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Factors Determining the Manufacturing Costs of Lithium-Ion Batteries for PHEVs

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Abstract

In this study, we developed a model for calculating the costs of lithium-ion batteries supporting electric drive in light duty passenger vehicles (LDVs). The model calculates the annual materials requirements from design criteria for the battery pack including power, capacity, number of cells, and cell chemistry parameters. The costs of capital equipment, plant area and labor for each step in the manufacturing process were estimated for a baseline plant. These costs are adjusted for each battery pack studied by comparing the processing rate pertinent for each step (area to be coated, number of cells to be tested, etc.) with that of the baseline process and applying correction factors. We applied the cost modelling method to batteries with four lithium-ion cell chemistries and for several levels of capacity and power. For quality assurance purposes, electrode coating thicknesses are limited to 100 microns by the model. The result of this restriction is that as the capacity of the cells is increased to achieve longer range under electric power, the electrode area and the cell power are also increased and the power of the entire battery pack is also increased. In simulations of our reference chemistry for 16, 32 and 48 -km PHEVs there is almost no cost increase for increasing the pack power from 40 to 60kW; for PHEVs with 48- and 64 km electric range, there was almost no additional cost for power up to 90 kW. For a set value of pack energy storage, a small number of high capacity cells are much less expensive to manufacture than a large number of low-capacity cells. The useable fraction of the state-of-charge range for a battery system is shown to be an important cost factor. In view of cost similarities, the choice of cell chemistry will probably depend more on proven safety, reliability, and long life rather than on initial cost.

Keywords: battery model, cost, lithium battery, parallel HEV, PHEV

1 Introduction

Lithium-ion batteries show promise for powering hybrid electric vehicles (HEV) and plug-in hybrid vehicles (PHEVs). However, there are many competing cell chemistries and cell designs with varying capabilities under study for these applications. Estimating the cost of manufacturing such battery cells and packs is an important part of assessing the relative merits of these systems and in setting vehicle design goals. We examined

cost of manufacturing vehicle battery packs at a rate of production of 100,000 packs per year for the following four cell chemistries:
(1) $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$/graphite (NCA-G),
(2) $LiFePO_4$/graphite (LFP-G),
(3) $Li_{1.06}Mn_{1.94}O_4/Li_4Ti_5O_{12}$ (LMO-TiO) and
(4) $Li_{1.06}Mn_{1.94}O_4$/graphite (LMO-G).
This effort consisted of a design study of battery packs over a wide range of power capability for HEVs and for PHEVs with depleting charge (DC) ranges of 16 to 64 km.
The emphasis in this paper is on using the model to determine the effects of design and cost parameters on the cost of batteries rather than on detailing the development of the model. The method of calculating the manufacturing costs has been established, but the values of some of the cost parameters are still under review.
It is well known that the required power and energy storage capability of the battery pack are the most important parameters in determining the cost of lithium-ion batteries for PHEVs. In previous publications, it has been estimated that for one HEV and multiple PHEV designs, the costs of battery packs per unit of energy was approximately a straight line function of the power-to-energy ratio. This was estimated first for nickel metal hydride (NiMH) batteries [1], and then generically for Li-ion batteries [2], lumping data for two chemistries together. If we ignore any limits on the thickness of the electrodes, our cost estimates, when plotted in this fashion, also exhibit this behavior.
The earlier work suggests that the following linear approximation might work generically.

$$(\$/E_t)_c = a_c + b_c \times (P/E_t) \quad (1)$$

$$\text{or } \$ = a_c \times u_{tc} \times E_t + b_c \times P \quad (2)$$

Where: $ = unit battery cost
E_t = nominal energy storage, kWh, for vehicle type t
u_{tc} = fraction of nominal kWh useable for the vehicle type, t and chemistry c
P = power, kW (~ constant across vehicle types)
a_c and b_c are constants specific to each chemistry.

However, with our more detailed investigation, we have found that for all of the cell chemistries we investigated in this study, a reasonable limit on the maximum electrode thickness of 100 microns would partially invalidate the above relationship between cost, power and battery energy. Up to a point, increase in battery energy at constant battery power is accommodated by an increase in electrode thickness, which results in the linear increase in cost expected by the above relationship. When the limit in electrode thickness is reached, further increase in energy can only come about by increasing the cell area and, thus, increasing the cell power and adding the additional cost factors associated with the additional power. The result is a sudden change in the slope of the cost curve at the point at which the limit on the electrode thickness takes affect. These effects are discussed in more detail in Section 4.1.

2 Modelling Battery Performance and Materials Requirements

Over a period of several years, Argonne scientists have developed methods based on modelling with Microsoft Excel spreadsheets to design lithium-ion batteries for hybrid-electric vehicles [3-5]. Samples of these spreadsheets were used to initiate this study. The initial efforts were concentrated on cells and batteries with $LiNi_{0.8}Co_{0.15}Al_{0.05}$ positive electrodes and graphite negative electrodes (NCA-G) and were later expanded to include several other systems including those discussed in this paper. Based on the physical and electrical parameters for these materials, complete batteries were designed that meet a broad range of performance criteria, including battery power, energy storage and voltage.
Various cell and battery design concepts are under development at battery manufacturers. It is assumed in this study that for any selected lithium-ion cell chemistry, these design variations have only a minor effect on the cost of a battery that meets a set of performance criteria. The most common cell designs are cylindrical wound cells, flat wound cells, and prismatic cells with flat plates. Cylindrical cells probably have a slight advantage for the assembly of the electrode-separator unit because of the ease of making a cylindrical winding. For the different cell designs, there are small differences in the weights of the terminal extensions and the procedures for connecting these extensions to the current collector sheets, with a small advantage for flat plate cells. The flat-wound and flat-plate cells form a more compact module and have better heat rejection capabilities than the cylindrical cells. For this model, it is assumed that cell configuration differences have negligible effects on the cost of battery cells and packs produced in high volume in mature production plants. We also assume that, over the range of pack attributes examined, there is no variation in pack cooling system requirement by chemistry, power, energy and/or power/energy

ratio. Air cooling was assumed. The initial cell design for this study involved flat wound cells because for that design a comprehensive battery design program, in a Microsoft Excel spreadsheet format, was already available.

The original starting spreadsheet was altered to automatically design all cells with a height-to-width ratio of approximately 1.4 and a thickness of approximately 20 mm. Slight variations in these values arise from the automatic adjustment of the number of windings to an exact integer. The imposition of these restrictions ensured that changes in the capacity and power of cells would result in near optimum designs and relatively smooth changes in the materials requirements without the need for additional design input requiring engineering judgment.

Based on the physical and electrical parameters for the various cell chemistries, complete packs were designed that meet a broad range of performance criteria. The spreadsheet calculates the weights and volumes of all of the parts of the cell and pack and their electrical and thermal performance. Five or more packs of different performance criteria are calculated on a single spreadsheet with a column dedicated to each design. All equations used in the spreadsheet calculations are the same for all of the packs and thus only differences in the input parameters cause the results to differ. All parts of the spreadsheet are interconnected so that a change in any input parameter for a pack will result in recalculation of the entire spreadsheet and changes in all values affected by the changed parameter value.

A study of the results for a large number of packs designed with the comprehensive battery design program with various cell chemistries and over a broad range of pack power and capacity indicated that the design criteria that affect cost could be derived with a less complex program that is not required to provide detailed cell and pack designs. What are needed for cost estimation are the battery materials requirements from input on the cell chemistry, the cell capacity, the number of cells, and the pack power, and these can be estimated with a much less complex program than the comprehensive design program.

A new modelling program was developed that provides the needed information and requires less than two pages of printout for five packs as compared to about 30 pages for the comprehensive battery design program. Semi-empirical estimating equations for several parameters including the resistance of the current collection system, the cell area, and the weights of materials and key components enabled construction of the condensed summary model. These equations were adjusted by comparing the results of the simplified program with the output of the comprehensive program. The adjustments brought the outputs of the two programs to within less than 2% for the annual throughputs of all of the materials for the cells and battery packs and for the total weights and volumes of the battery packs. Thus, the annual materials requirements needed for calculating manufacturing costs can be determined with the simplified program with more than adequate accuracy and these results apply for various cell designs including cylindrical, flat-wound and prismatic cells with stacked electrodes. The program also provides the weight and volume of the cells and pack, which are based on equations that are fitted to nearly reproduce the results of detailed designs for batteries of flat-wound cells with air cooling systems and insulated battery pack jackets with 10-mm thick insulation. The program slightly underestimates the volume of cylindrical-cell or prismatic-cell battery packs.

3 Development of Method to Estimate Manufacturing Costs

The manufacturing cost of the battery packs must be calculated from the limited data generated by the simplified design program; detailed designs are not available. With this in mind and to simplify the cost calculations, it was assumed that all hardware items for the cell, module and battery will be purchased from a vendor specializing in similar products. The costs for these items were estimated to be a fixed value plus an additional value proportional to the weight of the item, which is estimated by the simplified materials program. In mature manufacturing plants, toward which this study is directed, some items which are assumed to be purchased in this study might actually be internally manufactured from raw materials. This would increase the number of processing steps needed in our manufacturing simulation and thus complicate the cost calculations. However, the effect on the overall unit cost of the battery pack of purchasing items that could be fabricated in-house would be very small because the cost saved by not needing to purchase the items would be offset by the capital costs and labor costs associated with the in-house manufacture.

It is important to note that in this analysis of costs it is assumed that all costs are evaluated for a time

in the future when the large battery manufacturing plants are built and that these costs are brought back to 2009 with allowance for inflation. Some materials costs are lower than recent values, where we judged that processing improvements and a return to long term materials cost trends would lower long term high volume costs. The overall approach to estimating the manufacturing costs is outlined in Tables 1 and 2.

Each cost item was estimated for a baseline plant, which was designed to produce 100,000 battery packs per year with the following design criteria for the battery: NCA-G system, 50-kW power at 50% OCV, 30-Ah capacity, 8 modules, 12 cells per module, and 96 cells per battery. Estimates were made for the capital equipment, plant floor area, materials and purchased items, and labor costs for each processing step. The other costs were determined by multiplying these basic estimates by factors to determine the total investment cost and the unit battery pack cost for the baseline plant. A summary of the costs for the baseline plant are shown in Table 3 and Fig. 1.

Table: 1 Battery Pack Manufacturing Investment Costs

Investment Costs	Description	Method of Calculation
Capital Equipment	Equipment costs including installation	Estimates of costs for each processing step at baseline rates adjusted for actual rates.
Plant Floor Space	Space includes aisles and space for unfinished processing inventory plus land and utility costs.	Estimates of costs for each processing step at baseline rates adjusted for actual rates.
Launch Costs	Plant start-up, training, out-of-spec product.	5% of annual materials cost, 10% of direct labor plus variable overhead.
Working Capital	Cash to meet payroll, receivables, inventories of raw materials and of unfinished and finished product, minus payables.	30% of annual variable costs.

Table: 2 Unit Cost of Battery Pack

Variable Costs	Description	Method of Calculation
Materials and Purchased Items	All materials and purchased items in finished product and lost in processing.	Based on prices of materials, cost equations, yields.
Direct Labor	Labor costs for operations and immediate supervision.	Estimates of costs for each processing step at baseline rates adjusted for actual rates.
Variable Overhead	Indirect materials, labor, utilities, plant maintenance	60% of direct labor cost.
Fixed Expenses		
General, Sales, and Administration (GSA)	Plant office, control laboratory, sales, income and property taxes, insurance.	25% of direct labor and variable overhead plus 35% of depreciation.
Research and Development	On-going research needed to upgrade product and maintain competitive position.	50% of depreciation
Depreciation	Fund for replacement of equipment and plant.	12.5% of capital equipment cost plus 5% of plant floor space cost.
Profit	Return on invested capital after taxes.	5% of total investment costs.

Table 3: Baseline Manufacturing Costs

Calculated Battery Parameters	
Battery energy storage, kWh	10.2
Battery power, kW	50.0
Capacity, Ah	30
Number of cells	96
Battery weight, kg	82
Battery volume, L	52
Vehicle electric range, miles	20.5
Investment Costs	
Capital equipment cost, mil$	191
Building, Land and Utilities	43
Launch Costs	86
Working capital, mil$	58
Total investment, mil$	378
Unit Cost of Battery Pack, $	
Variable Cost	
Materials and Purchased Items	
Cell materials	1,214
Cell purchased Items	155
Module and battery	292
Total	1,660
Direct Labor	
Electrode processing	72
Cell assembly	40
Formation cycling	12
Module and battery assembly	20
Rejected cell and scrap recycling	9
Receiving and shipping	10
Total	162
Variable Overhead	97
Total Variable Cost	1,920
Fixed Expenses	
General, Sales, Administration	132
Research and Development	130
Depreciation	261
Total Fixed Expenses	523
Profits after taxes	189
Total unit cost per battery, $	2,632

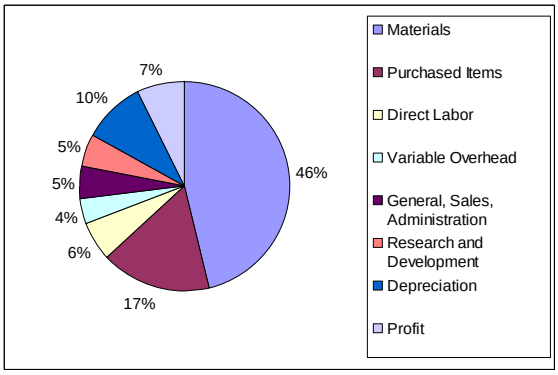

Figure 1: Summary of Unit Cost Shares for Manufacturing Baseline Batteries

For plants manufacturing packs differing in cell chemistry or pack design criteria from those of the baseline pack, the costs of each processing step was adjusted to account for the difference in the processing rate for that step in the process and that of the same step in the baseline plant. As noted in Table 4, there are five pertinent annual processing rates in addition to the overall number of batteries manufactured per year. This is because each of these rates affects the costs of one or more steps in the process and has no effect upon the costs of other steps in the process. For instance, when the user of the model increases the power of the battery packs without increasing the number of cells or their capacity, the model increases the area of the cells and decreases the electrode coatings thicknesses. Such changes would result in an increase in the cost of the coating equipment, the floor area occupied by the equipment, and in the direct labor for that step in the process. It would have no effect on the cost of mixing the materials to be coated because the amounts of these materials per pack are unchanged under the assumed conditions.

Table: 4 Baseline Manufacturing Rates and Yields

Manufacturing rate, packs/year	100,000
Cell yield, %	97
Materials yield, except electrolyte, %	95
Electrolyte yield, %	90
Baseline Annual Processing Rates	
Energy storage capacity, kWh	1,023,995
Number of cells adjusted for yield	9,896,907
Electrode area, m^2	10,114,827
Positive active material, kg	2,083,559
Negative active material, kg	1,387,543

A method that is often used to estimate the cost of a manufacturing plant with a desired capacity from the known cost of a plant of a different capacity is to multiply the known cost by a ratio of the two capacities raised to a power, usually about 0.6 to 0.7 [6]. This approach recognizes the cost advantage of increasing the scale of operations and is a valid approach if the plants produce the same product or product mix. However, in our study this method can not be applied to entire plants because the products of the plants are different (different battery pack powers, capacities, etc.) and because no single measure of the processing rate (annual energy storage capacity produced, annual

number of cells, annual electrode area, etc.) characterizes the production for the entire plant.

The general approach to cost estimation of multiplying a known cost by the ratio of processing rates raised to a power has also been applied to the capital cost of individual items of equipment [6]:

$$C_i = C_o(R_i/R_o)^p \quad (3)$$

Where: C_o = capital cost of an installed equipment item designed for the baseline processing rate, R_o,

p = the power factor relating the capital investment cost and the processing rate for the manufacturing step.

If the value of "p" were 1.0, it would imply that the cost of the equipment item, or the equipment items if there are several in parallel, would be directly proportional to the processing rate. However, the value of "p" for the cost of equipment is frequently about 0.6 to 0.7 for many manufacturing process steps because the equipment is larger for the higher processing rates and its cost is less than if it were directly proportional to the processing rate. For process steps requiring the addition of many identical pieces of equipment for scale up, such as may be true for formation cycling of battery cells, the value of "p" may be as high as 0.8 to 0.9. The value of "p" is unlikely to reach 1.0 because the equipment cost includes installation, for which there is some savings even in installing multiple units of the same processing capacity.

Similar equations have been applied for determining the effect of processing rate on the annual hours of labor and the plant area required for a manufacturing step. In general, the value of "p" is low for the labor equation [6], usually only 0.3 to 0.6, because only a relatively small addition to the labor crew permits operation of larger equipment or of operating several more units of the same processing capacity. The value of "p" for the plant area required for a processing step is slightly less than that for equipment. The floor area required for larger equipment or for more equipment items of the same size is proportionately less than the increase in the processing rate because of the more efficient use of the space occupied by the equipment and the savings in aisle area.

In this study, the battery manufacturing plant was divided into segments for which a single processing rate (Table 4) could be identified. Then the capital cost of the equipment, the associated floor area and the annual labor hours for each of these processing steps was estimated for the baseline processing rates that apply to each step. The value of the power factors for capital equipment, floor area, and labor were estimated for each of the processing steps.

To summarize the cost modelling program, the cell chemistry characteristics are selected on the first sheet of the program, which provides default values that can be overridden if desired, and cost values for the materials. On the next two pages, the annual materials requirements are calculated for five battery pack designs, each in separate columns, with input on the pack power, the cell capacity, the number of modules and the number of cells per module. Two additional pages provide the cost manufacturing parameters including the costs of capital equipment, plant area and labor for each step in the process for manufacturing the baseline battery and the parameters for correcting these values for the batteries being studied. The remaining pages in the modelling program calculate the cost of manufacturing the battery pack design and provide a summary of the capital costs and the unit cost (cost per battery pack) for the five designs.

4 Results

4.1 Effects of ASI and Power on Cost

The electrodes of lithium-ion batteries are coated on metal foil, usually copper foil for the negative electrode and aluminum foil for the positive electrode. Thick coatings result in a high weight fraction of electrode materials in the battery and high specific energy, but low specific power because of the limited electrode surface area per unit volume. Thus, batteries needing high power-to-energy ratio, such as HEV batteries, have thin electrode coatings, whereas PHEV batteries have thicker electrodes. The limit on electrode thickness is about 100 microns; above that limit the electrode tends to spall off of the current collector especially when flexed during winding. Also, the area-specific impedance (ASI), which is fairly constant over a broad range of electrode thicknesses (approximately 20 to 100 microns), begins to rise with increasing thickness especially at high depths of discharge for electrode coatings in excess of 100-micron thickness. If the power-to-energy ratio for the battery being designed would result in an electrode thickness greater than 100 microns, the modeling program is designed to increase the fraction of open-circuit voltage (OCV)

at which full power is attained from the normal set value of 80% of OCV resulting in an increase in the required area and, thus reducing the electrode thicknesses for a given cell capacity to 100-microns. How these variables interact to affect the cell design and the cost is illustrated in Table 5 and Figs. 2 and 3.

As the energy storage capacity increases at a constant battery power to accommodate a longer vehicle range, the electrode thicknesses increases with virtually no change in cell area until the thickest electrode (the negative electrode in the case of the NCA-G system) reaches the maximum allowed thickness of 100 microns. Further increase in cell capacity results in no increase in cell thickness, but increase in cell area and the OCV at which full power is delivered. Table 5 shows the effects of increasing the battery energy from that required for a HEV by amounts sufficient for increasing the charge depletion range of the vehicle by 8-km increments. Fig. 2 illustrates the sudden breaks in the design and cost curves that occur when the increase in capacity causes the thickness of the thickest electrode (the negative electrode for the NCA-G system) to reach the limit of 100 microns at a CD range of about 20.6 km. The values in Table 5 and Fig. 2 are for batteries of 60 cells and 40-kW power. For batteries with the same number of cells, and higher power, the thickness limit comes into play at longer CD ranges as illustrated in Fig. 3.

Table 5: Effect of Battery Energy on Design and Cost of 40-kW, NCA-G Batteries

Vehicle Performance					
Vehicle Range at 188 Wh/km	**HEV**	**16**	**24**	**32**	**40**
Power /Useable Energy, W/Wh	26.7	13.3	8.9	6.7	3.3
Power/Total Energy, W/Wh	18.7	9.3	6.2	4.7	2.3
Cell Performance (BOL)					
ASI for 10-s pulse at 25% SOC, ohm-cm	24.5	24.7	24.9	25.0	25.3
Cell area, cm	8,098	8,167	9,565	12,754	25,510
Negative electrode thickness, μm	39.0	77.8	100.0	100.0	100.0
Open circuit voltage at full power, %OCV	80.0	80.0	83.6	88.3	94.4
Cell voltage (50% SOC), V	3.68	3.68	3.68	3.68	3.68
Cell voltage (25% SOC), V	3.55	3.55	3.55	3.55	3.55
Cell power (25% SOC), W	667	667	667	667	667
Cell energy (100% discharge), Wh	35.7	71.4	107.1	142.9	285.7
Cell capacity, Ah	9.76	19.64	29.55	39.41	78.82
Battery Performance (BOL)					
Cells per battery pack	60	60	60	60	60
Voltage (50% SOC), V	221	221	221	221	221
Power (10-s burst, 25% SOC), kW	40	40	40	40	40
Energy (100% discharge), kWh	2.14	4.29	6.43	8.57	17.14
Fraction useable energy, %	70	70	70	70	70
Manufacturing Costs					
Plant capacity, (10^3 packs/y)	100	100	100	100	100
Investment ($10)	195	227	263	305	467
Unit Cost of Battery Pack, $					
Materials	378	554	758	1,001	1,959
Purchased items	306	322	338	325	396
Direct labor	110	117	125	136	170
Other variable overhead	66	70	75	82	102
Fixed expenses	304	337	376	424	591
Profits after taxes	98	114	132	153	234
Total unit cost per battery pack	1,262	1,513	1,803	2,120	3,452

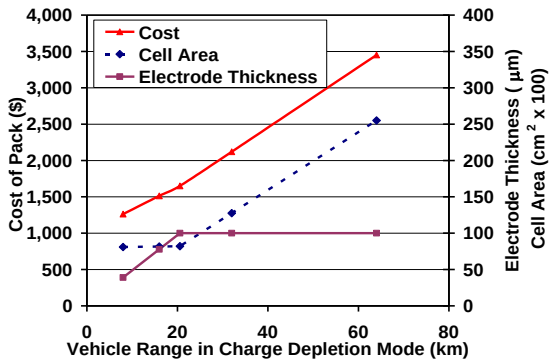

Figure 2: Effect of Vehicle CD Range on Cell Design and Cost for 40-kW NCA-G Packs

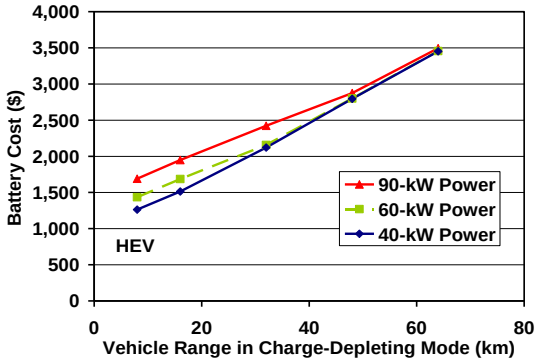

Figure 3: Effects of Vehicle CD Range and Power on Cost for 60-Cell, NCA-G Packs

As the power for NCA-G packs increases from 40 to 60 kW, there is very little effect on cost for packs with sufficient energy for CD ranges beyond 32 km; as power increases to 90 kW, there is very little effect on cost for CD ranges beyond 48 km. If the pack can maintain most of this high power throughout its useful life, vehicle designers can utilize the extra power with virtually no additional battery pack cost.

Packs of the other cell chemistries also show breaks in the curves of electrode thickness, cell area, and cost versus vehicle CD range, but at different distances than for NCA-G. For LFP-G the breaks occur at about 27 and 42-km CD ranges for 60 and 90 kW respectively and at about half of those values for LMO-TiO and LMO-G for the parameters used in this study.

4.2 Effect of Cell Capacity on Battery Cost

For a set level of energy storage, the capacity of the cells and the number of cells required to meet the desired storage capacity affect the cost of the pack, because of the cost of formation cycling and testing of individual cells and the cost of cell state-of-charge circuits needed for each cell. These combined effects make a substantial contribution to the cost of a large number of small cells for packs of all power capabilities as illustrated below for NCA-G batteries (Fig. 4). The small change of slope in the curves at very low number of cells (high capacity) results from increasing resistance in the current collection system as the cell is increased in capacity and, thus, increasing cell area in the battery (increasing cost) to meet the power requirement.

4.3 Effect of Useable State-of-Charge Range on Battery Cost

The available fraction of the state-of-charge (SOC) range that can be used without significantly affecting the life of the battery is an important factor influencing battery cost. The life of some packs with different battery chemistries, separators, or levels of manufacturing precision may be adversely affected either by charging to the full state of charge or by discharging to a low state of charge.

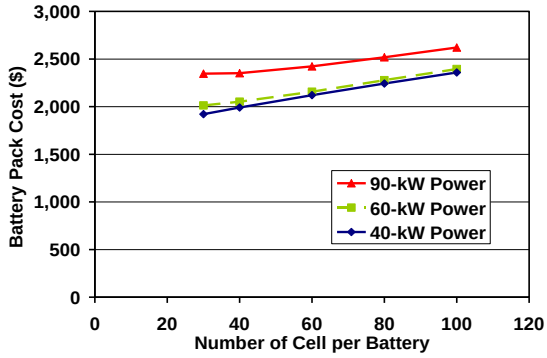

Figure 4: Pack Cost vs. Number of Cells for NCA-G Packs for 32-km PHEVs

The effect of the fraction of useable energy on the cost of a set of NCA-Graphite batteries is illustrated below (Fig. 5).

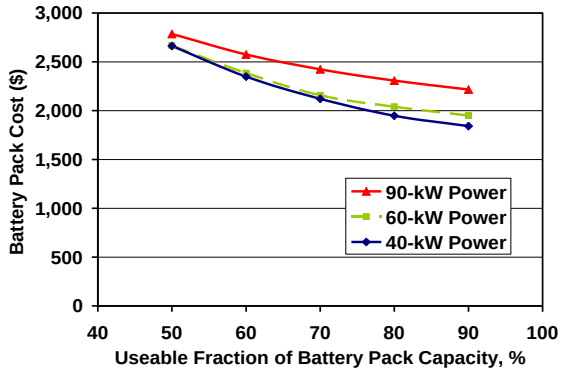

Figure 5: Pack Cost vs. Useable Fraction of Capacity for 32-km NCA-G Packs of Various Power Levels

For some cell chemistries, the battery may also be inhibited from receiving regenerative braking at a high rate until the vehicle has been driven for a few kilometers after a full charge because the battery would be damaged by high voltage resulting from a high charge rate at over 90% SOC. There is also a safety concern in charging the battery at a high voltage, which may cause deposition of metallic lithium. However, the restriction of a low charging rate for the battery at high SOC may not be functionally important because all PHEVs must have essentially the same mechanical braking system as standard vehicles and the superimposed regenerative braking is only for energy saving. Nevertheless, the first few kilometers from a house generally use braking more frequently, so differences in energy savings across chemistries at high SOC deserve consideration. In particular, battery packs with lithium titanate negative electrodes (LMO-TiO) would not be restricted from receiving regenerative braking at high SOC. Such battery packs could receive very high charge rates after the first acceleration of the vehicle, because the battery is not damaged by regenerative-braking charges at voltages well above the cutoff charging voltage, nor would lithium be deposited at charging voltages as much as 1.5 volts above the cut-off charging voltage.

4.4 Effects of Cell Chemistry on Battery Cost

The four differing cell chemistries that were studied have widely varying physical and electrical properties as shown in the printout of the system selection sheet from the cost modelling program presented in Table 6.

An accurate comparison of the costs of batteries of these systems would require accurate estimates of the materials costs and all of the processing parameters, which we do not yet have. However, the materials costs used for all pack designs are the same. Further, the fraction of the useable state of charge ranges for the four systems may differ and is a point of contention among advocates of the various chemistries. With lack of definite knowledge at the present time we have set the long term useable range as 70% (95% SOC to 25% SOC for all systems, except for the LMO-TiO system. The LMO-TIO system was allowed to charge to 100% because of the previously noted tolerance for high voltage and high charging rates near full charge. Table 7 and Fig. 6 compare the systems that are all designed with 60 cells for maximum power of 60 kW at 25% SOC.

4.5 Effect of Manufacturing Scale

The cost estimates in this study assume a stable rate of pack manufacture at a high rate of 100,000 packs/yr with the equivalent of 300 days per year *of continuous 24-hr operation* with 8-year depreciation of the equipment and 20-year depreciation of the plant. The investment costs under these conditions would range from about $220 million to $664 million for the plants manufacturing the batteries of Table 6. If the plants were designed for 10,000 battery packs per year, a reasonable production level for the first year for both a new battery pack design and a new vehicle, then the unit costs for the batteries would be approximately 60 to 80% higher than for the larger plants we have simulated here. If, in addition, the plants were designed to be expanded for future production or the plant equipment was amortized over a shorter period to allow for the uncertainty of future orders (discontinuous production), the unit battery prices would be even higher. *Thus, the low production rates anticipated for initial production of the batteries creates serious per vehicle battery cost barriers that must be subsidized either by vehicle manufacturers or governments in order to achieve a viable long-term PHEV battery market.*

4.6 Incremental Cost of Short Range PHEV

The most important conclusion to be drawn from this research is that the incremental pack cost if switching from HEV battery packs to packs that enable relatively short range PHEVs is quite low. Consider that none of the 2 to 2.14 kWh of HEV packs in Table 7 is useable to enable grid electricity to move the vehicle. However, roughly doubling the kWh capacity and presuming success in reaching 70% useable kWh of those packs, the shift from 2+ kWh to 4+ kWh allows about 3 useable kWh of grid electricity to become useable, at incremental costs from $205 to $407. This translates into a cost *per useable kWh of energy storage enabled* of ~ $70-$140/kWh.

Table 6: Default Properties of Cell Chemistries

	NCA-G	LFP-G	LMO-TiO	LMO-G
Positive Electrode				
Active material capacity, mAh/g:	150	155	100	100
Weight Fraction, %				
Active material	84	84	84	84
Carbon 1	4	4	4	4
Carbon 2	4	4	4	4
Binder	8	8	8	8
Void, Vol %	32	40	32	32
Density, g/cm^3				
Active material	4.78	3.45	4.23	4.23
Carbon 1	1.825	1.825	1.825	1.825
Carbon 2	1.825	1.825	1.825	1.825
Binder	1.77	1.77	1.77	1.77
Negative Electrode				
N/P capacity ratio after formation	1.25	1.25	1.10	1.25
Active material capacity, mAh/g:	290	290	170	290
Weight Fraction, %				
Active material	92	92	84	92
Carbon	0	0	8	0
Binder	8	8	8	8
Void, Vol %	34	34	40	34
Density, g/cm^3				
Active material	2.24	2.24	3.40	2.24
Carbon	1.95	1.95	1.95	1.95
Binder	1.77	1.77	1.77	1.77
Positive Foil				
Material	Aluminum	Aluminum	Aluminum	Aluminum
Thickness, mm	20	20	20	20
Negative Foil				
Material	Copper	Copper	Aluminum	Copper
Thickness, mm	12	12	20	12
Separator				
Thickness, mm	25	25	25	25
Density, g/cm^3	1.00	1.00	1.00	1.00
Void, Vol%	40	40	40	40
Electrolyte				
Density, g/cm^3	1.20	1.20	1.20	1.20
Cell Voltage and Resistance Parameters				
Open circuit voltage average for discharge, V	3.680	3.350	2.514	3.954
OCV at full power (25% SOC), V	3.551	3.350	2.408	3.819
Electrode system ASI for power, ohm-cm^2				
At 50% SOC	23.6	25	8.5	20
At end of PHEV range (25% SOC)	30	32	10	25
Electrode system ASI for energy, ohm-cm^2	51.9	55.0	14.2	44.0
Maximum electrode coating thickness, mm	100	100	100	100
Available battery energy, % of total	70	70	75	70

Table 7: Battery Performance and Cost Summary for Selected Systems

Battery Type	**NCA-G**			**LFP-G**			**LMO-TiO**			**LMO-G**		
Vehicle Range at 188 Wh/km	HEV	16	64	HEV	16	64	HEV	16	64	HEV	16	64
Power /Useable Energy, W/Wh	40	20	5.0	40	20	5.0	40	20	5.0	40	20	5.0
Power/Total Energy, W/Wh	28	14	3.5	28	14	3.5	30	15	3.8	28	14	3.5
Cell Performance (BOL)												
Thickness of limiting electrode, μm	25	51	100	31	61	100	62	100	100	50	100	100
Cell voltage (50% SOC), V	3.680	3.680	3.680	3.350	3.350	3.350	2.514	2.514	2.514	3.954	3.954	3.954
Cell voltage (25% SOC), V	3.551	3.551	3.551	3.350	3.350	3.350	2.408	2.408	2.408	3.819	3.819	3.819
Cell power (25% SOC), W	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cell energy (100 discharge), Wh	36	71	286	36	71	286	33	67	267	36	71	286
Cell capacity, Ah	9.7	19.6	78.8	10.7	21.5	86.5	13.3	26.6	106.6	9.1	18.2	72.8
Battery Performance (BOL)												
Cells per battery pack	60	60	60	60	60	60	60	60	60	60	60	60
Voltage (50% SOC), V	221	221	221	201	201	201	151	151	151	237	237	237
Power (10-s burst), kW	60	60	60	60	60	60	60	60	60	60	60	60
Energy (100% discharge), kWh	2.14	4.29	17.14	2.14	4.29	17.14	2.00	4.00	16.00	2.14	4.29	17.14
Fraction useable energy, %	70	70	70	70	70	70	75	75	75	70	70	70
Manufacturing Costs												
Plant capacity, (10^3 batteries/y)	100	100	100	100	100	100	100	100	100	100	100	100
Investment ($\$10^6$)	220	252	468	236	270	535	225	280	664	199	228	499
Unit Cost of Battery Pack, $												
Materials	480	656	1,960	547	733	2,291	454	722	2,797	349	476	1,841
Purchased items	313	328	400	318	337	435	318	342	495	311	328	417
Direct labor	119	126	170	124	132	185	121	135	216	113	120	186
Other variable overhead	72	76	102	75	79	111	73	81	130	68	72	112
Fixed expenses	340	374	591	362	397	672	351	416	849	316	351	676
Profits after taxes	110	126	234	118	135	267	112	140	332	99	114	250
Total unit cost per battery pack, $	1,434	1,686	3,456	1,544	1,812	3,962	1,429	1,836	4,818	1,256	1,461	3,482

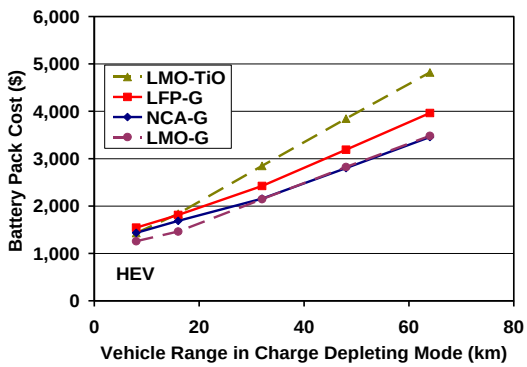

Figure 6: Pack Cost as Function of Vehicle CD-Range for Various cell Chemistries

5 Conclusions

For the chemistries and manufacturing assumptions implemented, additional power in the range of 40 to 60 kW is very inexpensive, especially for 64-km PHEVs. This results from restricting the maximum electrode coating thickness to 100 microns and, thus requiring additional capacity to be accompanied by additional cell area and additional power. Even though the power was defined conservatively as that available at the lowest state of charge, more than 60 kW is available for all systems in 32-km PHEVs at a voltage greater than 80% OCV.

For a set value of battery energy storage, a small number of high energy storage capacity cells are much less expensive to manufacture than a large number of low-capacity cells. The extra cost for a large number of cells results from the large number of cell hardware parts — especially state-of-charge regulators — and the extra equipment and labor required for formation cycling and cell testing.

Though not as important as the energy/power ratio, the useable fraction of the state-of-charge range for a battery system is an important $/kWh cost factor.

The differing features of the various cell chemistry systems have important effects on the battery cost, varying uniquely with our approximations of vehicle charge depleting electric range. Low area-specific impedance is important for HEV and short range PHEV battery packs, but its benefits decrease in importance as total pack kWh increase. High electrode specific capacity (mAh/g) and high cell voltage are important for all types of electric vehicles. High electrode density and low porosity for a given ASI are beneficial.

The choice of cell chemistry among those studied will probably depend more on proven safety, reliability, in-use average efficiency at all SOC levels and ambient temperatures,

and/or long life rather than on differences in initial cost.

The estimated incremental cost of enabling battery pack storage to be useable in short range PHEVs in place of HEVs is quite low, suggesting that manufacturers otherwise producing HEVs should strongly consider also producing PHEV variants of those vehicles with charge depleting ranges of 16-32 km.

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