AN EVALUATION OF CURRENT AND FUTURE COSTS FOR LITHIUM-ION BATTERIES FOR USE IN ELECTRIFIED VEHICLE POWERTRAINS

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ABSTRACT

Powertrain electrification is a concept which encompasses hybrid-electric vehicles (HEVs), plug-in hybrid-electric vehicles (PHEVs), and pure electric vehicles (EVs). Such vehicles have received attention recently as a potential solution for reducing the carbon intensity of the transportation sector. The fundamental challenge to the commercial success of electrified vehicles is energy storage. Consensus in the automotive industry is that lithium-ion (Li-ion) batteries are the most likely candidate for overcoming this challenge in the next decade. However, these batteries must meet five categories of goals in order for them to enable the success of electrified vehicles: energy, power, lifetime, safety, and cost.

Of these five goals, cost may be the most uncertain, and perhaps the most critical. This research examines the primary cost drivers for automotive Li-ion batteries at the cell-, module-, and pack-level. It then investigates how these costs may change over the next two decades, and what impact this may have on the cost-competitiveness of electrified vehicles. This is accomplished through the development of a bottom-up cost model that considers the materials cost, manufacturing cost, and other costs such as corporate overhead and research and development that contribute to overall Li-ion battery costs. Two scenarios of how these costs may change are developed: an optimistic case and a pessimistic case. Additionally, the level to which battery costs must decline in order for vehicles of varying levels of powertrain electrification to become economically competitive with their conventional internal combustion engine counterparts is calculated.

Results indicate that the primary cost drivers for Li-ion batteries at the pack-level are cell-level materials cost and manufacturing yields. Improvements in these areas will be key drivers for reductions in overall battery costs, and may make electrified vehicles cost-competitive with conventional automobiles. However, this cost-competitiveness is highly sensitive to fuel prices. Various policy and market mechanisms can significantly impact the economic viability of electrified vehicles and influence the rate at which they are adopted.

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INTRODUCTION

Light-duty vehicles (LDVs) have long relied on gasoline as the fuel for their internal combustion engines. Although the electric drivetrain is as old as the automobile itself, it has been dominated by its noisier, more complex, more polluting, less efficient, and lower performing rival for nearly a century.[1] There are several reasons for this, but the fundamental challenge for the success of electric vehicles is now, as it has always been, energy storage (Anderman, 2007; Mandel, 2007; Murphy, June 12, 2008; Rauch, 2008).

Recently, several factors have converged, stimulating renewed interest in powertrain electrification – a concept which encompasses hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and pure electric vehicles (EVs). The most obvious of these factors is the increase in the level and volatility of oil prices in recent years, which has resulted in a significant increase in the per-mile cost of driving due to the high price of gasoline. During 2008, such high gas prices resulted in a shift in the vehicle purchasing habits of American consumers, as large, inefficient trucks and SUVs remained on dealer lots while sales of smaller, more economical cars – especially HEVs – sharply increased (Agence France - Presse, 2008).[2] Secondly, Americans are increasingly accepting of the notion that global warming is, at least in part, anthropogenic, and are attempting to modify their behavior to reduce their energy use and carbon footprint (Business Wire, 2008; Smith & Murphy, December 30, 2008). Thirdly,

[1] Early electric carriages were available as early as the 1830s. Electric cars reached their prime around 1900, when 28% of the vehicles produced in the U.S. were electric drive. By the 1920s, however, electric cars were no longer commercially viable (PBS.org, 2006).

[2] Unfortunately for the electrified vehicle industry, as oil and gasoline prices plummeted in late 2008, demand for fuel-efficient vehicles softened (Smith & Murphy, December 30, 2008; White, 2009). The uncertainty in fuel prices in the future, however, as well as concerns over energy security and climate change prompted U.S. Senator Byron Dorgan (D-ND) to state, "there is no less urgency for the change we need at $2 per gallon gas than there was at $4 per gallon gas"(Electric Drive Transportation Association Conference).

significant advancements in the state of battery technology may soon solve the challenge of energy storage. This challenge has already been met for HEVs, as demonstrated by the success of vehicles such as the Toyota Prius and its nickel metal hydride (NiMH) battery, achieving a fuel economy of nearly 50 miles per gallon ("FuelEconomy.gov," 2008). Furthermore, automakers such as GM and Toyota have announced the introduction of next-generation HEVs and PHEVs as early as 2010, based on lithium-ion (Li-ion) battery technology (Mandel, 2007; Murphy, June 12, 2008). In fact, industry consensus is that Li-ion batteries will become the dominant technology for electrified powertrains, just as it has become the leading battery chemistry for consumer electronics such as laptop computers and cell phones (Axsen, Burke, & Kurani, 2008; Barnett, 2008; Kalhammer, Kopf, Swan, Roan, & Walsh, 2007; Kromer & Heywood, 2007). However, there are significant differences between Li-ion batteries for consumer electronics and those for automotive applications, specifically with regards to lifetime and safety requirements.

Unlike the term “nickel metal hydride,” which specifies one particular battery chemistry, the term “lithium-ion” refers to a family of battery chemistries of which there are many varieties. Each of these Li-ion battery chemistries has strengths and weaknesses with respect to the five categories of goals that must be met in order for large-scale commercialization of electric powertrains to be successful: energy, power, lifetime, safety, and cost (Axsen, et al., 2008). Energy, typically discussed in terms of energy density (watt-hours per liter, Wh/l) or specific energy (watt-hours per kilogram, Wh/kg), is important because it translates into vehicle range. High energy density is more important for PHEVs and EVs than for HEVs which use small batteries to recover energy from braking and coasting events and to provide complementary power for acceleration. Power, discussed in terms of power density (watts per liter, W/l) or

specific power (watts per kilogram, W/kg), is important because it translates into the motive force which provides vehicle acceleration. High power density is more important for HEVs than for PHEVs and EVs which have larger batteries that can still provide adequate power with lower power densities. Lifetime is important with respect to both calendar-life and cycle-life. Consumers expect vehicle batteries to last the life of the vehicle, which is now generally accepted to be fifteen years or 150,000 miles, and which could span thousands or hundreds of thousands of charge/discharge cycles depending on the application and use. Safety is important for obvious reasons – a small laptop battery experiencing a thermal runaway event is concerning, but a similar occurrence in a large EV battery could be catastrophic. Finally, cost is important as it is key for electrified powertrains achieving (or failing to achieve) commercial success, even if the other criteria are met.

Of the five criteria discussed above, cost may be the most uncertain. Energy and power densities can be accurately measured, and research shows that the practical limit for Li-ion technology is around 300 Wh/kg, approximately 50% greater than current technology, suitable for HEVs, PHEVs, and EVs (Kromer & Heywood, 2007). Various electrode materials are continually being developed, further increasing lifetime and safety characteristics so that major automotive OEMs, notoriously conservative when releasing new technology, are comfortable announcing forthcoming HEV and PHEV vehicles. The United States Advanced Battery Consortium (USABC) has outlined goals in terms of dollars per kilowatt-hour ($/kWh) that battery technology must reach to make various electrified vehicles commercially viable, approximately $200-$300/kWh (compared to current costs of $750-$1000/kWh) (Axsen, et al., 2008; Electrochemical Energy Storage Tech Team, 2006). It is generally believed that Li-ion batteries still have significant potential to achieve such cost reductions, more so than older

NiMH batteries (Irwin, 2008; Kromer & Heywood, 2007). Mechanisms by which battery costs may be reduced include the use of lower cost materials, increased packaging efficiencies, process improvements, economies of scale, and increased manufacturing yields (Hsiao & Richter, 2008; Irwin, 2008; Lache, et al., 2008). However, the rate at which these mechanisms may drive battery costs down is not precisely known. The most comprehensive publicly available studies on advanced automotive battery costs are one prepared for the California Air Resources Board by the Year 2000 Battery Technology Advisory Panel (Anderman, Kalhammer, & MacArthur, 2000) and updated in 2007 (Kalhammer, et al., 2007), and another by Argonne National Lab's Transportation Technology R&D Center (Gaines & Cuenca, 2000). These studies largely focus on current battery costs, while relying on industry estimates of how overall battery costs may scale with volume manufacturing. The most recent of these three studies concludes, "In the longer term, there appear to be good prospects for reduction of Li-ion battery costs…. The magnitude of this cost reduction potential cannot be assessed at this time " (Kalhammer, et al., 2007).

This research explores the path that Li-ion battery costs may take in the next twenty years under different scenarios of technological advancement and deployment. The detailed, spreadsheet-based technical cost model for Li-ion battery technology, developed as part of this research, disaggregates the numerous cost drivers and allows for the identification of the most important levers for reduction of total battery costs. Future battery costs are crucial to the success of electrified vehicles, and understanding the battery cost curve is valuable to investors who give financial backing to the numerous battery companies that are being created, to automobile manufacturers for whom cost is paramount and for whom product development cycles begin years in advance of new vehicle introductions, and for policy makers who need to

understand the economics associated with electrified powertrains in order to make decisions regarding technology policy as part of broader energy and climate change policy.

BACKGROUND

Lithium-Ion Battery Basics

Electricity is not easily stored. Thus, Li-ion batteries, like all other battery types, store energy electrochemically. Electricity is produced in the Li-ion battery via an electrochemical reaction that is enabled by the four major components of the battery cell: the positive electrode (the cathode), the negative electrode (the anode), the electrolyte, and the separator.[3] Figure 1 illustrates these components, as well as the flow of lithium ions and electrons during charge and discharge states.

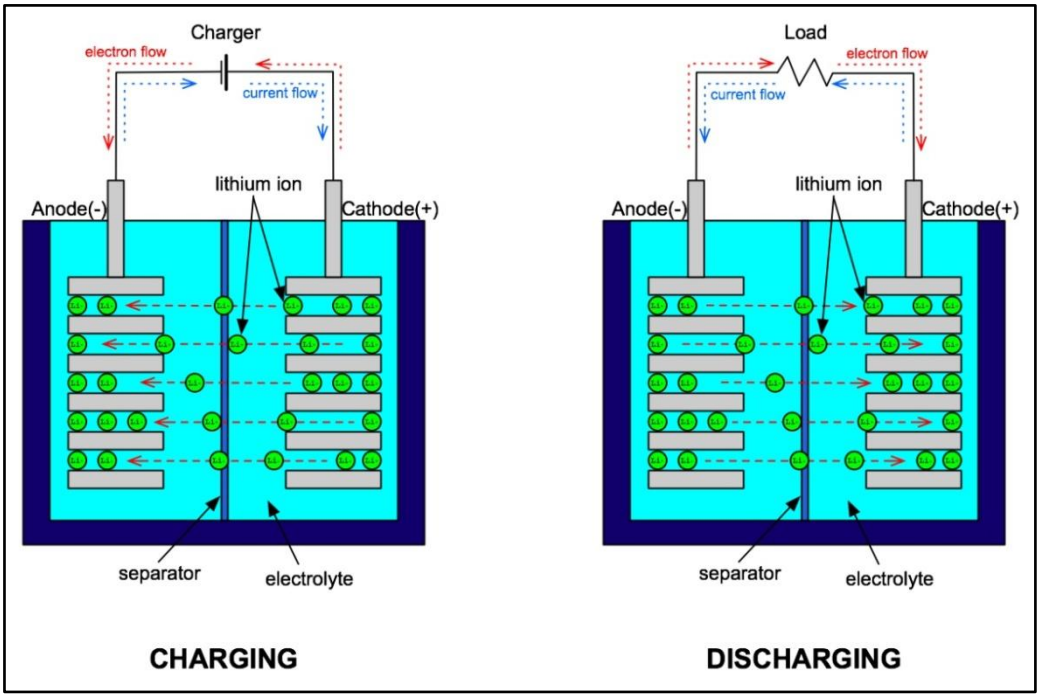

Figure 1: Electrochemical Storage in a Li-Ion Cell

[3] For a more complete description of the construction and basic operation of Li-ion batteries, refer to such commonly available sources as http://en.wikipedia.org/wiki/Lithium_ion_battery and (Buchman, 2005).

Both the cathode and the anode are comprised of intercalation compounds, which allow lithium ions to be inserted and removed during charge and discharge. The cathode in traditional Li-ion cells is a transition metal oxide such as lithium cobalt oxide ($LiCoO_2$), while the anode is typically comprised of carbon in the form of graphite (Beach, 2008). The electrolyte is typically a lithium salt such as lithium hexafluorophosphate ($LiPF_6$) dissolved in an organic solvent, while the separator may be made of polyethylene or polypropylene (Kalhammer, et al., 2007). The electrolyte provides an ionically conductive path through which the lithium ions migrate during charge and discharge, while the separator prevents short-circuiting between the cathode and anode while allowing ions to pass.

Though most research is aimed at improving Li-ion battery technology at the cell-level, it should be noted that, for automotive applications, individual cells are typically connected together in various configurations and packaged with associated control and safety circuitry to form a battery module. Multiple modules are then combined with additional control circuitry, a thermal management system, and power electronics to create the complete battery pack, such as the one made by A123 Systems shown in Figure 2 on the following page (Gaines & Cuenca, 2000). There are costs associated with each level of integration, and these must be considered when doing cost modeling since it is the cost of the complete battery pack that is relevant to the consumer.

Despite the fact that virtually all hybrid vehicles available today rely on NiMH batteries, current efforts to solve the energy storage problem for electrified vehicles focus on Li-ion battery technology. This is primarily due to Li-ion's advantages over NiMH with respect to energy density and cost. Li-ion batteries can store more energy per mass and volume than NiMH because lithium is a lightweight metal and because Li-ion's electrochemical properties result in a

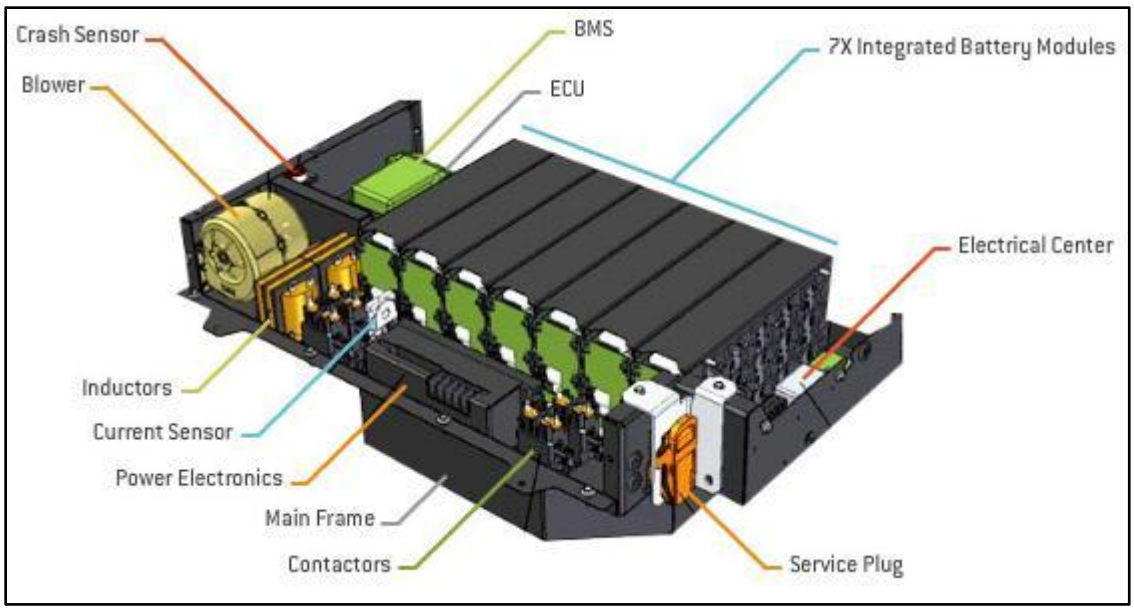

Figure 2: Li-Ion Battery Pack for a PHEV (A123 Systems, 2008b)

cell voltage between 3.3V and 4.3V compared to 1.2V for NiMH (Axsen, et al., 2008; Kromer & Heywood, 2007). Cost advantages arise due to the fact that Li-ion batteries scale more readily to high volume production and can be made with a variety of materials, allowing for cost reductions through material substitution. The cost for NiMH batteries, on the other hand, is inherently tied to the relatively expensive commodity price of nickel (Kromer & Heywood, 2007).

Lithium-Ion Cell Types and Materials

Li-ion battery cells come in a variety of form factors, but the most common for automotive applications are cylindrical cells and prismatic cells. Historically, the most ubiquitous cell-type has been the 18650 cylindrical cell, slightly larger than the "AA" type battery with which most consumers are familiar, though this format is typically considered too small to be of practical use in automotive applications.[4] Larger cylindrical cells are also

[4] Though the 18650 cell is not ideal for automotive use, Tesla Motors uses a total of 6,831 of these cells in the 53kWh, 450kg battery pack of its all-electric Roadster, along with sophisticated control circuitry to ensure safe operation. While this is not a cost-effective solution for the long term, the availability of the 18650 cells has allowed Tesla Motors to introduce its all electric super-car without relying on further advancements in battery technology.(Voelcker, 2007)

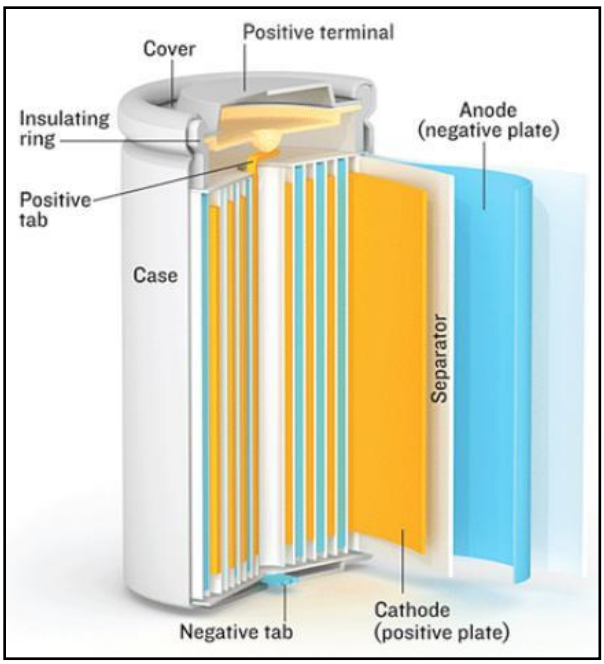

Figure 4: Cylindrical Cell Construction (Voelcker, 2007)

available. Cylindrical cells are constructed by spirally winding the cathode and anode, kept apart by the separator, into a cylindrical shape and housing the winding in a steel or aluminum can as shown in Figure 4 (Gaines & Cuenca, 2000; Voelcker, 2007). In 2000, most automotive cell designs were cylindrical (Gaines & Cuenca, 2000), though many manufacturers are now developing prismatic (i.e., rectangular) designs as shown in Figure 3 due to advantages in space utilization and thermal management.[5] However, prismatic cells are typically more expensive to manufacture than their cylindrical counterparts (Lache, et al., 2008).

An additional type of Li-ion cell package that warrants mention is the pouch cell. The pouch cell is essentially a prismatic cell without a rigid case, but instead housed in a flexible pouch enclosure. It has the advantage of higher packaging efficiencies and lighter packaging weight than standard prismatic cells, with the potential disadvantage of less structural integrity, though this may be mitigated with

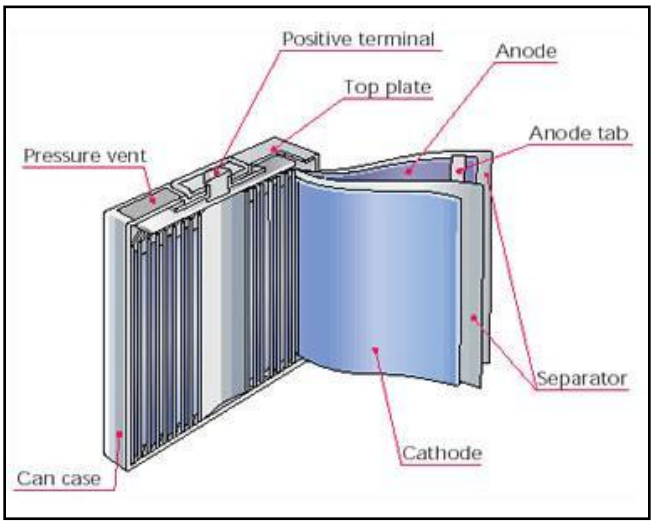

Figure 3: Prismatic Cell Construction (NEC/TOKIN, 2004)

[5] At the Electric Drive Transportation Association Conference in December, 2008, spokespersons for Electrovaya, A123 Systems, EnerDel, and ElectroEnergy all referred to development of automotive prismatic Li-ion cells. Gitanjali Das Gupta of Electrovaya even declared, "You *need* prismatic cells for the auto industry" (Electric Drive Transportation Association Conference).

appropriate design at the module- and pack-level. EnerDel is one domestic manufacturer of automotive Li-ion batteries that is working with prismatic pouch cells ("EnerDel Technical Presentation," 2005).

As previously discussed, Li-ion batteries can be made from a variety of materials. The traditional active materials used in Li-ion batteries for the consumer electronics market are a cathode of $LiCoO_2$ paired with a graphite anode; however, due to safety concerns, this chemistry is not considered suitable for automotive applications because of its unstable oxidation state which can lead to violent thermal runaway events (Hsiao & Richter, 2008; Kromer & Heywood, 2007). Thus, numerous other active materials are being developed for Li-ion batteries, with most of the research focused on the cathode material. Some of the more promising varieties are lithium nickel-cobalt-aluminum ($LiNi_{0.85}Co_{0.1}Al_{0.05}$, abbreviated NCA), lithium iron phosphate ($LiFePO_4$, or simply LFP), and lithium manganese spinel ($LiMn_2O_4$, or LMS), each paired with a carbon anode. Each of these materials improves on certain characteristics of traditional Li-ion batteries while compromising on others. For example, NCA has good energy and power density as well as adequate lifetime, but suffers from cost and safety concerns similar to traditional cobalt oxide. LFP appears to be a much more stable chemistry and has low cost due to its use of iron; however, it suffers from poor energy density, though this is mitigated to some degree by its ability to operate in a large state-of-charge window.[6] LMS similarly improves on cost at the expense of energy density and calendar life. Still, all of these chemistries are currently being developed by leading battery manufacturers and may have applications in the electrified automobile industry (Axsen, et al., 2008; Kromer & Heywood, 2007; Lache, et al., 2008).

[6] Li-ion batteries are typically charged no greater than 80%-90% of their maximum state-of-charge (SoC), and are not allowed to discharge below some minimum SoC, perhaps 30%, because operation at extremely high or low states of charge can dramatically reduce battery life. This narrow operating window effectively limits the overall energy density of the battery. LFP batteries have been shown to achieve cycle life characteristics similar to typical Li-ion batteries while operating at wide SoC windows.(A123 Systems, 2008a; Lache, et al., 2008)

Although most effort has been aimed at new cathode materials for Li-ion batteries, there have been developments in other areas. Lithium titanate batteries pair the LMS cathode described above with an anode of lithium titanate oxide ($Li_4Ti_5O_{12}$). Though this combination has a reduced cell-voltage (and thus lower energy density) compared to the graphite anode, it allows a usable SoC window of virtually 0%-100%, significantly increased life and safety, and good power density. Cost remains an issue, however (Lache, et al., 2008). Additional work has been done on other anode materials such as tin and silicon, as well as novel materials for the separator and electrolyte (Beach, 2008; Ritchie & Howard, 2006). However, many of the new materials being developed for Li-ion batteries are not yet past the laboratory phase.[7]

Li-ion battery cells may be optimized for energy density or power density, irrespective of the chemistry and format of the cell. For example, energy density may be increased by increasing the amount of active material used in the electrodes; however, the resulting increase in electrode thickness increases the impedance within the cell, causing a reduction in power density (Axsen, et al., 2008). Thus, it is possible to manufacture both high-energy cells (such as those suitable for PHEVs and EVs) and high-power cells (such as those used in conventional HEVs) using the same chemistry and packaging by altering the relative quantities of materials and design within the cell.

Lithium-Ion Battery Manufacturing

Given the variety of materials used and various sizes and formats of Li-ion battery cells, it is not straightforward to characterize Li-ion production with a single manufacturing process. However, since the cylindrical type is currently the most common, that is the process described

[7] A summary of various battery chemistries, including different Li-ion battery types, can be found in APPENDIX A: Summary of Various Battery Chemistries.

here, with differences for prismatic cell construction noted. The description is based on the production processes described in (Anderman, et al., 2000) and (Gaines & Cuenca, 2000).

Li-ion cell production begins with the manufacture of the cathode and anode, with the process being very similar for each. For the cathode, the active material is combined with a binder and other additives in a solvent to make a cathode paste which is then deposited onto the current collector, usually aluminum foil, in a coating process. For the anode, typically a graphite paste is made and deposited onto copper foil in an identical process. The coated electrode foils are then dried, and the thickness of the deposited material on the foil is made uniform through a process called calendaring. The foils are trimmed and cut to the proper size, and wound up with the separator material between them. (In the case of prismatic cells, the electrodes are not wound, but cut into rectangular shapes and stacked.) Tabs are also welded to the cathode and anode to provide electrical connections. The wound electrodes and separator are inserted into the canister, electrolyte is added (called "wetting"), ancillary components such as vents and safety devices are attached, and the cell canister is closed by crimping or welding a cover to the container. Individual cells are then packaged together into modules, which are further integrated with other systems into a complete battery pack as previously discussed. Figure 5 on the following page summarizes the Li-ion battery manufacturing process.

Though the manufacturing process is virtually the same for Li-ion cells for the consumer electronics industry as it is for automotive applications, quality control is typically much higher in the automotive industry (Chu, 2008; Hendrix, 2008). Thus, additional process controls and the resulting lower yields contribute to the higher cost of automotive Li-ion batteries.

Figure 5: Battery Manufacturing Process

METHODS

The initial phase of this research was devoted to analyzing the current state of Li-ion battery technology and identifying all materials and components of the lithium-ion battery manufacturing process that contribute to total costs. This was primarily accomplished by analyzing past and current research, including the aforementioned battery cost studies, (Anderman, et al., 2000), (Gaines & Cuenca, 2000), and (Kalhammer, et al., 2007). Additionally, interviews were held with representatives from several domestic Li-ion battery manufacturers, an investor in the battery space, and a major supplier to the Li-ion battery industry. The results of this phase are summarized in the previous sections.

The automotive Li-ion battery industry is rapidly gaining momentum, with numerous companies entering the sector, each with its own notion of how to overcome the energy, power, lifetime, safety, and cost challenges to make electrified vehicles commercially viable. Due to the intense competitive rivalry, much of the information regarding materials and processes is considered proprietary by the various industry players, and they are unwilling to share such information.[8] Because of the unavailability of detailed cost information[9], initial cell-level costs were taken from the previously mentioned Li-ion battery cost studies. Costs at the module- and pack-level were extrapolated from these studies as well as existing market research such as (Irwin, 2008).

[8] At the 2007 Advanced Automotive Battery Conference, several companies declined to comment on current and future battery developments. Regarding this, Ric Fulop of A123 Systems quipped, "The submarines have gone underwater and turned on their sensors. Everyone's preparing their attack." (Voelcker, 2007)

[9] Initially, a questionnaire was developed and distributed to battery manufacturers with whom contact had already been established. (See APPENDIX B: Battery Cost Inputs Questionnaire.) The questionnaire was intended to solicit detailed cost information for all of the materials, manufacturing steps, and overhead involved with Li-ion battery production at the cell-, module-, and pack-level. However, due to the reasons just discussed, the questionnaire received virtually no response.

Once the battery manufacturing process was mapped and costs identified, the cost model was developed in spreadsheet format. Three cost categories were considered: materials, manufacturing, and other (including corporate overhead, research and development, marketing, transportation, warranty costs, and profit). Each of these categories was disaggregated into cell-level, module-level, and pack-level components. Cell-level materials were further broken down into raw materials for the cathode, anode, separator, and electrolyte. Figure 6 illustrates the general structure of the model.

		Cost Category			***Total ($/kWh)***
		Materials	*Manufacturing*	*Other*	
Level of Integration	*Cell*	Cell-level Materials Cost	Cell-level Manufacturing Cost	Cell-level Other Cost	**Total Cell-level Cost**
	Module	Module-level Materials Cost	Module-level Manufacturing Cost	Module-level Other Cost	**Total Module-level Cost**
	Pack	Pack-level Materials Cost	Pack-level Manufacturing Cost	Pack-level Other Cost	**Total Pack-level Cost**

Figure 6: Structure of Li-Ion Battery Cost Model

The output of this model is a calculation of the cost per kilowatt-hour ($/kWh) for high-energy Li-ion batteries. Cost per kilowatt-hour is a common metric used frequently in both current academic research as well as market research focusing on energy storage technology, as it is energy capacity, rather than power, that is the main determinant of battery cost (Kromer & Heywood, 2007). Furthermore, this metric allows for the calculation of the total cost of a complete battery pack, because the energy required for various levels of powertrain electrification is reasonably well-known.[10] Analysis with the model was restricted to high-

[10] The USABC battery goals describe energy required for HEV, PHEV-40, and EV operation (Electrochemical Energy Storage Tech Team, 2006). Energy requirements for PHEVs with varying charge-depleting ranges can be extrapolated from this, as is done in (Kromer & Heywood, 2007) and (Kalhammer, et al., 2007)

energy Li-ion batteries, as that is what is needed to enable the commercialization of PHEVs and EVs.[11]

The model was then extended to a 30-year timeframe, from 2000 to 2030. Because much of the detailed cost information was taken from studies done in 2000, that year was chosen as the initial period. This provided a 9-year historical window with which to compare model outputs with actual Li-ion battery costs, as well as a check for the 2000 studies against the study from 2007. The model was used to evaluate how the Li-ion battery cost curve may evolve under various circumstances, by developing possible scenarios of how each of the cost drivers may change over time. Each of these scenarios is described in the RESULTS section of this document.

Outside the scope of the model, the break-even per-kWh cost of the battery pack was calculated for vehicles with various levels of powertrain electrification, over a range of fuel prices. The break-even cost is the cost at which the price-premium demanded for the electrified vehicle over a conventional internal combustion engine (ICE) vehicle is completely offset over the operating life of the vehicle by lower fuel costs and (for PHEVs and EVs) the lower per-mile cost of electricity compared to gasoline. This calculation indicates the level to which battery costs must fall in order for HEVs, PHEVs, and EVs to be economically competitive with their conventional counterparts. This analysis was done using both a non-discounted break-even analysis framework, and a method that considers the time value of money and the mileage patterns of vehicles over time.

[11] The studies by (Gaines & Cuenca, 2000) and (Kalhammer, et al., 2007) considered both high-energy and high-power Li-ion batteries, while the study by (Anderman, et al., 2000) implicitly considered only high-energy batteries as it focused solely on EVs. The model being developed here could be used for high-power Li-ion batteries as well, though the cost-per-energy ($/kWh) metric which is output is less meaningful for such battery type.

RESULTS

Cost Breakdown

The model demonstrates that materials dominate the costs for Li-ion batteries at the cell-, module-, and pack-level, accounting for approximately 75% of pack-level costs. This is expected, and is consistent with other current research. Additionally, cell-level materials cost account for approximately 85% of the pack-level materials cost. Figure 7 shows the total cost breakdown based on year 2000 battery information. In the figure, each level of integration includes the level before it. (For example, module-level costs include the costs associated with the cells used to build the module.) Additionally, the "other" category includes costs that cannot easily be attributed to a specific level of integration. The model used here assumes a 35% gross margin as suggested in (Gaines & Cuenca, 2000), 19% of which is attributed to the cell-level

Level of Integration	Cost Category			Total ($/kWh)
	Materials	Manufacturing	Other	
Cell	734.53	23.15	86.90	**844.59**
Module	771.79	26.77	86.90	**885.47**
Pack	864.38	31.68	230.27	**1126.33**

Figure 7: Costs for High-Energy Li-Ion Batteries ($/kWh) in Year 2000

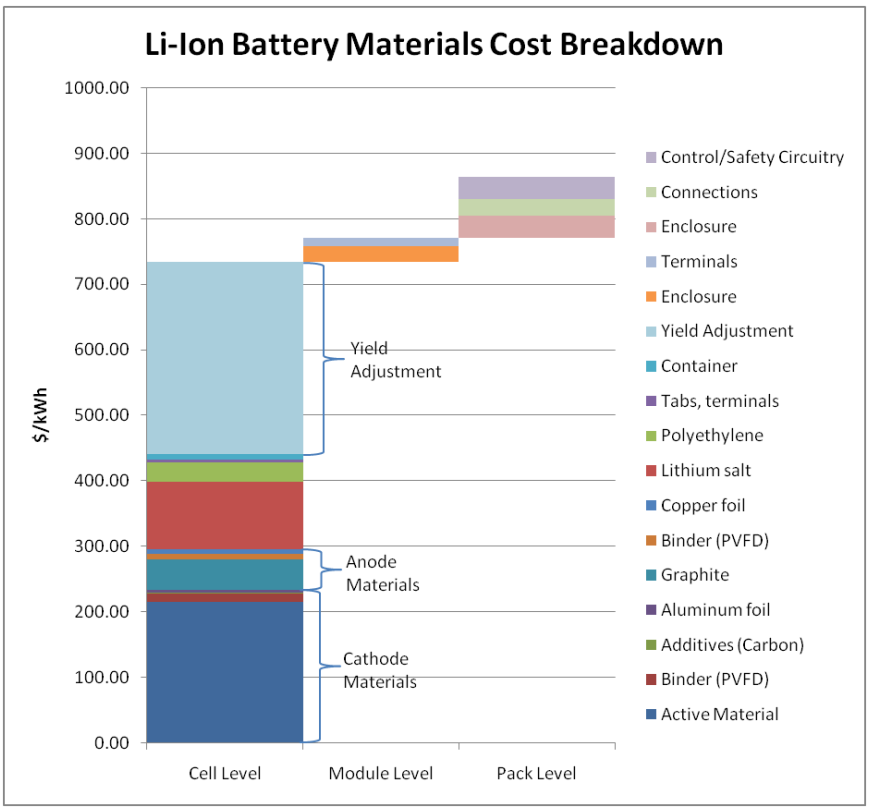

Figure 8: Materials Cost Breakdown for Li-Ion Batteries

for corporate overhead and R&D, and the remaining 16% attributed to the pack-level for marketing, transportation, warranty costs, and profit.

Figure 8 illustrates the materials cost breakdown at the cell-, module-, and pack-level. The obvious result at the cell-level is that the "yield adjustment" dominates all other contributors to cell-level materials cost. This yield adjustment represents the extra cost due to manufactured battery cells which do not meet the quality control requirements mandated by the automotive industry, and is essentially the result of dividing the other cell-level materials cost by the manufacturing yield. The manufacturing yield in the baseline year is assumed here to be 60%.[12] It is apparent that increased manufacturing yield is a critical factor in reducing battery costs at the cell-level.

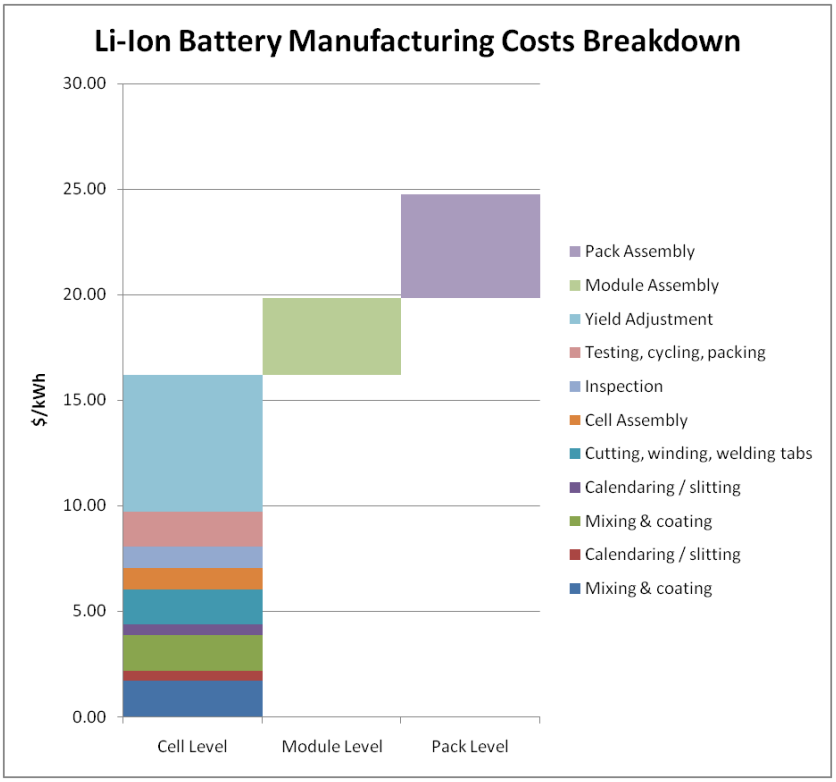

Figure 9: Manufacturing Cost Breakdown for Li-Ion Batteries

The second-most significant cost component at the cell-level is the cathode active material. Other cell-level cost contributors include the lithium salt used in the electrolyte and graphite used for the anode. The most dominant contributor to materials cost at the module-level is the cost of the cells

[12] Unfortunately, manufacturing yield is one of the parameters that is closely guarded by Li-ion battery manufacturers. Conversations with individuals close to the industry suggest that yields may currently be less than 50%, given the high quality constraints mandated by the automobile industry.

themselves, followed by the cost of the module enclosure and terminals. At the pack-level, nearly all of the per-energy cost of materials for a Li-ion battery is attributed to module (and cell) costs, with the remainder attributed to pack enclosure, connections, and the control system.

The manufacturing cost breakdown for each of the three levels of integration is shown in Figure 9. Similarly to the materials breakdown, the dominant cell-level cost component for manufacturing is the yield adjustment. Other manufacturing costs at the cell-level are fairly well distributed among each step of the cell production process. Per-energy manufacturing costs at the module- and pack-level are comprised of assembly at each level of integration, though these costs are less significant than the costs attributed to the cell-level.

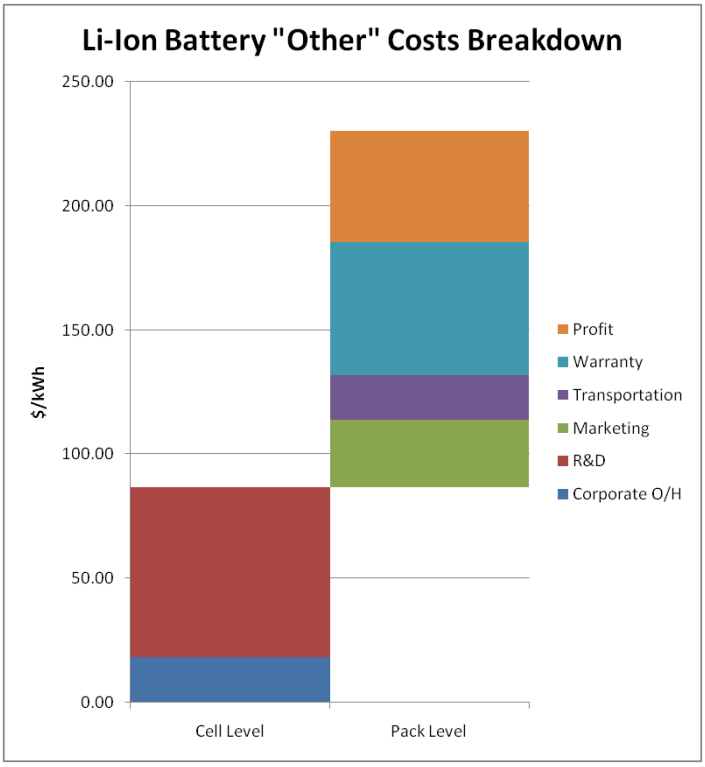

Figure 10: "Other" Costs Breakdown for Li-Ion Batteries

Other costs are broken down at the cell- and pack-level as previously mentioned, and illustrated in Figure 10. Note that no costs in this category are attributed to the module-level. It is assumed that module production is performed either by the cell manufacturer or by the pack manufacturer. The large majority of cell-level costs in this category are due to research and development, while the largest cost-contributors at the pack-level are warranty costs and profit to the battery manufacturer.

In examining the cost structure for Li-ion batteries, it is important to understand the effect that changes in the cost for each component has on the overall cost of the battery. Based on the previously discussed cost breakdown, the six most significant drivers of total battery cost are the manufacturing yield, the cathode active material, the lithium salt used in the electrolyte, cell-level R&D, warranty costs, and graphite for the anode. Obviously, a reduction in the cost of the component which accounts for the largest share of battery cost will have the greatest impact on overall battery cost; however, it is important to note that reductions of any realizable magnitude in any single cost driver will likely not achieve significant reductions in total battery costs. Also of note is the significant impact that manufacturing yield has on total battery cost, a result that was described earlier. Its impact arises from the multiplicative effect that it has on other materials and manufacturing costs. Thus, if any substantial cost reduction is to be achieved, it must be accomplished by an increase in manufacturing yields coupled with decreases in the costs of multiple components among the materials, processes, and other costs associated with Li-ion batteries.

Battery cost reductions may arise primarily through two mechanisms: economies of scale associated with increased production volume, and technological breakthroughs. Manufacturing yields will likely improve through the learning-by-doing process associated with economies of scale, though technological breakthroughs in the manufacturing process may also play a role. The cathode active material may be subject to both effects as well: per-unit cost for cathode materials is highly sensitive to quantity purchased (Gaines & Cuenca, 2000), and traditionally expensive cathode materials such as cobalt- and nickel-based oxides could be replaced with less expensive materials such as iron. Electrolytes and anode materials could also experience cost reductions from both effects, though economies of scale will likely be the overriding factor for

both. Research and development costs are currently high, and may remain so until the result of such R&D manifests itself in the production of batteries that are acceptable for automotive applications across the spectrum of goal categories. Finally, warranty costs will decrease once the technology, both from a materials standpoint and manufacturing standpoint, becomes mature, driven primarily by increased production volume.

Scenario Analysis

As shown in Figure 11, the historical per-energy cost for Li-ion batteries for consumer electronics has decreased rather steadily, though the rate of decrease has diminished in the last decade. The compound annual price decrease for the period 1998 – 2005 is 9.9%, while for the period 2002 – 2005 it is only 5.4%. The decline in Li-ion battery prices is due primarily to rapidly increased production volume in Asia, as well as increased packaging efficiencies through better space utilization at the cell-level (Beach, 2008). Based on this decelerating trend of declining prices, a baseline scenario was chosen that assumes a 4% per year decrease in the overall cost for automotive Li-ion batteries. Two additional scenarios were considered: an optimistic scenario in which substantial new investment is targeted to advanced battery development, leading to breakthroughs that accelerate the pace of cost reduction, as well as

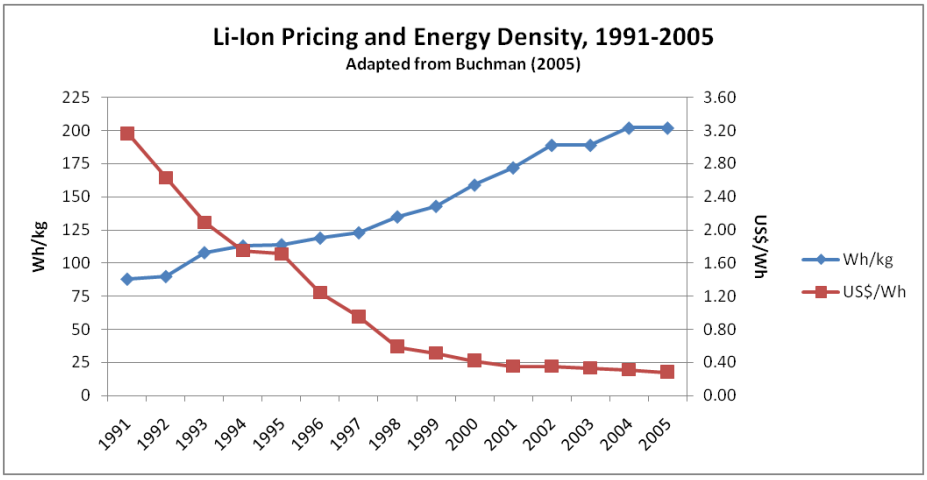

Figure 11: Historical Prices and Specific Energy Trends for Li-Ion Batteries

significant electrified vehicle adoption and cost reductions through economies of scale and increased manufacturing yields; and a pessimistic scenario, which assumes no significant new investment, slow adoption of electrified vehicles, no significant technological breakthroughs, and potential constraints in raw materials supply and manufacturing capacity.

The optimistic scenario appears to be emerging as the more likely of the two extremes. Recently passed federal legislation allocates $2-billion for advanced battery manufacturing, while other provisions such as tax-credits for PHEVs could have the effect of accelerating market adoption of such vehicles (Sonnenschein Nath & Rosenthal LLP, 2009). Furthermore, the primary focus of current development efforts by battery manufacturers and auto makers is cost-reduction.[13] As discussed earlier, numerous battery manufacturers and research labs are actively pursuing new cathode active materials, anode materials, electrolytes, and separators. As automotive-scale Li-ion battery manufacturing ramps up, unit-costs for batteries will likely decrease while manufacturing yields increase from the 60% assumed in the baseline scenario. In the optimistic scenario, the cathode is assumed to have a 20% per year cost decrease, driven largely by breakthroughs in low cost materials. The anode, electrolyte, and separator are each assumed to have a 10% per year cost decrease. (This is within the range, though above the average, of the historical yearly cost reduction rate for consumer Li-ion batteries.) Additionally, all manufacturing costs are assumed to be reduced by 10% per year, due to manufacturing economies of scale and better processes through learning-by-doing. Furthermore, corporate overhead costs are assumed to decrease by 10% per year on a per-kWh basis, as small battery manufacturers consolidate into larger corporate structures, reducing overall overhead. Warranty costs as well are assumed to decrease by 10% per year as battery technology matures and fewer

[13] GM, slated to introduce its PHEV-40 Chevy Volt in late 2010, is already working on subsequent generations of the Voltec platform. Rather than attempting to increase the range or reduce the size of the battery in these generations, the goal is to reduce the battery cost (Blanco, 2009).

faulty products are allowed to reach the market. Other costs that are assumed to decrease include the binders and additives used in the electrodes (5% per year, due to materials leverage), and packaging and connections at the module- and pack-level (5% per year, due to efficiencies gained through larger format automotive cells). All other costs are assumed to remain constant. Manufacturing yields are assumed to increase by 1% per year from the baseline.

The pessimistic scenario, on the other hand, is one in which any new investment is not significant. The previously mentioned $2-billion may in fact turn out to be inconsequential, considering the projected cost for a single new battery manufacturing facility may equal that amount (Clayton, 2009). Additionally, supply constraints and instability in regions where most of the world's lithium-carbonate is produced[14], as well as commodity bull markets such as the one earlier this decade, could cause raw materials prices to increase rather than decline. The pessimistic scenario used here assumes that the cost for cathode active material initially decreases at a rate of 5% per year, but eventually flattens out and increases by up to 5% per year in 2030. The cost for the anode material, electrolyte, and separator are assumed to decrease 5% per year. Manufacturing costs are assumed to decline by 5% per year (half of that assumed in the optimistic scenario) due to slower production ramp-up. Warranty costs are assumed to remain steady, with improvement in battery technology not enough to reduce the replacement rate for defective or lifetime-compromised batteries. Manufacturing yields are assumed to increase 0.5% per year, half the rate of the optimistic scenario. All other costs are assumed to remain steady.

[14] Much of the world's lithium reserves are in a small region in South America. The argument has been made that these lithium reserves are finite, and cannot support a large-scale ramp-up in Li-ion automotive battery production; however, it appears that lithium reserves may not be a constraint, but rather production capacity could be a bottleneck (Evans, 2008; Woulfin, 2008).

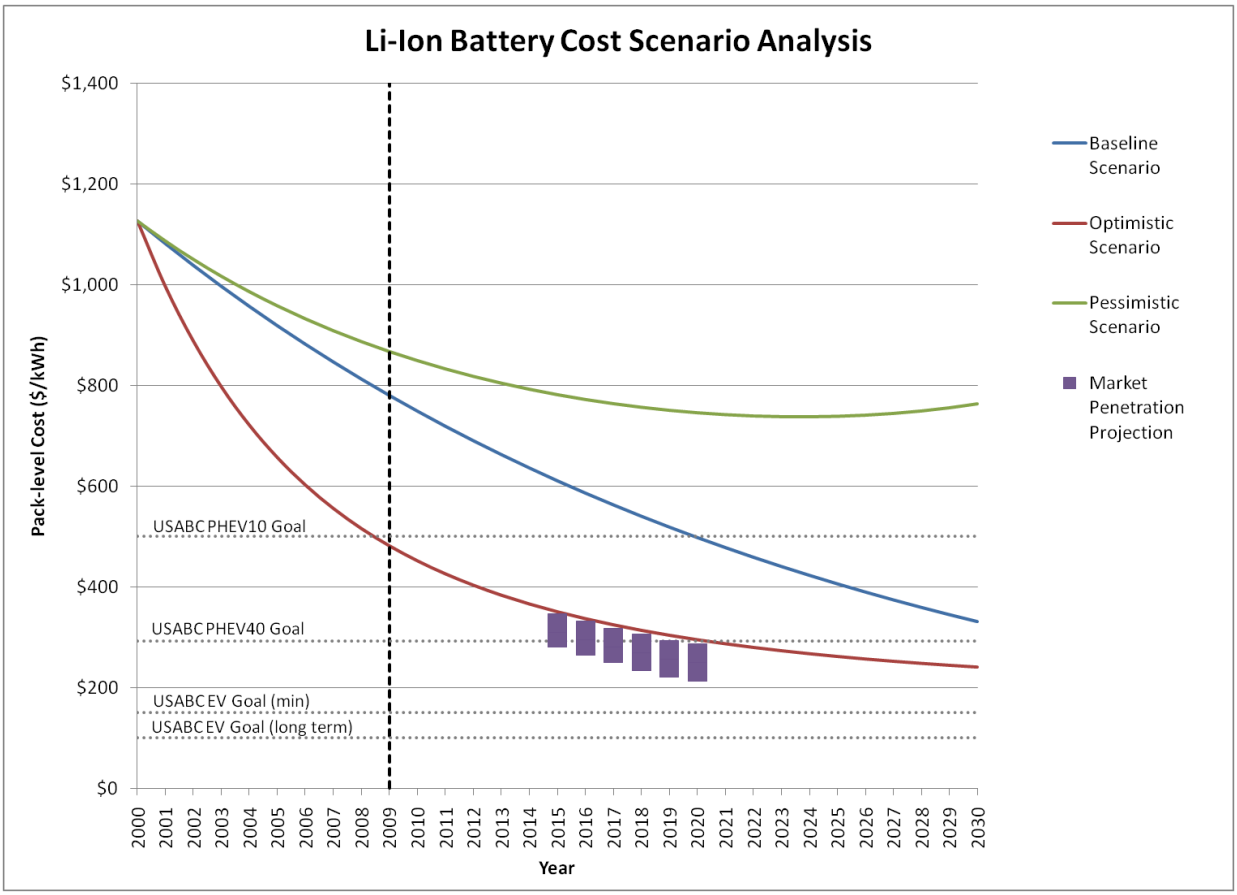

Figure 12: Possible Li-Ion Battery Cost Pathways

Figure 12 illustrates the result of each of the previously described scenarios. Note that the outcomes of the baseline scenario and the optimistic scenario in 2030 tend to converge, while the pessimistic scenario results in a much less significant decrease in the energy cost of Li-ion batteries, leveling off at approximately $730/kWh and then increasing. Additional data-points are plotted in Figure 12, representing the result of applying a frequently cited cost/volume curve taken from (Kromer & Heywood, 2007) to a generally accepted industry projection of worldwide electrified vehicle adoption taken from (Lache, et al., 2008). (To account for the fact that this cost/volume curve is specific to cell-level manufacture, a constant cell/pack cost ratio was used to translate it to the pack-level.) These data-points suggest that the cost model developed here may be too pessimistic. However, the market penetration data was produced prior to the drastic

downturn in the automotive sector that began in 2008, so it may be the case that these data-points are overly optimistic. The fact that current (2008) pack-level estimates for advanced Li-ion batteries range from about $750/kWh to $1000/kWh seems to substantiate the latter possibility. Additionally, the USABC battery cost goals for PHEV-10, PHEV-40, and pure EVs are shown in Figure 12. The relationship between these goals and potential battery cost scenarios indicated by the model suggest that the PHEV-10 goal will likely be met, and the PHEV-40 goal could potentially be met. However, both the minimum and long-term goals as defined by the USABC may be too optimistic to be realized in the next two decades.

Comparison of Costs for Electrified Vehicles and Internal Combustion Vehicles

The cost of the battery pack makes up the majority of the "cost premium" that is associated with electrified vehicles when compared with traditional internal combustion engine (ICE) vehicles (Irwin, 2008). In addition to the battery cost, this premium is due to the added complexity of other components such as the electric motor, a transmission with power-split capability (for parallel hybrid architectures), regenerative braking functionality, charging electronics (for PHEVs and EVs), and control systems. As the level of powertrain electrification increases, the portion of the cost premium attributed to the battery also increases. Therefore, the cost of the battery pack is a key determinant in whether electrified vehicles – especially PHEVs and EVs – can become economically viable. The cost premium (including the battery cost) is offset to varying degrees during the operating life of the vehicle by lower fuel costs due to reduced fuel consumption and the lower cost of electricity compared to gasoline. The magnitude of this offset is highly dependent upon the assumption of operating life, as well as the cost of

gasoline. While operating life is assumed here to be 150,000 miles[15], the volatility in gasoline prices in recent years makes analysis of the economic viability of electrified vehicles at any one fuel price meaningless. Therefore, the break-even cost of the battery pack for various levels of powertrain electrification was calculated for a range of fuel prices. The analysis was done using numerous assumptions from (Anderson, 2008) and (Kromer & Heywood, 2007), which are summarized in Figure 13.[16]

Vehicle Type	CD-Mode Range	Battery Capacity (kWh)	Cost Premium (excluding battery)	Utility Factor (% Miles in CD Mode)	Miles in Charge-Depleting (CD) Mode	Miles in Charge-Sustaining (CS) Mode
HEV-0	0	1.5	$1,500	0%	0	150,000
PHEV-10	10	4	$1,625	18%	27,000	123,000
PHEV-20	20	6	$1,750	31%	46,500	103,500
PHEV-30	30	8	$1,875	42%	63,000	87,000
PHEV-40	40	12	$2,000	51%	76,500	73,500
PHEV-60	60	16.5	$2,250	63%	94,500	55,500
BEV-200	200	48	$300	100%	150,000	0
Vehicle Lifetime (miles)		150,000	*ICE vehicle fuel efficiency (mpg)*			25
Cost of Electricity ($/kWh)		0.10	*HEV vehicle fuel efficiency (mpg)*			45

Figure 13: Assumptions for Battery Break-Even Cost Calculations

The results are illustrated in Figure 14, along with the cost range for Li-ion batteries as calculated by the cost-model for 2009. As expected, higher gasoline prices allow electrified vehicles to be cost-competitive with higher battery costs. Both the sensitivity of this cost-competitiveness to fuel prices and the battery break-even price is higher for lower levels of powertrain electrification (i.e., at a given fuel-price, lower levels of electrification do not require battery energy costs to be as low as higher levels of electrification). For example, at a July 2008 fuel price of $4.09/gallon, a PHEV-40 (plug-in hybrid electric vehicle with a 40-mile charge-depleting range, such as the Chevy Volt) is cost-competitive at a battery cost of $1,150/kWh, easily realized with current technology; however, only five months later, the average U.S. fuel price was $1.69/gallon, at which point the PHEV-40 battery would have to be approximately

[15] The NHTSA estimates the average lifetime mileage of the passenger car fleet in the U.S. to be 152,137 miles (National Highway Traffic Safety Administration, 2006).

[16] Additionally, it is assumed that a BEV-200 has an energy efficiency of 4 miles/ kWh, and that a PHEV achieves efficiency equal to that of a BEV-200 while in charge-depleting mode, and that of an HEV while in charge-sustaining mode.

$300/kWh, considerably lower than projected battery costs in the near term.[17] Conventional hybrid (HEV-0) vehicles, with a break-even battery cost of $2,000/kWh even at December's low gasoline prices, are economically competitive at virtually any reasonable battery cost. At the opposite extreme, pure electric vehicles with a 200-mile range (BEV-200) require aggressive battery cost reductions at all fuel prices in order to be economically viable.

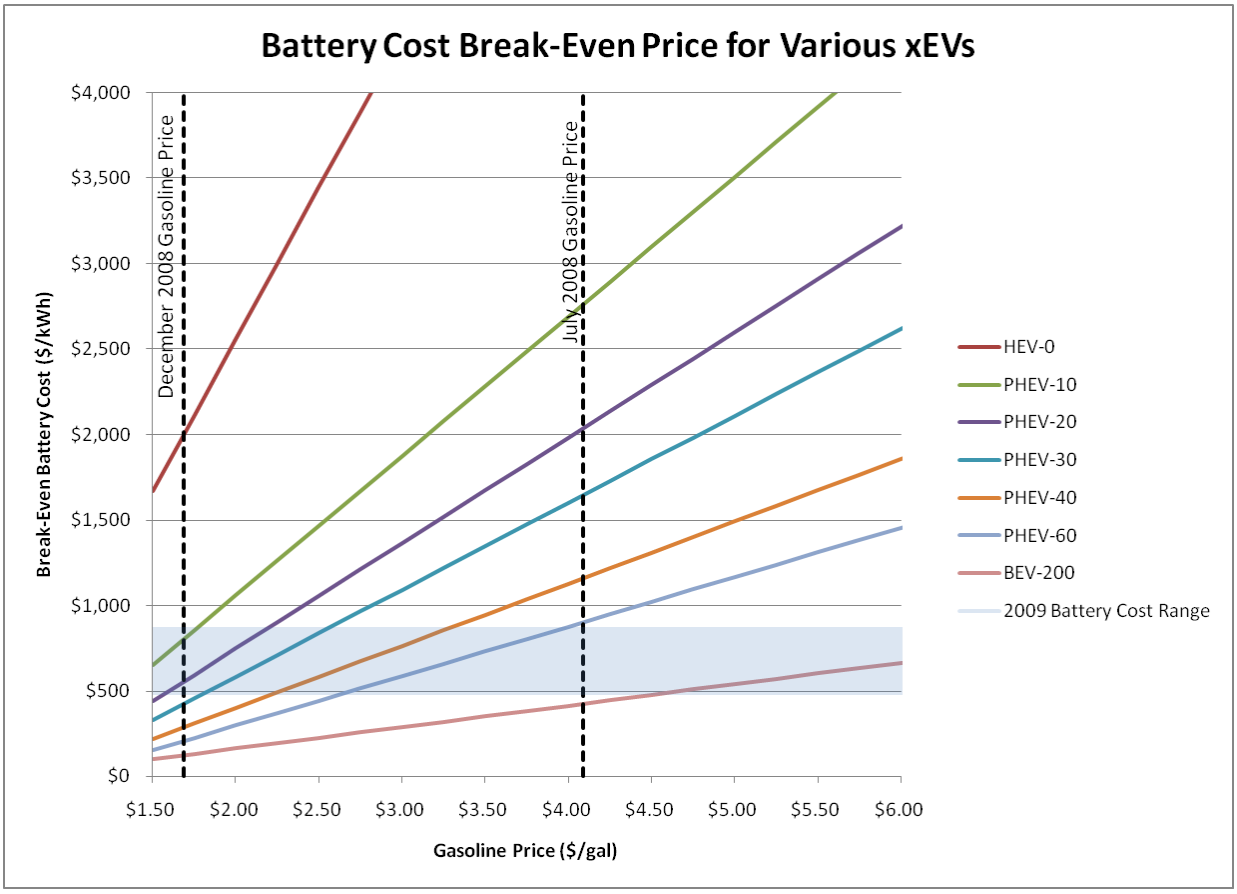

Figure 14: Battery Break-Even Costs

The previous analysis assumes that the break-even point is the battery price at which fuel cost-savings equals the premium paid for the electrified vehicle upon purchase. This fails to take into account the fact that the premium is paid initially, while the fuel cost-savings occur over the life of the vehicle. Generally, people demonstrate a rate of time preference, favoring present

[17] Historical fuel prices are taken from (Energy Information Administration, 2009).

consumption over future consumption (Moore, Boardman, Vining, Weimer, & Greenberg, 2004); thus, the benefits of future cost savings from reduced fuel usage must be discounted relative to the initial price premium. Additionally, the vehicle miles traveled (VMT) per year generally declines with the age of the vehicle.[18] The break-even analysis was repeated, assuming yearly VMT according to the NHTSA model, a lifetime of 11 years (resulting in lifetime VMT of 153,259 miles), and a discount rate of 7%.[19] The result of this analysis is shown in Figure 15.

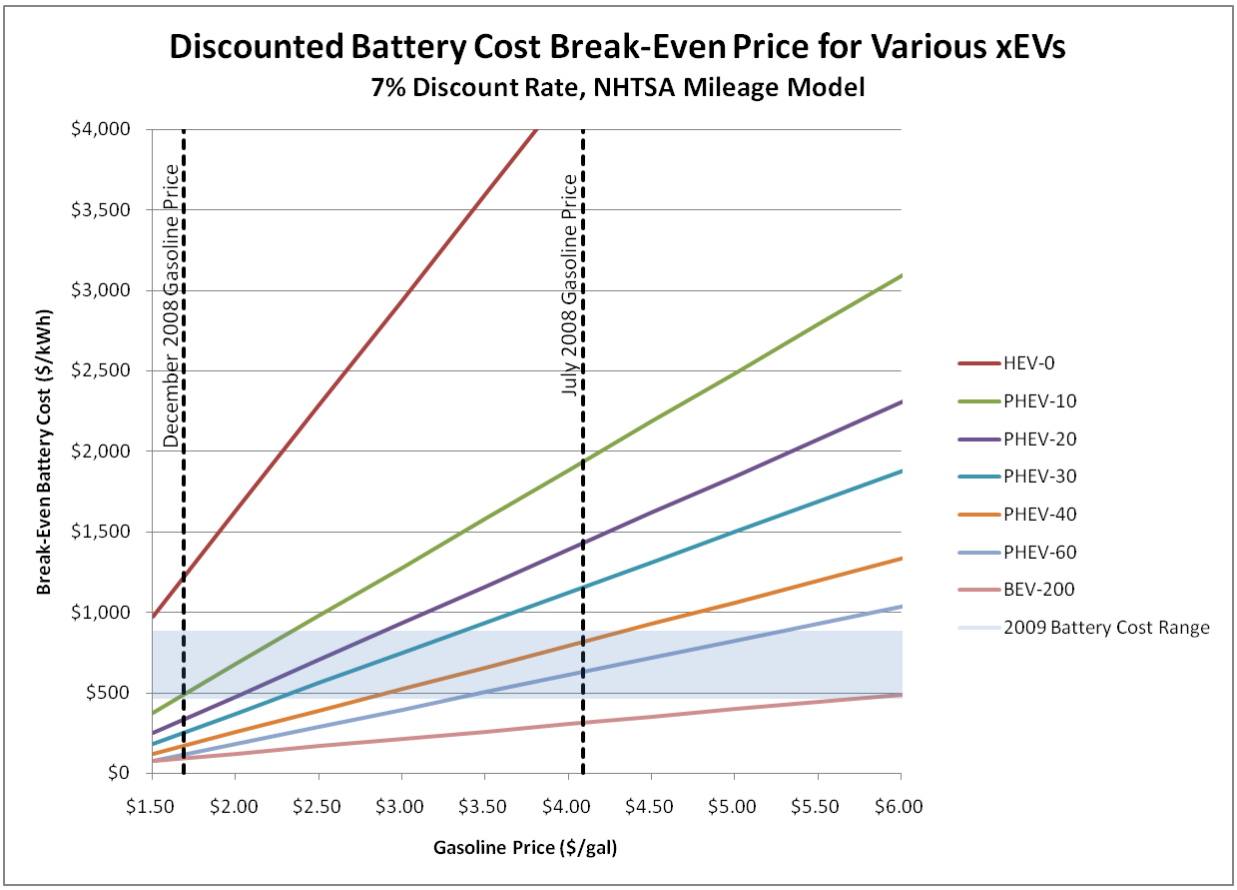

Figure 15: Discounted Battery Break-Even Costs

[18] A cubic polynomial model is used to estimate vehicle miles traveled: VMT = A x Age^3 + B x Age^2 + C x Age + D., where A = 0.3672131, B = -13.21949, C = -232.8491, D = 14,476.36, and Age is in years (National Highway Traffic Safety Administration, 2006).

[19] A discount rate of 7% is used as it is the average before-tax rate of return to private capital in the U.S. (Office of Management and Budget, 2003)

The trends using the discounted cost savings method are similar to those from the original break-even analysis. However, the cost-per-kWh that batteries must reach is lower. For example, for the PHEV-40 described in the prior analysis to be cost-competitive at July 2008 fuel prices, battery costs would have to be approximately $800/kWh; at December 2008 fuel prices, battery costs would have to decline to $170/kWh. These costs are 30% to 40% lower than the equivalent results from the former analysis, demonstrating the impact that discounting has on the value of the fuel cost savings.

DISCUSSION

The cost model developed here is a simple simulation model, which allows for analysis of the impact that each of the various cost-components of an electrified vehicle battery has on overall battery costs. It does not portend to predict future battery costs, but does help to identify pathways through which electrified vehicles can become cost-competitive, given the assumptions made due to the unavailability of precise cost information.

Economic Considerations

The USABC goals for battery costs range from $500/kWh for a PHEV-10, to $150/kWh ($100/kWh long-term) for EVs. The goal for a PHEV-40 is approximately $300/kWh. The results from the model presented here suggest that the goals for PHEVs (especially those with lower charge-depleting ranges) may be realizable, while the goals for EVs may be overly optimistic. The battery cost break-even analysis done here concurs with USABC goals, specifically at lower fuel prices such as those in December 2008. What is not evident in the USABC goals is the sensitivity of the break-even cost to fuel price. The drop in fuel prices over the five-month span from July to December 2008 was significant enough to drastically shift the

market viability of every type of electrified vehicle other than conventional HEVs. Such extreme volatility in fuel prices represents a risk to automobile manufactures whose product development cycles are much longer than recent cycles in fuel prices. It has been suggested that a price floor on gasoline would help to sustain demand for fuel-efficient vehicles such as HEVs, PHEVs, and EVs, by assuring their cost-competitiveness and reducing the risk for auto manufacturers to develop such vehicles (Sperling & Gordon, 2008). A variable gasoline (or more generally, fuel) tax is one mechanism by which such a gasoline price floor could be implemented.[20] However, any mention of such a fuel tax is traditionally a non-starter politically (LoBianco, 2008). More broadly, if the pump-price of gasoline were to reflect the "true cost", including all externalities associated with the extraction, transport, refining, and environmental consequences of fuel use, the economics associated with PHEV and EV batteries would be substantially shifted.

Battery warranty costs represent a further economic risk to automobile manufactures. Even with rigorous testing and qualification, one cannot know with certainty how Li-ion battery packs will respond to real-world use in the long-term. Consumers may be hesitant to adopt such new and relatively unproven technology without a guarantee from the manufacturer, while providing such a guarantee could be a significant financial liability to the automobile companies (unless they substantially raise the price of the battery pack). The end result of this catch-22 could be a decrease in the pace of deployment of electrified vehicles. One suggested policy mechanism to address this is a government-backed "battery guarantee fund" to soften the initial warranty burden to automobile manufacturers (Electric Drive Transportation Association Conference). Such a fund could reduce the risk to automobile manufacturers to mass-produce

[20] Rick Wagoner, former CEO of General Motors, suggested in March, 2009, that a gasoline tax to guarantee a minimum gasoline price of $4 per gallon might be a good idea (Dickson, 2009). Bill Ford, Executive Chairman at Ford Motor Company, reiterated this point in April, 2009 (Korzeniewski, 2009).

electrified vehicles without passing overly burdensome battery warranty costs on to the consumer.

The battery cost break-even analysis done here does not take into account many of the subtleties associated with vehicle purchase and ownership. For example, even when the discounted benefits of the reduced fuel-savings associated with electrified vehicles fully offsets the initial price-premium, buyers may still be averse or unable to provide the additional funds at purchase. Recently passed federal legislation (H.R. 1424) provides a tax-credit of up to $7,500 for PHEVs, based on the vehicle's battery energy capacity (U.S. Department of Energy, 2008), which should tend to reduce this effect as well as make the battery break-even cost more favorable once PHEVs become available in the market in 2010. Additionally, most buyers likely finance the purchase of vehicles rather than expend the full vehicle price up front. The break-even analysis does not consider the various financing terms possible, nor does it include potential differences in maintenance and insurance costs and trade-in values.

Another aspect which the discounted cash-flow break-even analysis fails to consider is the flexibility that a PHEV owner has in deciding which fuel – gasoline or electricity – will be used each day. There is value in having this flexibility. It has been suggested that a real options approach, whereby the premium associated with the battery cost represents the purchase of a strip of call options giving the owner the opportunity to purchase the least expensive fuel each day, may be more appropriate than a discounted cash-flow model (Lemoine, 2008). This framework models the decision to charge a vehicle from the grid on any given day as the exercise of a call option on that day. Conversely, the decision to use gasoline instead of electricity corresponds to the expiration of the call option. This model takes into account the uncertainty that surrounds both electricity prices and gasoline prices, and the break-even point is

the battery cost that equals the value of this series of options. The conclusion reached by Lemoine is that this real options framework raises the price at which a battery pack becomes cost-competitive, though fuel prices must still remain high and volatile for PHEVs to become commercially viable.

Non-economic Factors

Electrified vehicles must not only overcome the economic trade-offs associated with battery costs in order to be competitive in the mass market. Consumer acceptance is also a barrier, due to potential behavior changes needed for PHEVs and EVs. Though conventional HEVs account for only a few percent of new vehicle sales currently, with over a million sold in the U.S. market alone, their market acceptance has already occurred (Howell, 2009; Irwin, 2008). This acceptance is due in part to the fact that HEVs are operationally no different than traditional ICE vehicles. At the other extreme, pure EVs require frequent (and with today's technology, often time-consuming) charging, requiring consumers to charge their vehicle at home or at a charging station rather than having the option of a quick fill-up at a retail gasoline station. Although approximately 78% of commuters in the U.S. travel less than 40 miles per day (U.S. Department of Transportation, 2003) – a range well within the battery capacity constraints of EVs currently under development – the phenomenon of "range anxiety" remains a barrier. PHEVs could play an important role in enabling the transition from HEVs to EVs by changing consumer mindset and behavior; while a PHEV-40 could effectively operate as an EV for most commuters, it could also be operated as a conventional HEV (although at reduced fuel savings), and allay fears about limited range. Furthermore, the smaller capacity batteries in PHEVs compared to EVs will enable the commercialization of electrified vehicles at higher per-kWh battery costs than are required for EVs.

Other Energy Storage Technologies

Li-ion batteries must be considered in the broader context of the problem which they are meant to solve: energy storage. As previously discussed, most effort for the problem of vehicle energy storage is currently targeted to Li-ion batteries; however, there are other technologies under development, and breakthroughs in these technologies could have an impact on the success or failure of Li-ion batteries. The two leading technologies that could compete with Li-ion batteries are fuel-cells and ultracapacitors. A fuel-cell vehicle (FCV) is an EV in which the energy storage is in the form of hydrogen (typically) rather than a battery. Unlike a Li-ion battery, an FCV uses up its hydrogen fuel as it produces electricity, and must be refueled. Therefore, infrastructure must be developed to generate hydrogen, transport it, and deliver it to consumers. Hydrogen storage on-board the vehicle is another technical barrier that must be overcome to allow market success of FCVs. Hydrogen fuel-cells also lack the ability to capture energy from braking (i.e., "regenerative braking") as is done in virtually all HEVs, PHEVs, and EVs. Thus, FCVs often employ a smaller battery pack to recapture energy lost while braking and coasting, to further improve FCV efficiency. Li-ion batteries and fuel-cells may therefore be considered complementary, rather than competing, technologies.

Ultracapacitors are another energy storage mechanism which could be used in electrified vehicles. Unlike fuel-cells and Li-ion batteries, ultracapacitors store energy as electrons by accumulating them electrostatically (Miller, 2008). As a result, ultracapacitors are highly efficient, can be charged and discharged very rapidly, are able to operate at extreme temperatures, and do not degrade with many charge/discharge cycles. While they have very high power density, they currently suffer from poor energy density. These characteristics make them well-suited for use in conjunction with high-energy Li-ion batteries. In a PHEV or EV, Li-ion

batteries can be used for energy storage to provide adequate range, while ultracapacitors can be used to absorb energy from regenerative braking and provide power during acceleration. In this arrangement, the ultracapacitors act as a buffer to the battery pack, isolating it from high-current events and increasing battery life. Li-ion batteries and ultracapacitors are complementary technologies due to this synergistic relationship.

Other Concerns

It is likely that a large deployment of electrified vehicles could reduce oil consumption both in the U.S. and worldwide, achieving the associated environmental and energy-security benefits (Natural Resources Defense Council, 2007). However, it is also important to consider potential constraints and adverse effects of large-scale commercialization of the Li-ion batteries to power these electrified vehicles. One such concern involves raw material availability, specifically for the lithium-carbonate which is used in all Li-ion batteries. It has been estimated that 70% of the world's lithium resources are located in the "lithium triangle" – a small area in South America near the borders of Chile, Argentina, and Bolivia (*The Trouble with Lithium 2: Under the Microscope*, 2008). The argument can be made that displacing oil with Li-ion batteries has the effect of replacing one politically unstable energy source with another. There may be some truth to this, especially in Bolivia, where international companies have begun to seek deals with President Evo Morales, who has often clashed with western governments, to tap the country's lithium reserves (Romero, 2009).

Combined with the previously mentioned concern over the availability of lithium resources is the notion that materials from spent batteries could pose a tremendous waste-disposal challenge. A key solution for both of these problems is the establishment of extensive recycling infrastructure for Li-ion batteries, similar to that for automotive lead-acid batteries that

currently exists in the United States. The materials used in Li-ion batteries, including lithium, are virtually all recyclable; however, the cost of collecting and recycling these materials must be less than the revenue generated from the sale of the recovered materials plus the avoided costs of disposal for such a recycling program to be economically viable (Gaines & Cuenca, 2000). An alternative to immediately recycling spent automotive Li-ion batteries is to use them for other energy storage purposes once their useful life in automotive applications has been reached. Over time and with repeated cycling, a Li-ion battery may degrade to the point that it no longer meets the rigorous specifications required for its automotive application, though it may still be suitable for other stationary applications such as load leveling in electric power networks, renewable firming, peak shaving, and load following (Weinstock, 2002). Recycling is still possible after such second-use applications. If there were a viable market for batteries after their use as automotive energy storage, it could reduce the battery cost to the automotive consumer.

Second-use applications are just one business model being developed to extract more value from automotive Li-ion batteries and distribute their cost. The concept of vehicle-to-grid (V2G) technology has been developed to capture the benefits that a large market penetration of PHEVs and EVs could provide to the electric grid and to compensate owners of such vehicles for these benefits. A substantial number of plug-in vehicles represents are large pool of distributed energy storage, which could be used to store excess baseload power generation during periods of low power demand, and then to supply this energy back to the grid during peak-demand times.[21] Compensation that vehicle owners would receive for allowing their vehicles to be used in such an arrangement would further offset the battery price premium, though any adverse impacts that providing these services would have on battery life must be considered. Considerable effort has

[21] For additional information regarding the work being done on V2G, see: http://move.rmi.org/capabilities/smart-garage.html

been made to determine what sort of financial structure would appropriately reimburse consumers for providing energy, ancillary services, and merely agreeing to be called upon to provide these services.[22]

An alternative business model has been devised whereby the vehicle owner is not required to purchase the battery, but instead pays a mileage-based subscription fee to an operator who owns the battery, controls the charging infrastructure, and operates battery swap stations. The most well-known company developing such a framework is Better Place, a Palo Alto-based business that has already announced commitments for developing this subscription-based model for all-electric vehicles in various countries as well as regions in the U.S.[23] This arrangement addresses both the hurdle of the initial price-premium and the issue of range-anxiety from the consumer's point of view. The challenge here is overcoming the enormous economic and technical barriers to deploying the immense infrastructure required to make the business model feasible. Revenues from subscription fees must exceed the investment and operating costs of the charging and battery swap infrastructure, in addition to the cost of the fleet of battery packs used by subscribers. Here again, battery costs are a critical determinant of the commercial success or failure of electrified vehicles.

CONCLUSION

There is currently a significant push to decarbonize transportation through powertrain electrification coupled with low-carbon sources of electricity. The most significant barrier that must be overcome for this to take place is the problem of energy storage. For automotive

[22] A V2G contract between a utility and an electrified vehicle owner may consist of two components: payment for the actual energy services provided, driven by energy prices; and payment for helping to meet the utility's installed capacity requirement, driven by capacity markets. For more information regarding the economics associated with these markets, see (Stoft, 2002).

[23] For additional information about Better Place, see their website: http://www.betterplace.com/

applications, the most likely energy storage solution in the near term is the Li-ion battery. The key determinant of electrified vehicles becoming commercially viable is the cost of this battery. The results of this research indicate that it is possible that Li-ion battery costs can feasibly decrease in the next two decades to the point that PHEVs and EVs will become economically competitive. The results also demonstrate that this competiveness is highly sensitive to fuel prices. Additionally, there may be scenarios in which battery costs do not decrease as rapidly as expected, and may even increase if resource constraints become a factor. However, this worst-case scenario is probably unlikely.

There are numerous battery-related mechanisms through which electrified vehicles may become economically competitive. Battery costs could continue to decline to the point that their price premium is offset by fuel savings during the life of the vehicle. Such cost reduction may occur through the use of lower cost materials, increased packaging efficiencies, process improvements, economies of scale, and increased manufacturing yields. Alternatively, sustained high fuel prices, either as a result of oil markets or policy intervention, would allow this offset to occur at higher battery costs. Risk and liability to the manufacturers could be reduced by policies that shift the warranty burden from manufacturers to the government, if such a program were found to be of positive social value. Finally, new business models may emerge, such as second-use markets, V2G services, and subscription-based arrangements that could offset or eliminate the battery-related price premium otherwise borne by electrified vehicle owners.

Regardless of the economics associated with electrified vehicle adoption, public perception of these vehicles must shift if they are to gain market acceptance. The current worldwide economic turmoil and state of the automotive industry, especially in the U.S., has brought the notion of more fuel-efficient vehicles into the public consciousness. Concurrently,

battery manufacturers have announced plans to scale up automotive Li-ion battery production, both in the U.S. and abroad. Market forces are such that we are likely at the beginning of a large-scale shift towards electrified vehicles enabled by Li-ion batteries. The pace of this shift will be substantially influenced by energy and climate policy.

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APPENDIX A: Summary of Various Battery Chemistries

Source: (Axsen, et al., 2008; Kalhammer, et al., 2007; Kromer & Heywood, 2007; Nelson & Amine)

Chemistry		Stage of Development	USABC Goal Categories: Power	Energy	Life	Safety	Low Cost	Notes
	Pb-Acid	Mass Commercialization	Very limited power density	Extremely limited energy density.	Proven cycle and calendar life for conventional vehicles, but not adequate for xEV applications.	Proven record of safety. Environmental impact mitigated by extensive lead recycling infrastructure.	Very low cost.	Very well understood technology with proven reliability, safety, & cost for ICE vehicles, but little chance of usefulness for xEV applications.
	Ni-Cd	Mass Commercialization	Limited power density.	Very limited energy density.	Good cycle and calendar life.	Proven safety record in consumer electronics. Cadmium is toxic.	Relatively high cost with little room for reduction.	"Memory effect" if not fully discharged. All but abandoned due to shortcomings compared to NiMH and Li-Ion.
	NiMH	Mass Commercialization	Limited power density.	Limited energy density.	Proven longevity for calendar and cycle life.	Proven history of safety.	Limited prospects for cost reductions.	Mature technology with little room for further improvements in energy, power, and cost.
Li-Ion	**$LiCoO_2$/Graphite (LCO)**	Commercialization	Good power density.	Good energy density.	Cycle life is suitable for consumer electronics, but poor for automotive applications.	Low to moderate: thermal runaway problems would be disastrous in automotive applications.	High: cost of cobalt is a limiting factor for cost-reduction possibilities.	Most common chemistry for consumer electronics, though may not be suitable for automotive applications.
Li-Ion	**$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$/ Graphite (NCA)**	Pilot	Good power density.	Good energy density.	Good cycle life and calendar life.	Moderate: nickel-based eletrodes are thermally unstable and degrade at high states of charge.	Moderate: limited cost reductions due to use of cobalt and nickel.	Other similar chemstries are being developed to mitigate safety and cost concerns.
Li-Ion	**$LiFePO_4$/Graphite (LFP)**	Pilot	Good power density.	Moderate energy density.	Good - can be operated at wide SoC window and still achieve good cycle life.	Moderate to good: stable cathode material does not release oxygen, but graphite anode still reactive with electrolyte.	Low: one of the least expensive Li-Ion chemistries due to iron-based cathode.	May be one of the most promising chemistries, due to advantages in cost, safety, & cycle life.
Li-Ion	**$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ / Graphite (NCM)**	Pilot	Moderate power density.	Moderate to good energy density.	Poor cycle life.	Moderate: nickel-based eletrodes are thermally unstable and degrade at high states of charge.	Moderate: limited cost reductions due to use of cobalt and nickel.	Similar to NCA, intended to be cheaper than NCA. Capable of high cell-voltage.
Li-Ion	**$LiMn_2O_4$/Graphite (LMS)**	Developmental	Moderate power density.	Moderate energy density.	Moderate to excellent: potential for above-average cycle life, calendar life may have issues.	Good: manganese-based eletrode material is potentially safe.	Moderate: low cost per kg, but cost per kWh limited due to limited energy density.	Manganese dissolves in electrolyte, reduces at anode, reducing cell performance.
Li-Ion	**$LiMn_2O_4/L_{i4}Ti_5O_{12}$ (LTO)**	Developmental	Moderate power density.	Moderate energy density, mitigated due to large SoC operating window.	Good to excellent cycle life.	Very stable cathode/anode combination that promises good to excellent safety.	High: potentially high cost due to use of titanium.	Promising technology which solves many of the problems associated with LMO batteries.
Li-Ion	**$LiMn_{1.5}Ni_{0.5}O_4$ / $Li_4Ti_5O_{12}$ (MNS)**	Research	Good power density.	Moderate energy density.	Unknown.	Excellent.	Moderate.	Promising technology, some impedance issues which limit power must be solved.
Li-Ion	**$Li_{1.2}Mn_{0.6}Ni_{0.2}O_2$ / Graphite (MN)**	Research	Excellent power density.	Excellent energy density.	Unknown.	Excellent.	Moderate.	Highest capacity chemistry developed at Argonne.
	Zinc-Air	Commercialization	Limited power density.	High energy density.	Long life for mechanically rechargeable type. Life unknown for electrically rechargeable type.	Very safe in storage, use, and disposal.	Low cost (driven by cost of zinc).	Typically not rechargeable except mechanically by replacing zinc in anode. Electrically-rechargeable zinc-air batteries are in research phase.
	NaNiCl (ZEBRA)	Pilot	Limited power density.	High energy density.	Low cycle life.	Very safe components, safe in operation and disposal.	Moderate cost, though potentially high cost due to use of nickel.	Requires high temperature (270˚C) to operate correctly.

APPENDIX B: Battery Cost Inputs Questionnaire

Battery Cost Inputs Questionnaire

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1. Please give general specifications for a representative Li-ion battery cell / module / pack used in automotive applications:

	Cell-level	*Module-level*	*Pack-level*
1.1. Capacity (Wh or Ah)	_____	_____	_____
1.2. Nominal voltage (V)	_____	_____	_____
1.3. Mass (g)	_____	_____	_____
1.4. Cost ($)	_____	_____	_____

2. For each of the following, please indicate the quantity and cost of raw materials that are used for the production of the Li-ion battery cell specified in #1. Cost may be indicated as a dollar-amount, or as a percentage of total cost of the battery. If cost for a listed component is insignificant, please specify it as such. If any major cost contributors have been omitted, please add information for these.

2.1. Cell-Level:		*Quantity*	*Cost*
2.1.1.Cathode:			
2.1.1.1.	Lithium-carbonate	_____	_____
2.1.1.2.	Binder	_____	_____
2.1.1.3.	Solvent	_____	_____
2.1.1.4.	Aluminum	_____	_____
2.1.1.5.	Other	_____	_____
2.1.2.Anode:			
2.1.2.1.	Graphite	_____	_____
2.1.2.2.	Binder	_____	_____
2.1.2.3.	Solvent	_____	_____
2.1.2.4.	Copper	_____	_____
2.1.2.5.	Other	_____	_____
2.1.3.Electrolyte:			
2.1.3.1.	Lithium Salt	_____	_____
2.1.3.2.	Solvent	_____	_____
2.1.3.3.	Other	_____	_____
2.1.4.Separator:			
2.1.4.1.	Polypropylene	_____	_____

2.1.4.2.	Polyethylene	_____	_____
2.1.5.Packaging:			
2.1.5.1.	Steel	_____	_____
2.1.5.2.	Aluminum	_____	_____
2.1.5.3.	Plastics	_____	_____
2.1.5.4.	Tabs	_____	_____
2.1.5.5.	Safety valves	_____	_____
2.1.5.6.	Other	_____	_____
2.1.6.Other		_____	_____
2.2. Module-Level:			
2.2.1.Packaging		_____	_____
2.2.2.Connectors		_____	_____
2.2.3.Terminals		_____	_____
2.2.4.Safety Components		_____	_____
2.2.5.Other		_____	_____
2.3. Pack-Level:			
2.3.1.Packaging		_____	_____
2.3.2.Connectors		_____	_____
2.3.3.Terminals		_____	_____
2.3.4.Components:			
2.3.4.1.	Crash Sensors	_____	_____
2.3.4.2.	Current Sensors	_____	_____
2.3.4.3.	Management System	_____	_____
2.3.4.4.	Cooling System	_____	_____
2.3.4.5.	Power Electronics	_____	_____
2.3.5.Other		_____	_____

3. For each of the following, please indicate the cost, lifetime, and throughput of the capital equipment, and personnel required for each step of the manufacturing process.

3.1. Cell-Level:		*Capital Cost*	*Lifetime*	*Throughput*	*Personnel*
3.1.1.Mixing		_____	_____	_____	_____
3.1.2.Coating		_____	_____	_____	_____
3.1.3.Drying		_____	_____	_____	_____
3.1.4.Calendaring / cutting		_____	_____	_____	_____
3.1.5.Other		_____	_____	_____	_____
3.1.6.Cell Assembly:					
3.1.6.1.	Winding	_____	_____	_____	_____
3.1.6.2.	Packaging	_____	_____	_____	_____
3.1.6.3.	Welding tabs	_____	_____	_____	_____
3.1.6.4.	Insulating	_____	_____	_____	_____
3.1.6.5.	Sealing	_____	_____	_____	_____
3.1.6.6.	Safety Sys.	_____	_____	_____	_____
3.1.6.7.	Inspection	_____	_____	_____	_____

3.1.6.8. Other	_____	_____	_____	_____
3.2. Module-Level:				
3.2.1.Packaging	_____	_____	_____	_____
3.2.2.Safety system integration	_____	_____	_____	_____
3.2.3.Inspection	_____	_____	_____	_____
3.2.4.Other	_____	_____	_____	_____
3.3. Pack-Level				
3.3.1.Packaging	_____	_____	_____	_____
3.3.2.Safety system integration	_____	_____	_____	_____
3.3.3.Battery Mgmt sys integ.	_____	_____	_____	_____
3.3.4.Inspection	_____	_____	_____	_____
3.3.5.Other	_____	_____	_____	_____

4. What are the other costs involved with advanced Li-ion battery production? Please quantify them as practically as possible.

	Cost
4.1. Warranty costs	_____
4.2. Testing	_____
4.3. Recycling	_____
4.4. Factory space	_____
4.5. Other	_____

5. Of the components and manufacturing steps listed above, do you anticipate any experiencing significant or sudden changes in cost in the future? Please explain. _____

6. Of the components and manufacturing steps listed above, do you anticipate any becoming obsolete or being replaced by different materials or processes? Please explain. _____

7. The historical trends in Li-ion battery development (primarily for the consumer electronics market) show a 7% per year improvement in energy density and an 8% per year reduction in per-Wh cost. Do you anticipate the trends for automotive Li-ion battery development to be similar to, to improve upon, or to fall behind these historical trends? Please explain._____

8. In your opinion, what effect would a 10x increase in federal government funding for automotive battery development have on the pace of Li-ion battery cost reductions and the mass-commercialization of Li-ion powered PHEVs and EVs._____