Peer Review of the Draft Report "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles"

Revised Final Report

United States
Environmental Protection
Agency

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Revised Final Report

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

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Contents

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Executive Summary

Under a contract with the U.S. Environmental Protection Agency (EPA), ICF International (ICF) coordinated an external peer review of the Argonne National Laboratory (ANL) Draft Report "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles." ICF identified and selected a peer review panel of five subject matter experts and screened them for conflicts of interest. The peer review charge for this review is presented in Appendix A, and the peer reviewer resumes are provided in Appendix B. This report summarizes the reviewer comments according to technical, manufacturing, and tool categories.

Throughout this report, care has been taken to summarize and distill comments without editorializing them. The full reviewer comments are available in Appendix C, sorted by charge question. Appendix D provides the reviewer comments in the form they were submitted.

The peer reviewer comments were quite detailed. Some high-level summary points from the peer review include the following.

- **Assumptions –** Reviewers agreed that most assumptions were reasonable but that they should be verified, and the report should provide better clarification of options. Some specific comments on assumptions addressed cell construction and format, thermal management issues, battery electrode design, calculating component dimensions, calculation of battery operation, battery design, and other technical assumptions. In addressing thermal management issues, reviewers commented that the model should have addressed liquid cooling in the design of the battery pack, either in place of or in addition to the existing air cooling approach.
- **Materials and Manufacturing** - Reviewers raised concern about the ways in which material costs were represented in the battery costing model and that they may not take into account the additional costs of proprietary materials. All reviewers were concerned about the embedded or default values chosen by the model authors. In addition, there was concern about the effect of demand on raw material costs as modeled.
- **Manufacturing Volumes and Production Levels** – Reviewers noted some issues with effect of production level on manufacturing and material costs and the handling of safety and manufacturability in the model. Most reviewers felt that the general scaling methods on manufacturing and material costs were not presented clearly in the report.
- **Business and Fiscal Issues** – Reviewers noted concern about how depreciation, return on investment, warranty costs, and research and development costs were handled in the model. Reviewers disagreed on if the model over- or under-estimated certain cost components.
- **ANL Spreadsheet Tool** - All reviewers commented on the adequacy of user-specifiable parameters and their allowable ranges. In addition, there was concern about how the model handles baseline plant design and scaling. All reviewers provided suggestions on how to make the model easier to use and more complete.

Introduction

As EPA develops programs to reduce greenhouse gas (GHG) emissions and increase fuel economy of light-duty highway vehicles, there is a need to evaluate the costs of technologies necessary to bring about such improvements. Some potential technology paths that manufacturers might pursue to meet future standards may include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs). The cost of batteries for these vehicles is a major component of their total incremental cost and is subject to some uncertainty, particularly with respect to future scales of production and demand.

The U.S. Department of Energy (DOE) has funded a large number of research and scientific programs to support the electrification of light duty vehicles for more than a decade. This has included many programs to support advanced lithium-ion batteries for automotive applications. Among the programs funded by DOE has been the development of a number of cost prediction models, including a detailed, bottom-up costing model developed by ANL.

EPA has identified the ANL battery costing model as one potential tool for predicting future battery costs to auto manufacturers. The model allows a user to design a lithium-ion battery pack matched to user-specified power and energy requirements, and estimates its cost to an auto manufacturer at a user-specified production level in the year 2020. This model is documented in the ANL draft report "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles."

In order to validate and review this work, EPA, in coordination with DOE's Office of Vehicle Technology, has contracted with ICF to oversee a peer review of the ANL model and documentation. This report documents the peer review process and comments by the peer reviewers.

The Peer Review Process

From December 2010 to March 2011, EPA contracted with ICF to coordinate this peer review. ICF coordinated the peer review in compliance with EPA's *Peer Review Handbook* (3rd Edition).

EPA requested that the peer reviewers represent subject matter expertise in automobile packaging, battery chemistry, battery mass production, and/or commodities/raw materials. If possible, representation from different types of organizations was also requested, i.e., academia, auto manufacturers, battery manufacturers, and tier 1 suppliers.

ICF developed a list of qualified candidates from the following sources: (1) ICF experts in this field with knowledge of relevant professional society membership, industry, academia, and other organizations, and (2) suggestions from the technical staff from U.S. EPA and the National Highway Traffic Safety Administration.

ICF identified 44 qualified individuals as candidates to participate in the peer review. ICF sent each of these individuals an introductory screening email to describe the needs of the peer review and to gauge the candidate's interest and availability. ICF attached to the email the reviewer charge to ensure each candidate was familiar with the scope of work. ICF also asked candidates to provide an updated resume or *curriculum vitae* (CV). Several candidate reviewers were unable to participate in the peer review due to previous commitments, and several others did not respond. ICF reviewed the responses and evaluated the resumes/CVs of the interested and available individuals for relevant experience and demonstrated expertise in the above areas, as demonstrated by educational degrees attained, research and work experience, publications, awards, and participation in relevant professional societies.

ICF reviewed the interested, available, and qualified candidates with the following objectives in mind. As stated in the EPA's Peer Review Handbook, the group of selected peer reviewers should be "sufficiently broad and diverse to fairly represent the relevant scientific and technical perspectives and fields of knowledge; they should represent a balanced range of technically legitimate points of view." As such, ICF selected peer reviewers to provide a complimentary balance of expertise of the above criteria.

ICF selected and proposed the initial list of candidate reviewers to EPA. Based on input from EPA, ICF identified additional potential peer reviewers to better cover the expertise areas needed. Two of the final candidates declined to participate due to unforeseen circumstances. Two alternate candidates were recommended by ICF. EPA approved all of the final peer reviewers recommended by ICF.

The following five individuals agreed to participate in the peer review:

1. Dr. M. Stanley Whittingham, Binghamton University
2. Mr. Kurt Kelty, Tesla Motors
3. Dr. Erin O'Driscoll, Dow Kokam
4. Mr. Joseph Adiletta, A123 Systems
5. Mr. Michael Bly, General Motors

Exhibit 1 shows the representation of the peer reviewers in the required areas of expertise.

Exhibit 1. Chart of Peer Reviewer Expertise Areas

Peer Reviewers	S. Whittingham, Binghampton University	K. Kelty, Tesla Motors	E. O'Driscoll, Dow Kokam	J. Adiletta, A123 Systems	M. Bly, General Motors
Auto Packaging		✓			✓
Battery Chemistry	✓	✓	✓		
Battery Mass Production		✓		✓	
Commodities/ Raw Materials		✓	✓		✓

Prior to distributing the review materials, ICF sent each of the reviewers a conflict of interest (COI) disclosure and certification form to confirm that no real or potential conflicts of interests existed. The disclosure form addressed topics such as employment, investment interests and assets, property interests, research funding, and various other relevant issues. Upon review of each form, ICF determined that each peer reviewer had no COI issues. ICF executed subcontract agreements with all but Mr. Bly, who performed the review *gratis*. Mr. Bly signed a memorandum of understanding.

ICF provided reviewers with the following materials:

- The draft Report by ANL, entitled, "Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles," dated January 15, 2011;
- A supporting spreadsheet detailing a bottom-up approach of the costing;
- The Peer Reviewer Charge to guide their evaluation; and
- A template for the comments organized around the Peer Reviewer charge.

The Peer Reviewer Charge provided peer reviewers with general guidelines, as well as example questions, for preparing their overall review, with particular emphasis on assumptions found within the model, numerical inputs, values, and specific parameters, costing methodology, performance methodology, and the cost components of battery pack manufacturing. In addition, EPA asked each reviewer to provide recommendations on the "overall adequacy of the model for predicting future battery prices, and on any improvements that might reasonably be adopted by the authors to improve the model."

A mid-review teleconference was held on February 17, 2011, to discuss the charge, the purpose of the review, and to answer any outstanding questions the reviewers might have. The call was moderated by ICF and attended by reviewers Mr. Kelty, Dr. O'Driscoll, and Dr. Whittingham, as well as EPA staff Cheryl Caffrey and Joe McDonald, who were familiar with the model and report.

The charge to peer reviewers is provided in **Appendix A**. The CVs for the reviewers are included in **Appendix B**.

Peer Reviewer Comments in Response to Charge Questions

The charge questions for the peer reviewers are listed **Exhibit 2**. Reviewers provided responses to six charge questions that address aspects of the report related to (1) assumptions, (2) inputs and parameters, (3) cost methodology, (4) performance methodology, (5) completeness, and (6) recommendations. Example assumptions or specific topics were provided in the charge to help the reviewers respond to the questions in a detailed manner.

ICF entered the peer reviewer comments into a spreadsheet and sorted them by charge question and assumption/topic. **Appendix C** provides a report that was generated from this spreadsheet. The spreadsheet itself is also being delivered with this report to allow alternate sorting and filtering of the comments. **Appendix D** provides the peer review comments in the form they were received.

Exhibit 2. Peer Review Charge Questions

1. **Assumptions.** Please comment on the validity of any assumptions embedded in the model that could affect projected battery pack price or performance. Please comment on any assumptions that appear to be unstated and/or implicit.
2. **Inputs and Parameters.** Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Please comment on any caveats or limitations that these inputs and parameters entail with respect to use of the results as the basis for estimating the manufacturing cost or performance of lithium-ion battery packs.
3. **Cost Methodology.** Please comment on the validity and applicability of the methodologies used in estimating battery manufacturing costs. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations.
4. **Performance Methodology.** Please comment on the validity and applicability of the methodologies used in calculating the power and energy performance of the designed battery. Please comment on any apparent unstated or implicit assumptions (e.g., regarding ambient temperatures or other factors that may affect battery performance) and on any related caveats or limitations.
5. **Completeness.** Please comment on whether the model adequately identifies the cost components of battery pack manufacturing.
6. **Recommendations**. Please comment on the overall adequacy of the model for predicting future battery prices, and on any improvements that might reasonably be adopted by the authors to improve the model.

Summary of Peer Reviewer Comments

In addition to the verbatim sorted comments provided in **Appendix C**, a written summary of the peer reviews is provided here. In this summary, reviewer comments were combined and summarized by topic, and grouped into three areas: comments on technical issues, comments on manufacturing, and comments on the modeling tool.

Technical Comments

Reviewers provided several comments on **cell construction and format**. While Dr. Whittingham agreed with the choice of flat prismatic cells as the best cell format, other reviewers suggested that cylindrical cells, such as those used today in HEV designs, should also be considered. Mr. Adiletta noted that the choices for cell construction produce a generally usable view of the market, but several reviewers noted that the model does not include optimized designs that individual manufacturers are exploring. Specifically, the reviewers identified options for metal-canned prismatic cells and alternative methods for manufacturing individual electrodes (winding vs. back-and-forth folding). The assumptions for electrode thickness should be verified, and the report should be clarified to better explain the model's design choices. In addition, Mr. Kelty recommended that the report document how the choice of battery form factor would impact costs.

All reviewers expressed concerns about how the model addressed **thermal management issues**. Dr. Whittingham noted that thermal management was the most challenging aspect of large batteries, and he believed that the choice of air-cooling was not practical in the long term. He recommended that liquid cooling be modeled instead. Although, he noted that current EV designs such as the Nissan Leaf rely on air cooling. Dr. O'Driscoll agreed and notied that while 2020 battery packs may be able to achieve acceptable performance using air cooling alone, the model should justify the choice of this approach. Mr. Adiletta recommended including a variety of cooling strategies, including air and liquid cooling, as well as active and passive designs. Mr. Bly commented that the thermal management requirements did not appropriately recognize the trade offs of life and thermal effects and said that much further model refinements would be needed to improve the model's accuracy.

Reviewers questioned the model's approach to many technical aspects of **battery electrode design**. Mr. Kelty noted that the effect of electrode volumetric change is not considered in the model, and Dr. O'Driscoll recommended that a 10% change over the full state of charge range would be more reasonable. Dr. Whittingham stated that volumetric changes would not be a major concern for the electrode materials chosen in the model. However, an exception would be the use of lithium titanium oxide (LTO) as the anode material. As a zero-expansion material, volume changes in LTO would not compensate for volume changes in the cathode.

The model's approach to **calculating component dimensions** was generally supported, with the exception of certain components and usage. Drs. O'Driscoll and Whittingham agreed that the battery design model seems sound; however, Dr. Whittingham raised concerns about how the effective tap density of the materials is incorporated into the model. Mr. Adiletta noted several problems with the approach for cell thickness and number of layers. The model produced unrealistic results for certain inputs – for a standard 10mm PHEV unit, the model calculated a 16um cathode size, which would require an unrealistically large number of 64 layers. As an alternate approach, he recommended targeting a thickness based on the type of cell desired, and subsequently varying the number of layers to achieve differing mileage and capacity packs. There was not necessarily a need to constrain the thickness of the cell based on the cell type. In non-standard designs, the thickness may be chosen once capacity and footprint targets have been determined. Dr. Whittingham further noted that assumptions about the thickness of PHEV cells did not match the model used for the Toyota Prius.

Similarly, the model's methodology with respect to **calculation of battery operation** was found to be generally reasonable. Dr. Whittingham supported the approach for calculating power, capacity, voltage and current, while Dr. O'Driscoll supported the theory behind these calculations. Mr. Adiletta questioned why the power was a user input rather than calculated from area-specific impedance (ASI), which was painstakingly calculated elsewhere in the model.

Further, the limiting discharge rate (C-rate) will vary depending on the type of application for which the battery is designed. Dr. O'Driscoll expressed reservations about how a full scale cost model was built from basic battery theory, without correlation to actual data. Real-world properties of these materials, such as the storage capacity, often vary from theoretical modeling. She recommended validating the model with at least one example showing a cell and/or battery pack.

Dr. Whittingham argued that the model's approach to **battery design** insufficiently captured the variety of designs that will reach the market. Today's designs range from the planned Toyota Prius, with 3 batteries (one power and two energy) and an all-electric range of 8 to 10 miles, to the GM Volt with a 15 kWh battery, an electric generator and an all-electric drive-train and a range of around 40 miles. He noted that the documentation comment about increasing levels of electrification is incorrect; the Volt PHEV is all electric drive, the HEV buses are all electric drive with around a 11 kWh lithium-ion battery and more than 2 million total miles demonstrating reliability.

Reviewers provided several additional comments on **other technical assumptions**. Mr. Adiletta questioned the assumption that all negative electrodes necessarily will use a water-based binder system, especially given the range of cell-types being investigated – micro-HEV through EV. In addition, he noted that a 300um thick electrode coating was somewhat aggressive to expect performance out of the design. For example, the oxide-based chemistries often used ceramic coatings on the separator or anode to compensate for the inferior abuse tolerance of that chemistry, the cost of which should be included in the cell cost. Mr. Kelty noted that the key relationship used to design the battery is an estimate of the relationship between impedance and electrode thickness. He said that these measurements were made for a few different electrodes and are now applied to all electrodes. He questioned the lack of data that would show that this is a reasonable assumption. In applying the model to battery design, Dr. Whittingham asked how easy is it to manipulate and optimize the plate size, assuming that the model methodology allows for increasing the current collector thickness as the plate size increases so that the resistive losses do not increase. Further, he noted that on page 63, the effect of manipulating the active material thickness is described so that the energy stored can be increased by thickening the electrodes and therefore reducing the area of the current collectors and separators needed.

Comments on Materials and Manufacturing

Comments on materials and component costs

Reviewers raised concerns about the ways in which **material costs** were represented in the battery costing model. Dr. Whittingham expressed concerns regarding materials and components costs, noting that the assumptions for material costs were poorly explained. He argued that many of these materials are used in large quantities and extensively in the industry today, so the report should include today's costs as well as explanations for how and why the estimated cost differs from these values. As an example, he pointed to the material $LiFePO_4$, which is not low cost, even though the raw materials are low cost. Dr. Whittingham pointed specifically to Table 4.1 of the report, noted that there was no explanation (in the table or the text) for the three numbers under the TIAX 2010 column, and suggested adding a footnote to explain the different numbers to the reader. Further, he questioned why there was not a number for LCO in the ANL 2010 column. In his view, this number must be well-known and would represent a good baseline against which the other numbers and the spreadsheet model could be evaluated. He pointed out that while the prices for cobalt and nickel metal prices were given, the formation of the metal can be very expensive, and the price of the metal oxide should be considered instead.

Dr. Whittingham and Mr. Adiletta further noted that assumptions about material costs do not take into account the additional costs of **proprietary materials**. Dr. Whittingham noted that there is no allowance made for the cost of using proprietary materials, such as licensing costs, and that this may be important in comparing one material with another. The cost of some of the key components may not drop dramatically if one material is sufficiently superior and the manufacturer has patent protection. Proprietary technology should also be included in materials costs. Dr. Whittingham highlighted recent litigation that has shown that a lower cost method for production is well patented,[1] and those who need to produce and/or sell in the United States are going to have to pay licensing fees. Mr. Adiletta commented that the cost of licensing technology has not been included in the model. He stated that no single outfit is going to have complete “ownership” of the materials and design. This was not been built into the methodology.

All reviewers provided comments about **embedded or default values** chosen by the model authors. Dr. Whittingham found that the values seemed adequate, but in some cases, changing the inputs had less impact on cost than he expected. He used the example that switching the battery charge density from the default value of 155 to 50 Ah/kg had less than a 20% effect on cost. Mr. Adiletta noted that since electrode design specifications are often unique to individual manufacturers, the values might be adjusted based on other publicly available information and that materials cost inputs do not necessarily match with going rates in volume production. Dr. O’Driscoll found the report values in line with her expectations. Mr. Kelty raised concerns about the lack of validation data, or documentation of validation, in the default values. Mr. Bly noted that the model underestimated the cost of energy and consumables used in manufacture.

Dr. Whittingham, Mr. Adiletta both commented on the **effect of demand on raw materials costs**. Dr. Whittingham stated that he thought the approach was fine as described in the report, but mentioned that the model should keep away from low availability materials, where the battery market is a prime user of the material, such as cobalt and nickel. As noted in the report, iron and manganese prices are fine. He also mentioned that rare earth metals needed in the electric motors are a bigger cost driver than the battery for electric vehicles. Dr. Whittingham noted that while this is outside the scope of this report, the user of the model needs to be aware that other items than the battery may be cost controlling. Mr. Adiletta agreed that the effects of

[1] Valence Technology, Inc. v. Phostech Lithium Inc. 2011 FC 174, Gauthier J.

low-availability materials did not seem to be addressed. The effect is real, quantifiable and quite different for each battery manufacturer depending on volume and relationship. Especially in 2020 and beyond, some reasonable assumptions must be made based on today's high volume cost rates. It does not appear that this was taken into account. At the very least a single input for percent decrease based on volume might be added.

Addressing the overall approach to battery costs, Mr. Bly noted that the cost models do not seem aggressive enough for the 2020 forecasted total costs.

Comments on manufacturing volumes and production levels

Dr. Whittingham and Mr. Adiletta commented on the **effect of production level on manufacturing and material costs**. Dr. Whittingham found that the document's methodology examples appeared reasonable, noting that the manufacturing cost will decrease with increased knowledge from larger scales of production. Mr. Adiletta noted that there will be a significant difference in materials costs based on expected production volume. He stressed that this should be added to the model, even if in vague terms via percent cost downs based on specific manufacturing thresholds. He recommended constructing the model to be based on number of vehicles produced. In addition, coating facilities run at speeds entirely dependent on the chemistry and cell design, thus drastically altering the amortization of costs to the cell, and this augmentation might be considered.

All reviewers provided comments about **safety and manufacturability**. Dr. Whittingham noted that an issue with all batteries is protection in the case of crashes, and the report did not really address that issue. He suggested that if the battery insulation was intended to serve as a crash protector, these costs need to be included. Mr. Adiletta agreed with the addition of certain components to ensure safety. Dr. O'Driscoll noted that safe handling of inorganic metal powder is not addressed well, arguing that EPA guidelines for handling materials with nickel and cobalt are much different than those for iron, and hence, one would expect different cost structure to handle the materials in the process. Specifically, section 4.3.2 of the report did not address moving powder through the process and cleaning up safely. She also expressed concern about how the model includes the handling of large quantities of electrolytes without contamination and asked what size container is expected and how the material is kept clean and dry at this scale. Mr. Kelty commented that assumptions about the safety features in the battery pack are not clearly documented. Finally, Dr. Whittingham noted that, while no cost was assumed for water, the cost of handling the contaminated waste water was not included. There are several companies trying to use dry processing to eliminate these costs.

Dr. Whittingham, Mr. Adiletta and Mr. Bly commented on the **general scaling methods on manufacturing and material costs**. Dr. Whittingham expressed confusion about the numbers in Table 4.8 and the corresponding description on pages 46 and 48. He believes that a more important metric from the user and consumer perspective is the cost per kWh or per mile driven, not just battery capacity. He recognized that if more power is desired, then it is going to cost more. But if more energy per cell is desired, then the cost of the cell per kWh goes down. Whittingham recommended that this section should be rewritten to emphasize what is of interest to the end-user. Mr. Adiletta noted that at a certain volume, significant changes to manufacturing process will be required, which will bring associated reductions in cost. The model seemed to be based on today's methodologies, but applied to 2020, which may not be realistic. Additionally, the material cost structure as outlined was not indicative of today's pricing, which would imply significantly higher costs than what he would expect to see in 2020. Further, he was critical of the assumption that manufacturing costs would scale independently of cell design. As an example, while the cost of forming a cell may scale linearly with the number of cell layers, the depreciation costs of the stacking equipment will not. Mr. Bly noted that the estimated yield rates are overly conservative. While the model applies a yield rate of 92%, some suppliers target a 98% yield rate.

Comments on battery end-of-life and recycling

Dr. Whittingham, Mr. Adiletta, Dr. O'Driscoll, and Mr. Bly commented about **scrap rates and associated costs**. Dr. Whittingham stated that the percent scrap rate appears reasonable, but noted that no value is assigned to the scrap. Although by 2020, if the market is indeed there, there should be a thriving recycling business that would take the scrap away. Mr. Adiletta asked if scrap rates were inclusive of end of line testing and also noted that the NMP recycling number seemed high. Mr. Bly noted that the scrap rates did not represent benchmark practices and suggested that they should be re-evaluated. Dr. O'Driscoll found that the scrap rates looked reasonable.

Dr. Whittingham noted that the value of recycled batteries were not discussed, even though it is presumed by other ANL reports that eventually most of the lithium (and presumably any expensive other elements) would come from recycled batteries. He also noted that the model does not include any end-of-life scenarios, such as "spent" EV batteries for utility/alternative energy load leveling/smoothing, which would reduce the effective life-time cost of a battery.

Comments about business and fiscal issues

Dr. Whittingham, Mr. Adiletta, Mr. Kelty, and Mr. Bly commented on how **depreciation** was included in the ANL model. Dr. Whittingham found no real justification for how the model approached depreciation costs. He said it was probably too low at 12.5%, which assumed an 8-year life. For a new and likely changing technology, a shorter depreciation time would be needed, at least for the first 5 to 10 years. Mr. Adiletta asked if the report accounted for government subsidies in the acquisition of capital equipment and argued that 8 years on manufacturing equipment seemed a bit long. Mr. Kelty stated that 5-year depreciation would be more appropriate. Mr. Bly agreed and notied that an 8-year amortization was slightly higher than the current norms in the industry.

Dr. Whittingham also stated that the **return-on-investment** (ROI) appears too low at 5%. He noted that the model fixes profit at 5% of total investment costs and says this seems too low for a risky investment. An ROI closer to 10% would be more reasonable. Mr. Adiletta expressed that it would make more sense to target a before-tax profit and structure the model around tax margin. Predicting and/or modeling the going corporate tax rate would be difficult. He noted that the profit rate looks a bit lower than expected over the long-term. Dr. Whittingham questioned why the model includes built-in assumptions for inflation rate, rather than allowing the user to include a term for inflation. Mr. Bly commented that the model's assumptions about profit and selling, general, and administrative expenses (SG&A) seemed to be very high compared to the current market.

Reviewers commented on the model's approach for **warranty costs**. Dr. Whittingham stated that for a new product the warranty cost assumptions of 1% failure per year appear too low. He argued that since no lithium battery has been used in the proposed duty cycle for anywhere close to 10 years, justification for this assumption should be made. The costs assumed appeared to be those purely due to replacing the battery, not including other issues such as liability insurance. Mr. Kelty stated that he would expect warranty assumptions to be somehow related to performance, such as cycle life or calendar life. He believed an assumption related to cooling system and life would make more sense but would be challenging to build into this model at this point. Mr. Adiletta noted usually warranties are expressed as a percentage of cost, which he assumed is what the authors intended by "added to price," rather than a percent of the final price. Dr. O'Driscoll stated that without correlation to data, warranty assumptions appeared reasonable.

Mr. Adiletta provided comments about **research and development costs**. He stated that research and development comes in two forms, support for the manufacturing operation and developing new products. It is not clear which of these the authors intended. He noted that it is more typical to talk about research and development costs as a percent of revenue rather than of depreciation.

On many aspects, the reviewers **disagreed about the overall cost estimates.** While Mr. Kelty and Dr. O'Driscoll commented that the model underestimated costs of battery production, Mr. Bly commented that in some ways the model overestimated the costs. Mr. Kelty ran the model using several scenarios and found that the calculated costs of battery packs were lower than anticipated, perhaps due to the extremely thick electrodes that the model predicted. He suggested that the electrode thickness should be a user-defined value, with a value less than 200 microns. However, Mr. Bly suggested the costs were overestimated and argued that most of the cost models did not seem aggressive enough for 2020 forecasted total costs. Specifically, he said that the labor costs used in the model were appropriate only within the United States. Further, Dr. Whittingham noted that the cost of handling contaminated wastewater was not considered in the calculations. Overall, Mr. Bly concluded that the model for building costs did not seem realistic, unless the model assumed continuous government incentives. He further noted that the costs calculated in the model may vary regionally, and the cost structure lacked detail in burden cost. Specifically, the estimate of the impact of depreciation on burden cost was 1.5 times too high. Lastly, Mr. Kelty recommended that the authors summarize in the report how the model accounts for costs in 2020. He suggested that the model appeared to use cost as a user input. He recommended that cost projections should focus on the cost of the active material, which is the largest component of battery costs.

Comments on the ANL Spreadsheet Tool

All reviewers commented on the adequacy of **user-specifiable parameters** and their allowable ranges. Dr. Whittingham found no difference in the battery cost whether the operation hours per day were 10 hours, 24 hours (or even 48 hours, which should be outside the bounds of the model) and noted that depreciation should cause some effect. The spreadsheet should be programmed so that values exceeding 24 hours cannot be used. Mr. Adiletta stated that for micro-HEV and HEV, it would make sense for the user to specify power required, rather than the choices currently available: capacity, energy or range. This is especially true if half (two out of four) of the options are HEV related (micro and full). He also assumed that some of the user inputs are considered in the model for future use, specifically that the ASI seems to be calculated but not necessarily applied, as do entries like temperature rise. Dr. O'Driscoll said it was difficult for her fully assess the model in the time period given. Mr. Kelty noted that more parameters should be user specifiable and that there are too many limitations currently on what can be changed. Specifically, he identified five user-defined inputs, including a metric for acceleration, such as the time it takes to accelerate from 0-60 miles per hour at a specified temperature.

Dr. Whittingham, Mr. Adiletta, and Mr. Bly made comments about how the model handled **baseline plant design and scaling**. Dr. Whittingham said that the general approach seemed fine, but wondered how the model handleed the scaling of processes such as calendering, which is modeled with one person per shift. No person is going to work continuously without a break. He wondered how these breaks are covered when the process is presumed continuous, and asked whether there would be flexibility for this issue to be built into the cost methodology. Mr. Adiletta thought that the initial plant design looked reasonable, and suggested that the model should consider scalability based on volume assumptions. At some point, volumes could become large enough such that a transition to new manufacturing strategies would make sense in order to continue down the cost curve. Using this approach, scaling would be done incrementally based on capacity ramp-ups. To that extent, the model seemed to function linearly with respect to invested capital, whereas in reality a large amount of capital is invested for a fixed capacity which may or may not be fully utilized, which would affect the cost. Mr. Bly noted that the 20-year amortization of capital investment was much lower than actual practice in the Asia supply base. He commented that the model for building cost did not seem realistic, unless the model assumes continuous government incentives, which he stated would not be realistic in this timeframe. Further, the total costs for buildings and land appeared to be too conservative.

Mr. Adiletta and Mr. Kelty suggested that the **model's ease-of-use** could be improved, especially for users who are not well versed in specifics of chemistry. For instance, the model's inputs and outputs may not be clear to the user. There were sheets that contained foundational information, but these might not be used by someone performing a top-level analysis. Further, a user on the outside of industry may not have the detailed information required for the model, as many of the details will be held privately by individual manufacturers. Mr. Kelty recommended that the model include documentation on adjusting Microsoft Excel's settings for iterative calculations.

Mr. Adiletta and Mr. Kelty made additional comments about how the **model's design** allowed the user to determine battery costs. He stated that since the model will likely be reviewed by OEMs as well as small startups and suppliers, it would be beneficial to break out the cost analysis into cell and non-cell components. Because some OEMs will be buying cells and will likely be interested the full cost analysis, the model's approach of combining all labor, overhead and SGA into single buckets may not be the most appropriate strategy. Mr. Kelty commented that the model's outputs could be altered to be more useful, for instance by showing the battery pack costs over time for each chemistry type. In addition, he noted that outputs such as costs per kw-hour at the cell and pack level would be helpful.

All reviewers noted specific opportunities to **make the model more complete**. Dr. O'Driscoll stated that labor costs seemed low and there was no flexibility in the model to consider improvements in automation that would further reduce labor costs in the manufacturing process. Mr. Adiletta stated that manufacturing would require an inspection step with labor and equipment costs, which were not considered. He further observed the omission of small manufacturing costs such as the cost of tape in the cell (acknowledged to be small) and found the overall cost of terminal assemblies to be low. Mr. Kelty noted the omission of the cost of critical safety features in the battery, but acknowledged that these costs will be small in comparison to drivers such as the active material. Dr. Whittingham recommended a more rigorous approach to utility costs, including how utility costs may increase with plant automation or the climate of the plant's location. He commented that unanticipated breakthroughs can significantly reduce costs, but acknowledged the impossibility of anticipating these breakthroughs. With regard to labor costs, Mr. Bly noted that the labor cost assumptions were appropriate only for the United States.

Appendix A: Charge to Peer Reviewers

Peer Reviewer Charge

Charge to Peer Reviewers of "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles"

As EPA and NHTSA develop programs to reduce greenhouse gas (GHG) emissions and increase fuel economy of light-duty highway vehicles, there is a need to evaluate the costs of technologies necessary to bring about such improvements. Some potential technology paths that manufacturers might pursue to meet future standards may include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs). The cost of batteries for these vehicles is a major component of their cost and is subject to some uncertainty, particularly with respect to future scales of production and demand.

EPA has identified a battery costing model developed by Argonne National Laboratories (ANL) as a potential tool for predicting future battery costs to auto manufacturers. The model designs a lithium-ion battery pack matched to user-specified power and energy requirements, and estimates its cost to an auto manufacturer at a user-specified production level in the year 2020. This model is documented in the ANL draft report "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles".

EPA is seeking the reviewers' expert opinion on the methodologies used in this model and whether they are likely to yield realistic estimates of the cost of lithium-ion battery packs likely to be produced for vehicles in the year 2020. We ask that each reviewer comment on all aspects of the ANL model, with particular emphasis on the assumptions inherent to the model, sources of information employed in the model, methods of calculation and any other key issues the reviewer may identify. Findings of the peer review may be used toward validation and improvement of the model by ANL and to inform EPA and NHTSA staff on potential use of the model for predicting future battery costs. No independent data analysis will be required for this review.

Reviewers are asked to orient their comments toward the six (6) general areas listed below. Some possible topics in each area are provided as illustrative examples. Reviewers are expected to identify additional topics or depart from these examples as necessary to best apply their particular set of expertise toward review of the model.

(1) Assumptions. Please comment on the validity of any assumptions embedded in the model that could affect projected battery pack price or performance. Examples might include assumptions regarding: cell construction and format, and comparability to competing cell formats; cooling and thermal management requirements; electrode volumetric change; limiting parameters affecting cell dimensions or performance (for example, allowable A-hr capacity per cell, maximum electrode thickness, etc); warranty costs and profit; scrap rates; safety and manufacturability; anticipated industry design trends, and similar factors. Please comment on any assumptions that appear to be unstated and/or implicit.

(2) Inputs and Parameters. Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Examples might include: any embedded or default values chosen by the authors (for example, those that represent default material costs, material percentages, preferred dimensions, experimentally measured values, etc); and the adequacy of user-specifiable parameters and their allowable ranges (for example, those that specify performance requirements, or those that relate to cell chemistries or cell/module/pack configuration possibilities). Please comment on any caveats or limitations that these inputs and parameters entail with respect to use of the results as the basis for estimating the manufacturing cost or performance of lithium-ion battery packs.

(3) Cost methodology. Please comment on the validity and applicability of the methodologies used in estimating battery manufacturing costs. Examples of such methodologies might include: general scaling methods, effect of production level on manufacturing and material costs, method of accounting for warranty costs and profit, effect of demand on raw material costs, baseline plant design and scaling, etc. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations.

(4) Performance methodology. Please comment on the validity and applicability of the methodologies used in calculating the power and energy performance of the designed battery. Examples of such methodologies might include: how the physical properties and dimensions of cell components are calculated from the inputs; how power, energy capacity, resistances, currents, etc. are calculated; etc. Please comment on any apparent unstated or implicit assumptions (e.g., regarding ambient temperatures or other factors that may affect battery performance), and on any related caveats or limitations.

(5) Completeness. Please comment on whether the model adequately identifies the cost components of battery pack manufacturing. Examples of such cost components might include: physical components of the cells and assembled packs, manufacturing steps, raw materials and labor, energy inputs and consumables used in manufacture, capital equipment, research and development costs for battery design development and production implementation, battery control systems, etc.

(6) Recommendations. Please comment on the overall adequacy of the model for predicting future battery prices, and on any improvements that might reasonably be adopted by the authors to improve the model. Please note that the authors intend the model to be open to the community and transparent in the assumptions made and the methods of calculation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.

Comments should be sufficiently clear and detailed to allow readers familiar with the report to thoroughly understand their relevance to the material provided for review. EPA requests that the reviewers not release the peer review materials or their comments until ANL makes its report/cost model and supporting documentation public. EPA will notify the reviewers when this occurs.

If a reviewer has questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If a reviewer has any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory by phone (734-214-4017) or through e-mail (schenk.ruth@epa.gov).

Appendix B. Reviewer Resumes

1. Dr. M. Stanley Whittingham, Binghamton University
2. Mr. Kurt Kelty, Tesla Motors
3. Dr. Erin O'Driscoll, Dow Kokam
4. Mr. Joseph Adiletta, A123 Systems
5. Mr. Michael Bly, General Motors

M. Stanley Whittingham

(http://materials.binghamton.edu/WHITTINGHAM/whit.html)

1. Education & Training

Oxford University, UK	Chemistry	B. A., 1960-1964
Oxford University, UK	Solid State Chemistry	M. A., D. Phil., 1964-1968
Stanford University, CA	Materials S&E	Research Associate, 1968-1972

2. Employment History

2001-Present	Professor of Materials Science, Director Materials Science and Engineering Program
1997-2001	Co-Chair, Research Advisory Council of SUNY
1994-2000	Vice-Chair, Board of Directors, Research Foundation of SUNY.
1993-1999	Vice-Provost Research at Binghamton
1988-Present	Professor of Chemistry, State University of New York at Binghamton.
1988-Present	Director of the Institute for Materials Research, State University of New York at Binghamton.
1984-1988	Director of Physical Sciences and Member of Scientific Staff, Schlumberger-Doll Research.
1972-1984	Director of Solid State and Catalytic Sciences Laboratory; Manager, Chemical Engineering Technology Division; and Member of Scientific Staff, Exxon Research & Engineering Company.

3. Awards and Honors

ACS-NERM Award for “Achievements in the Chemical Sciences”, 2010
GreentechMedia top 40 innovators for contributions to advancing green technology, 2010
SUNY Chancellors Award for Excellence in Scholarship and Creative Activities, 2007
Research Foundation of SUNY Research Award, 2007
Fellow, The Electrochemical Society, 2004
Battery Research Award, The Electrochemical Society, 2002
JSPS Fellow, Physics Department, Tokyo University, 1993
Electrochemical Society Young Author Award, 1971
Gas Council Scholar, Oxford University, 1964-1967

4. Contributions to the Public

Leading a Binghamton consortium to bring to the public the excitement of new materials and chemistry. We were one of 20 winning consortia in the US, who will work with WGBH in Boston in the winter of 2011 to involve the public at the time of the NOVA broadcasts (February). BU, BCC, the local schools, Oakdale Mall, Roberson Museum, and the local PBS station are all participating. Seed funding has been provided.

Presentations to local groups on energy in Oswego and Binghamton

Radio broadcasts in 2010

- BBC Radio “From NYC to Copenhagen” – discussion on the discovery of the Li battery
- NPR NYC on “What is a battery?” live broadcast with Q&A (40 mins)
- WSKG Radio on “Renewable and Alternative Energy”, live with Q&A (60 mins)

5. Contributions to Scientific Organizations

American Chemical Society

Advisory Board of the Petroleum Research Fund
Past Chair, Solid-State Sub-Division
Past Chair, Binghamton local section
Organizer of several symposia, including superconductivity, and solid state chemistry of energy (both published as books by ACS)
Organized the local Chemistry Olympiad one year in Binghamton.

The Electrochemical Society

Past Chair, New York Metropolitan Section
Organized numerous symposia at National and International meetings, most recently in Vienna, Austria 2009

The Materials Research Society

Chair, Student Chapters (until 2010)
Chair, Academic Affairs Committee (from 2010)
Organized numerous symposia in both science and education areas.

American Physical Society

Lifetime member. Lectured on both science and education

International Society for Solid State Ionics

Presently President (until 2009-2011)
Co-organized International meeting in Lake Louise, Canada and co-chair 2011 meeting in Warsaw, Poland.

Gordon Research Conferences

Chaired two meetings in New Hampshire on Solid State Chemistry, and on Solid State Ionics. Co-chaired Solid State Chemistry conference in Oxford, England.

International Symposium on the Reactivity of Solids

Past President of the International Board
Chaired international meeting in Princeton in 1988.

6. Contributions to Scientific Publications

Solid State Ionics

Principal Editor 1980-1999; Founding Editor 2000-present.

Professional Journal Boards

Have been on the editorial advisory boards of Chemistry of Materials, Materials Research Bulletin, J. Applied Electrochemistry.

Reviewing for Journals

Very active in reviewing manuscripts for many major journals in chemistry, physics and materials. Requests exceed 10 per week.

7. Contributions to Government Activities

NSF

Served on a number of committees, that resulted in reports advising the future direction of Solid State Chemistry
Workshop participant, most recently at MIT on extending the drug discovery techniques to the Energy Area.
Panel reviewer and proposal reviewer

DOE

Served on a number of committees, most recently on the extended workshop on future directions for Energy Storage Research (2007). Co-chair of chemical energy storage group (aka Batteries). Presented results of workshop at the National meetings of the American Chemical Society and the Materials Research Society

Served on numerous proposal panels and as reviewer of proposals.
On the External Advisory Boards of two EFRCs, one at Cornell and one at Argonne National Lab.,

New York State

Served on committees in the formation of NYBEST (New York Battery and Energy Storage Technology Consortium.
Binghamton's representative on NYBEST
Elected vice-chair for academia on the Board of Directors of NYBEST, 2010.

8. Externally Supported Research

NSF

My research has been continuously supported by NSF since 1989, as a single PI investigator.
I organized the Solid State Chemistry Summer Program (REU-type activity) for five years at Binghamton.
I have also received several education grants from NSF, both for bringing infrastructure, research and teaching to Binghamton.
I was also co-leader of the NSF funded "bringing materials into the chemistry curriculum" activity based at U. Wisconsin.

DOE

My research has been continuously supported by DOE-EERE since 1993, as a single PI investigator.
In 2009, I was part of the winning team of the DOE-BES-EFRC on energy storage, and am now Associate Director of the activity. (15M$ over 5 years).

NYSERDA

This year NYSERDA initiated research in the battery area, and I received two awards. One of these involves collaboration with two colleagues in the Chemistry Department (with all the funds going to them), and the second involves collaboration with Brookhaven National Laboratory to bring more of their forefront analytical techniques to the battery areaMy research has been continuously supported by DOE-EERE since 1993, as a single PI investigator.

Other

I have received funding from other federal agencies, such as DARPA, and from industry from time to time. We also assist local industry in characterizing their materials.

9. Student Education

General

I initiated a specialization in Materials Chemistry at both the undergraduate and graduate levels, including development of new courses and curricula. Also revamped the Chem 111 introductory course in Chemistry to make it more relevant and rigorous. Enabled the introduction of computers into the curriculum by lobbying the administration for two computer PODS in Science 2. Introduced listserves into chemistry classes, and participated in the early days of distance learning through the SUNY Learning network. This course had initially around 40 students and recently peaked at over 400.
Took a lead role with colleagues in Chemistry and Physics to initiate a graduate program in Materials Science (now Materials Science & Engineering), and steered it successfully through its first "7-year" external review.

Graduate

Numerous graduate students have received their PhD's under my guidance initially in chemistry and now also in Materials. These students are now in teaching positions, in National Laboratories or in Industry, both in the US and overseas.

Ken Reis (PhD), James Li (PhD), Jindong Guo (PhD), Hatem Maraqah (PhD), Tom Chirayil (PhD 6/98-Englehard), Gerald Janauer (PhD 1/98), Rongji Chen (PhD 12/98); Curtis Weeks (MS 12/97 US Air Force); Greg Moore (PhD 5/99), Fan Zhang (PhD 12/99), Sergei Zarembo (PhD 01/01), Arthur Dobley (PhD 08/01), John Ngala (PhD 8/03), Shoufeng Yang, (PhD 07/03) Yanning Song (PhD 03/04), Samuel Lutta (PhD 10/04), Miaomiao Ma (PhD, 2006), Joel Christian (PhD 12/07), Michael Chin (MS 09/04) Chen Chen (PhD 12/07), Fan Quan (PhD), Jiajun Chen (PhD), Jian Hong (PhD), Shijun Wang (PhD), Jie Xiao (PhD, 2009), Chunmei Ban (PhD 2009) Chris Jacobs (MA), Megan Roppolo (PhD, 2010); Joel Miller, Ruigang Zhang, Wenchao Zhou, Zheng Li, Fred Omenya, Hui Zhou, Heng Yang, et al.

Undergraduate

A number of undergraduate students have worked in my group, and most have gone onto graduate school.

Charlotte Zaremba* (PhD-UC Santa Barbara); David Schoonmaker‡; Adam Skoczylas‡; Paul Schnier*‡(PhD-UC Berkeley); Jennifer Monteith*‡ (now at Columbia University); Gregory Moore, Tom Chirayil, Stacia Wagner, Jacki Hinz*, Caroline Freitag*, James Reho* (PhD-Princeton), Billlie Abrams, Lisa Boylan (Corning), Sean Kelly (now at UNC), Mark Mamac (Honors Thesis), Melissa McCartney (MRS award winner), Kinson Kam‡ (MRS award winner, and Honors Thesis), Michael Chin*, Wai Chun Lan, Luke Moseley, Christine Manlulu, Melanie Thornhill, Gene Nolis. [*Participated in NSF-DMR summer program in Solid State Chemistry; ‡ Chemistry degree with emphasis in Materials.]

10. Publications (a selection)

1. Jiajun Chen and M. Stanley Whittingham, "**Hydrothermal Synthesis of Lithium Iron Phosphate**", Electrochem. Commun., 2006, 8: 855-858. (Top 25 most cited articles in the journal – ISE meeting September 2010)
2. Jiajun Chen, Michael J. Vacchio, Shijun Wang, Natalya Chernova, Peter Y. Zavalij, M. Stanley Whittingham, **"The hydrothermal synthesis and characterization of olivines and related compounds for electrochemical applications"**, Solid State Ionics, 2008, 178: 1676-1693. (2nd most downloaded article in the journal)
   M. S. Whittingham, "**Materials Challenges Facing Electrical Energy Storage**", Mater. Res. Soc. Bulletin, 2008, 33: 411-420
3. M. S. Whittingham: **Lithium Batteries and Cathodes,** Chemical Rev., 104: 4271-4301 (2004)
4. M. S. Whittingham, "**Inorganic nanomaterials for batteries**", Dalton Transactions, 2008, 5424-5431.
5. Joel Christian, Sean P.E. Smith, M. Stanley Whittingham and Héctor D. Abruña, **"Tungsten based electrocatalyst for fuel cell applications"**, Electrochem. Commun. 2007, 9: 2128–2132.
6. N. A. Chernova, M. Ma, J. Xiao, M. S. Whittingham, J. Breger and C. P. Grey "**Layered $Li_xNi_yMn_yCo_{1-2y}O_2$ Cathodes for Lithium-Ion Batteries: Understanding Local Structure via Magnetic Properties**", Chem. Mater., 2007, 19: 4682-4693
7. J. Hong, C. S. Wang, X. Chen, S. Upreti, and M. S. Whittingham, "**Vanadium Modified $LiFePO_4$ Cathode for Li-Ion Batteries**", Electrochem. Solid-State Letters, 2009, 12: A33-A38.
8. Y. Song, P. Y. Zavalij, N. A. Chernova, and M. S. Whittingham: **Synthesis, Crystal Structure, Electrochemical and Magnetic Study of New Iron (III) Hydroxyl-Phosphates, Isostructural with Lipscombite**. Chem.Mater., 17: 1139-1147 (2005).
9. N. A. Chernova, M. Roppolo, A. Dillon and M. S. Whittingham, "**Layered vanadium and molybdenum oxides: batteries and electrochromics**", J. Mater. Chem., 2009, 19: 2526-2552.
10. V. Petkov, P. Y. Zavalij, S. Lutta, M. S, Whittingham, V. Paranov, S. Shastri: **Structure beyond Bragg: Study of V_2O_5 nanotubes,** Phys. Rev., B69: 085410 (2004).

11. Y. Song, P. Y. Zavalij, M. S. Whittingham: **ε-$VOPO_4$: Electrochemical Synthesis and Enhanced Cathode Behavior,** J. Electrochem. Soc., 152: A721-A728 (2005).
12. Jie Xiao, Natasha A. Chernova, and M. Stanley Whittingham, **"Influence of Manganese Content on the Performance of $LiNi_{0.9-y}Mn_yCo_{0.1}O_2$ ($0.45 \le y \le 0.60$) as a Cathode Material for Li-Ion Batteries"**, Chem. Mater., 2010, 22: 1180-1185.
13. Laura S. Rhoads, William T. Silkworth, Megan L. Roppolo, and M. Stanley Whittingham, **"Cytotoxicity of nanostructured vanadium oxide on human cells in vitro"**, Toxicology in Vitro, 2009, 24: 292-296.
14. Anurag Mishra, Afsar Ali, Shailesh Upreti, M. Stanley Whittingham and Rajeev Gupta, **"Cobalt complex as building blocks: Synthesis, characterization, and catalytic applications of {Cd^{2+}-Co^{3+}-Cd^{2+}} and {Hg^{2+}-Co^{3+}-Hg^{2+}} heterobimetallic complexes"**, Inorganic Chemistry, 2009, 48, 5234–5243.
15. Natasha A. Chernova, Megan Roppolo, Anne Dillon and M. Stanley Whittingham, **"Layered vanadium and molybdenum oxides: batteries and electrochromics"**, J. Mater. Chem., 2009, 19: 2526-2552.
16. Kazuo Eda, Yu Ohshiro, Noriko Nagai, Noriyuki Sotani, and M. Stanley Whittingham, **"Transition metal tetramolybdate dihydrates $MMo_4O_{13}\cdot 2H_2O$ (M=Co,Ni) having a novel pillared layer structure"**, J. Solid State Chem., 2009, 182: 55-59.
17. Chunmei Ban, Natalya Chernova, M. Stanley Whittingham, **"Electrospun Nano-Vanadium Pentoxide Cathode"**, Electrochem. Commun., 2009, 11: 522-525.
18. Jie Xiao, Natasha A. Chernova, and M. Stanley Whittingham, "**Layered Mixed Transition Metal Oxide Cathodes with Reduced Cobalt Content for Lithium Ion Batteries**", Chemistry of Materials, 2008, 20: 7454-7464.
19. Quan Fan, Peter Chupas and M. Stanley Whittingham, **"Characterization of Amorphous and Crystalline Tin–Cobalt Anodes"**. Electrochem. Solid State Letters, 2007, 10: A274-A278.
20. Quan Fan and M. Stanley Whittingham, **"Electrospun Manganese Oxide Nanofibers as Anodes for Lithium-Ion Batteries"**, Electrochem. Solid-State Letters, 2007, 10: A48-A51.

11. Patents (a selection)

1. Jin-Ming Chen, Yingjeng J. Li, Weir-Mirn Hurng and M. Stanley Whittingham, **"Secondary lithium battery using a new layered anode material"**, U. S. Patent 5,514,490.
2. M. Stanley Whittingham, **"Chalcogenide Battery",** U. S. Patent 4,049, 052.
3. M. Stanley Whittingham **"Preparation of stoichiometric titanium disulfide"**, U. S. Patent 4,007,055.
4. M. Stanley Whittingham and Allan J. Jacobson, **"High energy density plural chalcogenide cathode-containing cell"**, U. S. Patent 4,233,375.
5. M. Stanley Whittingham, **"Preparation of intercalated chalcogenides",** U. S. Patent U. S. patent 4,040, 917.
6. M. Stanley Whittingham, **"Electrochemical cells with cathode-active materials of layered compounds"**, U. S. Patent 4,049,887.
7. M. Stanley Whittingham, **"Alkali metal/niobium triselenide cell having a dioxolane-based electrolyte"**, U. S. Patent 4,084,046.
8. Allan J. Jaconson and M. Stanley Whittigham, **"Cells having cathodes derived from ammonium-copper-molybdenum-chalcogen compounds"**, U. S. Patent 4,139,682.
9. Allan J. Jacobson, Russell R. Chianelli and M. Stanley Whittingham, **"Cells having cathodes containing chalcogenide compounds of the formula M_aFeX_b and species thereof exhibiting alkali metal incorporation"**, U. S. Patent 4,143,213.
10. Allan J. Jacobson, Russell R. Chianelli and M. Stanley Whittingham, **"Method of making cathodes derived from ammonium-metal-chalcogen compounds",** U. S. Patent 4,243,624.

Bio:

Kurt Kelty

Director,
Battery Technology

Tesla Motors
3500 Deer Creek Road
Palo Alto, CA 94030
650-413-4077
kurt@teslamotors.com

Kurt Kelty is the Director of Battery Technology at Tesla Motors. His team is responsible for setting and implementing Tesla's battery cell usage. He is particularly focused on evaluating the safety, performance and reliability of cells. His team then develops basic cell packaging concepts for modules to enable the safe and efficient packaging of the cells. Once the module and pack is designed, Mr. Kelty's team validates the pack performance under extreme environmental conditions that might be observed in the vehicle application.

Mr. Kelty is responsible for the technical exchanges and commercial negotiations with each of the battery cell suppliers. He also leads the battery pack recycling and regulatory efforts at Tesla. He is a member of SAE J2929 Electric and Hybrid Vehicle Propulsion Battery System Safety Standard to create abuse standards for vehicle battery packs.

Mr. Kelty also leads the battery pack lifetime modeling and degradation efforts.

Before joining Tesla, Mr. Kelty worked for Matsushita (Panasonic) for nearly fifteen years, seven of those years in Japan. At Panasonic, Mr. Kelty worked in various planning and marketing capacities related to Ni-MH and Li-ion batteries. During the last 5 years, he founded and led Panasonic's battery research lab in Silicon Valley and created R&D alliances between Panasonic and other battery and fuel cell developers in the U.S.

He is the author of 12 patents

Mr. Kelty received his B.A. in Biology from Swarthmore College in 1986 and his MSc from the Stanford University Graduate School of Business in 1997.

Erin O'Driscoll **erinod@charter.net**

3856 Ken's Lane, Midland, MI 48642 989-859-9517

EXPERIENCE:

Dow Kokam, LLC, Global Research and Development Director 3/10 to Present

A innovative lithium ion battery technology company, providing batteries and packs into a variety of advance applications.

Responsible for leading product development and innovation for Lithium Ion cell technology.

- Currently building R&D capabilities from nothing. Includes hiring R&D team, converting empty space into appropriate lab space (wet chemistry lab, pilot coating lab, cell testing lab, cell assembly capabilities).
- Developed and implement R&D strategy to double energy density as compared to current products.

Dow Koakm, Global Research and Development Director 3/10 to Present

Responsible for leading product development and innovation aligned to three markets, Pharma Excipients, Food & Nutrition Additives and Industrial Specialty Additives. Managed $35 MM budget with 120 people globally.

- Led transition of R&D organization from a product driven effort into application and market focused organization.
- Enabled development of unique breakthrough in chemistry and process to transition into valued added products aligned to critical market needs.

The Dow Chemical Company, Midland, MI 1990-3/2010

A leading science and technology company, providing innovative chemical, plastic and agricultural products and services to many essential consumer markets.

Dow Wolff Cellulosics, Global Research and Development Director 3/09 to 3/2010

Responsible for leading product development and innovation aligned to three markets, Pharma Excipients, Food & Nutrition Additives and Industrial Specialty Additives. Managed $35 MM budget with 120 people globally.

- Led transition of R&D organization from a product driven effort into application and market focused organization.
- Enabled development of unique breakthrough in chemistry and process to transition into valued added products aligned to critical market needs.

BioScience Platform, Global Research and Development Director 10/07 to 3/09

Responsible for accelerating Dow's commercialization of biobased products by establishing new strategic growth platform.

- Responsibilities include developing and implementing internal R&D program, managing $11 MM R&D budget and research staff of approximately 15 leaders. Other responsibilities include negotiating key academic, institutional and business relationships, making recommendations on Corporate Venture Capital investments and setting corporate strategy in advocacy and public relations related to BioSciences.

Polyurethanes, New Business Development Manger 2/05 to 10/07

Responsible for developing and implementing the business plan to commercialize natural oil-based polyols. Plan included a market entry strategy with key milestones for decisions on implementation of a market growth strategy to meet Polyurethanes market and financial goals.

- Key decisions in developing market entry plan included setting scope of products offered, raw material sourcing, scale of market development, breath of geographic launch, and product positioning and pricing.
- Key responsibilities in implementation of market entry strategy included, building a multifunctional team, negotiating manufacturing contract, commissioning life cycle analysis, overseeing customer trials, training sales teams geographies worldwide, establishing communication plan, preparing Dow's investor relations personnel, conducting media interviews, and establishing and tracking income statement. Responsible for $20 MM budget and staff of 10 functional leaders.
- RENUVA was launched in September of 2007.

Responsible for biobased aspects of Dow's alternative feedstock strategy development.

- Developed corporate talking points around biobased products, outlined US-based advocacy strategy, participated in issues management teams, established market research program on biobased market drivers.
- Led preparation of multiple feedstock strategy documents for review by senior leadership resulting in the creation of the BioSceinces Platform and my role as R&D director.

New Ventures/Natural Resources, <u>Application Development Leader</u> 1/04 to 2/05

Responsible for identifying and developing business growth options to diversify Dow's feedstock into renewable materials.

- Developed understanding of the market dynamics for key biomass feedstocks and surveyed technologies to convert these feedstocks in products that fit with Dow's portfolio of products. Result was a business case for projects in soybean oil based derivatives, cellulose polymers and a number of glycerin based products.
- Production of Epicholorohyrin from glycerin by Dow's Epoxy business is targeted for China in 2009. Soybean oil derivatives projects were transferred to Polyurethane business and products were launched in 2007.

Core R&D/New Products, <u>Resource Leader</u> 4/98 to 1/04

Led R&D group focused on new product development in area of coatings and functional polymers.

- Managed 28 people, $8 MM budget spread over 10-15 projects focused on developing opportunities for existing Dow business. Technologies included supercritical CO_2 decompressive spray, plasma based siloxane coatings, low-dielectric coatings, living free-radical polymers, and photo-cured coatings.

DowBrands R&D, <u>Project Leader</u> 2/91 to 4/98

Developed new products and led teams in the development of new household and personal care products. Launched three new products and had two new products in test market from 1996-1998. Represented DowBrands in two nationally televised T.V. and print ad campaigns.

Research Assignments Program, <u>Senior Research Chemist</u> 4/90 to 2/91

Completed projects in on-line analytical instrumentation, polymer kinetics, and consumer product development.

Education:

Ph.D. in Physical Chemistry, University of Colorado-Boulder; Boulder, CO, 1990
B.S. in Chemistry, Boston College; Boston, MA, 1985

JOSEPH X. ADILETTA

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Education

2001 - 2003 **MIT SLOAN SCHOOL OF MANAGEMENT** **Cambridge, MA**
Master of Business Administration, June 2003

1992 - 1997 **CORNELL UNIVERSITY** **Ithaca, NY**
MEng - Civil Engineering, Management Option, May 1997
BS - Mechanical Engineering, May 1996

Experience

2006 – Present **A123 SYSTEMS** **Watertown, MA**
Senior Manager, Market Intelligence (2010 – Present)

- Developed and implemented a comprehensive market intelligence program for the company.
- Ensured long-term differentiation of A123 products across three vertical market segments.
- Directed R&D technical and cost targets based on likely competitive development scenarios.

Senior Product Manager (2007 – 2010)

- Utilized emerging technology trends, customer application input and competitive product knowledge to provide strategic guidance and technical insight to next-generation cell development team.
- Managed technical development program for multiple small format products from business conception through material selection and early pre-production runs.
- Supported focused cost reduction activities on highest value materials and processes.

Product Manager (2006 – 2007)

- Translated customer needs into product specifications and drove development process.
- Overhauled key marketing assets, including website redesign, brand messaging, tradeshow strategy and press release content and timing.

2006 **GEN3 PARTNERS** **Boston, MA**
Consultant

- Developed and implemented front-end innovation methodologies to identify latent customer needs and advance products' main parameters of value.
- Provided critical insight to clients by leveraging relationship with Russian technical team.

2003 – 2005 **PRODUCT GENESIS** **Cambridge, MA**
Strategic Innovation Consultant

- Unearthed client/customer needs using advanced innovation techniques such as Lead User analysis, Voice of the Customer and Scenario Planning to assist Fortune 500 clients with next generation product design and development.
- Researched and analyzed clients' businesses to develop key future scenario models based on analogous and historical adoption.

2002 **BUYERZONE** **Watertown, MA**
Category Manager

- Augmented existing marketing programs through P&L analysis of fifteen business categories, producing 35% revenue growth, and 24% net revenue growth.
- Analyzed opportunities to expand business into additional marketplaces, down-selecting five markets from a pool of fifty, which were added to active sales list.

1997 - 2001 **MICROSTRATEGY** **Vienna, VA**
Angel.com – Product Manager (2000-2001)

- Created go-to-market strategy for incubated voice-technology venture, based on market research and input from organized focus groups.

Various Functions (1997 -2000)

- Developed and implemented new technical support offering geared towards high-end customer needs, driven by sales and marketing analysis, and resulting in additional $1M in annual support revenue within twelve months.
- Managed resolution of escalated technical support issues for Global 2000 client base, reducing overall support case-count by 50 percent based on thorough case tracking analysis.
- As Quality Engineer, improved cutting-edge broadcast technology product and ensured early release to market while exceeding quality standards.

Michael (Micky) J. Bly
General Motors Executive Director, Group Global Functional Leader
Global Electrical Systems, Hybrids, Electric Vehicles, Batteries, Infotainment & OnStar Engineering

Micky Bly is Executive Director, Group Global Functional Leader of Vehicle Engineering's Electrical Systems, Hybrids, Electric Vehicles, Batteries, Infotainment and OnStar Engineering for General Motors. Named to this position in June of 2010, Bly oversees the company's design and development of traditional electrical and infotainment systems, OnStar engineering, hybrid and electric vehicles, which includes the Chevrolet Volt's vehicle integration and advanced battery development.

Previously, he was Executive Director of Engine Hardware Analysis, Design, Development and Validation.

From 2006-2008, Bly was Director of Global Hybrid Integration and Controls. He oversaw the teams responsible for the production and development of GM's multiple hybrid vehicles, and contributed to the integration work on the Volt. Bly's team of engineers made sure all of the components – from the engine, transmission, brakes and batteries, to the controllers and software – came together seamlessly. He is particularly proud of the 2008 Chevrolet Tahoe Hybrid, which was named Green Car Journal's "Green Car of the Year."

Bly joined GM as a student intern in 1986 and was hired to GM's Powertrain Engineering staff after graduating from Georgia Tech with a bachelor's degree in mechanical engineering in 1990. In 2003, he received a master's degree in engineering from Rensselaer Polytechnic Institute.

In his 20 years at GM, Bly has worked on various powertrain programs in the United States, England and Germany. His first position was in Warren, Mich., as a Powertrain Development and Validation engineer. He held positions of increasing responsibility in the Small Block V8 engine group, including lead development engineer for the iconic Corvette C5 V8 engine group. In 1997, he was transferred to Lotus Cars in Norwich, England, and promoted to Engine Management Systems engineer for GM's highly successful Ecotec L4 – GM's first global four-cylinder engine program. He also was vehicle system engineer for powertrain for the Opel Corsa and Vectra programs at Opel engineering in Russelheim, Germany.

Upon returning to the U.S. in 2000, Bly was appointed engineering group manager for North America Emission Controls Hardware. Two years later, he assumed the role of V6 Calibration System manager at GM's Milford Proving Grounds. In 2003, he was appointed to oversee all technical briefings and staff facilitation on behalf of the GM Powertrain group vice president and continued this work until his executive appointment overseeing hybrid vehicle integration in 2006.

Bly is GM's key executive for the Georgia Institute of Technology and serves as a member of the Woodruff School of Mechanical Engineering Advisory Board. He is Co-Director of the General Motors/ University of Michigan Advanced Battery Coalition for Drivetrains, which is a joint research program focused on spanning the gap between battery material synthesis and vehicle controls integration while developing the next generation of battery engineers. He became a board member for Hughes Research Laboratories in October 2009 and a board member of Michigan FIRST Robotics in 2010. Bly is the former co-executive GM lead for EcoCAR, one of North America's premier college automotive engineering competitions that is sponsored by GM and the U.S. Department of Energy.

July 2010

Appendix C. Peer Reviewer Comments on "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles," Sorted by Charge Question

Question 1: Assumptions - (a) Propriety materials		
1	Whittingham	There is no allowance made for the cost of using proprietary materials, such as licensing costs. This may be important in comparing one material with another. Also see [Wittingham's comments] below.
2	O'Driscoll	No comments
3	Kelty	No comments
4	Adiletta	No comments
207	Bly	No comments
Question 1: Assumptions - (b) Estimates of materials cost		
5	Whittingham	In a number of places, it is stated that "it is estimated that the cost of" for example the separator is $2 per square meter, or the NMP is x.
6		These are well known materials that are used in large quantities and extensively in the industry today. What are today's costs, and the authors need to explain how and why the estimated cost differs from today's costs if they do.
7		The cost of some of the key components may not drop dramatically if one material is sufficiently superior and the manufacturer has patent protection, for example the separator (Celgard). See page 29, 1st full paragraph, where the first full paragraph justifies the cost because the raw materials are low cost. It ignores the proprietary technology that must be included in the cost. Separators are not simple, they must close down the battery if necessary, prevent dendrite formation etc. Today's cost should be clearly listed. We all know that $LiFePO_4$ is not low cost, even though the raw materials are low cost.
8		In Table 4.1 there is no explanation (in the table or the text), that I could find, for the three numbers under the TIAX 2010 column. A footnote under the table on the same page could easily explain the different numbers to the reader.
9		In Table 4.1, why is there not a number for LCO in the ANL 2010 column? This number must be well-known and would represent a good and solid baseline to compare the other numbers against (and to test the spreadsheet model against).
10		On page 28, 3rd line the prices for cobalt and nickel metal prices are given. The relevant costs are those of the oxide or other raw material that will actually be used in the manufacturing process; the formation of the metal can be very expensive. So perhaps the price of the oxide should be substituted here.
11		On page 30 section 4.2.1.4 "No cost is assumed for water" But what about the cost of handling the contaminated waste water? There are several companies trying to use dry processing to eliminate the cost of handling NMP and water.
12	O'Driscoll	No comments
13	Kelty	No comments
14	Adiletta	No comments
208	Bly	No comments
Question 1: Assumptions - (c) Units of capacity		
15	Whittingham	In some sentences, the weight of the material is in kg and then the capacity is given in mAh/g. The latter should be changed throughout into Ah/kg for these large batteries. The numbers stay the same.
16	O'Driscoll	No comments
17	Kelty	No comments
18	Adiletta	No comments
209	Bly	No comments

Appendix C. Peer Reviewer Comments on "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles," Sorted by Charge Question

Question 1: Assumptions - (d) Cell construction and format		
19	Whittingham	The flat plate format chosen (prismatic/pouch cells) chosen for this study appears to be the most appropriate. This part of the report perhaps could be made clearer.
20	O'Driscoll	It is ambiguous if the cell is pouch or can in early sections (drawing is misleading). Later it become clear.
21		Construction and format are within norms, but many folks at winding with individual electrodes, not using the back and forth folding method.
22	Kelty	Other form factors could be considered.
23		The cell size is arbitrarily limited.
24	Adiletta	Opposite-side tabbing structures for energy-based systems goes against most common cell formats (canned or pouch), which have same-side terminals.
25		Specific material assumptions produce a generally usable view of the market, yet do not use optimized designs that specific manufacturers are likely to employ.
26		Thicknesses of substrates might be double-checked/triangulated.
210	Bly	Seems reasonable and appropriate
Question 1: Assumptions - (e) Comparability to competing cell formats		
27	Whittingham	The most likely alternative as used today in HEV (cars, buses) is the cylindrical 18650 cell, which are almost certainly more expensive for large batteries (too many cells with all their contacts etc). Larger cylindrical cells are likely to have more severe thermal management issues. So the flat plate prismatic cells chosen are best choice
28	O'Driscoll	No comments
29	Kelty	No comments
30	Adiletta	The model assumes an opposite-end tabbed cell design in pouch form factor. Organizations such as VDA are employing specifications for metal-canned prismatic cells as well, which offer differing price/performance characteristics.
31		Cylindrical cells for HEV are not considered, nor are wound electrode designs in general.
211	Bly	Seems reasonable and appropriate
Question 1: Assumptions - (f) Cooling and thermal management requirements		
32	Whittingham	Thermal management is inadequately covered. As described, the battery pack will have one cm of insulation around it and be air-cooled. How does the battery get cooled in the summer when it is operating? I do not believe that air cooling is realistic (or is there a refrigerator built in for cooling the air). The battery pack will need liquid cooling (or heating in extreme environments) to maintain a lifetime listed as 10 years. (I realize that the Nissan Leaf only has air cooling, but is that realistic)
33		My recollection is that Lew Gaines (from Exxon Enterprises in the 1970s) found that thermal management was the most challenging aspect of large batteries (paper published in Intersociety Energy Conversion Conference ?)
34	O'Driscoll	Air cooling is often inadequate for EV packs today. It could be that pack in 2020 can achieve good performance with air cooling alone, but this assumption should be spelled out more clearly.
35	Kelty	Cooling and thermal management requirements: This needs to improve for EV.
36		Cooling and thermal management requirements: Temperature effects should be considered.
37	Adiletta	A wide variety of cooling strategies necessitates flexibility here, though perhaps with some built-in functionality/choice around air vs liquid cooling and/or active versus passive.
212	Bly	Does not appropriately recognize the trade offs of life and thermal effects.
213		Much further model refinement would be needed to improve the models accuracy

Question 1: Assumptions - (g) Electrode volumetric change		
38	Whittingham	Electrode volumetric change: I did not see this item discussed in the report; but I do not view it as a major concern for the materials considered. The electrodes must be kept under compression to maintain capacity on cycling. As the anode contracts the cathode will expand.
39		Electrode volumetric change: The one exception is the use of LTO as the anode. This is a zero expansion material so that the volume changes in the cathode cannot be compensated by the anode change.
40	O'Driscoll	Assumption of zero volumetric change is optimistics 10% over full SOC range is more reasonable.
41	Kelty	This is not considered.
42	Adiletta	No comments
214	Bly	No comments
Question 1: Assumptions - (h) Limiting parameters affecting cell dimensions or performance (for example, allowable A-hr capacity per cell, maximum electrode thickness, etc.)		
43	Whittingham	These are all well described, but then hand-waived away by "successful cell manufacturers will engineer ways to overcome these challenges to increase energy density and lower cost". This gives no guidance to the user of the excel model.
44	O'Driscoll	Numbers are within standards today. I would assume by 2020 there would be higher capacity materials that would give higher energy densities in smaller sizes.
45	Kelty	These are not validated in the paper and seem arbitrary.
46	Adiletta	Assuming that all chemistries have a similar usable energy window (within 5% of one another) is not valid in practice. This is true for both PHEV and EV. A larger disparity between oxides and phosphates exists.
47		There will definitely be a max electrode thickness based on the specific chemistry involved. More pointedly, there will be a max thickness based on the specific cell TYPE that is being developed: microHEV, HEV, PHEV or EV.
215	Bly	No comments
Question 1: Assumptions - (i) Warranty costs and profit		
48	Whittingham	For a new product the warranty cost assumptions of 1% failure per year appear too low. The costs assumed appear to be those purely due to replacing the battery, not including other issues such as liability insurance.
49		The ROI appears too low at 5%
50	O'Driscoll	I would expect warranty assumptions to be somehow related to performance like cycle life or calendar life. This is especially concerning in air cooled pack. I think an assumption related to cooling system and life would make more sense but would be challenging to build into this model now.
51	Kelty	No comments
52	Adiletta	I think that it would make more sense to target a before-tax profit and structure the model around target margin. Predicting and/or modeling the going corporate tax rate would likely be difficult in and of itself.
53		Profit rate looks a bit lower than expected over the long-term.
216	Bly	See cooling and thermal management requirements
Question 1: Assumptions - (j) Scrap rates and associated costs		
54	Whittingham	The % scrap rate appears reasonable
55		No value is assigned to the scrap, although by 2020, if the market is indeed there, there should be a thriving recycling business that would take the scrap away.
56	O'Driscoll	Looks reasonable.
57	Kelty	No comments
58	Adiletta	Are scrap rates inclusive of end of line testing?
59		NMP recycling number seems high.

217	Bly	Looks reasonable.
Question 1: Assumptions - (k) Recycling value		
60	Whittingham	The value of the recycled battery is not discussed, even though it is presumed by other ANL reports that eventually most of the lithium (and presumably any expensive other elements) would come from recycled batteries.
61		There is also talk about using "spent" EV batteries for utility/alternative energy load leveling/smoothing. Surely this would reduce the effective life-time cost of a battery.
Question 1: Assumptions - (l) Safety and manufacturability		
62	Whittingham	An issue with all batteries is protection in the case of crashes. This report does not really address that issue. Is it the intent that the one cm insulation will also serve as a crash protector? Such protection costs money, and needs to be included.
63	O'Driscoll	Safe handling of inorganic metal powder is not addressed well at all here. EPA guidelines for handle materials with Ni an Co are much different than Fe and hence one would expect different cost structure to handle the materials in the process. Section 4.3.2 does not address moving powder through the process and cleaning up safely.
64		Handling of large quantities of electrolyte without contamination is also not handled well. What size container is expected and how is the material kept clean and dry at this scale?
65	Kelty	Where are the safety features in the battery pack? CID?
66		No comments
67	Adiletta	Certainly the addition of certain components to ensure safety must be accounted for. For example, the oxide-based chemistries often use ceramic coatings on the separator or anode to compensate for the inferior abuse tolerance of that chemistry. The cost of this must be included in the cell cost.
68		I think that a 300um, thick electrode coating is somewhat aggressive to expect performance out of the design.
218	Bly	No comments
Question 1: Assumptions - (m) Anticipated industry design trends, and similar factors		
69	Wittingham	No comments
70	O'Driscoll	I believe that by 2020 there will be some non-slurry coating manufacturing approaches on the market. In this case the solid electrode would be directly deposited on current collector – difficult to model now but I believe this will be validated by then.
71	Adiletta	The industry seems to be attempting to move towards a more standardized form factor – VDA specifications, as well as SAE proposals.
72		From a cost perspective, you'll likely have to assume some take-off in overall volumes. There is some sensitivity to where this will all play out, but it will have a profound effect on materials costs for specific manufacturers. Thus, constructing the model to be based on number of vehicles produced makes sense.
219	Bly	No comments

Question 1: Assumptions - (n) PHEV types and drive train		
73	Whittingham	PHEV types and drive train: Table 3.1 addresses only one class of PHEV battery, whereas today's scenario goes all the way from the planned Toyota Prius, with 3 batteries (one power and two energy) each essentially the same size as in todays HEV Prius with a dual drivetrain (IC and electric) and an all-electric range around 8-10 miles to the GM Volt with around a 15 kWh battery, an electric generator and an all-electric drive-train and a range of around 40 miles. So the assumptions made for PHEV may not be optimum or even correct. [the comment about increasing levels of electrification is incorrect; the Volt PHEV is all electric drive, the HEV buses are all electric drive with around a 11 kWh lithium-ion battery – more than 2 million total miles, so building up reliability experience]
Question 1: Assumptions - (o) Unanticipated breakthroughs		
74	Whittingham	It is almost impossible to anticipate a significant cost breakthrough, as occurred when the Chinese decided that the common MCMB carbon used as the anode was too expensive and they replaced it with a much lower cost graphitic carbon. MCMB is no longer manufactured.
Question 1: Assumptions - (p) Additional reviewer comments		
75	Adiletta	I mention this below, so you'll see it twice, but the way the cells are designed given the thickness of electrodes and number of layers in many ways doesn't follow conventional design strategy. For instance, in the base case sent around (PHEV done by mileage), the thickness of the electrodes varies, which it wouldn't in practice, leading to higher overall current collector costs in smaller capacity/range systems. In fact, it would work the other way: You would settle on a single electrode design for the cell-type (HEV, PHEV, EV) and then vary the number of layers based on that design to accommodate different ranges.
220	Bly	In general most of the cost models do not seem aggressive enough for 2020 forecasted total costs
Question 2: Inputs and Parameters - (a) Embedded or default values chosen by the authors (for		
76	Whittingham	Embedded or default values chosen by the authors: These seemed adequate, and I found that I could change them and they had an effect on the resulting cost, but not nearly as much as I would have expected. For example switch the capacity of LFP from the default value of 155 to 50 Ah/kg had less than a 20% effect. Can this be right?
77	O'Driscoll	Embedded or default values chosen by the authors: Look in line with my expectations.
78	Kelty	Active material cost projections would be helpful.
79		Dimensions for cells should be user defined & not specified by the model.
80		What values were measured experimentally? There is no validation data in the report. The key relationship used to design the battery is an estimation for the relationship between impedance and electrode thickness. Presumably these measurements were made for a few different electrodes & are now applied to all electrodes. Where is the data to show that this is a reasonable assumption?
81	Adiletta	Electrode design specifications are often unique to individual manufacturers. The existing values might be adjusted based on other publicly available information.
82		Materials costs inputs do not necessarily match with going rates in volume production.
83		The assumption that all negatives will necessarily use a water-based binder system should be questioned, especially given the range of cell-types being investigated – micro-HEV through EV.
221	Bly	Seems appropriate for this study

Question 2: Inputs and Parameters - (b) The adequacy of user-specifiable parameters and their		
84	Whittingham	The adequacy of user-specifiable parameters and their allowable ranges: I found no difference in the battery cost whether the operating hours per day were 10 hours, 24 hours or 48 hours. Surely depreciation should cause some effect, and the spreadsheet should be set-up so that no value over 24 hours can be input.
85	O'Driscoll	The adequacy of user-specifiable parameters and their allowable ranges: Difficult to fully assess this in the time period given.
86	Kelty	More parameters should be user specifiable. There are a lot of limitations currently on what can be changed.
87	Adiletta	For micro-hev and HEV, it would make sense to specify power required, rather than the choices currently available: Capacity, Energy or Range. This is especially true if 2/4 of the options are HEV related (micro and full).
88		I assume that some of the user inputs are considered in the model for future use? For instance, ASI seems to be calculated but not necessarily applied, as do entries like temperature rise, etc.
89		I understand as reviewers we are supposed to focus on the quantitative aspects of the model; however, structuring the model for use by someone not well versed in specifics of chemistry would be useful. For instance, it's not quite clear exactly what all of the inputs and outputs are. There are clearly sheets that contain foundational information but might not be used by someone doing top-level analysis.
222	Bly	Seems appropriate for this study
Question 2: Inputs and Parameters - (c) Additional reviewer comments - cell		
90	Adiletta	Any reason to not consider 2p configurations? Are you assuming that by 2020 all cells will be optimally sized for the application?
91		You assume that manufacturing costs scale independently of cell design, which is not entirely appropriate. For instance, the cost of forming a cell may be linear to the number of cell layers, but the depreciation cost on a per cell basis of the stacking equipment will not be, given that your cell designs do not appear to scale number of layers linearly with capacity.

Question 2: Inputs and Parameters - (c) Additional reviewer comments - pack		
92	Adiletta	Looking at today's vastly different pack structures/constructions, it would make sense to account for some variation there. Two examples: (1) I did not see a liquid versus air cooling entry point; (2) Some packs use aluminum cooling plates as separators, others use only passive-type cooling with no structural support.
93		Have government subsidies on capex purchases been factored in here as well?
Question 3: Cost Methodology - (a) Dollar values		
94	Whittingham	On page 25, it is stated that "All dollar values are brought back to 2010 with allowance for inflation". What does that mean? Why not use 2010 dollars in the first place and let the user include a term for inflation, and build into the model.
95		As mentioned by this reviewer elsewhere, processing improvements that would potentially reduce costs are likely to come with licensing fees.
96	O'Driscoll	No comments
97	Adiletta	No comments
223	Bly	No comments

Question 3: Cost Methodology - (b) General scaling methods on manufacturing and material costs		
98	Whittingham	I am somewhat confused by the numbers in Table 4.8 and the cursory description on pages 46 and 48. As the text reads the cost of the double capacity goes up, but surely what the model user/consumer wants to know what is the cost per kWh or per mile driven. Then does not the cost go down when the capacity is increased? The writing is confusing. I understand that if you want more power, then it is going to cost more, but if you want more energy per cell then the cost of the cell per kWh goes down. This part should be rewritten to emphasize what is of interest to the end-user: it will cost you $279/kWh for a 8.7 kWh battery and only $206/kWh for a 17.1 kWh battery with the same number of plates?
99		Using the argument in the two lines above, I assume the model methodology allows for increasing the current collector thickness as the plate size increases so that the resistive losses do not increase. How easy is it to manipulate and optimize the plate size.
100		On page 63, the effect of manipulating the active material thickness is described so that the energy stored can be increased by thickening the electrodes and therefore reducing the area of the current collectors and separators needed.
101	O'Driscoll	No comments
102	Adiletta	I would only comment that at a certain volume, significant changes to manufacturing process will be required, which will bring associated reductions in cost. This model seems based on today's methodologies, however applied to 2020, which may not be realistic.
103		The material cost structure (BOM) as outlined is not indicative of TODAY's pricing, which would imply significantly higher costs than what we would expect to see in 2020.
224	Bly	Raw material scaling costs are reasonable for this study
Question 3: Cost Methodology - (c) Effect of production level on manufacturing and material costs		
104	Whittingham	Effect of production level on manufacturing and material costs: Several examples are given of the methodology are given and appear reasonable.
105		Effect of production level on manufacturing and material costs: On page 28, it is argued that the manufacturing cost will decrease with increased knowledge form larger scales of production. This is related to a discussion of LFP. However, a recent litigation has shown that a lower cost method for production is well patented (Valence vs Phostech), and those who need to produce and/or sell in the US are going to have to pay licensing fees. [LFP does not require a reducing atmosphere and a carbon coating step – it can be done in one stop by the carbothermal process of Valence using low cost ferric raw materials].
106	O'Driscoll	See previous comment on warranty. Without correlation to data warranty assumptions are reasonable. Profit assumptions are reasonable.
107	Adiletta	There is going to be a significant delta in materials costs based on expected production volume. This should be able to be added, even if in vague terms via percent cost downs based on specific manufacturing thresholds.
108		Coating facilities run at speeds entirely dependent on the chemistry and cell design, thus drastically altering the amortization of costs to the cell. This augmentation might be considered.
225	Bly	No comments

Question 3: Cost Methodology - (d) Method of accounting for warranty costs and profit accounting for		
109	Whittingham	It is not clear that a method was used for warranty costs and profit.
110		Profit is fixed at 5% of total investment costs. This seems too low for a risky investment. An ROI closer to 10% would be more reasonable.
111		The cost methodology for warranty costs is not too sound. Where did the writers come up with an annual failure rate of 1% (page 46)? What is it today for the much simpler HEV cell in the Prius or in the Honda (where I gather there may be an early failure problem). No lithium battery has been used in the proposed duty cycle for anywhere close to 10 years. Justification for this assumption should be made.
112		Insurance is mentioned in a couple of places, but it seems to be associated with the manufacturing plant. What is the need for liability insurance in the case of an injury related incident of the finished product when in use?
113	O'Driscoll	No comments
114	Adiletta	Typically we'd talk about warranty as a % of cost, which I assume is what "added to price" means, rather than a % of final price.
226	Bly	Warranty cost model seems to be appropriate for this study
227		SG&A and profit seem to be very high compared to current market and will not improve to these levels with current over capacity projects in the free trade markets
Question 3: Cost Methodology - (e) Effect of demand on raw material costs		
115	Whittingham	This is fine as described: keep away from low availability materials, where the battery market is a prime user of the material, such as cobalt. The report also mentions the high cost of nickel.
116		As noted in the report, iron and manganese are fine.
117		A bigger issue than the battery for electric vehicles is probably the rare earth metals needed in the electric motors. This naturally is not a part of this report, but the user of the model needs to be aware that other items than the battery may be cost controlling.
118	O'Driscoll	No comments
119	Adiletta	This does NOT seem to be accounted for. The effect is real, quantifiable and quite different for each battery manufacturer depending on volume and relationship.
120		Especially out in 2020 and beyond, some reasonable assumptions must be made based on today's high volume cost rates. It does not appear that this was taken into account. At the very least a single input for % decrease based on volume might be added.
228	Bly	Demand assumptions do not show an obvious strong influence of material cost and seems reasonable
Question 3: Cost Methodology - (f) Depreciation		
121	Whittingham	No real justification for model used for depreciation – appears to be pulled out of the air. Probably too low at 12.5%; this value assumes an 8-year life. For a new and probably changing technology a shorter depreciation time is needed at least for the first 5-10 years.
122	O'Driscoll	No comments
123	Kelty	5-year depreciation is more appropriate.
124	Adiletta	Have you accounted for government subsidies in the acquisition of capital equipment?
125		8 years on manufacturing equipment seems a bit long.
229	Bly	Model shows an 8 year amortization which is slightly higher than current norms in the industry

Question 3: Cost Methodology - (g) Research and development		
126	Whittingham	R&D comes in two forms, support for the manufacturing operation (quality control etc), as well as developing new products, that is to remain state-of-the-art. It is not clear which is intended here.
127		As mentioned in this review elsewhere, the cost of licensing technology has not been included. No one outfit is going to have complete “ownership” of the materials and design. This is not built into the methodology.
128	O’Driscoll	No comments
129	Adiletta	Typically we’d talk about R&D as a % of revenue rather than of depreciation.
230	Bly	No comment. Too variable in this fast pace development area
Question 3: Cost Methodology - (h) Baseline plant design and scaling		
130	Whittingham	Seems fine, but I wonder how the model handles for example 4.3.4 Callendering, which has 1 person per shift. No person is going to work continuously without a break. How are these breaks covered whne the process in presumably continuous. This is perhaps asking is there flexibility built into the cost methodology.
131	O’Driscoll	Working capital seems low.
132	Adiletta	Initial plant design looks reasonable. I think you should consider scalability based on volume assumptions. At some point, volumes could become large enough that a transition to new manufacturing strategies would make sense in order to continue down the cost curve.
133		Scaling would be done incrementally based on capacity ramp-ups. To that extent, the model seems to function linearly with respect to invested capital, whereas that’s not the “true” effect, where 100s of millions are invested for a fixed capacity which may or may not be fully utilized, and thus cost affected.
231	Bly	20 year amortization of capital investment is much lower than actual practice in Asia supply base
232		Model for building cost does not seem realistic, unless model assumes continuous government incentives, which is not realistic in this timeframe.
Question 3: Cost Methodology - (i) In-house vs purchasing outside (page 25 bottom)		
134	Whittingham	The methodology here is probably OK, as you would do in-house for several reasons: lower cost, security of supply, proprietary steps.
135		For each of the above reasons, the cost is presumed to be lower than purchasing outside, so methodology and numbers probably OK.
136	Adiletta	No comments

Question 4: Performance Methodology - (a) How the physical properties and dimensions of cell		
137	Whittingham	The battery design model seems OK
138		The only are [sic] I have concern with is how the effective tap density of the materials is incorporated into the model. It appears to be through the void volume.
139	O'Driscoll	Theory looks sound.
140	Kelty	See above comment regarding lack of validation data for ASI assumptions
141	Adiletta	It seems that the cell thickness and number of layers are oddly calculated. In the standard 10mi PHEV case, you end up with a 16um cathode – obviously unrealistic, which then required 64 layers? I think an alternate approach would be to target a thickness based on the type of cell desired, and subsequently vary the number of layers to achieve differing mileage/capacity packs.
142		As with thicknesses, densities are variable based on chemistry employed and desired cell type – HEV vs EV.
143	Adiletta	You would not necessarily constrain the thickness of the cell based on the cell type, for instance 10mm for PHEV. In non-standard designs (those outside of a footprint standard like VDA), you might float the thickness to achieve a given capacity once you have a footprint in mind.
233	Bly	No comments
Question 4: Performance Methodology - (b) How power, energy capacity, resistances, and currents		
144	Whittingham	These, like voltage at maximum power, seem very reasonable
145		As noted under (1), some generic statements like "PHEV cells should be much larger than HEV cells and thus a cell thickness of 10 mm is assumed" are almost certainly not entirely correct if Toyota's Prius model is to be believed.
146	O'Driscoll	Theory looks sound.
147	Kelty	No comments
148	Adiletta	I'm curious as to why the power was a user input rather than calculated from the ASI, which seemed to be painstakingly calculated. When comparing chemistry to chemistry, the delivered power based on the cell design is important.
149		Your limiting C-rate is not going to be constant, it will vary based on cell design and chemistry, which is also based on the application you would be designing the cell for: micro-HEV, HEV, PHEV, EV.
234	Bly	No comments
Question 4: Performance Methodology - (c) Additional reviewer comments		
151	O'Driscoll	In general I have concerns that with the approach from theory only to full scale cost model. Any theory should be correlated with experimental results. I am surprise that no correlation is made to actual data. While properties of materials like mA/g are true in theory many times they are not accurate in practice. At least one example showing a cell and/or pack that correlates to this model is necessary for credibility that this approach is valid.
Question 5: Completeness - (a) Physical components of the cells and assembled packs		
152	Whittingham	Yes [complete]
153	O'Driscoll	No comments
154	Kelty	CID?
155	Adiletta	Physical components of the cells and assembled packs: Cost of terminal assemblies seems low.
156		Physical components of the cells and assembled packs: No cost accounted for tape in cell (albeit small cost).
235	Bly	Seem appropriate

Question 5: Completeness - (b) Support circuitry such as for cell charge control and balancing		
157	Whittingham	Yes [complete]
158	O'Driscoll	Active cell balance is new but should be standard for 2020.
159	Kelty	No comments
160	Adiletta	No comments
236	Bly	Model assumptions simplify the circuitry to represent a state of the art battery management system
Question 5: Completeness - (c) Manufacturing steps		
161	Whittingham	Yes [complete]
162	O'Driscoll	Very standard.
163	Kelty	No comments
164	Adiletta	There are certainly inspection steps that require personnel and equipment not included in the process steps.
237	Bly	No comments
Question 5: Completeness - (d) Raw materials and labor		
165	Whittingham	Yes, but see earlier comments about situation where only one person ahs been assigned to the task (what happens in breaks)
166	O'Driscoll	Labor is low across the board. Labor may be lower in 2020 but I don't see additional automation build in to achieve a decrease in labor.
167	Kelty	See above comment regarding projecting future costs for active materials.
168	Adiletta	No comments
238	Bly	Labor rates are appropriate only for US
Question 5: Completeness - (e) Energy inputs and consumables used in manufacture		
169	Whittingham	Consumables discussed, but impact of cleaning resulting waste streams did not appear to be covered.
170		Energy input (aka utility costs) were not specifically covered, except as in "Variable Overhead" in Table 4.7 and these are assumed to be 60% of the direct labor costs. This is probably not ideal, as the more automated the plant the lower the labor costs and the higher the utility costs. Building the plant in a low humidity climate, such as Tucson, might result in lower utility costs than in humid Michigan because of the extensive dry-rooms that must be used.
171	O'Driscoll	No comments
172	Kelty	No comments
173	Adiletta	No comments
239	Bly	This model significantly underestimates energy input cost. Unrealistic as presented
Question 5: Completeness - (f) Capital equipment		
174	Whittingham	Yes [complete]
175	O'Driscoll	No comments
176	Kelty	No comments
177	Adiletta	No comments
240	Bly	Very much underestimate capital investment required for cell manufacturing with state of the cell technologies

Question 5: Completeness - (g) Research and development costs for battery design, development,		
178	Whittingham	As noted elsewhere, the whole are of licensing fees has been neglected, even though lithium batteries are the subject of many expensive litigations these days.
179	O'Driscoll	No comments
180	Kelty	No comments
181	Adiletta	No comments
241	Bly	Unable to comment
Question 5: Completeness - (h) Battery control system hardware and software		
182	Whittingham	Yes [complete]
183	O'Driscoll	No comments
184	Kelty	This is lacking in completeness. Critical safety features are not included (isolation contactors, etc.). The argument could be made however, that these costs are an insignificant cost of the total battery pack – the active materials being the key cost driver. This then leads to the argument that the model should be much more focused on the costs of these active materials.
185	Adiletta	No comments
242	Bly	Seems appropriate based on state of the art design
Question 5: Completeness - (i) Additional reviewer comments		
186	Adiletta	It would be nice to have an overall summary sheet that compared packs of different chemistries side by side.
187		The targeted user should be considered when structuring the model's inputs/outputs such that someone not completely versed in battery chemistry/manufacturing structure might be able to use the tool.
188		From a general completeness standpoint, I would say that the model has MOST aspects well covered. The real issue is with generalizing battery manufacturing. Every manufacturer deals with a specific chemistry, with specific designs, with specific manufacturing processes, subsidies, etc. This makes this type of information extremely difficult to not only publicly disclose, but also to model with reliable and useful results. Being on the outside of the industry looking in is a difficult position to be in relative to modeling each of these parameters such that a lay-person might understand the key issues that a specific manufacturer has to tackle.
189		Augmenting the model with the capability to size a system based on desired capacity/energy rather than dealing with system sizes as prescribed by the model.
243	Bly	Model seems to have a very high level of cost structure with lack of details in burden, interest, maintenance, and indirect labor.

Question 6: Recommendations - (a) Recommendations		
190	Whittingham	1 Clearly the spreadsheet needs to be made user-friendly, yet not allow for the non-expert to make unrealistic inputs and assumptions. a. For example daily operating time should not be allowed to exceed 24 hours b. To be user-friendly one should be able to just select the system of interest, and not have to cut and paste it in the System Selection screen. c. There is a heading issue with the cost input screen. When switching from NCA to LFP, the cathode heading does not change to LFP but the numbers do. d. The description for users needs to be generalized. Page 49 – There is no “Options” under the “Tools” drop-down menu on the Mac excel 2011; it can be found under the main Excel drop down menu (by going to Preferences , then to calculation).
191		2 The weakness of any model is that a major scientific/technological breakthrough might transform the playing field.
192		3 Keep the wording simple, for example what kind of dollars are being used. Stick to 2010 dollars and let the user consider inflation.
193		4 The model needs to include better thermal management. Long-lived batteries will almost certainly need liquid cooling or heating in certain climates in winter.
194	O’Driscoll	The article is very ambitious in its goals. As I wrote in my comments, I have concerns with the approach from theory to full scale cost model without correlating theory to data.
195	Kelty	We simulated a few EV packs and the price is lower than anticipated. This may be due in part to the extremely thick electrodes that the model predicted. The model should limit electrode thickness to a user defined value, we suggest less than 200 micron.
196		Please summarize somewhere clearly in the report how the model accounts for the cost in 2020. It appears that current costs are input, and the spreadsheet does not appear to be adjusting anything except the plant scale.
197		User-defined inputs are currently: 1. Battery power 2. # of cells & modules 3. Target voltage at max power 4. Battery pack energy or vehicle electric range & efficiency. I think that this model would be improved with this input also (or in place of #1): 1. A metric for acceleration such as the time it takes to accelerate from 0-60 mph at a specified temperature.
198		Metal pricing is ignored. This model claims to be forecasting pack cost in 2020 but does not appear to be accounting for changes in the cost of active materials over time. This paper would benefit from an overview early on as to how typical battery pack cost breaks down. By far and large, the main component of pack cost is battery active material cost. Cost projections should focus on the impact of this – the biggest slice of the pie.
199		The impact of form factor is not given much attention. The assumption is made that form factor will not make much of a difference at high volume. It would help to see some calculations backing up this assumption. Show that a cylindrical cell will cost about the same as a stacked prismatic or indicate the anticipated differences in cost.

200	Kelty	The model solves iteratively for pack energy or range, varying cell capacity & electrode thickness & then determines the mass, volume & material requirements to make the car. These requirements are used to calculate cost. We think that the output from this model could be much more useful. We'd like to see pack cost over time for each chemistry. There was no data shown to validate the assumptions that were made in calculating electrode thickness from ASI measurements for each chemistry. Impedance measurements change drastically depending on not just electrode thickness, but also chemistry, particle size, separator thickness, current-collector thickness, choice of electrolyte, and temperature, etc. This model is making some very big assumptions and it is not clear what error may be introduced. Does it make sense to use the same assumptions for HEV, PHEV and EV batteries (for example, current collector thickness)? What error could be introduced? Can this be quantified? This should be discussed.
201		It is mentioned as a future work item – the model needs a cooling/heating system and to capture the effects of temperature.
202		The model would benefit from increasing the # of user definable inputs, such as SOC window of operation for an EV (80% is too conservative).
203		The model attempts to capture the fixed costs for the battery pack, but ends up making some very simplified assumptions. If this section remains in the model, we suggest that it involve many user-defined inputs. The model currently does not capture the cost of safety features such as isolation contactors.
204		5-year depreciation is commonly used in the battery industry. The study is using 8 year, which is too long.
205		Please include instructions for how to turn on iterations for other versions of Excel, including 2007. The pointer about closing all open Excel documents worked for us but was given over email.
206		It would be helpful to see $/Wh cell and pack costs in the spreadsheet.
244	Bly	Overall the model is very comprehensive in its design and structure. The information provided in the modeling uses publically recognized inputs but has a wide variation in cost that may be regionally dependent. All costs are projected for calendar year 2020 and are based on a high level structure that lacks detail in burden cost (missing energy cost, interest, machine maintenance, in-directed labor, etc).
245		Additionally, there are several areas in which the assumptions are very conservative when compared to what has been achieved in production today. For example: Manufacturing Yield rate (92%) estimated by ANL is conservative for 2020. Targets from Tier 1 suppliers have been a minimum of 98%
246		Additionally, there are several areas in which the assumptions are very conservative when compared to what has been achieved in production today. For example: Labor Cost – ANL did not specify an hourly rate of labor but estimated a rate of $1.62 per cell. Production labor cost is significantly less based on a per cell basis.
247		Additionally, there are several areas in which the assumptions are very conservative when compared to what has been achieved in production today. For example: Depreciation Cost – The assembly line process capacity does not seem realistic and will have a direct impact of the total cost for the Electrode and Assembly. As a result, the estimate for impact to burden cost is greater than 1.5 times too high.
248		Additionally, there are several areas in which the assumptions are very conservative when compared to what has been achieved in production today. For example: Area Cost – The building construction cost does not seem realistic and is lower in years amortized for capital investment and total dollars for building and land.

249	Bly	Additionally, there are several areas in which the assumptions are very conservative when compared to what has been achieved in production today. For example: SGA and Profit – ANL estimated 25% of direct labor and variable overhead plus 35% of depreciation for SGA. ANL also estimated 5% of investment cost for profit. Again, these estimates result in a cost impact greater than 1.5 times too high.
250		Additionally, there are several areas in which the assumptions are very conservative when compared to what has been achieved in production today. For example: Warranty Cost – The warranty cost for the pack alone seems too high.
251		It is expected that by 2020 there will be significant improvements in cost. With the cost numbers in this report already conservative when compared to what has been achieved in production today, the cost model may be overstated by the time actual 2020 costs are realized.

Appendix D: Peer Reviewer Comments as Submitted

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Peer review of the report, "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles"

Report by: M. Stanley Whittingham

Date of Report: February 20th 2011

As a reviewer you are to orient your comments toward the six (6) general areas listed below. You are expected to identify additional topics or depart from these examples as necessary to best apply your particular set of expertise toward review of the model.

Comments should be sufficiently clear and detailed to allow readers to familiarize with the report to thoroughly understand their relevance to the material provided for review. EPA requests that the reviewers not release the peer review materials or their comments until ANL makes its report/cost model and supporting documentation public. EPA will notify the reviewers when this occurs.

Below you will find a template for your comments. You are free to use this template to facilitate the compilation of the peer review comments, but do not feel constrained by the format. You are free to revise as needed; this is just a starting point.

If you have questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If you have any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory by phone (734-214-4017) or through e-mail (schenk.ruth@epa.gov).

(1) **Assumptions.** Please comment on the validity of any assumptions embedded in the model that could affect projected battery pack price or performance. Please comment on any assumptions that appear to be unstated and/or implicit.

Assumptions	**Reviewer Comment(s)**
Proprietary Materials	• There is no allowance made for the cost of using proprietary materials, such as licensing costs. This may be important in comparing one material with another. Also see below.
Estimates of Materials costs	• In a number of places, it is stated that "it is estimated that the cost of" for example the separator is \$2 per square meter, or the NMP is x. • These are well known materials that are used in large quantities and extensively in the industry today. What are today's costs, and the authors need to explain how and why the estimated cost differs from today's costs if they do. • The cost of some of the key components may not drop dramatically if one material is sufficiently superior and the manufacturer has patent protection, for example the separator (Celgard). See page 29, 1st full paragraph, where the first full paragraph justifies the cost because the raw materials are low cost. It ignores the proprietary technology that must be included in the cost. Separators are not simple, they must close down the battery if necessary, prevent dendrite formation etc. Today's cost should be clearly listed. We all know that $LiFePO_4$ is not low cost, even though the raw materials are low cost. • In Table 4.1 there is no explanation (in the table or the text), that I could find, for the three numbers under the TIAX 2010 column. A footnote under the table on the same page could easily explain the different numbers to the reader. • In Table 4.1, why is there not a number for LCO in the ANL 2010 column? This number must be well-known and would represent a good and solid baseline to compare the other numbers against (and to test the spreadsheet model against). • On page 28, 3rd line the prices for cobalt and nickel metal prices are given. The relevant costs are those of the oxide or other raw material that will actually be used in the manufacturing process; the formation of the metal can be very expensive. So perhaps the price of the oxide should be substituted here. • On page 30 section 4.2.1.4 "No cost is assumed

	for water" But what about the cost of handling the contaminated waste water? There are several companies trying to use dry processing to eliminate the cost of handling NMP and water.
Units of capacity	• In some sentences, the weight of the material is in kg and then the capacity is given in mAh/g. The latter should be changed throughout into Ah/kg for these large batteries. The numbers stay the same.
Cell construction and format	• The flat plate format chosen (prismatic/pouch cells) chosen for this study appears to be the most appropriate. This part of the report perhaps could be made clearer.
Comparability to competing cell formats	• The most likely alternative as used today in HEV (cars, buses) is the cylindrical 18650 cell, which are almost certainly more expensive for large batteries (too many cells with all their contacts etc). Larger cylindrical cells are likely to have more severe thermal management issues. So the flat plate prismatic cells chosen are best choice.
Cooling and thermal management requirements	• Thermal management is inadequately covered. As described, the battery pack will have one cm of insulation around it and be air-cooled. How does the battery get cooled in the summer when it is operating? I do not believe that air cooling is realistic (or is there a refrigerator built in for cooling the air). The battery pack will need liquid cooling (or heating in extreme environments) to maintain a lifetime listed as 10 years. (I realize that the Nissan Leaf only has air cooling, but is that realistic) • My recollection is that Lew Gaines (from Exxon Enterprises in the 1970s) found that thermal management was the most challenging aspect of large batteries (paper published in Intersociety Energy Conversion Conference ?)
Electrode volumetric change	• I did not see this item discussed in the report; but I do not view it as a major concern for the materials considered. The electrodes must be kept under compression to maintain capacity on cycling. As the anode contracts the cathode will expand. • The one exception is the use of LTO as the anode. This is a zero expansion material so that the volume changes in the cathode cannot be compensated by the anode change.
Limiting parameters affecting cell dimensions or performance (for example, allowable A-hr capacity per cell, maximum electrode thickness, etc)	• These are all well described, but then hand-waived away by "successful cell manufacturers will engineer ways to overcome these

	challenges to increase energy density and lower cost". This gives no guidance to the user of the excel model.
Warranty costs and profit	• For a new product the warranty cost assumptions of 1% failure per year appear too low. The costs assumed appear to be those purely due to replacing the battery, not including other issues such as liability insurance. • The ROI appears too low at 5%.
Scrap rates and associated costs	• The % scrap rate appears reasonable • No value is assigned to the scrap, although by 2020, if the market is indeed there, there should be a thriving recycling business that would take the scrap away.
Recycling value	• The value of the recycled battery is not discussed, even though it is presumed by other ANL reports that eventually most of the lithium (and presumably any expensive other elements) would come from recycled batteries. • There is also talk about using "spent" EV batteries for utility/alternative energy load leveling/smoothing. Surely this would reduce the effective life-time cost of a battery.
Safety and manufacturability	• An issue with all batteries is protection in the case of crashes. This report does not really address that issue. Is it the intent that the one cm insulation will also serve as a crash protector? Such protection costs money, and needs to be included. •
Anticipated industry design trends, and similar factors	• •
PHEV types and drive train	• Table 3.1 addresses only one class of PHEV battery, whereas today's scenario goes all the way from the planned Toyota Prius, with 3 batteries (one power and two energy) each essentially the same size as in todays HEV Prius with a dual drivetrain (IC and electric) and an all-electric range around 8-10 miles to the GM Volt with around a 15 kWh battery, an electric generator and an all-electric drive-train and a range of around 40 miles. So the assumptions made for PHEV may not be optimum or even correct. [the comment about increasing levels of electrification is incorrect; the Volt PHEV is all electric drive, the HEV buses are all electric drive with around a 11 kWh lithium-ion battery – more than 2 million total miles, so building up reliability

	experience]
Unanticipated Breakthroughs	• It is almost impossible to anticipate a significant cost breakthrough, as occurred when the Chinese decided that the common MCMB carbon used as the anode was too expensive and they replaced it with a much lower cost graphitic carbon. MCMB is no longer manufactured.

(2) **Inputs and Parameters.** Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Please comment on any caveats or limitations that these inputs and parameters entail with respect to use of the results as the basis for estimating the manufacturing cost or performance of lithium-ion battery packs.

Example Assumptions	**Reviewer Comment(s)**
Embedded or default values chosen by the authors (for example, those that represent default material costs, material percentages, preferred dimensions, experimentally measured values, etc)	• These seemed adequate, and I found that I could change them and they had an effect on the resulting cost, but not nearly as much as I would have expected. For example switch the capacity of LFP from the default value of 155 to 50 Ah/kg had less than a 20% effect. Can this be right? •
The adequacy of user-specifiable parameters and their allowable ranges (for example, those that specify performance requirements, or those that relate to cell chemistries or cell/module/pack configuration possibilities)	• I found no difference in the battery cost whether the operating hours per day were 10 hours, 24 hours or **48** hours. Surely depreciation should cause some effect, and the spreadsheet should be set-up so that no value over 24 hours can be input. •

(3) **Cost methodology.** Please comment on the validity and applicability of the methodologies used in estimating battery manufacturing costs. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations.

Example Assumptions	**Reviewer Comment(s)**
Dollar Values	• On page 25, it is stated that "All dollar values are brought back to 2010 with allowance for inflation". What does that mean? Why not use 2010 dollars in the first place and let the user include a term for inflation, and build into the model. • As mentioned by this reviewer elsewhere, processing improvements that would potentially reduce costs are likely to come with licensing fees.
General scaling methods on manufacturing and material costs	• I am somewhat confused by the numbers in Table 4.8 and the cursory description on pages 46 and 48. As the text reads the cost of the double capacity goes up, but surely what the model user/consumer wants to know what is the cost per kWh or per mile driven. Then does not the cost go down when the capacity is increased? The writing is confusing. I understand that if you want more power, then it is going to cost more, but if you want more energy per cell then the cost of the cell per kWh goes down. This part should be rewritten to emphasize what is of interest to the end-user: it will cost you $279/kWh for a 8.7 kWh battery and only $206/kWh for a 17.1 kWh battery with the same number of plates? • Using the argument in the two lines above, I assume the model methodology allows for increasing the current collector thickness as the plate size increases so that the resistive losses do not increase. How easy is it to manipulate and optimize the plate size. • On page 63, the effect of manipulating the active material thickness is described so that the energy stored can be increased by thickening the electrodes and therefore reducing the area of the current collectors and separators needed.
Effect of production level on manufacturing and material costs	• Several examples are given of the methodology are given and appear reasonable. • On page 28, it is argued that the manufacturing cost will decrease with increased knowledge form larger scales of production. This is related to a discussion of LFP. However, a recent litigation has shown that a lower cost method for production is well patented (Valence vs Phostech), and those who need to produce and/or sell in the US are going to have to pay

	licensing fees. [LFP does not require a reducing atmosphere and a carbon coating step – it can be done in one stop by the carbothermal process of Valence using low cost ferric raw materials].
Method of accounting for warranty costs and profit Accounting for liability insurance	• It is not clear that a method was used for warranty costs and profit. • Profit is fixed at 5% of total investment costs. This seems too low for a risky investment. An ROI closer to 10% would be more reasonable. • The cost methodology for warranty costs is not too sound. Where did the writers come up with an annual failure rate of 1% (page 46)? What is it today for the much simpler HEV cell in the Prius or in the Honda (where I gather there may be an early failure problem). No lithium battery has been used in the proposed duty cycle for anywhere close to 10 years. Justification for this assumption should be made. • Insurance is mentioned in a couple of places, but it seems to be associated with the manufacturing plant. What is the need for liability insurance in the case of an injury related incident of the finished product when in use?
Effect of demand on raw material costs	• This is fine as described: keep away from low availability materials, where the battery market is a prime user of the material, such as cobalt. The report also mentions the high cost of nickel. • As noted in the report, iron and manganese are fine. • A bigger issue than the battery for electric vehicles is probably the rare earth metals needed in the electric motors. This naturally is not a part of this report, but the user of the model needs to be aware that other items than the battery may be cost controlling.
Depreciation	• No real justification for model used for depreciation – appears to be pulled out of the air. Probably too low at 12.5%; this value assumes an 8-year life. For a new and probably changing technology a shorter depreciation time is needed at least for the first 5-10 years.
Research and development	• R&D comes in two forms, support for the manufacturing operation (quality control etc), as well as developing new products, that is to remain state-of-the-art. It is not clear which is intended here. • As mentioned in this review elsewhere, the cost of licensing technology has not been included.

	No one outfit is going to have complete "ownership" of the materials and design. This is not built into the methodology.
Baseline plant design and scaling	• Seems fine, but I wonder how the model handles for example 4.3.4 Callendering, which has 1 person per shift. No person is going to work continuously without a break. How are these breaks covered whne the process in presumably continuous. This is perhaps asking is there flexibility built into the cost methodology.
In-house vs purchasing outside (page 25 bottom)	• The methodology here is probably OK, as you would do in-house for several reasons: lower cost, security of supply, proprietary steps. • For each of the above reasons, the cost is presumed to be lower than purchasing outside, so methodology and numbers probably OK.

(4) **Performance methodology.** Please comment on the validity and applicability of the methodologies used in calculating the power and energy performance of the designed battery. Please comment on any apparent unstated or implicit assumptions (e.g., regarding ambient temperatures or other factors that may affect battery performance) and on any related caveats or limitations.

Example Assumptions	**Reviewer Comment(s)**
How the physical properties and dimensions of cell components are calculated from the inputs	• The battery design model seems OK • The only are I have concern with is how the effective tap density of the materials is incorporated into the model. It appears to be through the void volume.
How power, energy capacity, resistances, currents, are calculated	• These, like voltage at maximum power, seem very reasonable. • As noted under (1), some generic statements like "PHEV cells should be much larger than HEV cells and thus a cell thickness of 10 mm is assumed" are almost certainly not entirely correct if Toyota's Prius model is to be believed.

(5) **Completeness.** Please comment on whether the model adequately identifies the cost components of battery pack manufacturing.

Example Assumptions	**Reviewer Comment(s)**
Physical components of the cells and assembled packs	• Yes •
Support circuitry such as for cell charge control and balancing	• Yes •
Manufacturing steps	• Yes •
Raw materials and labor	• Yes, but see earlier comments about situation where only one person ahs been assigned to the task (what happens in breaks) •
Energy inputs and consumables used in manufacture	• Consumables discussed, but impact of cleaning resulting waste streams did not appear to be covered. • Energy input (aka utility costs) were not specifically covered, except as in “Variable Overhead” in Table 4.7 and these are assumed to be 60% of the direct labor costs. This is probably not ideal, as the more automated the plant the lower the labor costs and the higher the utility costs. Building the plant in a low humidity climate, such as Tucson, might result in lower utility costs than in humid Michigan because of the extensive dry-rooms that must be used.
Capital equipment	• Yes •
Research and development costs for battery design, development, and production implementation	• As noted elsewhere, the whole are of licensing fees has been neglected, even though lithium batteries are the subject of many expensive litigations these days. •
Battery control system hardware and software	• Yes •

(6) **Recommendations.** Please comment on the overall adequacy of the model for predicting future battery prices, and on any improvements that might reasonably be adopted by the authors to improve the model. Please note that the authors intend the model to be open to the community and transparent in the assumptions made and the methods of calculation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.

1 Clearly the spreadsheet needs to be made user-friendly, yet not allow for the non-expert to make unrealistic inputs and assumptions.
   a. For example daily operating time should not be allowed to exceed 24 hours
   b. To be user-friendly one should be able to just select the system of interest, and not have to cut and paste it in the System Selection screen.
   c. There is a heading issue with the cost input screen. When switching from NCA to LFP, the cathode heading does not change to LFP but the numbers do.
   d. The description for users needs to be generalized. Page 49 – There is no "Options" under the "Tools" drop-down menu on the Mac excel 2011; it can be found under the main Excel drop down menu (by going to Preferences , then to calculation).

2 The weakness of any model is that a major scientific/technological breakthrough might transform the playing field.

3 Keep the wording simple, for example what kind of dollars are being used. Stick to 2010 dollars and let the user consider inflation.

4 The model needs to include better thermal management. Long-lived batteries will almost certainly need liquid cooling or heating in certain climates in winter.

Peer review of the report, “Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles”

Report by: Kurt Kelty

Date of Report: Feb. 17, 2011

As a reviewer you are to orient your comments toward the six (6) general areas listed below. You are expected to identify additional topics or depart from these examples as necessary to best apply your particular set of expertise toward review of the model.

Comments should be sufficiently clear and detailed to allow readers to familiarize with the report to thoroughly understand their relevance to the material provided for review. EPA requests that the reviewers not release the peer review materials or their comments until ANL makes its report/cost model and supporting documentation public. EPA will notify the reviewers when this occurs.

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If you have questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If you have any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA’s Quality Office, National Vehicle and Fuel Emissions Laboratory by phone (734-214-4017) or through e-mail (schenk.ruth@epa.gov).

(1) **Assumptions.** Please comment on the validity of any assumptions embedded in the model that could affect projected battery pack price or performance. Please comment on any assumptions that appear to be unstated and/or implicit.

Example Assumptions	**Reviewer Comment(s)**
Cell construction and format	• Other form factors could be considered. • The cell size is arbitrarily limited.
Comparability to competing cell formats	• •
Cooling and thermal management requirements	• This needs to improve for EV. • Temperature effects should be considered.
Electrode volumetric change	• This is not considered. •
Limiting parameters affecting cell dimensions or performance (for example, allowable A-hr capacity per cell, maximum electrode thickness, etc)	• These are not validated in the paper and seem arbitrary. •
Warranty costs and profit	• •
Scrap rates	• •
Safety and manufacturability	• Where are the safety features in the battery pack? CID? •
Anticipated industry design trends, and similar factors	• •
Additional reviewer comments	• See additional document •
Additional reviewer comments	• •

(2) **Inputs and Parameters.** Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Please comment on any caveats or limitations that these inputs and parameters entail with respect to use of the results as the basis for estimating the manufacturing cost or performance of lithium-ion battery packs.

Example Assumptions	**Reviewer Comment(s)**
Embedded or default values chosen by the authors (for example, those that represent default material costs, material percentages, preferred dimensions, experimentally measured values, etc)	• Active material cost projections would be helpful. • Dimensions for cells should be user defined & not specified by the model. • What values were measured experimentally? There is no validation data in the report. The key relationship used to design the battery is an estimation for the relationship between impedance and electrode thickness. Presumably these measurements were made for a few different electrodes & are now applied to all electrodes. Where is the data to show that this is a reasonable assumption?
The adequacy of user-specifiable parameters and their allowable ranges (for example, those that specify performance requirements, or those that relate to cell chemistries or cell/module/pack configuration possibilities)	• More parameters should be user specifiable. There are a lot of limitations currently on what can be changed. •
Additional reviewer comments	• •
Additional reviewer comments	• •

(3) **Cost methodology.** Please comment on the validity and applicability of the methodologies used in estimating battery manufacturing costs. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations.

Example Assumptions	**Reviewer Comment(s)**
General scaling methods on manufacturing and material costs	• •
Effect of production level on manufacturing and material costs	• •
Method of accounting for warranty costs and profit	• •
Effect of demand on raw material costs	• •
Depreciation	• 5-year depreciation is more appropriate. •
Research and development	• •
Baseline plant design and scaling	• •
Additional reviewer comments	• •
Additional reviewer comments	• •

(4) **Performance methodology.** Please comment on the validity and applicability of the methodologies used in calculating the power and energy performance of the designed battery. Please comment on any apparent unstated or implicit assumptions (e.g., regarding ambient temperatures or other factors that may affect battery performance) and on any related caveats or limitations.

Example Assumptions	**Reviewer Comment(s)**
How the physical properties and dimensions of cell components are calculated from the inputs	• See above comment regarding lack of validation data for ASI assumptions. •
How power, energy capacity, resistances, currents, are calculated	• •
Additional reviewer comments	• •
Additional reviewer comments	•

(5) **Completeness.** Please comment on whether the model adequately identifies the cost components of battery pack manufacturing.

Example Assumptions	**Reviewer Comment(s)**
Physical components of the cells and assembled packs	• CID? •
Support circuitry such as for cell charge control and balancing	• •
Manufacturing steps	• •
Raw materials and labor	• See above comment regarding projecting future costs for active materials. •
Energy inputs and consumables used in manufacture	• •
Capital equipment	• •
Research and development costs for battery design, development, and production implementation	• •
Battery control system hardware and software	• This is lacking in completeness. Critical safety features are not included (isolation contactors, etc.). The argument could be made however, that these costs are an insignificant cost of the total battery pack – the active materials being the key cost driver. This then leads to the argument that the model should be much more focused on the costs of these active materials. •
Additional reviewer comments	• •
Additional reviewer comments	• •

(6) **Recommendations.** Please comment on the overall adequacy of the model for predicting future battery prices, and on any improvements that might reasonably be adopted by the authors to improve the model. Please note that the authors intend the model to be open to the community and transparent in the assumptions made and the methods of calculation. Therefore <u>recommendations for clearly defined improvements that would utilize publicly available information would be preferred</u> over those that would make use of proprietary information.

See additional document.

Review of “Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles”

Kurt Kelty

Tesla Motors

2/22/11

Comment #1:

We simulated a few EV packs and the price is lower than anticipated. This may be due in part to the extremely thick electrodes that the model predicted. The model should limit electrode thickness to a user defined value, we suggest less than 200 micron.

Comment #2:

Please summarize somewhere clearly in the report how the model accounts for the cost in 2020. It appears that current costs are input, and the spreadsheet does not appear to be adjusting anything except the plant scale.

Comment #3:

User-defined inputs are currently:

1. Battery power
2. # of cells & modules
3. Target voltage at max power
4. Battery pack energy or vehicle electric range & efficiency

We think that this model would be improved with this input also (or in place of #1):

1. A metric for acceleration such as the time it takes to accelerate from 0-60 mph at a specified temperature.

Comment #4

Metal pricing is ignored. This model claims to be forecasting pack cost in 2020 but does not appear to be accounting for changes in the cost of active materials over time. This paper would benefit from an overview early on as to how typical battery pack cost breaks down. By far and large, the main component of pack cost is battery active material cost. Cost projections should focus on the impact of this – the biggest slice of the pie.

Comment #5

The impact of form factor is not given much attention. The assumption is made that form factor will not make much of a difference at high volume. It would help to see some calculations backing up this assumption. Show that a cylindrical cell will cost about the same as a stacked prismatic or indicate the anticipated differences in cost.

Comment #6

The model solves iteratively for pack energy or range, varying cell capacity & electrode thickness & then determines the mass, volume & material requirements to make the car. These requirements are used to calculate cost. We think that the output from this model could be much more useful. We'd like to see pack cost over time for each chemistry.

There was no data shown to validate the assumptions that were made in calculating electrode thickness from ASI measurements for each chemistry. Impedance measurements change drastically depending on not just electrode thickness, but also chemistry, particle size, separator thickness, current-collector thickness, choice of electrolyte, and temperature, etc. This model is making some very big assumptions and it is not clear what error may be introduced. Does it make sense to use the same assumptions for HEV, PHEV and EV batteries (for example, current collector thickness)? What error could be introduced? Can this be quantified? This should be discussed.

Comment #7

It is mentioned as a future work item – the model needs a cooling/heating system and to capture the effects of temperature.

Comment #8

The model would benefit from increasing the # of user definable inputs, such as SOC window of operation for an EV (80% is too conservative).

Comment #9

The model attempts to capture the fixed costs for the battery pack, but ends up making some very simplified assumptions. If this section remains in the model, we suggest that it involve many user-defined inputs. The model currently does not capture the cost of safety features such as isolation contactors.

Comment #10

5-year depreciation is commonly used in the battery industry. The study is using 8 year, which is too long.

Comment #11

Please include instructions for how to turn on iterations for other versions of Excel, including 2007. The pointer about closing all open Excel documents worked for us but was given over email.

Comment #12

It would be helpful to see $/Wh cell and pack costs in the spreadsheet.

Peer review of the report, "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles"

Report by: Erin O'Driscoll

Date of Report:

As a reviewer you are to orient your comments toward the six (6) general areas listed below. You are expected to identify additional topics or depart from these examples as necessary to best apply your particular set of expertise toward review of the model.

Comments should be sufficiently clear and detailed to allow readers to familiarize with the report to thoroughly understand their relevance to the material provided for review. EPA requests that the reviewers not release the peer review materials or their comments until ANL makes its report/cost model and supporting documentation public. EPA will notify the reviewers when this occurs.

Below you will find a template for your comments. You are free to use this template to facilitate the compilation of the peer review comments, but do not feel constrained by the format. You are free to revise as needed; this is just a starting point.

If you have questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If you have any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory by phone (734-214-4017) or through e-mail (schenk.ruth@epa.gov).

(1) **Assumptions.** Please comment on the validity of any assumptions embedded in the model that could affect projected battery pack price or performance. Please comment on any assumptions that appear to be unstated and/or implicit.

Example Assumptions	**Reviewer Comment(s)**
Cell construction and format	• It is ambiguous if the cell is pouch or can in early sections (drawing is misleading). Later it become clear. • Construction and format are within norms, but many folks at winding with individual electrodes, not using the back and forth folding method.
Comparability to competing cell formats	• •
Cooling and thermal management requirements	• Air cooling is often inadequate for EV packs today. It could be that pack in 2020 can achieve good performance with air cooling alone, but this assumption should be spelled out more clearly •
Electrode volumetric change	• Assumption of zero volumetric change is optimistics 10% over full SOC range is more reasonable. •
Limiting parameters affecting cell dimensions or performance (for example, allowable A-hr capacity per cell, maximum electrode thickness, etc)	• Numbers are within standards today. I would assume by 2020 there would be higher capacity materials that would give higher energy densities in smaller sizes. •
Warranty costs and profit	• I would expect warranty assumptions to be somehow related to performance like cycle life or calendar life. This is especially concerning in air cooled pack. I think an assumption related to cooling system and life would make more sense but would be challenging to build into this model now. •
Scrap rates	• Looks reasonable. •
Safety and manufacturability	• Safe handling of inorganic metal powder is not addressed well at all here. EPA guidelines for handle materials with Ni an Co are much different than Fe and hence one would expect different cost structure to handle the materials in the process. Section 4.3.2 does not address moving powder through the process and

	cleaning up safely • Handling of large quantities of electrolyte without contamination is also not handled well. What size container is expected and how is the material kept clean and dry at this scale?
Anticipated industry design trends, and similar factors	• I believe that by 2020 there will be some non-slurry coating manufacturing approaches on the market. In this case the solid electrode would be directly deposited on current collector – difficult to model now but I believe this will be validated by then •
Additional reviewer comments	• •
Additional reviewer comments	• •

(2) **Inputs and Parameters.** Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Please comment on any caveats or limitations that these inputs and parameters entail with respect to use of the results as the basis for estimating the manufacturing cost or performance of lithium-ion battery packs.

Example Assumptions	**Reviewer Comment(s)**
Embedded or default values chosen by the authors (for example, those that represent default material costs, material percentages, preferred dimensions, experimentally measured values, etc)	• Look in line with my expectations •
The adequacy of user-specifiable parameters and their allowable ranges (for example, those that specify performance requirements, or those that relate to cell chemistries or cell/module/pack configuration possibilities)	• Difficult to fully assess this in the time period given. •
Additional reviewer comments	• •
Additional reviewer comments	• •

(3) **Cost methodology.** Please comment on the validity and applicability of the methodologies used in estimating battery manufacturing costs. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations.

Example Assumptions	**Reviewer Comment(s)**
General scaling methods on manufacturing and material costs	• •
Effect of production level on manufacturing and material costs	• •
Method of accounting for warranty costs and profit	• See previous comment on warranty. Without correlation to data warranty assumptions are reasonable. Profit assumptions are reasonable. •
Effect of demand on raw material costs	• •
Depreciation	• •
Research and development	• •
Baseline plant design and scaling	• •
Additional reviewer comments	• Working capital seems low •
Additional reviewer comments	• •

(4) **Performance methodology.** Please comment on the validity and applicability of the methodologies used in calculating the power and energy performance of the designed battery. Please comment on any apparent unstated or implicit assumptions (e.g., regarding ambient temperatures or other factors that may affect battery performance) and on any related caveats or limitations.

Example Assumptions	**Reviewer Comment(s)**
How the physical properties and dimensions of cell components are calculated from the inputs	• In theory looks good •
How power, energy capacity, resistances, currents, are calculated	• Theory looks sound •
Additional reviewer comments	• In general I have concerns that with the approach from theory only to full scale cost model. Any theory should be correlated with experimental results. I am surprise that no correlation is made to actual data. While properties of materials like mA/g are true in theory many times they are not accurate in practice. At least one example showing a cell and/or pack that correlates to this model is necessary for credibility that this approach is valid. •
Additional reviewer comments	• •

(5) **Completeness.** Please comment on whether the model adequately identifies the cost components of battery pack manufacturing.

Example Assumptions	**Reviewer Comment(s)**
Physical components of the cells and assembled packs	• •
Support circuitry such as for cell charge control and balancing	• Active cell balance is new but should be standard for 2020 •
Manufacturing steps	• Very standard •
Raw materials and labor	• Labor is low across the board. Labor may be lower in 2020 but I don't see additional automation build in to achieve a decrease in labor. •
Energy inputs and consumables used in manufacture	• •
Capital equipment	• •
Research and development costs for battery design, development, and production implementation	• •
Battery control system hardware and software	• •
Additional reviewer comments	• •
Additional reviewer comments	• •

(6) **Recommendations.** Please comment on the overall adequacy of the model for predicting future battery prices, and on any improvements that might reasonably be adopted by the authors to improve the model. Please note that the authors intend the model to be open to the community and transparent in the assumptions made and the methods of calculation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.

Statement in Dr. O'Driscoll's e-mail during submission of comments:

The article is very ambitious in its goals. As I wrote in my comments, I have concerns with the approach from theory to full scale cost model without correlating theory to data.

Peer review of the report, "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles"

Report by: Joe Adiletta, A123 Systems

Date of Report: 2/28/11

As a reviewer you are to orient your comments toward the six (6) general areas listed below. You are expected to identify additional topics or depart from these examples as necessary to best apply your particular set of expertise toward review of the model.

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Below you will find a template for your comments. You are free to use this template to facilitate the compilation of the peer review comments, but do not feel constrained by the format. You are free to revise as needed; this is just a starting point.

If you have questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If you have any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory by phone (734-214-4017) or through e-mail (schenk.ruth@epa.gov).

(1) **Assumptions.** Please comment on the validity of any assumptions embedded in the model that could affect projected battery pack price or performance. Please comment on any assumptions that appear to be unstated and/or implicit.

Example Assumptions	**Reviewer Comment(s)**
Cell construction and format	• Opposite-side tabbing structures for energy-based systems goes against most common cell formats (canned or pouch), which have same-side terminals • Specific material assumptions produce a generally usable view of the market, yet do not use optimized designs that specific manufacturers are likely to employ • Thicknesses of substrates might be double-checked/triangulated
Comparability to competing cell formats	• The model assumes an opposite-end tabbed cell design in pouch form factor. Organizations such as VDA are employing specifications for metal-canned prismatic cells as well, which offer differing price/performance characteristics • Cylindrical cells for HEV are not considered, nor are wound electrode designs in general
Cooling and thermal management requirements	• A wide variety of cooling strategies necessitates flexibility here, though perhaps with some built-in functionality/choice around air vs liquid cooling and/or active versus passive •
Electrode volumetric change	• •
Limiting parameters affecting cell dimensions or performance (for example, allowable A-hr capacity per cell, maximum electrode thickness, etc)	• Assuming that all chemistries have a similar usable energy window (within 5% of one another) is not valid in practice. This is true for both PHEV and EV. A larger disparity between oxides and phosphates exists. • There will definitely be a max electrode thickness based on the specific chemistry involved. More pointedly, there will be a max thickness based on the specific cell TYPE that is being developed: microHEV, HEV, PHEV or EV
Warranty costs and profit	• I think that it would make more sense to target a before-tax profit and structure the model around target margin. Predicting and/or modeling the going corporate tax rate would likely be difficult in and of itself • Profit rate looks a bit lower than expected over the long-term

Scrap rates	• Are scrap rates inclusive of end of line testing? • NMP recycling number seems high
Safety and manufacturability	• Certainly the addition of certain components to ensure safety must be accounted for. For example, the oxide-based chemistries often use ceramic coatings on the separator or anode to compensate for the inferior abuse tolerance of that chemistry. The cost of this must be included in the cell cost. • I think that a 300um, thick electrode coating is somewhat aggressive to expect performance out of the design
Anticipated industry design trends, and similar factors	• The industry seems to be attempting to move towards a more standardized form factor – VDA specifications, as well as SAE proposals • From a cost perspective, you'll likely have to assume some take-off in overall volumes. There is some sensitivity to where this will all play out, but it will have a profound effect on materials costs for specific manufacturers. Thus, constructing the model to be based on number of vehicles produced makes sense.
Additional reviewer comments	• I mention this below, so you'll see it twice, but the way the cells are designed given the thickness of electrodes and number of layers in many ways doesn't follow conventional design strategy. For instance, in the base case sent around (PHEV done by mileage), the thickness of the electrodes varies, which it wouldn't in practice, leading to higher overall current collector costs in smaller capacity/range systems. In fact, it would work the other way: You would settle on a single electrode design for the cell-type (HEV, PHEV, EV) and then vary the number of layers based on that design to accommodate different ranges. •
Additional reviewer comments	• •

(2) **Inputs and Parameters.** Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Please comment on any caveats or limitations that these inputs and parameters entail with respect to use of the results as the basis for estimating the manufacturing cost or performance of lithium-ion battery packs.

Example Assumptions	**Reviewer Comment(s)**
Embedded or default values chosen by the authors (for example, those that represent default material costs, material percentages, preferred dimensions, experimentally measured values, etc)	• Electrode design specifications are often unique to individual manufacturers. The existing values might be adjusted based on other publicly available information • Materials costs inputs do not necessarily match with going rates in volume production • The assumption that all negatives will necessarily use a water-based binder system should be questioned, especially given the range of cell-types being investigated – micro-HEV through EV
The adequacy of user-specifiable parameters and their allowable ranges (for example, those that specify performance requirements, or those that relate to cell chemistries or cell/module/pack configuration possibilities)	• For micro-hev and HEV, it would make sense to specify power required, rather than the choices currently available: Capacity, Energy or Range. This is especially true if 2/4 of the options are HEV related (micro and full) • I assume that some of the user inputs are considered in the model for future use? For instance, ASI seems to be calculated but not necessarily applied, as do entries like temperature rise, etc. • I understand as reviewers we are supposed to focus on the quantitative aspects of the model; however, structuring the model for use by someone not well versed in specifics of chemistry would be useful. For instance, it's not quite clear exactly what all of the inputs and outputs are. There are clearly sheets that contain foundational information but might not be used by someone doing top-level analysis.
Additional reviewer comments - cell	• Any reason to not consider 2p configurations? Are you assuming that by 2020 all cells will be optimally sized for the application? • You assume that manufacturing costs scale independently of cell design, which is not entirely appropriate. For instance, the cost of forming a cell may be linear to the number of cell layers, but the depreciation cost on a per cell basis of the stacking equipment will not be, given that your cell designs do not appear to scale number of layers linearly with capacity
Additional reviewer comments - pack	• Looking at today's vastly different pack structures/constructions, it would make sense to account for some variation there. Two

	examples: (1) I did not see a liquid versus air cooling entry point; (2) Some packs use aluminum cooling plates as separators, others use only passive-type cooling with no structural support • Have government subsidies on capex purchases been factored in here as well?

(3) **Cost methodology.** Please comment on the validity and applicability of the methodologies used in estimating battery manufacturing costs. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations.

Example Assumptions	**Reviewer Comment(s)**
General scaling methods on manufacturing and material costs	• I would only comment that at a certain volume, significant changes to manufacturing process will be required, which will bring associated reductions in cost. This model seems based on today's methodologies, however applied to 2020, which may not be realistic • The material cost structure (BOM) as outlined is not indicative of TODAY's pricing, which would imply significantly higher costs than what we would expect to see in 2020
Effect of production level on manufacturing and material costs	• There is going to be a significant delta in materials costs based on expected production volume. This should be able to be added, even if in vague terms via percent cost downs based on specific manufacturing thresholds • Coating facilities run at speeds entirely dependent on the chemistry and cell design, thus drastically altering the amortization of costs to the cell. This augmentation might be considered
Method of accounting for warranty costs and profit	• Typically we'd talk about warranty as a % of cost, which I assume is what "added to price" means, rather than a % of final price •
Effect of demand on raw material costs	• This does NOT seem to be accounted for. The effect is real, quantifiable and quite different for each battery manufacturer depending on volume and relationship • Especially out in 2020 and beyond, some reasonable assumptions must be made based on today's high volume cost rates. It does not appear that this was taken into account. At the very least a single input for % decrease based on volume might be added
Depreciation	• Have you accounted for government subsidies in the acquisition of capital equipment? • 8 years on manufacturing equipment seems a bit long
Research and development	• Typically we'd talk about R&D as a % of revenue rather than of depreciation •
Baseline plant design and scaling	• Initial plant design looks reasonable. I think you should consider scalability based on

	volume assumptions. At some point, volumes could become large enough that a transition to new manufacturing strategies would make sense in order to continue down the cost curve. • Scaling would be done incrementally based on capacity ramp-ups. To that extent, the model seems to function linearly with respect to invested capital, whereas that's not the "true" effect, where 100s of millions are invested for a fixed capacity which may or may not be fully utilized, and thus cost affected.
Additional reviewer comments	• Quick point of presentation. Given that the model will likely be reviewed by OEMs as well as small startups and suppliers, it would be beneficial to break out your cost analysis into Cell and non-cell components. Some OEs will be just buying cells and will likely be interested in your analysis, thus lumping all labor, OH and SGA into single buckets may not be the most appropriate strategy. •
Additional reviewer comments	• •

(4) **Performance methodology.** Please comment on the validity and applicability of the methodologies used in calculating the power and energy performance of the designed battery. Please comment on any apparent unstated or implicit assumptions (e.g., regarding ambient temperatures or other factors that may affect battery performance) and on any related caveats or limitations.

Example Assumptions	**Reviewer Comment(s)**
How the physical properties and dimensions of cell components are calculated from the inputs	• It seems that the cell thickness and number of layers are oddly calculated. In the standard 10mi PHEV case, you end up with a 16um cathode – obviously unrealistic, which then required 64 layers? I think an alternate approach would be to target a thickness based on the type of cell desired, and subsequently vary the number of layers to achieve differing mileage/capacity packs • As with thicknesses, densities are variable based on chemistry employed and desired cell type – HEV vs EV • You would not necessarily constrain the thickness of the cell based on the cell type, for instance 10mm for PHEV. In non-standard designs (those outside of a footprint standard like VDA), you might float the thickness to achieve a given capacity once you have a footprint in mind.
How power, energy capacity, resistances, currents, are calculated	• I'm curious as to why the power was a user input rather than calculated from the ASI, which seemed to be painstakingly calculated. When comparing chemistry to chemistry, the delivered power based on the cell design is important • Your limiting C-rate is not going to be constant, it will vary based on cell design and chemistry, which is also based on the application you would be designing the cell for: micro-HEV, HEV, PHEV, EV
Additional reviewer comments	• •
Additional reviewer comments	• •

(5) **Completeness.** Please comment on whether the model adequately identifies the cost components of battery pack manufacturing.

Example Assumptions	**Reviewer Comment(s)**
Physical components of the cells and assembled packs	• Cost of terminal assemblies seems low • No cost accounted for tape in cell (albeit small cost)
Support circuitry such as for cell charge control and balancing	• •
Manufacturing steps	• There are certainly inspection steps that require personnel and equipment not included in the process steps •
Raw materials and labor	• •
Energy inputs and consumables used in manufacture	• •
Capital equipment	• •
Research and development costs for battery design, development, and production implementation	• •
Battery control system hardware and software	• •
Additional reviewer comments	• It would be nice to have an overall summary sheet that compared packs of different chemistries side by side • Augmenting the model with the capability to size a system based on desired capacity/energy rather than dealing with system sizes as prescribed by the model • The targeted user should be considered when structuring the model's inputs/outputs such that someone not completely versed in battery chemistry/manufacturing structure might be able to use the tool
Additional reviewer comments	• From a general completeness standpoint, I would say that the model has MOST aspects well covered. The real issue is with generalizing battery manufacturing. Every manufacturer deals with a specific chemistry, with specific designs, with specific manufacturing processes, subsidies, etc. This makes this type of information extremely difficult to not only publicly disclose, but also

	to model with reliable and useful results. Being on the outside of the industry looking in is a difficult position to be in relative to modeling each of these parameters such that a lay-person might understand the key issues that a specific manufacturer has to tackle.

(6) **Recommendations.** Please comment on the overall adequacy of the model for predicting future battery prices, and on any improvements that might reasonably be adopted by the authors to improve the model. Please note that the authors intend the model to be open to the community and transparent in the assumptions made and the methods of calculation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.

Peer review of the report, "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles"

Report by: Michael Bly

Date of Report: Feb 28, 2011

As a reviewer you are to orient your comments toward the six (6) general areas listed below. You are expected to identify additional topics or depart from these examples as necessary to best apply your particular set of expertise toward review of the model.

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(1) **Assumptions.** Please comment on the validity of any assumptions embedded in the model that could affect projected battery pack price or performance. Please comment on any assumptions that appear to be unstated and/or implicit.

Example Assumptions	**Reviewer Comment(s)**
Cell construction and format	• Seems reasonable and appropriate •
Comparability to competing cell formats	• Seems reasonable and appropriate •
Cooling and thermal management requirements	• Does not appropriately recognize the trade offs of life and thermal effects. • Much further model refinement would be needed to improve the models accuracy.
Electrode volumetric change	• •
Limiting parameters affecting cell dimensions or performance (for example, allowable A-hr capacity per cell, maximum electrode thickness, etc)	• •
Warranty costs and profit	• See cooling and thermal management requirements •
Scrap rates	• Scraps rates do not represent benchmark practices … should be re-evaluated.
Safety and manufacturability	• •
Anticipated industry design trends, and similar factors	• •
Additional reviewer comments	• In general most of the cost models do not seem aggressive enough for 2020 forecasted total costs.
Additional reviewer comments	• •

(2) **Inputs and Parameters.** Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Please comment on any caveats or limitations that these inputs and parameters entail with respect to use of the results as the basis for estimating the manufacturing cost or performance of lithium-ion battery packs.

Example Assumptions	**Reviewer Comment(s)**
Embedded or default values chosen by the authors (for example, those that represent default material costs, material percentages, preferred dimensions, experimentally measured values, etc)	• Seems appropriate for this study •
The adequacy of user-specifiable parameters and their allowable ranges (for example, those that specify performance requirements, or those that relate to cell chemistries or cell/module/pack configuration possibilities)	• Seems appropriate for this study •
Additional reviewer comments	• •
Additional reviewer comments	• •

(3) **Cost methodology.** Please comment on the validity and applicability of the methodologies used in estimating battery manufacturing costs. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations.

Example Assumptions	**Reviewer Comment(s)**
General scaling methods on manufacturing and material costs	• Raw material scaling costs are reasonable for this study •
Effect of production level on manufacturing and material costs	• •
Method of accounting for warranty costs and profit	• Warranty cost model seems to be appropriate for this study • SG&A and profit seem to be very high compared to current market and will not improve to these levels with current over capacity projects in the free trade markets
Effect of demand on raw material costs	• Demand assumptions do not show an obvious strong influence of material cost and seems reasonable •
Depreciation	• Model shows an 8 year amortization which is slightly higher than current norms in the industry •
Research and development	• No comment. Too variable in this fast pace development area •
Baseline plant design and scaling	• 20year amortization of capital investment is much lower than actual practice in Asia supply base • Model for building cost does not seem realistic, unless model assumes continuous government incentives, which is not realistic in this timeframe.
Additional reviewer comments	• •
Additional reviewer comments	• •

(4) **Performance methodology.** Please comment on the validity and applicability of the methodologies used in calculating the power and energy performance of the designed battery. Please comment on any apparent unstated or implicit assumptions (e.g., regarding ambient temperatures or other factors that may affect battery performance) and on any related caveats or limitations.

Example Assumptions	**Reviewer Comment(s)**
How the physical properties and dimensions of cell components are calculated from the inputs	• •
How power, energy capacity, resistances, currents, are calculated	• •
Additional reviewer comments	• •
Additional reviewer comments	• •

(5) **Completeness.** Please comment on whether the model adequately identifies the cost components of battery pack manufacturing.

Example Assumptions	**Reviewer Comment(s)**
Physical components of the cells and assembled packs	• Seem appropriate •
Support circuitry such as for cell charge control and balancing	• Model assumptions simplify the circuitry to represent a state of the art battery management system •
Manufacturing steps	• •
Raw materials and labor	• Labor rates are appropriate only for US •
Energy inputs and consumables used in manufacture	• This model significantly underestimates energy input cost. Unrealistic as presented •
Capital equipment	• Very much underestimate capital investment required for cell manufacturing with state of the cell technologies •
Research and development costs for battery design, development, and production implementation	• Unable to comment •
Battery control system hardware and software	• Seems appropriate based on state of the art design •
Additional reviewer comments	• Model seems to have a very high level of cost structure with lack of details in burden, interest, maintenance, and indirect labor. •
Additional reviewer comments	• •

(6) **Recommendations.** Please comment on the overall adequacy of the model for predicting future battery prices, and on any improvements that might reasonably be adopted by the authors to improve the model. Please note that the authors intend the model to be open to the community and transparent in the assumptions made and the methods of calculation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.

Overall the model is very comprehensive in its design and structure. The information provided in the modeling uses publically recognized inputs but has a wide variation in cost that may be regionally dependent. All costs are projected for calendar year 2020 and are based on a high level structure that lacks detail in burden cost (missing energy cost, interest, machine maintenance, in-directed labor, etc). Additionally, there are several areas in which the assumptions are very conservative when compared to what has been achieved in production today. For example:

- Manufacturing Yield rate (92%) estimated by ANL is conservative for 2020. Targets from Tier 1 suppliers have been a minimum of 98%.
- Labor Cost – ANL did not specify an hourly rate of labor but estimated a rate of $1.62 per cell. Production labor cost is significantly less based on a per cell basis.
- Depreciation Cost – The assembly line process capacity does not seem realistic and will have a direct impact of the total cost for the Electrode and Assembly. As a result, the estimate for impact to burden cost is greater than 1.5 times too high.
- Area Cost – The building construction cost does not seem realistic and is lower in years amortized for capital investment and total dollars for building and land.
- SGA and Profit – ANL estimated 25% of direct labor and variable overhead plus 35% of depreciation for SGA. ANL also estimated 5% of investment cost for profit. Again, these estimates result in a cost impact greater than 1.5 times too high.
- Warranty Cost – The warranty cost for the pack alone seems too high.

It is expected that by 2020 there will be significant improvements in cost. With the cost numbers in this report already conservative when compared to what has been achieved in production today, the cost model may be overstated by the time actual 2020 costs are realized.