PHEV Battery Cost Assessment

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Project ID# ES111

Overview

Timeline

- Start: August 2010
- Finish: September 2014
- ~20% Complete

Budget

- Total project funding
  - 100% DOE
- FY2010: $300K
- FY2011: $300K

Barriers

- Development of a PHEV40 with a maximum price of $3,400 at 100k units/yr, weighing less than 120 kg, and being smaller in size than 80 L.
  - Calculating total battery mass, volume, & cost from individual components
  - Predicting methods & materials that enable manufacturers to reach goals

Partners (Collaborators)

- Ira Bloom, Argonne
- Dan Santini, Argonne

Project Objectives, Milestones & Approach

- The objective of this task is to develop and utilize *efficient* simulation and design tools for Li-ion batteries to predict:
  - Precise overall (and component) mass and dimensions
  - Cost and performance characteristics
  - Battery pack values from bench-scale results
- Milestones for this year
  - Fully integrate single spreadsheet-model to predict battery pack price to OEM for PHEVs (first version completed)
  - Document methodology and assumptions feeding into design and cost model to support distribution (completed and under peer-review)
  - Initiate model of advanced Li-ion electrochemical couples (completed)
- Our approach is to design a battery based on power and energy requirements for a specific cell chemistry, feeding into a cost calculation that accounts for materials & processes required

Major Technical Accomplishments & Progress

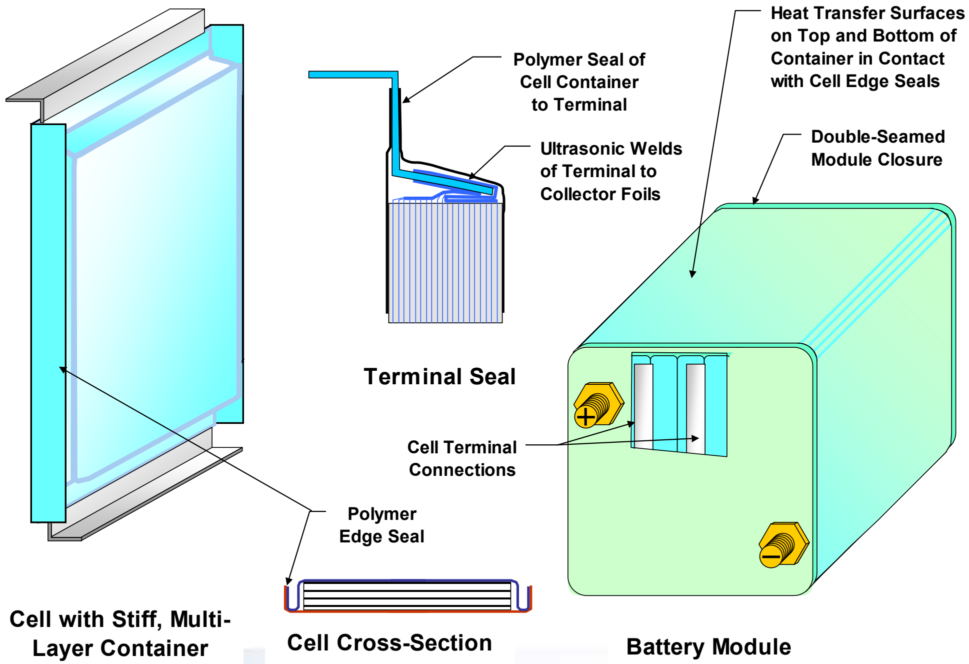
- Development of enhanced area-specific impedance (ASI) calculation to account for physical limitations in performance
- Fully integrated model to design and predict high volume costs for PHEVs, as well as HEVs & EVs, based on user defined requirements (pack voltage, power, efficiency, cell chemistry)
- Documented design and cost calculation methodology to support peer-review and *free* & *open* distribution of Li-ion battery design and cost model
- Initiated battery performance and cost calculations for advanced Li-ion electrochemical couples (LMR-NMC, LNMO, Gr-Si composite)

Approach

- Builds off of foundation of work by Paul Nelson at Argonne
- Designs Li-ion battery and required manufacturing facility based on user defined performance specifications for an assumed cell, module, and pack format
  - Power, energy, efficiency, cell chemistry, production volume
- Calculates the price to original equipment manufacturer (OEM) for the battery pack produced in the year 2020
  - Not modeling the cost of today's batteries but those produced by successful companies operating in 2020
  - Some advances have been assumed while most processes are similar to well-established high-volume manufacturing practices
- Coupling design and cost allows the user to quantify the impact of underlying properties on the total battery pack cost (cell chemistry, parallel cells, electrode thickness limits, P/E)

Assumed battery format

- Assuming a battery format allows for the direct calculation of all components that comprise the unit
- Previous efforts were based on flat-wound and cylindrical cells
- Our assumed format is most likely not the best design, however those successful in producing batteries in the year 2020 will reach similar energy densities and costs through other means
- Stiff pouch cells
- Sealed in modules
- Cooling of module walls



Battery design calculations

Pack Requirements

- Power
- Energy or range
- # of cells
- Fade over lifetime

Key Constraints

- Max electrode thickness
- Target cell potential, V, at peak power
- Assumed cell/module format

Iterative Spreadsheet

Determines cell properties

1. Cell capacity
2. Cell area
3. Electrode thickness
4. Internal resistance

And designs battery pack

Cell Chemistry

Measured Properties

- Pulse Power ASI
- Discharge ASI
- mAh/g, mAh/L
- Electrode porosity
- SOC window
- Physical properties

ASI = area specific impedance

Calculated Battery Properties

- Volume and weight
- Specific energy, power
- Materials required

Battery cost calculations

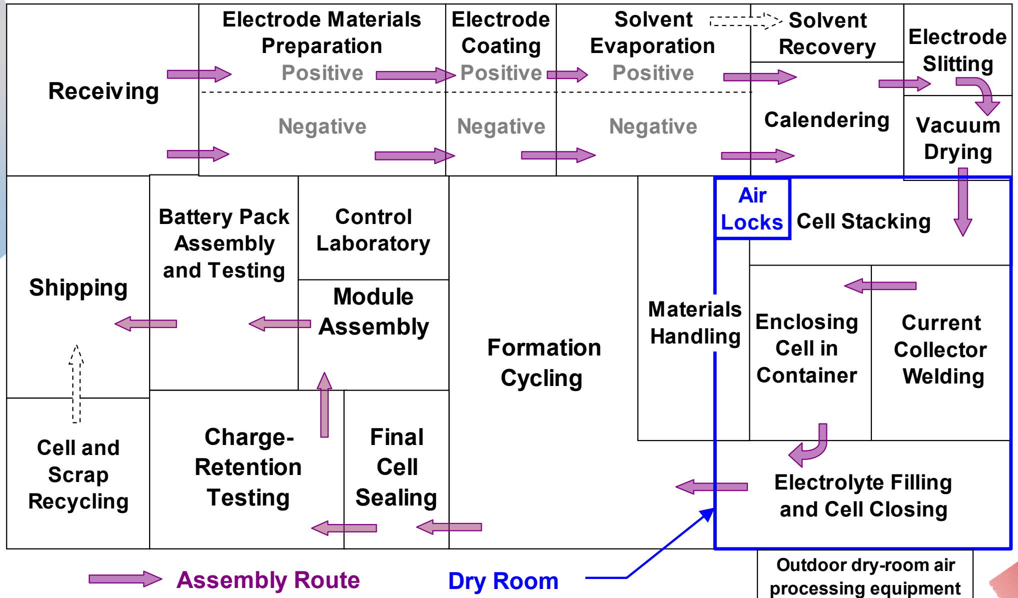
Calculated Battery Properties
- Volume and weight
- Specific energy, power
- Materials required

Key input values
- Active material costs
- Production volume
- Baseline plant
  - Designed for 100k/yr
  - Operation in 2020
- Costs derived from discussions with industry, publications, and engineering estimations

Baseline Lithium-Ion Battery Manufacturing Plant Schematic Diagram

100,000 battery NCA-Gr packs per year, 50-kW battery power, 40-Ah capacity, 60 cells per battery

Operating year: 300 days with three 8-hr shifts per day (two shifts for receiving and shipping)



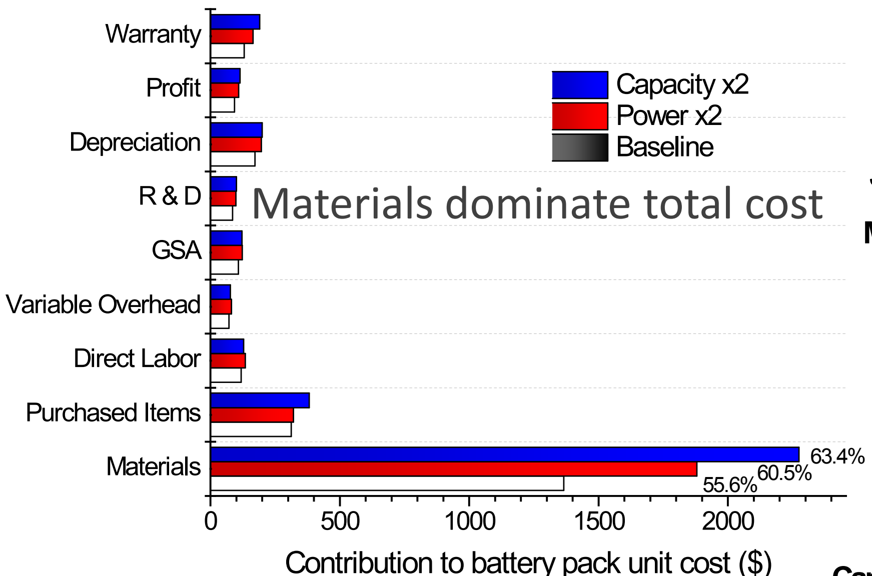
The areas in this diagram for each processing step are approximately proportional to the estimated plant areas in the baseline plant.

$$Cost = Cost_0 \left(\frac{\text{Processing Rate}}{\text{Processing Rate}_0} \right)^p$$

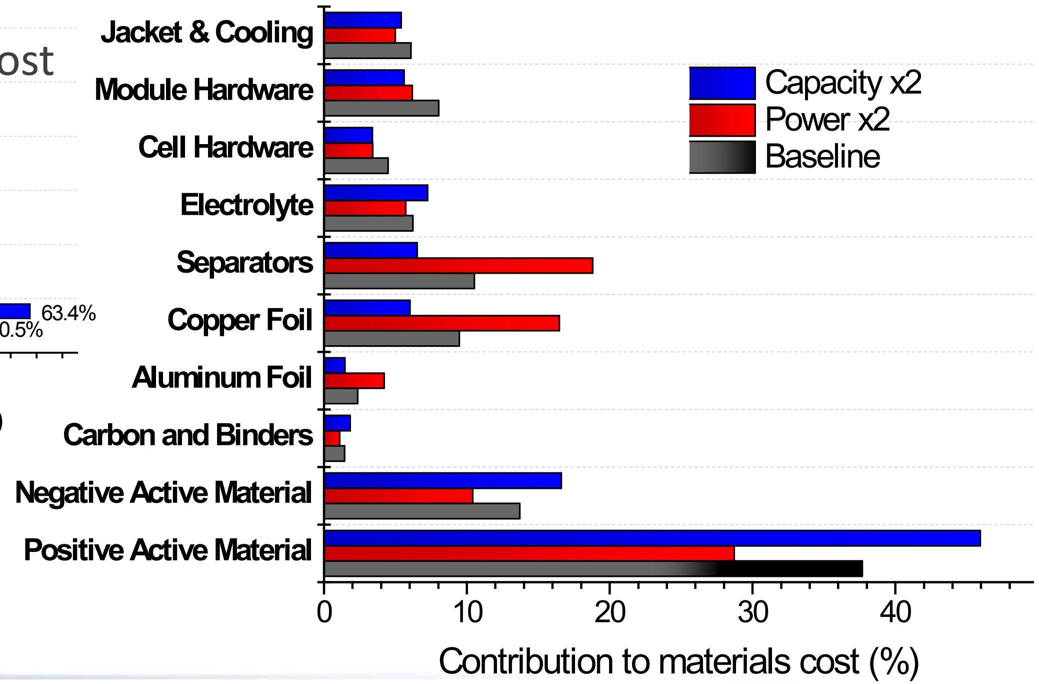
Battery Pack Price to OEM
- Materials & purchased items
- Individual process steps
- Overhead, depreciation, etc
- Warranty

Variation from baseline plant

- Model accounts for changes in materials and processing costs
- Examine simple changes to baseline battery and plant
  - 2x power (50 to 100kW) increases cost 26%
  - 2x capacity (40 to 80 Ah) increases cost 46%



Materials that scale with area become more important at higher P/E ratios



NCA/ Gr, 60 cells, [V/U]=0.8

100 μm max electrode thickness

Baseline: 50 kW, 8.7 kWh_{tot}

Model Predictions for PHEV40 Goals

- Battery packs designed to meet PHEV40 goals
  - 17 kWh, 40 kW max power achieved at 80 % of open-circuit voltage (OCV)
  - 70 % useable capacity, max power measured at 25% SOC
  - Battery pack OCV at 50% SOC = 360 ± 15 V (80-144 cells in series)
  - 100 μm maximum electrode thickness
- Established chemistries: 222-301 $\$/kWh_{total}$ & 79-165 Wh/kg
- Advanced Li-ion: 183-193 $\$/kWh_{total}$ & 201-218 Wh/kg (early numbers)

	NMC-333 / Gr	NMC-441 / Gr	NCA / Gr	LFP / Gr	LMO / Gr	LMO / LTO	LMR-NMC / Gr	LNMO / Gr
Price to OEM ($)	4380	3833	4243	4608	3782	5125	3112	3275
$\$/kWh_{total}$	258	225	250	271	222	301	183	193
$\$/kWh_{useable}$	368	322	357	387	318	402	262	275
kg	110	103	108	141	133	214	78	93
L	65	62	64	90	76	125	50	54
Wh/kg	155	165	158	120	128	79	218	201
Wh/L	261	274	265	189	223	136	340	336

NMC-333 = $Li_{1.05}(Ni_{1/3}Mn_{1/3}Co_{1/3})_{0.95}O_2$ / NMC-441 = $Li_{1.05}(Ni_{4/9}Mn_{4/9}Co_{1/9})_{0.95}O_2$ / NCA = $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$

LFP = $LiFePO_4$ / LMO = $Li_{1.06}Mn_{1.94}O_4$ / LNMO = $LiNi_{0.5}Mn_{1.5}O_4$ / LMR-NMC = $Li_2MnO_3 \cdot LiMO_2$ / LTO = $Li_4Ti_5O_{12}$

New Approach to Impedance Calculation

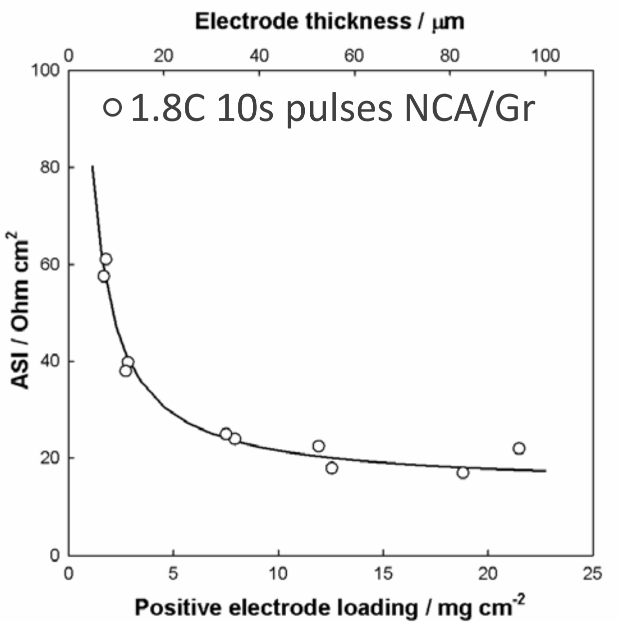
- Development of enhanced ASI calculation to account for
  - Changes in electrode thickness
  - Limiting currents

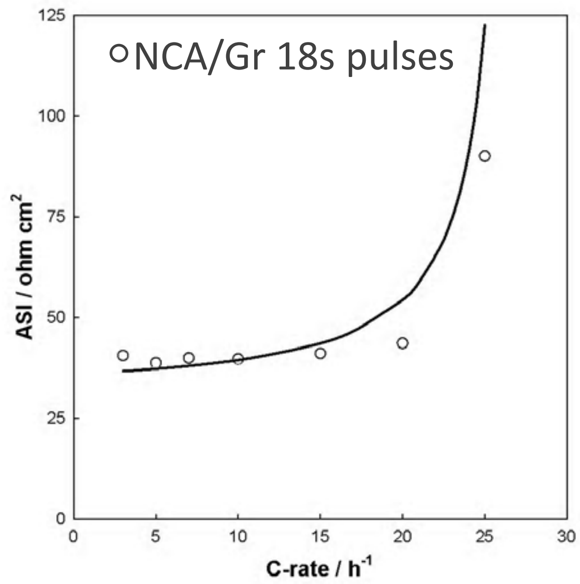
$$ASI_{\text{intf}}^{\text{pos}} = \frac{1}{L}\left[\frac{RT}{ai_oF}\left\{\left(1-\frac{I}{I_{\text{lim}}^{ionic}}\right)\left[1-\left(\frac{r_C}{r_{C,\text{lim}}}\right)^2\right]\right\}^{-0.5} - \frac{dU}{dy}\frac{t_{pulse}}{3600Q\rho\varepsilon_{act}}\right]$$

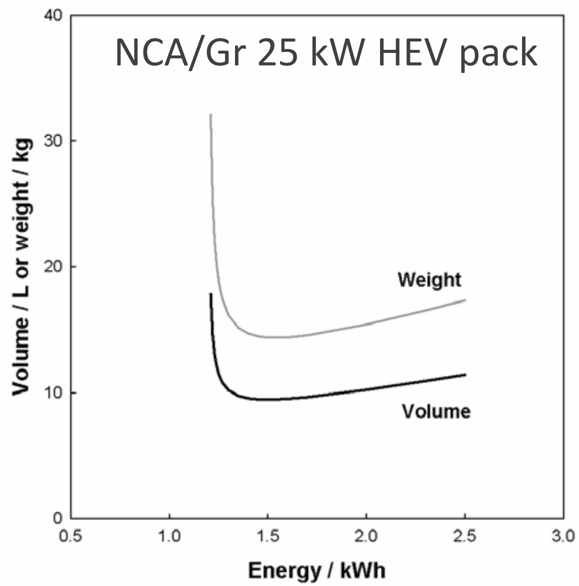
Kinetic & concentration   Thermo factor

- Improved treatment of ASI allows for calculation of battery design and cost for many different power to energy (P/E) ratios

$$ASI_{\text{echem}} = ASI_{\text{intf}}^{pos} + ASI_{\text{intf}}^{neg} + ASI_{\text{const}}$$

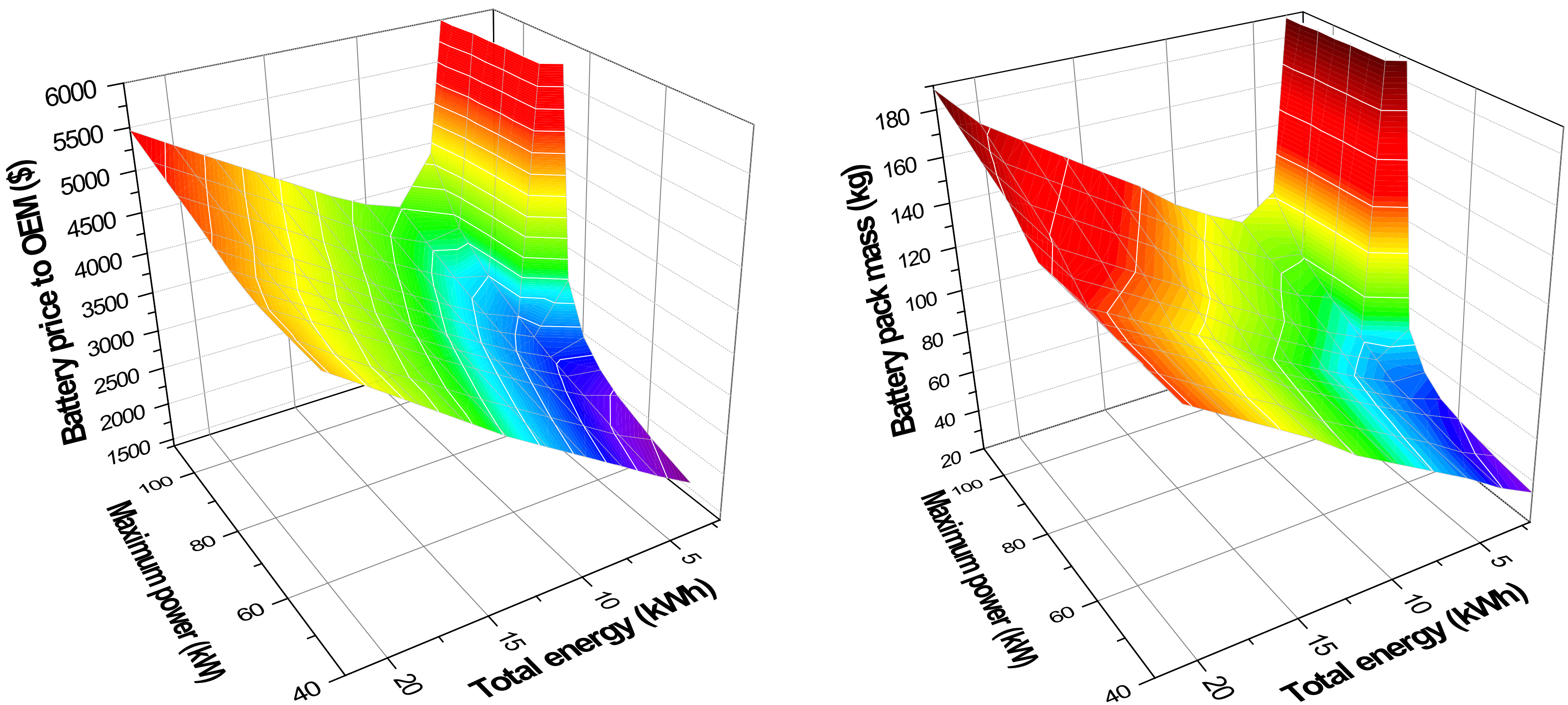






Model allows design of complete P/E space

- Price, mass and volume track together
- High P/E ratios (chemistry specific) will cause increase in cost even at low total energy



NMC-333 / Gr, 96 cells, [V/U]=0.8
200 μm max electrode thickness

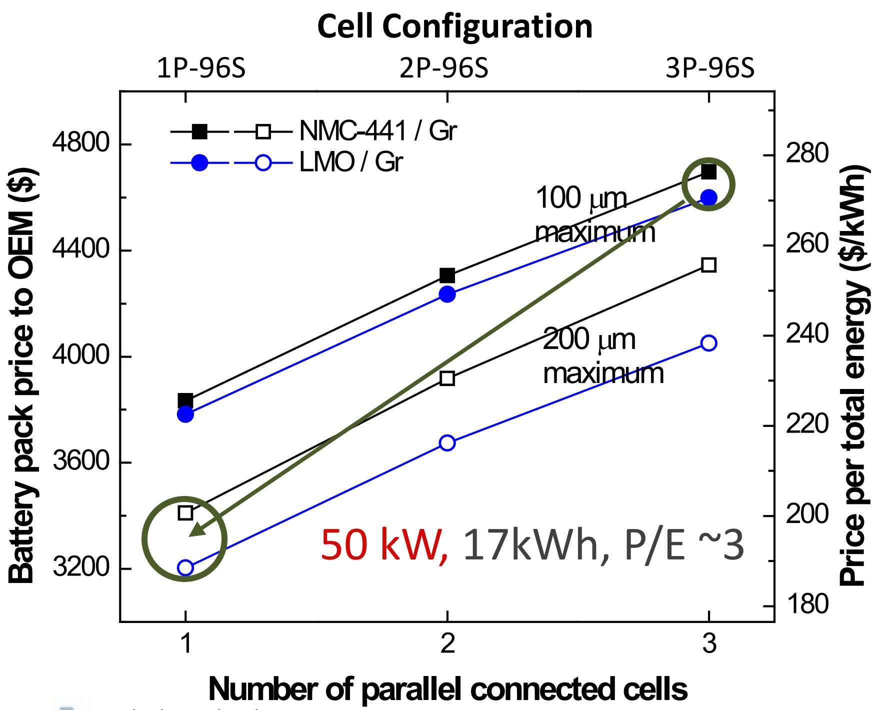
Reducing Inactive Material Burden

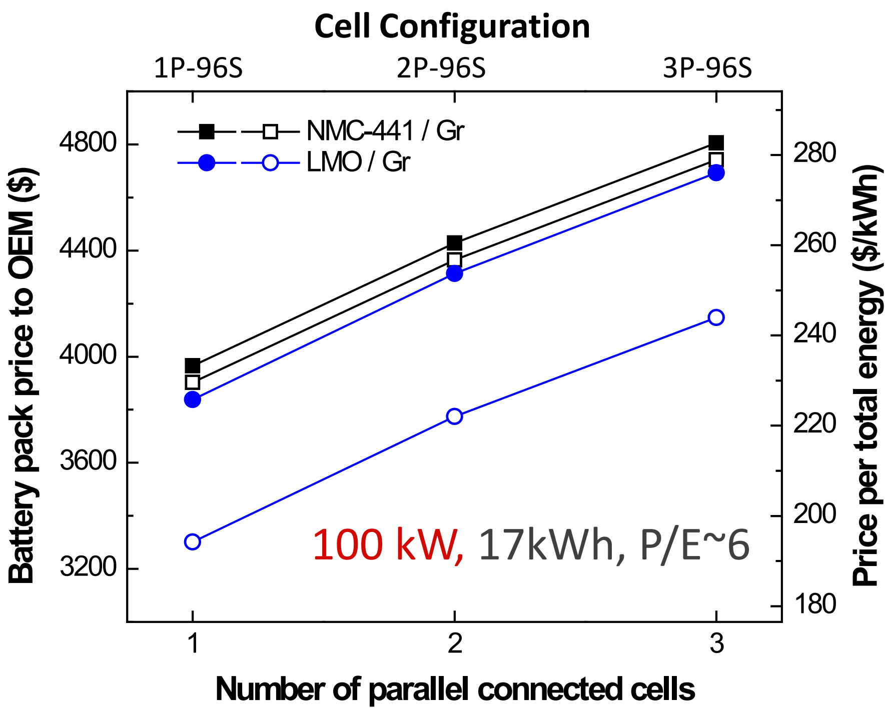
- Current battery designs incorporate large amounts of inactive material
  - Active materials are only 20-40 % of total cost and ~50 % of battery mass
- How do we minimize inactive material within current design paradigm of coated current collector foils separated by a porous insulator?
- Large format cells
  - Reduces number of tabs, parallel-cell interconnects, increases volumetric density
  - Reduces number of cells through packing, filling, sealing, and formation cycling
- Larger electrode thicknesses
  - For lower P/E ratios, optimal electrode thickness may be greater than 100 μm
  - Moving from 100 to 200 μm reduces the amount of foil and separator by ½
  - The manufacturing steps based on area will require less throughput (m^2/yr)
  - Designed optimal thickness depends on active material and cell properties

$$L = \frac{U_{ocv}\left(1-[V/U]\right)}{(P/E)\left(\mathrm{mAh/cm^3}\right)ASI_{power}}$$

Battery design approaches to lowering cost

- Large format cells and large electrode thicknesses reduce the contribution of inactive materials to total cost of PHEV batteries
  - $400-500/parallel cell added; <$600 for 100 to 200 μm
- Manufacturing & durability issues present challenges to implementation
- At higher P/E, only LMO / Gr benefits from allowing thicker electrodes





Capacity, Ah of individual cells increasing

Increasing Energy Density to Lower Cost

- Lithium and manganese rich transition metal oxides (LMR-NMC)
  - Often called "layered-layered" or high capacity layered oxides

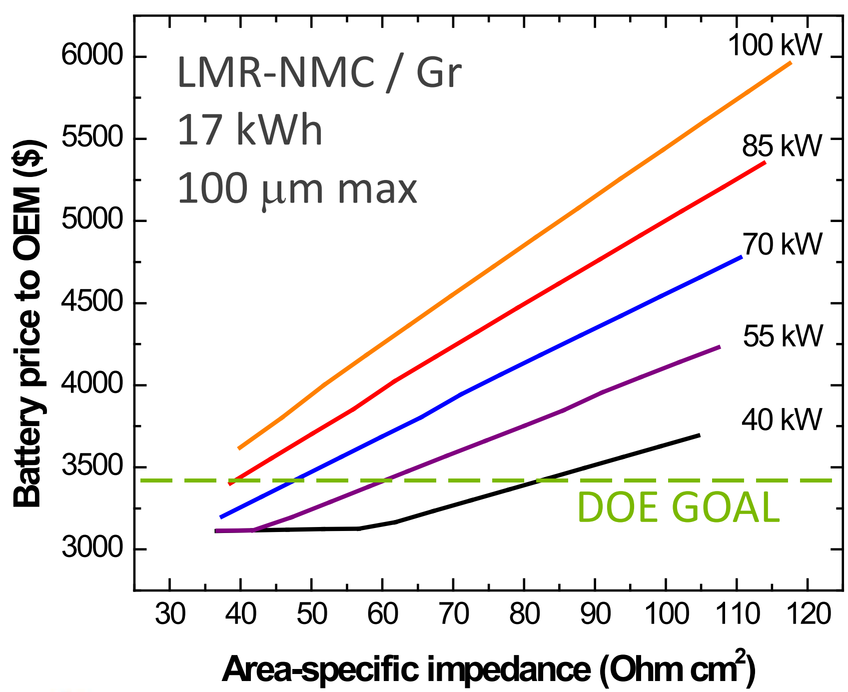
$$xLi_2MnO_3 \cdot (1-x)LiNi_yMn_zCo_{1-y-z}O_2$$

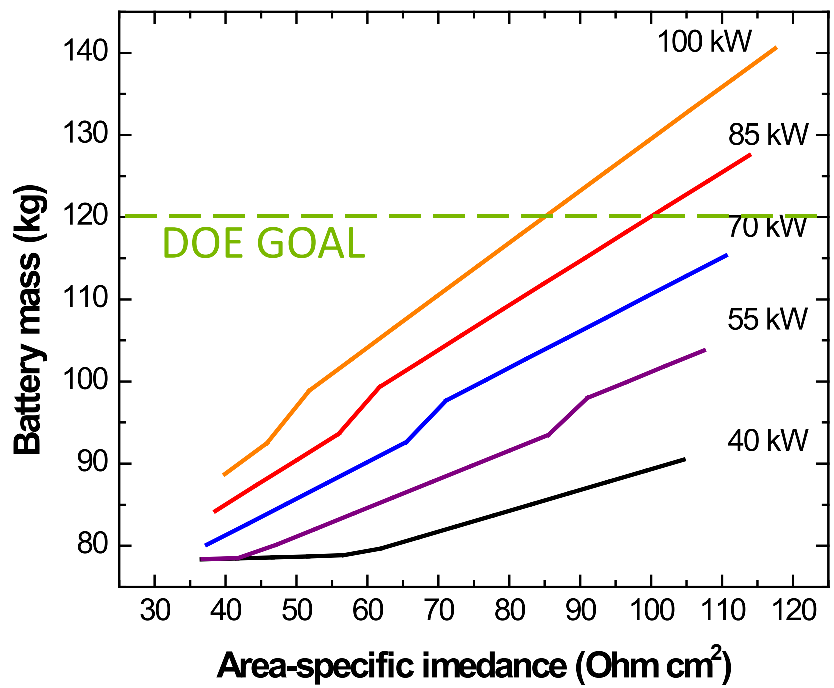
- Benefits of LMR-NMC family of compounds
  - Large reversible capacity (~250 mAh/g)
  - Good full-cell voltages, U_{ocv} ~3.75 and 3.5 V at 50% and 25% SOC
  - High manganese content significantly lowers mass specific cost
  - Higher energy density requires less material, further reducing cost
- Materials cost for NMC compounds based on correlation
  - NMC-333 estimated to be ~$39/kg
  - LMR-NMC estimated to be $22-30/kg depending on stoichiometry
    - $25/kg assumed for calculations in this presentation
    - Inherent variability in metal prices is minimized by increasing Mn content

$$C\left(\frac{\$}{kg}\right) = C_0 + \frac{1}{MW}\sum_i \left[x_i C_i MW_i\right]$$

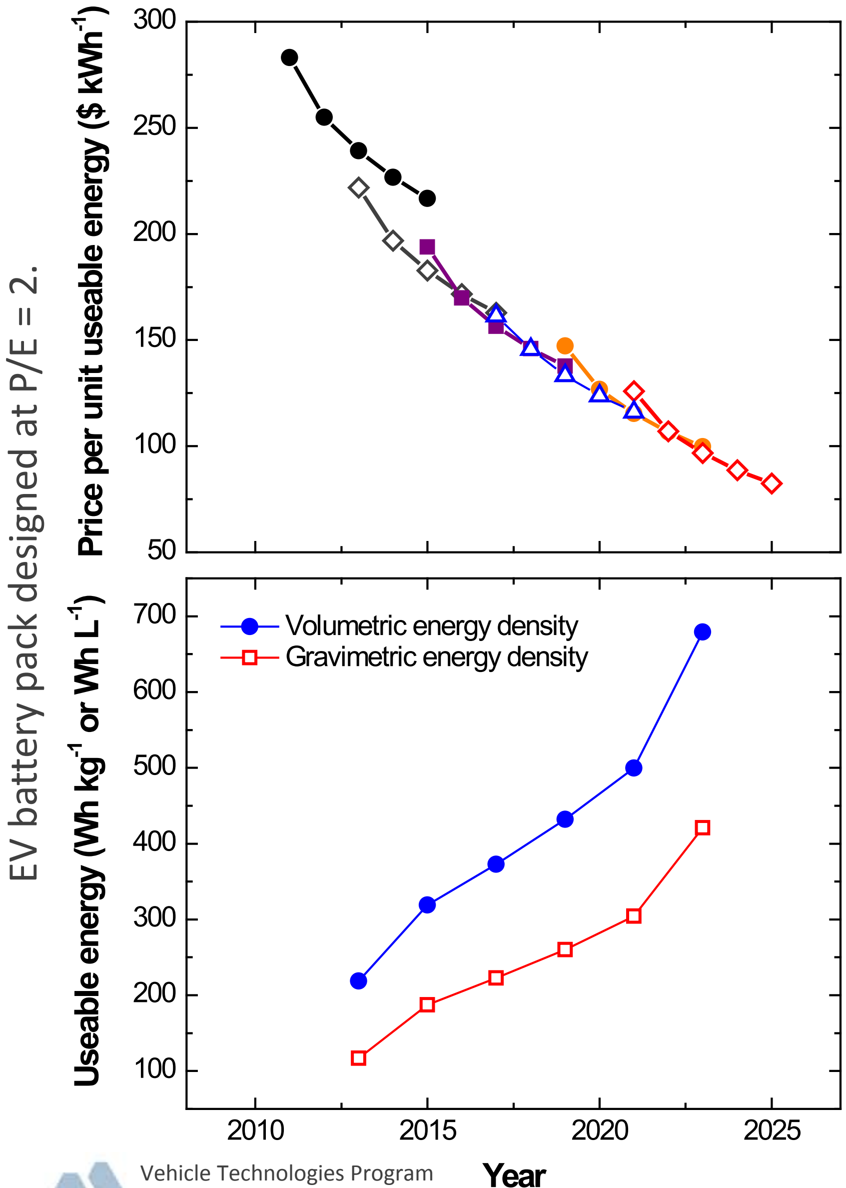
Relationship between performance & cost

- Challenges to implementation
  - High voltage during activation: 4.6 V vs Li^0
  - Stability of the material and energy fade over extended cycling
  - Low 1st cycle efficiency ~77% (developers now achieving 90 %)
  - Large initial ASI at low SOC: **What ASI do we need to meet goals?**





Path Forward for Lithium Based Batteries



◇ **UK-HV-HC / Li metal**
Safe and reversible cycling of Li metal
Market entry >2021

● **UK-HV-HC / Gr-Si**
Discovery of high voltage electrolyte >4.8 V
Discovery of reversible unknown high-voltage high-capacity cathode: 250 mAh/g @ 4.8 V
Market entry > 2019

△ **Li_2MXO_4 / Gr-Si**
Discovery of path to reversible multi-electron cathode material with 4V cell voltage
Market entry > 2017

■ **LMR-NMC / Gr-Si**
Stabilization of silicon
Market entry > 2015

◇ **LMR-NMC / Gr**
Stabilization of LMR-NMC
Market entry > 2013

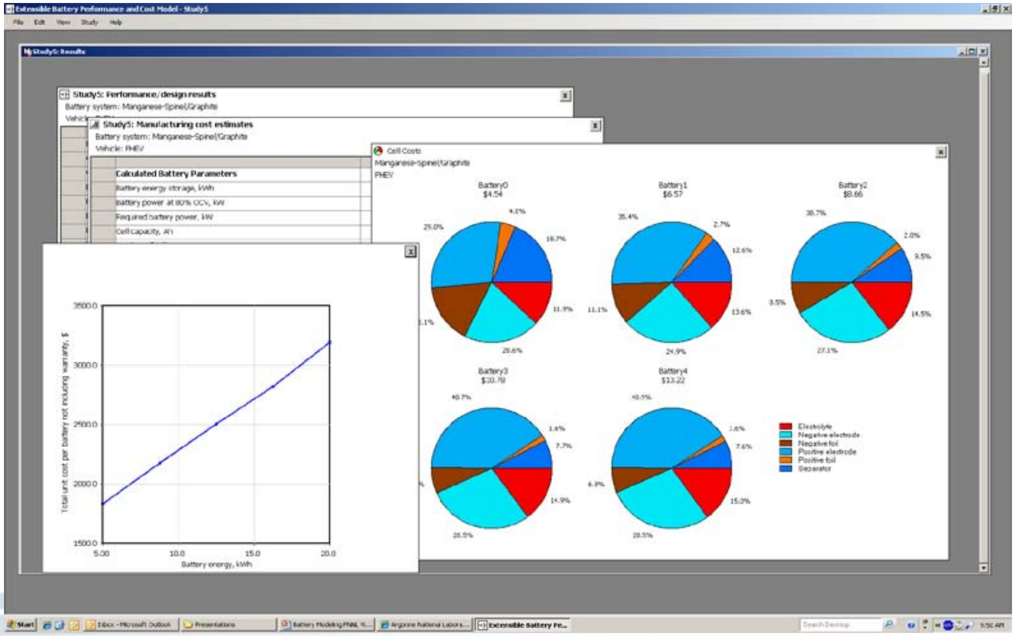
● **LMO / Gr**

If high-risk research is successful, then a 60 % reduction in battery cost and 260 % increase in energy density is possible from materials advances

Pack price to OEM and dimensions do not include components required to integrate battery into vehicle or meet electrical safety standards. Peer reviewed through EPA. Numbers for all materials assume 3-5 years of engineering advances in cell and pack design as compared to 2011.

Distribution of Performance & Cost Model

- Completed ANL report documenting methodology, assumptions, and instructions for use of the model
  - Blind peer-review sponsored by EPA (completion tgt'd April 15, 2011)
  - Reviewed by various research and industrially institutions
- Battery Performance and Cost model (BatPaC)
  - Hard-coded, windows-based software developed by **Ira Bloom** (ANL)
  - Less likely to corrupt during use (unlike complex spreadsheets)
  - Provides a user-friendly environment for design and cost modeling
- Distribute to public
  - No cost
  - Summer 2011



Future Work

- Advance thermal management portion of design & cost model
  - Add liquid-cooled module walls with aluminum plate heat conductors
- Distribute model to public (targeting Summer 2011)
- Estimate cost reduction from moving to advanced negative and positive electrode active materials
- Continuous refinement of model input parameters
  - Collaborate to identify battery pack integration component costs
    - Argonne's CTR, OEMs
- Milestones for next year
  - Implement initial active thermal management into model
  - Publish documentation as Argonne report
  - Distribute model openly
  - Refine cost behavior of some advanced Li-ion couples (Gr-Si / LMR-NMC and Gr-Si / LNMO)

Summary

- The objective of this task is to *efficiently* calculate Li-ion battery pack mass, dimensions, and cost from a specified power & energy requirement
- The approach is to design the Li-ion battery and required manufacturing facility based on user defined performance specifications using an assumed cell, module, and pack format
- Technical accomplishments
  - Fully integrated Li-ion design and cost model into single spreadsheet
  - Completed documentation of methodology, currently under review
  - Demonstrated potential cost reduction from increased electrode thicknesses and large-format pouch cells
  - Calculated cost reduction from advanced Li-ion cathode materials and the performance requirements necessary to realize savings
- Future plans involve improving thermal management aspect of model, a full release of model to public, and potential savings of moving to advanced Li-ion negative electrodes

Acknowledgements & Collaborators

- Support for this work from DOE-EERE, Office of Vehicle Technologies is gratefully acknowledged
  - David Howell & Peter Faguy

Collaborators:

- Institutions that have provide some form of review/comments
  - Ralph Brodd (now at Argonne) reviewed our baseline plant in detail
  - EPA: Joe McDonald initiated peer-review
  - EPRI: Fritz Kalhammer, Satish Rajagopalan, Haresh Kamath
  - Multiple domestic cell manufacturers and a domestic OEM
- Argonne National Laboratory
  - Ira Bloom and Dan Santini
  - Khalil Amine, Sun-Ho Kang, Wenquan Lu

Support Slides

The following slides are for the use of the Peer Reviewers only and will not be shown as part of the presentation at the Review.

Description of Battery Design & Cost Model

- Model is largely based off a linear system (Ohm's law)
- Electrode thickness (loading) is calculated from the area-specific impedance (ASI), power-to-energy ratio (P/E), and efficiency
- The electrode thickness (loading) determines the separator and electrode area necessary to meet the capacity requirement
- The materials and equipment costs are mostly derived from personal communications or engineering estimations
  - NMC based materials are calculated based off of a correlation
- The model scales the capital, labor, & plant area costs based on the level of production compared to the "baseline plant"
- The calculation happens in a fraction of a second
  - Hundreds of battery & plant designs in an afternoon

Governing Equations for Battery Design

- Assumes a linear system
- Defines battery pack voltage at maximum power as a fraction of the open-circuit voltage
  - [V/U] = battery voltage at P_{max} / open-circuit voltage
  - Our designs commonly assume [V/U] = 0.8
    - Allows for moderate power fade, cold-cranking power
    - A balance between efficiency & cooling requirements against initial cost

$$E = N_{cell} C \left(U_{ocv,E} - \frac{C}{3} \frac{ASI_{energy}}{A_{pos}} \right)$$

$$I = \frac{P_{batt}}{A_{pos} N_{cell} U_{ocv,P} \left[\frac{V}{U} \right]}$$

$$\mathrm{ASI} = \frac{\alpha + f(I)}{L_{pos}} + \beta$$

$$A_{pos} = \frac{ASI_{power} P_{batt}}{N_{cell} \left(U_{ocv,P} \right)^2 \left[\frac{V}{U} \right] \left(1 - \left[\frac{V}{U} \right] \right)}$$

$$L_{pos} = \frac{C}{Q \rho \varepsilon_{act} A_{pos}}$$

ASI Equations for Battery

- ASI measured in coin cells translated to battery impedance
- ASI equation fit to data from coin cell (at end of pulse, no SOC effect)
  - Interfacial $$ASI_{\text{intf}}^{\text{pos}} = \frac{1}{L}\left[\frac{RT}{ai_o F}\left\{\left(1-\frac{I}{I_{\text{lim}}^{ionic}}\right)\left[1-\left(\frac{r_C}{r_{C,\text{lim}}}\right)^2\right]\right\}^{-0.5}\right]$$
  - Lumps ohmic behavior in ASI_{const} $$ASI_{\text{echem}} = ASI_{\text{intf}}^{pos} + ASI_{\text{intf}}^{neg} + ASI_{\text{const}}$$
- ASI from cell current collectors uses equivalent length of H/3
  - Verified analytically and numerically $$ASI_{cc} = \frac{H^2}{3}\left(\frac{1}{\sigma_{pos,cc}} + \frac{1}{\sigma_{neg,cc}}\right)$$
- Battery pack ASI for power includes all other resistances

$$ASI_{power} = ASI_{echem,P} + ASI_{cc} + ASI_{term}^{cell} + \frac{R_{cnct} A_{pos}}{N_{cells}}$$

- Battery pack ASI_{energy} has larger ASI_{const} from gradients

Cost Modeling Assumptions

- All dollar values are in year 2011 dollars
- Manufacturing costs are scaled from the “baseline plant”
  - PHEV-20 $LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$ vs Graphite (NCA-Gr)
  - 8.7 kWh_{total} w/ 70% useable, 50 kW at [V/U] = 0.8
  - 60 cells connected in series, each 40 Ah in capacity
  - 100,000 battery packs produced annually
- Each processing step is scaled based on the ratio of the annual processing rates

$$Cost = Cost_0 \left(\frac{\text{Processing Rate}}{\text{Processing Rate}_0} \right)^p$$

- “p” factors chosen based on perceived sensitivity of process step to changes in required annual rate
  - Labor factors have low “p” values (0.4-0.5)
  - Steps already highly automated tend to have higher “p” values (0.8)
    - Cell stacking, current collector welding

Baseline plant summary

	Annual Baseline Rate (R_o)		Direct Labor No./shift	Direct Labor Hours/yr	Direct Labor p Factor	Cap. Equipment $MM	Cap. Equipment p Factor	Plant Area m^2	Plant Area p Factor
Receiving (two-shift operation)	869,420	kWh energy	3	14,400	0.4	3.60	0.6	600	0.5
Materials preparation									
Positive electrode	1,712,524	kg active material	3	21,600	0.5	4.00	0.7	400	0.6
Negative electrode	1,208,957	kg active material	3	21,600	0.5	4.00	0.7	400	0.6
Electrode coating									
Positive electrode	8,169,835	m^2 cell area	4	28,800	0.5	6.00	0.8 (0.2)*	500	0.8
Negative electrode	8,169,835	m^2 cell area	4	28,800	0.5	6.00	0.8 (0.2)*	500	0.8
Solvent recovery	2,309,021	kg NMP	2	14,400	0.4	3.00	0.6	150	0.6
Calendering									
Positive electrode	8,169,835	m^2 cell area	1	7,200	0.5	1.00	0.7	150	0.6
Negative electrode	8,169,835	m^2 cell area	1	7,200	0.5	1.00	0.7	150	0.6
Materials handling#	8,169,835	m^2 cell area	4	28,800	0.7	1.50	0.7	600	0.6
Electrode slitting	8,169,835	m^2 cell area	4	28,800	0.5	2.00	0.7	200	0.6
Vacuum drying	8,169,835	m^2 cell area	2	14,400	0.5	1.60	0.7	200	0.6
Control laboratory	869,420	kWh energy	4	28,800	0.5	1.50	0.7	200	0.6
Cell Assembly in Dry Room									
Cell stacking	6,315,789	total cells	6	43,200	0.7	5.00	0.8 (0.3)**	400	0.8
Current collector welding	6,315,789	total cells	6	43,200	0.7	5.00	0.8	400	0.8
Enclosing cell in container	6,315,789	total cells	4	28,800	0.5	3.00	0.7	400	0.6
Electrolyte filling, and cell sealing	6,315,789	total cells	6	43,200	0.5	6.00	0.7	600	0.6
Dry room control and air locks	2,000	m^2 operating area#	2	14,400	0.4	20.00	0.6	75	0.4
Formation cycling	6,315,789	total cells	8	57,600	0.7	30.00	0.8 (0.3)**	1,500	0.8
Final cell sealing	6,315,789	total cells	2	14,400	0.5	7.50	0.7	300	0.6
Charge retention testing	6,315,789	total cells	3	21,600	0.4	4.75	0.7	600	0.6
Module assembly	6,000,000	finished cells	6	43,200	0.5	6.00	0.7	400	0.6
Battery pack assembly and testing	100,000	battery packs	6	43,200	0.5	6.00	0.7 (0.3)***	600	0.6
Rejected cell and scrap recycle	6,315,789	total cells	5	36,000	0.7	2.50	0.7	400	0.6
Shipping (two-shift operation)	869,420	kWh energy	6	28,800	0.5	5.00	0.7	600	0.6
Total			95	662,400		135.95		10,325	

#One-third of the space for materials handling is within the dry room.

The baseline capital cost electrode coating, C_o, is based on the evaporation of the baseline annual solvent weight (Rs_o). For batteries requiring different solvent evaporation rates Rs, the cost is multiplied by ratio of rates raised to the 0.2 power. Thus, Cost = Co(R/Ro)^0.8*(Rs/Rso)^0.2.

**The baseline costs of the capital equipment for cell stacking and formation cycling is for 40-Ah cells. To correct the baseline cost (C_o) for cells of different capacity, the cost is multiplied by the capacity ratio, (Cap)/ 40 Ah, raised to the 0.3 power. Thus, Cost = C_o*(R/R_o)^0.8*(Cap/40)^0.3.

***The baseline cost of the capital equipment for battery assembly is for a battery with four modules. To correct the baseline cost for a different number of modules (Mod), the cost is multiplied by the ratio of modules, (Mod)/4 raised to the 0.3 power. Cost = C_o*(R/R_o)^0.7*(Mod/4)^0.3.

Cost Modeling Assumptions

- 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 for purchased items and 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, taxes on income and property, cost of sales and insurance expenses.	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	Provides funds for new investments to replace those in current 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.
Warranty	Funds set aside for reimbursing customers for battery pack failures.	5.6% added to price based on present worth of projected payments.

Materials costs used in calculations

- The cost of Ni, Mn, & Co containing cathode materials based on a correlation to allow calculation for any stoichiometry (cost of metal carbonates in precursor)

$$C\left(\frac{\$}{kg}\right) = C_0 + \frac{1}{MW}\sum_i \left[x_i C_i MW_i\right]$$

Baseline cost, C_0 = 16-20 \$/kg; C_{Li2CO3} = \$6/kg; C_{NiSO4} = \$5.5/kg; C_{MnSO4} = \$1/kg; C_{CoSO4} = \$32/kg;

Material	Chemistry	Abbreviation	unit	ANL 2010	TIAX 2010
Manganese spinel cathode	$Li_{1.06}Mn_{1.94}O_4$	LMO	\$/kg	10	12 - 16 - 20
5V spinel cathode*	$LiNi_{0.5}Mn_{1.5}O_4$	LNMO	\$/kg	21	-
Phospholivine cathode	$LiFePO_4$	LFP	\$/kg	20	15 - 20 -25
Layered oxide cathode*	$LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$	NCA	\$/kg	37	34 - 40 - 54
Layered oxide cathode*	$Li_{1.05}(Ni_{1/3}Mn_{1/3}Co_{1/3})_{0.95}O_2$	NMC-333	\$/kg	39	40 - 45 -53
Layered oxide cathode*	$Li_{1.05}(Ni_{4/9}Mn_{4/9}Co_{1/9})_{0.95}O_2$	NMC-441	\$/kg	29	-
Li & Mn rich layered cathode*	$xLi_2MnO_3{\cdot}(1-x)LiNi_yMn_zCo_{1-y-z}O_2$	LMR-NMC	\$/kg	22-30	24 - 31 - 39
Graphite anode	C_6	Gr	\$/kg	19	17 - 20 - 23
Titanate spinel anode	$Li_4Ti_5O_{12}$	LTO	\$/kg	12	9 - 10 - 12
Electrolyte	1.2 M $LiPF_6$ in EC:EMC		\$/kg	19	18.5 - 21.5 -24.5
Separator	PP/PE/PP		\$/m^2	2	1 - 2.5 -2.9
Current collector foil	Copper		\$/m^2	3.00	-
Current collector foil	Aluminum		\$/m^2	0.80	-

* The cost of cathode materials using co-precipitation of Ni, Mn, and/or Co are based off of a correlation

Model predictions for PHEV40 goals

- Battery packs designed to meet PHEV40 goals (200 μm allowed)
  - 17 kWh, 40 kW at [V/U] = 0.8
  - 70 % useable capacity, max power measured at 20% SOC
  - Battery pack OCV at 50% SOC = 360 ± 15 V (80-144 cells in series)
  - **200 μm maximum electrode thickness**
- Established chemistries: 188-262 $/kWh$_{total}$ & 85-179 Wh/kg
- Advanced Li-ion: 169-178 $/kWh$_{total}$ & 221 Wh/kg

	NMC-333 / Gr	NMC-441 / Gr	NCA / Gr	LFP / Gr	LMO / Gr	LMO / LTO	LMR-NMC / Gr	LNMO / Gr
Price to OEM ($)	3970	3407	3812	3921	3204	4448	3025	2867
$/kWh$_{total}$	234	200	224	231	188	262	178	169
$/kWh$_{useable}$	334	286	320	329	269	349	254	241
kg	102	95	100	128	121	201	77	85
L	62	59	61	84	71	117	49	51
Wh/kg	167	179	171	133	140	85	221	201
Wh/L	275	290	280	201	238	146	347	336

NMC-333 = $Li_{1.05}(Ni_{1/3}Mn_{1/3}Co_{1/3})_{0.95}O_2$ / NMC-441 = $Li_{1.05}(Ni_{4/9}Mn_{4/9}Co_{1/9})_{0.95}O_2$ / NCA = $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$

LFP = $LiFePO_4$ / LMO = $Li_{1.06}Mn_{1.94}O_4$ / LNMO = $LiNi_{0.5}Mn_{1.5}O_4$ / LMR-NMC = $Li_2MnO_3 \cdot LiMO_2$ / LTO = $Li_4Ti_5O_{12}$