decreasing active material cost by 90% can lower total battery costs by 15-25%.

### Comments

The TIAX study only considers batteries manufactured from very small cells (type 18650 with less than 3Ah capacity). As shown in the ARB ZEV study (see C. below) and discussed in more detail in Chapter 4, small cells result in batteries with higher specific costs than batteries with cell sizes optimized for a given capacity, e.g. for the 6-7 kWh of total capacity typically required for a PHEV-20 . The TIAX result that a 90% reduction of active materials cost reduces battery cost by only 15-25% is surprising, given the general consensus that in mass-produced lithium ion batteries active materials contribute about 50% to total cost.

## *C. Lithium Ion Battery Costs (2007 ZEV ARB Study)*

*Battery cost projection: $340 – 420/kWh (500 MWh per year equivalent to 80,000 packs/year), $240 – 280/kWh (2500 MWh per year equivalent to 400,000 packs/year). All cost data for PHEV-20 battery of 6.25 kWh total capacity*

In 2007, an independent expert panel constituted by the California Air Resources Board (CARB) presented its findings to the Board in a formal report [3]. These findings included a cost study of lithium ion batteries for PHEVs and BEVs. The Panel's model is not a bottoms-up cost model,

but based on a systematic comparison of battery costs projections provided on a confidential basis by a number of manufacturers. These projections were made available for various battery chemistries as well as for a variety of cell and battery capacities produced at different rates.

In the ZEV Panel report the manufacturers' data (with sources not identified) are first converted into module-level specific costs using scaling factors developed from the cell, module, and/or battery cost data provided. Similarly, the data were used to derive scaling factors for specific costs as a function different cell sizes for the same technology. Using these factors, module level costs were then normalized to a specific cell size (40-45Ah) and battery capacity (20-25kWh) considered representative of a majority of PHEV and EV cells and batteries. Key features of the model are that, in mass production, (1) module and battery specific costs increase continuously as cell size decreases, and (2) the cost increment going from modules to complete batteries increases with decreasing battery size.

### Comments

The ARB Panel study provides practical evidence of the strong impact of cell size on battery specific cost and, also, the increasing contribution of balance of system cost to total battery cost as battery size decreases. The first effect can be attributed to the higher percentage of inactive cell material and manufacturing costs per Ah as cell size decreases. The second effect is due to the fact that balance of (battery) system costs increase less than proportionally with capacity, as also shown by the ANL model. Both effects are discussed further in Chapter 4 since they are very important for meaningful representations and comparisons of battery specific costs.

## *D. MIT Study of Lithium Ion Battery Costs (Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet)*

*Battery cost projection: BEVs: $250/kWh by 2030 ($210 kWh when assuming a 3.5% annual decrease in materials cost); PHEVs: $420/kWh by 2030 (Optimistic cost projection for PHEV-30, 8 kWh battery)*

The cost model developed by Kromer *et al* generates cost projections for both high energy and high power lithium ion batteries [4]. The model is not a bottoms-up cost model but uses the framework established by the ARB BTAP (Battery Technology Advisory Panel) in 2000 [5].. The MIT model projects over a 20 to 30 years time frame, and it assumes that material costs from the BTAP baseline decrease by 40% over the next 20 years at a rate of 2.5% per year. It further assumes battery costs and margins unchanged from the BTAP projection. Finally, the model presents specific costs as a linear function of battery (peak) power-to-energy ratio.

### Comments

The MIT study is based on a cost model that by now is ten years old and does not include dependencies of battery specific cost on cell and battery size, thus limiting the capability of the model to deal with a variety of battery designs. The presentation of battery costs as linear function of the battery power-to-energy ratio is of questionable validity and modeling value given that many lithium ion technologies can be designed for very different specific power levels with little impact on specific energy.

### *E. Assessment of Future Lithium Ion Battery Production Costs (German Aerospace Center (DLR))*

*Battery cost projection: $210 - $375/kWh (High Energy); $400 - $625/kWh (High Power)*
*(Range depends on active materials and production volume; unspecified battery capacity)*

This model is a comprehensive bottoms-up cost model [6] based largely on the Argonne model. It progresses through four levels: a. Materials, b. Components, c. Cells, and d. Modules/packs. Raw material costs are estimated based on projected future availability, market price fluctuations, and future outlook for demand. Component level costs for anodes, cathodes, and electrolytes are then evaluated. These individual costs are used to calculate cell costs, taking into account mass and volume of electrodes, volume of separators, electrode thickness, and mass and volume of electrolyte. Finally, pack cost is determined from the number of cells and the cost of balance of plant components. The model predicts present-day costs as well as cost estimates for 2015. Several battery chemistries are evaluated including LCO, LMO, LNO, LNC, and NCM. The model identifies the key factors impacting battery costs and considers the impact of economies of scale.

#### Comments

It appears that the model does not consider production processes, capital costs, labor costs, overheads, and mark-ups in detail. As a result, it remains unclear whether production parameters such as line speed that have a significant influence on costs can be considered. Further, it is unclear whether the model can handle variations in cell size, and it does not provide a battery capacity against which to reference specific costs. These shortcomings limit the applicability of the model across a variety of cell and battery designs.

### *F. Tesla, Electric Vehicle, and Battery Update: Scale Alone Will Not Achieve Battery Cost Targets (Morgan Stanley Research)*

*Battery cost projection: $500/kWh*
*(Manufacturing rate of about 30,000 packs/year, small cell size ~2.5-2.8 Ah, 50 kWh battery capacity)*

The primary aim of the Morgan Stanley study was to assess the impact of production scale on battery costs. The study concludes that increasing current production scale can be expected to substantially reduce battery costs. Specifically, a production rate of 30,000 packs per year could lower current Tesla battery specific costs (estimated at around $650-800/kWh) by 15-30%. However, even that scale-based reduction would not be sufficient to lower specific costs below the $500/kWh level. The report concludes that further cost reductions would be possible only through major technological advancements.

#### Comments

Tesla's battery packs are built from very large numbers of small format (2.5-2.8Ah) cylindrical lithium ion cells. As discussed in more detail in Chapter 4, it is unlikely that batteries consisting of such small cells will drop below approximately $500/kWh at the production levels planned by Tesla.

### *G. Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles (National Research Council of the National Academy of Sciences)*

*Battery cost projection: $1,750/kWh in 2010 dropping to $1,000/kWh in 2030 (PHEV 40 with battery capacity of 16 kWh total, 8 kWh in practical use, manufacturing rate of 100,000 packs per year)*

The NRC study projects that the cost of a 16 kWh PHEV-40 battery (8 kWh of energy used in practical operation) would probably decline from $1,750/kWh in 2010 to $1,000/kWh in 2030. For a 4 kWh PHEV-10 battery (2kWh used in practice), battery specific cost is projected to decline from $1,650/kWh now to $950/kWh in 2030. Battery costs projections are given for a conservative as well as an optimistic scenario. An annual battery fade of 2.5% is assumed. The report concludes that scale will not have much impact on battery costs as several billion cells are already manufactured annually, implying that the study considers small-cell batteries only. The report further concludes that balance of plant components constitute 50% of the total battery cost, with the cell costs comprising the remaining 50%; and it states that balance of plant costs are fixed and will not change with production scale.

#### Comments

The NRC battery cost study makes a number of assumptions that compromise the significance of its results. For example, limiting the practically used battery capacity range to 50% of total capacity is very conservative, given that several OEM batteries operate today in the 65-70% range [9]. Assuming no production cost learning for the entire balance of plant cannot be considered realistic. Ignoring the effects of cell and battery sizes (see, for example the nearly identical specific costs projected for 16kWh and 4kWh batteries, respectively) is unrealistic and renders the study results questionable.

A more detailed effort to understand the basis for the NRC study and rationale for its results was not possible because the study does not develop cell costs using a rigorous bottom-up cost approach. Further, the report does not document the various assumptions used for the three different “severity” scenarios, nor is the methodology used to derive future cost projections presented. In summary, although the Committee issuing the report consisted of a number of highly reputed scientists and engineers, the credibility of its battery cost study portion compares unfavorably with the other studies reviewed as part of this study.

## Summary of Battery Specific Cost Projections

Table 2-1 summarizes the lithium ion battery specific costs of the above cost studies. For the sake of completeness, data from other cost studies have also been included. These additional data were taken from [10, 11].

## Comparative Evaluation of Existing Battery Cost Models

The cost studies reviewed in this study and summarized in Table 2-2 will now be compared with each other on the basis of the quality of the model, the completeness and realism of assumptions, and key cost factors such as battery chemistries and production rates. Important cost sensitivities will be identified.

The cost models of ANL, TIAX LLC, and DLS are comprehensive bottom-up cost models. These models have well documental and reasonable assumptions of material costs, production rates, battery chemistries, and manufacturing costs. The battery costs projected by these models are similar to each other. The cost studies conducted by Kalhammer and Kromer are high level cost projections, both derived (directly by Kalhammer, indirectly by Kromer) from actual data from battery manufacturers. The cost study by Paradise *et al* is specifically performed for the unique case of Tesla battery packs that consist of large number of small cells from current high volume commercial production. The cost study of the NAS Committee is both conservative and limited in its applicability since it does not consider the influence of cell and battery size, factors that are known to impact battery specific cost substantially. Also, its model and key assumptions are not adequately documented.

Based on our review to date, it is the opinion of the authors that the bottom-up cost models and their projections are the most meaningful among current cost models and they should be the basis for further efforts to refine models and validate their results through dialog with battery manufacturers. The specific costs developed by Kalhammer *et al* are useful as reference points due to their development from actual manufacturer data, bearing in mind, however, that a number of factors driving lithium ion battery costs are likely to have changed appreciably since the ARB Panel study four years ago.

**Table 2-1**
**$/kWh Projections from Lithium Ion Battery Cost Studies (PHEV-20)**

| Cost Model | Target Year | Battery Chemistry | Production Rate | $/kWh[1,2] |
|---|---|---|---|---|
| USABC (Target, not a model) | 2016 | Average | Mass rate | 200(U) |
| Nelson, et al / ANL | 2020 | Average | 100,000 | 200-272(T) |
| Bartlett et al / TIAX LLC | NA | Average | 500,000 | 265-710 |
| Kalhammer et al / ARB 2007 | NA | Average | 80,000 | 320-420(T) |
| | | | 400,000 | 240-280(T) |
| Kromer at. al. / MIT | NA | Average | 100,000 | 250 |
| Mock / DLR | 2015 | Average | NA | 210-375 |
| Paradise et al / Morgan Stanley | NA | | 30,000 | 500 |
| NRC/NAS | 2020 | Average | NA | 1,120(T) |
| Anderman 2010 | 2018-2020 | Average | NA | 675-900 |
| Deutsche Bank | 2020 | Average | NA | 400-500 |

[1]U: cost per kWh of usable capacity, T: cost per kWh of total capacity;

[2] Most but not all of specific costs shown are for PHEV-20 batteries of roughly 6 kWh capacity.

**Table 2-2**
**Comparative Evaluation of Battery Cost Studies**

| | Bottom-up cost model | Clear, well-documented assumptions | Representative production rate | Multiple battery chemistries | Discussion of sensitivities |
|---|---|---|---|---|---|
| Nelson, et al / ANL | Yes | Yes | Yes | Yes | Yes |
| Bartlett et al / TIAX LLC | Yes | Yes | Yes | Yes | Yes |
| Kalhammer et al / ARB 2007 | No | Yes | Yes | Yes | Yes |
| Kromer at. al. / MIT | No | Yes | Yes | No | Yes |
| Mock / DLR | Yes | Yes[1] | Yes | Yes | Yes |
| Paradise et al / Morgan Stanley | No | Yes | Yes[2] | No | Yes |
| NRC/NAS | No | No | NA | No | No |

NA: Not Available

[1]Complete set of assumptions not made available to authors.

[2]Applies specifically to Tesla.

# 3
# COMPARATIVE EVALUATION OF BOTTOM-UP COST MODELS

## Assumptions

Because they are considered suitable as basis for further development, the TIAX and ANL2020 bottom-up cost models are compared in more detail in this section. (Due to a lack of complete model information, the DLR bottom-up cost model is not considered further in this study. This omission is not considered serious because the DLR model is derived from, and closely related to, the ANL model).

Table 3-1 compares the basic battery design and production assumptions of the TIAX and ANL2020 models. It is apparent that the TIAX and ANL2020 model assumptions are quite similar, and the models cover a similar range of battery chemistries.

**Table 3-1**
**Battery Design Assumptions between ANL2020 and TIAX**

| Factor | ANL2020 | TIAX |
|---|---|---|
| **Manufacturing Rate** | 100,000 (variable) | 500,000 |
| **Battery Size** | 3.6; 5.4; 7.1; 10.7; 14.3 (nameplate capacity)<br>(10/20/30/40/50 miles) | 5.5 (usable capacity)<br>20 miles |
| **Battery Power** | 60 @ 80% OCV | 40 @ 10-90%SOC |
| **Battery Chemistries** | LMO-G; NCA-G; NMC-G; LFP-G; LMO-titanate | NCA-G; NCM-G; LFP-G; LMO-G; |
| **Cell Design** | Flat wound | 3 form factors: Cylindrical; Wound/Stacked Prismatic |
| **Battery Capacity Range Used** | 70-75% | 80% |

Table 3-2 compares the material, component, and labor costs used in the ANL2020 and TIAX models. A few cost data supplied by one manufacturer also are included. Although incomplete the data provide a reasonable cross-validation of the assumptions used in the models and by one manufacturer.

**Table 3-2**
**Material, Component, and Labor Cost Assumptions between ANL2020 and TIAX**

| | ANL2020 ($/kg) | TIAX ($/kg) | Manufacturer[1] ($/lg) |
|---|---|---|---|
| **LFP** | 20 | 20 (L: 15; H: 25) | |
| **LMO** | 10 | 16 (L: 12; H: 20) | |
| **NCA** | 36 | 40 (L: 34; H: 54) | 25 |
| **NMC** | 33 | 45 (L: 40; H: 53) | |
| **Graphite** | 19 | 20 (L: 17; H: 23) | |
| **Titanate** | 12 | 10 (L: 9; H: 12) | |
| **Separator ($/sq-m)** | 2 | 2.5 (L: 1.0; H: 2.9) | 1.4 |
| **Electrolyte** | 16 $/liter | $ 21.5 (L: 18.5; H: 24.5) | 21 |
| **Process Yield (%)** | 95 | 100 (L: 98; H: 100) | |
| **Wage rate ($/Hr)** | 25 (18 baseline) | 25 (L: 21; H: 29) | |
| **Cell components ($/cell)** | 0.4 | 2.5 (L: 2.1; H: 2.9) | |

[1]Manufacturer costs are provided for a 25 kWh battery; costs are based on euro-dollar exchange rates as of Nov 07, 2010.

While the two models thus use similar inputs, there are still some unknowns:

- The TIAX model factors in battery fade. It is unclear whether the ANL 2020 model includes a placeholder for battery fade in its capacity requirements for the various PHEV ranges.
- The ANL2020 model provides estimates for a range of manufacturing rates (30,000 – 300,000 per year). It is unclear whether the TIAX model includes this degree of flexibility.
- The ANL2020 model places a limit on electrode thickness, which affects cell and battery specific costs. It is unknown if the TIAX model uses a similar or different limitation.
- For both models, insufficient details are provided to understand their basis for design and cost of thermal management and battery controls.

### *Cell Module and Module Battery Incremental Costs*

An understanding of the increase in specific costs going from lithium ion cells to a module and then from modules to a pack is key to understanding the impact on battery specific cost of various system components, from active materials, cell inactive materials, and cell and module-level safety features to battery electrical and thermal management systems.

We used the ANL 2020 model to calculate these increasing costs and used them to derive specific cost scaling factors for going from the cell to the module level and from the module to the battery pack level, using the following assumptions:

- **Cell cost** = Cost to build 15 cells (material and labor)
- **Module cost** = Cell cost + module state of charge regulator cost + intercell connection assembly cost + balance of module materials cost

- **Battery Cost** = Cost for 4 modules + cooling/enclosure cost + recycling + shipping + overhead + fixed expenses + markup + warranty
- **Cell-to-Module Scaling Factor** = Module cost/Cell cost
- **Module-to-Battery Scaling Factor** = Battery cost/Cost for 4 modules

In Table 3-3, these factors are compared with the corresponding scaling factors derived by Kalhammer *et al* using actual manufacturer data. (The TIAX model does not have sufficient parameter flexibility for a determination of these factors.) Table 3-3 demonstrates a reasonable match of the data, with the ANL numbers being systematically higher by about 4% for cell-to-module factors and by 7-10% for module-to-pack factors. We consider the closeness of these estimates a valuable cross-validation of these completely different methods.

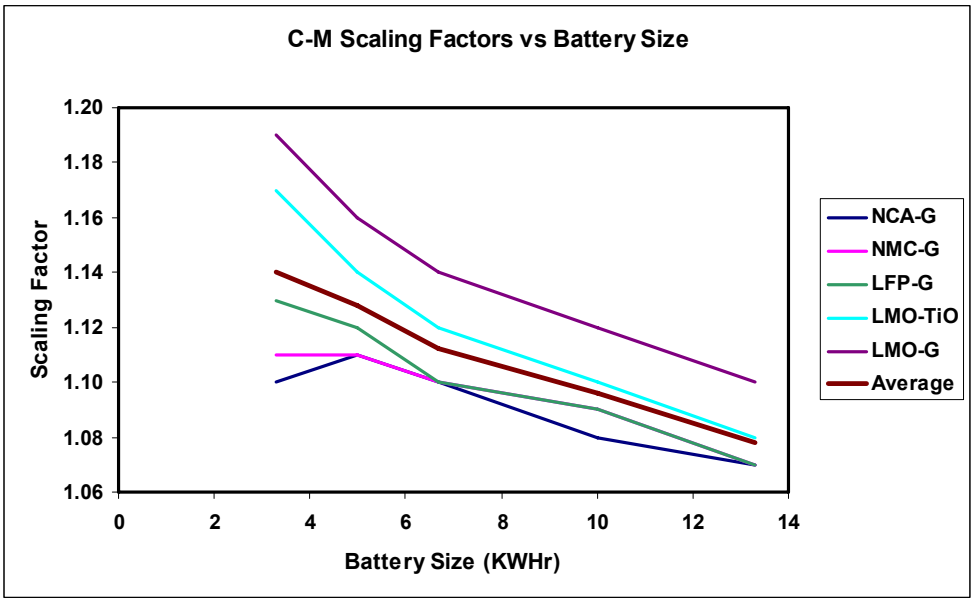
**Table 3-3**
**Cell to Module and Module to Battery Scaling Factor Comparison between ANL2020 and Kalhammer *et al***

| Scaling Factors | ANL2020[1] | Kalhammer *et al*[1] |
|---|---|---|
| **Battery Size: 6.7 kWh** | | |
| Cell to Module | 1.11 | 1.07 |
| Module to Battery | 1.51 | 1.42 |
| **Battery Size: 13.3 kWh** | | |
| Cell to Module | 1.08 | 1.05 |
| Module to Battery | 1.46 | 1.33 |

[1]Scaling factors are averages of the factors for the different battery chemistries considered.

In Figure 3-1, these scaling factors are plotted as a function of battery size. These plots show that the scaling factors decrease as the battery size increases. This decrease can be explained by the fact that the balances of plant costs for the battery become a smaller fraction of total battery costs as battery size increases. In other words, the balance of system costs do not increase proportionally with battery capacity, with the result that active material costs increasingly dominate battery costs as battery size increases.

Figure 3-2 shows the variation of the scaling factors across various battery chemistries for various battery sizes. The figures show a significant variation of scaling factors across the battery chemistries. The reason for this variation still remains to be understood.



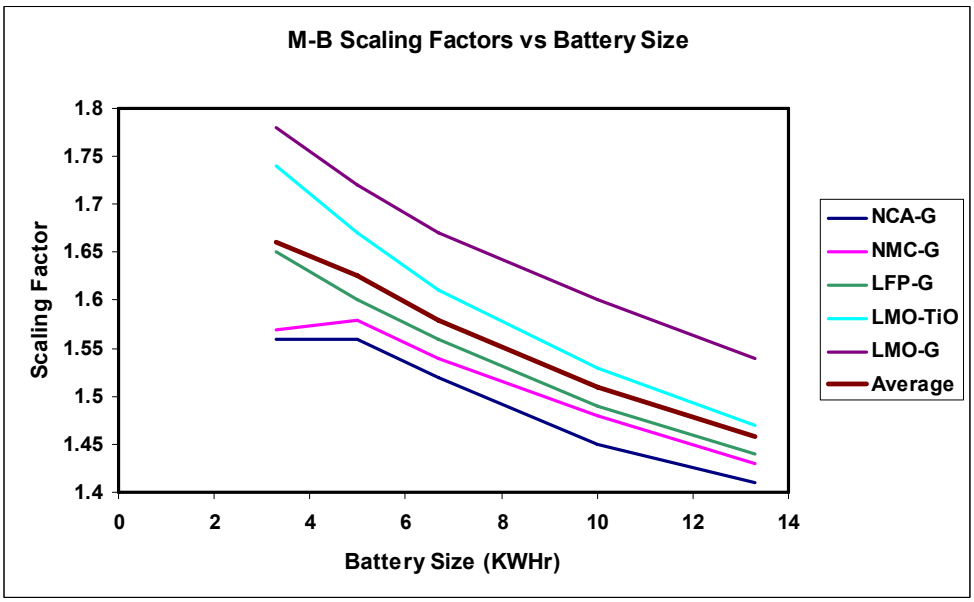
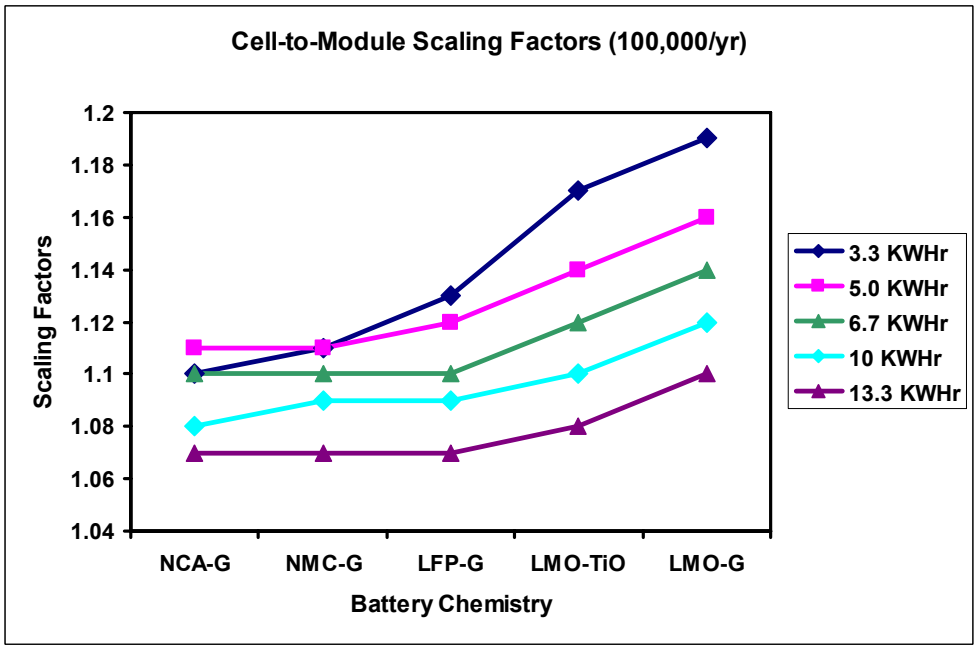




**Figure 3-1**
**Variation of cell to module and module to pack scaling factors as a function of battery size**



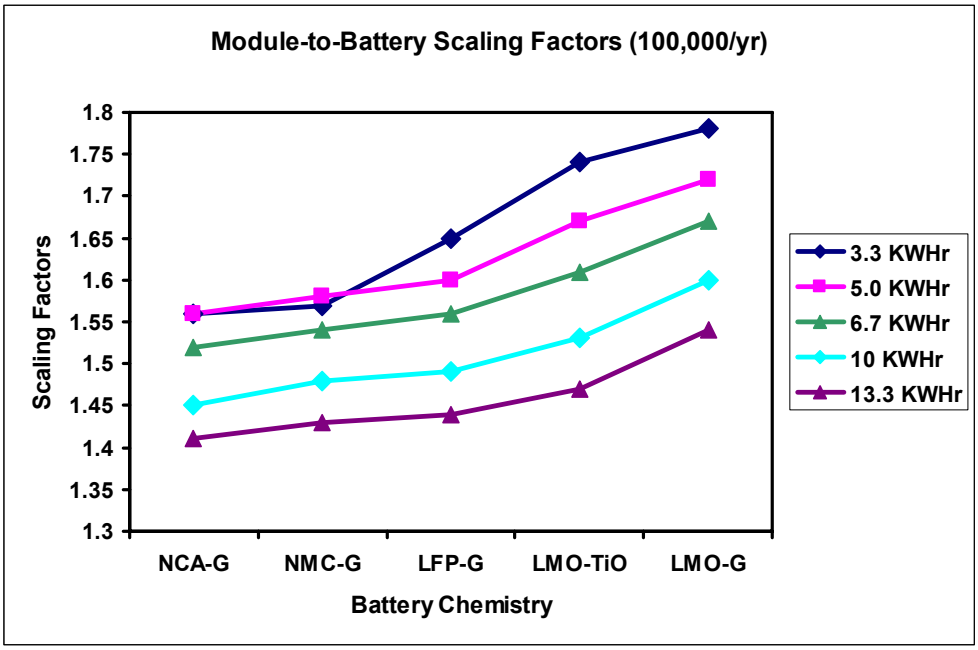




**Figure 3-2**
**Variation of cell to module and module to pack scaling factors across various battery chemistries**

## Model Predictions: Per-kWh Cell Cost

The ARB ZEV Panel study of Kalhammer et al. (see [3], Table 3-12) uses cell-, module, and battery-level cost date from manufacturers to show that the specific (per-kWh) cost of lithium ion cells increases substantially with decreasing cell size (in Ah). This important indicator of the cost penalty associated with going to smaller cell sizes can be derived quantitatively also from the ANL 2020 model, the only model with sufficient detail to permit this calculation. Table 3-4

shows the cell specific costs extracted from the ANL 2020 model for various cell sizes. Table 3-5 presents scaling factors for going from larger to smaller cell sizes derived from the ANL- data in Fig. 3-4 and compares them to the scaling factors derived Kalhammer *et al*. The scaling factors are in reasonable agreement, providing another useful cross-validation of empirical and modeling approaches to determining lithium ion cost battery cost.

For the purpose of this study, the following definition is used for cell-level specific costs: The $ per kWh of cells is the cost of one kWh of energy storage capacity made up of cells of a given total energy storage capacity. As an example, consider cells of 20 Ah charge storage capacity and a nominal average cell voltage of 3.57 V. It can now be inferred that one cell has an energy storage capacity of 20x3.57=71.4 Wh. It takes 1000/71.4=14 cells to make up one kWh. Assuming the cost of one mass-manufactured 20 Ah cell to be $20, the specific cost (i.e. cost per nominal kWh storage capacity) of this cell type would be 14 cells/kWh x $20/cell = $280/kWh.

**Table 3-4**
**Specific Cell Costs for Various Cell Sizes Derived From ANL 2020 Model**

| Ah | 15 | 30 | 45 | 60 | 120 |
|---|---|---|---|---|---|
| **$/kWh** | 212 | 144 | 122 | 110 | 99 |

**Table 3-5**
**Comparison of Scaling Factors for Lithium Ion Technology Specific Costs: From larger to smaller cell sizes**

| From-To Cell Size (Ah) | ANL 2020 (Nelson et al) | Kalhammer et al |
|---|---|---|
| 120→60 | 1.11 | 1.20 |
| 60→45 | 1.11 | 1.12 |
| 45→30 | 1.18 | 1.14 |
| 30→15 | 1.47 | 1.33 |

## Summary

The TIAX and ANL 2020 battery cost models have reasonable and rather similar assumptions. Their assumptions for material costs are consistent also with actual material costs from manufacturers. The fact that the TIAX specific cost projections are significantly higher than the ANL model predictions is due to the details in cell designs and manufacturing processes and also to the greater rate of capacity fade assumed by TIAX.

Only the ANL2020 model permits calculation of the dependencies of battery specific (per-kWh) costs as a function of cell capacity and battery size. These substantial dependencies are cross-validated through the modeling calculations of Kalhammer et al. based on manufacturers data. In summary, the ANL 2020 bottom-up cost model promises to provide reasonably accurate projections of the costs of large-format PHEV lithium ion batteries and of the dependency of these costs on the major materials and manufacturing cost factors. These factors also include cell and battery capacities. The ANL model is therefore selected for further study and refinement in EPRI's continuing efforts to develop credible projections for a wide range of lithium ion battery technologies produced at various rates.

# 4
# FACTORS INFLUENCING PHEV LITHIUM ION COST PROJECTIONS: ADDITIONAL CONSIDERATIONS

## Cell and Battery Size

### *Cell Size*

The importance of cell size on battery specific and total cost emerges clearly from our comparison of lithium ion battery cost studies. In particular, from an extrapolation of the data in Table 3-5 to cell sizes around 2-3 Ah, it seem likely that the specific cost of mass-produced cells in the 30-60 Ah range will be only half of the specific costs of 18650 type cells. This prediction is broadly consistent with Tesla's cost projection (reference, Chapter 2) of about $250/kWh for mass-produced high quality small (~2.5-2.8 Ah) cells and the assumption that cells make up 50% of a battery cost of $500/kWh. (30,000 Tesla 50 kWh battery packs/year contain about 200 million cells, which approaches cell mass production volumes.) However, 30,000 units per year is not yet mass production for the balance of the battery pack. Consistent with this "partial mass production" scenario, cells are only 50% of projected Tesla battery costs rather than the 60-70% fraction often mentioned by battery manufacturers for mass production of all battery components.

### *Battery Size*

The ANL2020 model and the ARB Panel (Kalhammer *et al*) empirical battery cost model show quantitatively that battery specific costs depend strongly on battery size. The ANL data (Figure 3, [1]) show that total battery cost as a function of battery size over the range of practical interest for PHEV applications can be approximated closely by the following relationship:

$$C_{tb} = A + B \times c \qquad \text{Equation 4-1}$$

where $C_{tb}$ is the total battery cost in $, c is the battery capacity in kWh, and A and B are constants for a given battery chemistry and design.

Dividing the above equation by the capacity c results in the following relationship:

$$C_{tb}/c = C_{sb} = A/c + B \qquad \text{Equation 4-2}$$

where $C_{sb}$ is the specific battery cost in $/kWh.

The first relationship indicates that the costs of lithium ion batteries of a given cell chemistry and design tend toward a constant value (in the Argonne model around $1,000-1,500, depending on battery power) for batteries of small capacity. The second relationship shows that battery specific cost declines with increasing battery capacity. It also indicates that the specific battery cost for rather large batteries approaches the constant B.

One key conclusion from the Argonne model is thus that comparisons of battery specific costs are meaningful only for batteries of the same capacity. If the specific costs of batteries with different capacities are to be compared in a meaningful way, the relationships discussed above need to be known.

## Usable vs. Total Battery Capacity

The specific cost of a battery can be stated in terms of either the total (nameplate) or the usable capacity. The total capacity normally is defined as the capacity of a fully charged battery discharged at the 3-hour (c/3) rate to a minimum cut-off voltage specified for the particular battery type. The usable capacity generally is assumed to be in the range of 50%-80% of total capacity. This capacity use restriction tends to increase the cycle life of the battery and allows for normal capacity and/or power fade over its useful life.

Some of the cost models reviewed use usable capacity, others total capacity. As a consequence, there are large specific cost differences for the same battery. In the opinion of the authors, the most rational way of stating specific battery cost is as $/kWh of the total battery capacity as defined above. This cost is numerically around 20-40% lower than specific cost based on usable capacity, depending on the maximum battery capacity utilization specified for the battery in the particular vehicle and/or application.

## Economies of Scale

Each of the major factors contributing to specific and total battery costs scales differently with production volume: materials, cell manufacturing, balance of (battery) system such as electronic controls including the battery management system (BMS), battery assembly, and very likely also each of the various overhead factors that contribute substantially to the battery cost (price) paid by OEMs. As a result, these factors will make different contributions to battery specific and total costs at different production rates. These differences become quite large with smaller and smaller production rates and plant capacities (say, less than 30,000 packs per year). On the other hand, for sufficiently large rates, the scale effects for all cost factors are likely to become quite small because production plants are likely to reach an upper size limit; and further increases in production rate will be achieved by building additional plants. For example, the currently largest plants of Panasonic Electric Vehicle Energy (PEVE) for production of NiMH hybrid electric vehicle (HEV) batteries seem to have a production capacity of about 500,000 packs per year.

Different cost studies have different views on the effect of scale in lowering lithium ion battery costs. Some studies suggest that scale cannot lower battery costs since some types of lithium ion cells are already manufactured in the 100s of millions. However, these mass manufactured lithium ion cells are typically small form factor 18650 cells. Only a few auto manufacturers such as Tesla plan to build battery packs using such small cell sizes (2-2.5 Ah). In such cases, scale may not have much potential to lower pack costs. For example, Tesla plans to build bout 30,000 packs a year, which translates to about 200 million cells (considering a 50 KW pack). This level can be considered as large-scale manufacture where the cell cost is already at an optimal level.

However, future mass manufactured PHEV Lithium packs can be expected to use larger cell sizes, for example 15-30Ah) optimized for specific applications. Such cells are presently manufactured in small quantities only and are thus expensive. In mass production the specific (i.e., per kWh) costs for larger Li ion cells promise to be considerably lower than those of small

cells. This significant potential for lowering cell costs is demonstrated in Figure 4-1.which shows cost projections for LPO-G cells produced at different rates. As the scale increases from 30,000 to 300,000, specific costs are shown to first decrease significantly and then level off at large manufacturing rates. For projections of future lithium ion battery costs, it thus is most important to identify the likely future production rate: is it 30,000, 100,000, or 500,000 packs per year? The answer to this open question is at least partially related to standardization of the major battery components. Clearly, the benefits of truly large scale production – e.g. 500,000 packs per year -- will be very difficult to realize (and capture in a battery cost model) if auto manufacturers insist on redesigning the pack for every new model of vehicle.

A related question, in practice but also for cost modeling purposes, is whether packs/year is the best measure of production capacity. Packs/year measure is appropriate for examining scale effects for the cost of batteries of a given capacity. However, when trying to extrapolate scaling factors to batteries of substantially different capacities, a better measure may be to compare plants of comparable MWhs per year. This will be especially so for very large, completely automated plants because for batteries produced by such plants materials are likely to account for well over 50% of costs; and the costs of MWhs will be largely proportional to materials costs.

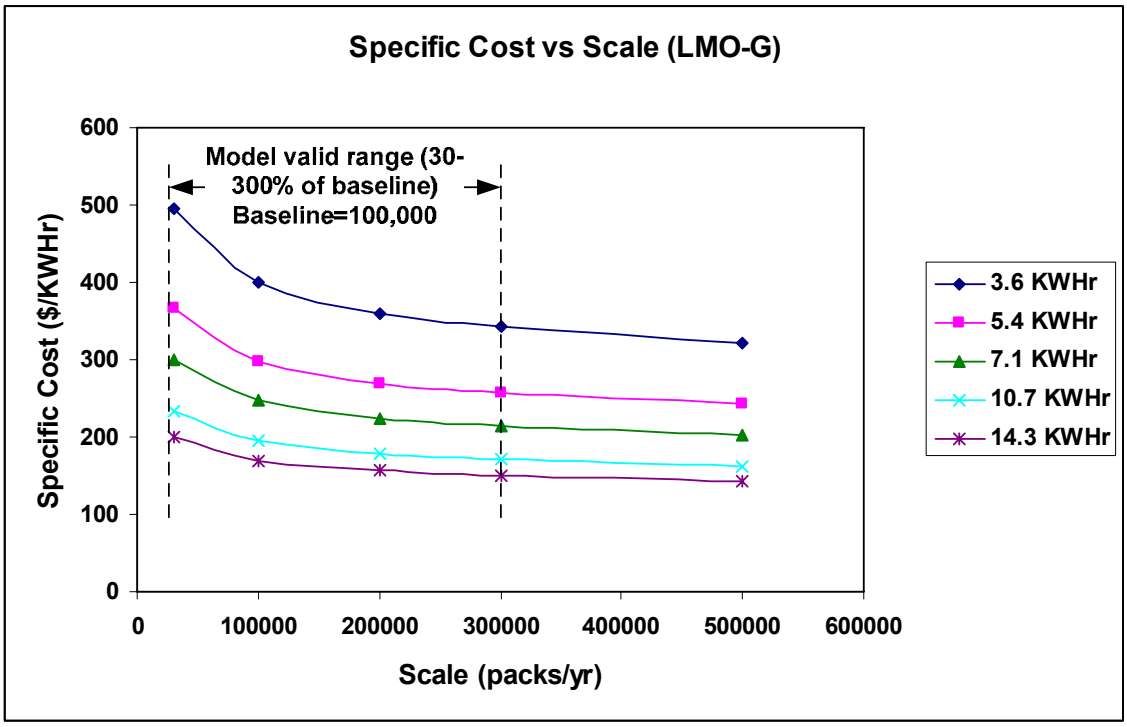



**Figure 4-1**
**Variation of Battery Specific Cost versus Scale (LMO-G from ANL 2020)**

## Standardization

Standardization is of obvious importance in the reduction of battery costs, but it will be difficult to achieve with the entry of so many players into the lithium ion battery development and production arena. Several OEMs state that progress on standardization is slow at best. Besides, the general opinion seems to be that differences in cell chemistry make if difficult to establish a

high degree of standardization for prismatic cells, at least at present. However, standardization should be easier to achieve in battery electronics, disconnects, communication, connectors, and at least some safety devices, such as disconnects and fuses.

A possible and promising path towards standardization across a number of battery and vehicle manufacturers may be to standardize one or a few cell sizes for a series of EV and PHEV applications by using series and parallel combinations of standardized intermediate cell sizes (somewhere in the 15-45 Ah range) to build batteries for different applications. Clearly, if any manufacturer of EVs and/or PHEVs succeeds in achieving large volume, this success will be the most effective driver toward standardization of every component of lithium ion batteries.

# 5
# CONCLUSIONS AND NEXT STEPS

## Summary and Conclusions

This research presents a first-cut review and comparison of credible PHEV lithium ion battery cost studies. Key factors driving battery costs have been identified. A detailed analysis of key assumptions and methodologies of two of the best-known bottom-up cost models has been conducted. The ANL2020 model is selected for further analysis, development, and validation because of its flexibility and the assumption that it will remain publicly available. To provide a basis for identification of promising directions for refinement, expansion, and validation of that model, a set of questions was compiled for discussion and cooperation between ANL and EPRI. These questions are presented below. The answers to them should help validate and improve the model to accurately represent the cost of lithium ion batteries for PHEV (and very likely also BEV) applications.

## ANL2020 Model Questionnaire

### *Materials Costs (per kg)*

- Are production scale effects on material costs accounted for?
- What about longer-term materials cost reduction prospects (through new materials, for instance)?
- How accurate is the cost of materials? Per EVS24 paper [1], accurate calculation is difficult as processing parameters are unknown. Will this have a significant effect on the cost?

### *Cell Manufacturing Specific Costs (per kWh)*

- What, if any, assumptions have been made about manufacturing automation? What are the effects on cost?
- What, if any, assumptions have been made about line speed? What are the effects on cost?
- What is the basis for the statement that costs don't depend much on cell design?
- Cell size effects (scaling factors): how generic are they likely to be?
- What is the basis of the model's assumed production scale effects on cost, and at what production levels are these effects likely to become insignificant?
- What is cost impact of (nominal) cell voltage? Is it in inverse proportion?
- Since the inflection point in the cost chart reflects the effect of the thickness of the electrode, representing a tradeoff between capacity, internal resistance, and durability, what is a reasonable assumption for negative electrode thickness today and in the future?

### *Module Specific Costs (Increment over cells, per kWh)*

- What are the main contributions of the module materials? Does the ANL 2020 model allow for a module-level contribution of thermal management to module costs?
- How do labor cost contributions change with module production rate/automation?
- Does incremental cost for modules depend on cell design? On cell size?

### *Battery Specific Costs (Increment over modules, per kWh)*

- Has battery fade been accounted for? If so, what is a reasonable fade percentage? (Fade would depend on battery chemistry, with spinel being most susceptible.)
- Have thermal considerations been factored into battery pack calculations? (We think cooling cost represents this but would like to verify this assumption).
- Have BMS and controls been accounted for? If so what level of BMS/controls has been assumed?
- How can we explain the significant variation in the incremental costs among various battery chemistries?
- Which battery components are included in the ANL 2020 model?
- What would be a reasonable production rate? Is it better to quantify this as MWh instead of number of packs?
- Which assumptions are made on automation in battery assembly and do they affect battery cost significantly?
- What are the effects of battery size on battery specific cost?
    - How generic is the following relationship that is indicated in Paul Nelson's EVS-24 paper: TBC($) = A + B($/kWh) x C(kWh) where TBC = total battery cost, A = constant, B = a constant closely related to specific battery cost, and C = battery nominal capacity
    - What are the physical interpretations of A and of B?
- Which are the main effects of production rate on battery cost?

# 6
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