PHEV Battery Cost Assessment

Kevin G. Gallagher, Dennis Dees and Paul Nelson
Chemical Sciences and Engineering Division

May 9-13th, 2011

Vehicle Technologies Program Annual Merit Review
and Peer Evaluation Meeting

Washington D.C.

Project ID# ES111

This presentation does not contain any proprietary, confidential, or otherwise restricted information
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
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

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

ASI = area specific impedance

Iterative Spreadsheet
Determines cell properties
1. Cell capacity
2. Cell area
3. Electrode thickness
4. Internal resistance
And designs battery pack

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

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

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

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.

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 dominate total cost

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

Vehicle Technologies Program
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\textsubscript{total} & 79-165 Wh/kg

- Advanced Li-ion: 183-193 $/kWh\textsubscript{total} & 201-218 Wh/kg (early numbers)

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

NMC-333 = Li\textsubscript{1.05}(Ni\textsubscript{1/3}Mn\textsubscript{1/3}Co\textsubscript{1/3})\textsubscript{0.95}O\textsubscript{2} / NMC-441 = Li\textsubscript{1.05}(Ni\textsubscript{4/9}Mn\textsubscript{4/9}Co\textsubscript{1/9})\textsubscript{0.95}O\textsubscript{2} / NCA = LiNi\textsubscript{0.8}Co\textsubscript{0.15}Al\textsubscript{0.05}O\textsubscript{2} / LFP = LiFePO\textsubscript{4} / LMO = Li\textsubscript{1.06}Mn\textsubscript{1.94}O\textsubscript{4} / LNMO = LiNi\textsubscript{0.5}Mn\textsubscript{1.5}O\textsubscript{4} / LMR-NMC = Li\textsubscript{2}MnO\textsubscript{3}·LiMO\textsubscript{2} / LTO = Li\textsubscript{4}Ti\textsubscript{5}O\textsubscript{12}
New Approach to Impedance Calculation

- Development of enhanced ASI calculation to account for:
  - Changes in electrode thickness
  - Limiting currents
- Improved treatment of ASI allows for calculation of battery design and cost for many different power to energy (P/E) ratios

\[
ASI_{\text{chem}} = ASI_{\text{inf}^+} + ASI_{\text{inf}^-} + ASI_{\text{const}}
\]

![Graphs showing electrode thickness, positive electrode loading, and volume vs. energy](image)
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 \( \mu \)m
  - Moving from 100 to 200 \( \mu \)m reduces the amount of foil and separator by \( \frac{1}{2} \)
  - The manufacturing steps based on area will require less throughput (m\(^2\)/yr)
  - Designed optimal thickness depends on active material and cell properties

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

![Graphs showing battery pack price to OEM and price per total energy](image-url)

- Cell Configuration: NMC-441 / Gr vs. LMO / Gr
- Capacity, Ah of individual cells increasing

![Graphs showing battery pack price to OEM and price per total energy](image-url)
Increasing Energy Density to Lower Cost

- Lithium and manganese rich transition metal oxides (LMR-NMC)
  - Often called “layered-layered” or high capacity layered oxides
    \[ x\text{Li}_2\text{MnO}_3 \cdot (1-x)\text{LiNi}_y\text{Mn}_z\text{Co}_{1-y-z}\text{O}_2 \]
  - Benefits of LMR-NMC family of compounds
    - Large reversible capacity (~250 mAh/g)
    - Good full-cell voltages, \( U_{ocv} \approx 3.75 \) 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

\[
C \left( \frac{\$}{kg} \right) = C_0 + \frac{1}{MW} \sum_i \left[ x_i \cdot C_{i\cdot MW_i} \right]
\]
Relationship between performance & cost

- Challenges to implementation
  - High voltage during activation: 4.6 V vs Li⁰
  - 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?

**Diagram:**

- Battery price to OEM ($)
- Area-specific impedance (Ohm cm²)
- LMR-NMC / Gr
  - 17 kWh
  - 100 µm max

**DOE GOAL:**

- Battery mass (kg)
- Area-specific impedance (Ohm cm²)

- 100 kW
- 85 kW
- 70 kW
- 55 kW
- 40 kW

- DOE GOAL
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

- **Li₂MXO₄ / 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 > 2017

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

- **LMO / Gr**
  - Market entry > 2013

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 provided 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 \(P_{\text{max}}\) / 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

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

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

\[
ASI = \frac{\alpha + f(I)}{L_{\text{pos}}} + \beta
\]

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

\[
L_{\text{pos}} = \frac{C}{Q \rho \epsilon_{\text{act}} A_{\text{pos}}}
\]
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
    \[
    ASI_{\text{intf}}^{\text{pos}} = \frac{1}{L} \left[ \frac{RT}{a_i F} \left( 1 - \frac{I}{I_{\text{lim}}} \right) \right]
    \]
  - Lumps ohmic behavior in \( ASI_{\text{const}} \)
    \[
    ASI_{\text{chem}} = ASI_{\text{intf}}^{\text{pos}} + ASI_{\text{intf}}^{\text{neg}} + ASI_{\text{const}}
    \]
- ASI from cell current collectors uses equivalent length of \( H/3 \)
  - Verified analytically and numerically
    \[
    ASI_{\text{cc}} = \frac{H^2}{3} \left( \frac{1}{\sigma_{\text{pos,cc}}} + \frac{1}{\sigma_{\text{neg,cc}}} \right)
    \]
- Battery pack ASI for power includes all other resistances
  \[
  ASI_{\text{power}} = ASI_{\text{chem, P}} + ASI_{\text{cc}} + ASI_{\text{term}} + \frac{R_{\text{cnct}} A_{\text{pos}}}{N_{\text{cells}}}
  \]
- Battery pack \( ASI_{\text{energy}} \) has larger \( ASI_{\text{const}} \) 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$_{\text{total}}$ 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

<table>
<thead>
<tr>
<th>Operation</th>
<th>No./shift</th>
<th>Hours/yr</th>
<th>p Factor</th>
<th>Direct Labor</th>
<th>Cap. Equipment</th>
<th>Plant Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiving (two-shift operation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>600</td>
</tr>
<tr>
<td>Materials preparation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive electrode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative electrode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrode coating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive electrode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative electrode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solvent recovery</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calendering</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive electrode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative electrode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials handling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrode slitting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control laboratory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell Assembly in Dry Room</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell stacking</td>
<td>6</td>
<td>43,200</td>
<td>0.7</td>
<td></td>
<td>5.00</td>
<td>400</td>
</tr>
<tr>
<td>Current collector welding</td>
<td>6</td>
<td>43,200</td>
<td>0.7</td>
<td></td>
<td>5.00</td>
<td>400</td>
</tr>
<tr>
<td>Enclosing cell in container</td>
<td>4</td>
<td>28,800</td>
<td>0.5</td>
<td></td>
<td>3.00</td>
<td>400</td>
</tr>
<tr>
<td>Electrolyte filling, and cell sealing</td>
<td>6</td>
<td>43,200</td>
<td>0.5</td>
<td></td>
<td>6.00</td>
<td>600</td>
</tr>
<tr>
<td>Dry room control and air locks</td>
<td>2</td>
<td>14,400</td>
<td>0.4</td>
<td></td>
<td>20.00</td>
<td>75</td>
</tr>
<tr>
<td>Formation cycling</td>
<td>6</td>
<td>57,600</td>
<td>0.7</td>
<td></td>
<td>30.00</td>
<td>1,500</td>
</tr>
<tr>
<td>Final cell sealing</td>
<td>6</td>
<td>14,400</td>
<td>0.5</td>
<td></td>
<td>7.50</td>
<td>300</td>
</tr>
<tr>
<td>Charge retention testing</td>
<td>3</td>
<td>21,600</td>
<td>0.4</td>
<td></td>
<td>4.75</td>
<td>600</td>
</tr>
<tr>
<td>Module assembly</td>
<td>6</td>
<td>43,200</td>
<td>0.5</td>
<td></td>
<td>6.00</td>
<td>400</td>
</tr>
<tr>
<td>Battery pack assembly and testing</td>
<td>6</td>
<td>43,200</td>
<td>0.5</td>
<td></td>
<td>6.00</td>
<td>600</td>
</tr>
<tr>
<td>Rejected cell and scrap recycle</td>
<td>5</td>
<td>36,000</td>
<td>0.7</td>
<td></td>
<td>2.50</td>
<td>400</td>
</tr>
<tr>
<td>Shipping (two-shift operation)</td>
<td>6</td>
<td>28,800</td>
<td>0.5</td>
<td></td>
<td>5.00</td>
<td>600</td>
</tr>
</tbody>
</table>

### Notes:
- One-third of the space for materials handling is within the dry room.
- The baseline capital cost electrode coating, $C_0$, is based on the evaporation of the baseline annual solvent weight ($R_{o}$). For batteries requiring different solvent evaporation rates $R_s$, the cost is multiplied by ratio of rates raised to the 0.2 power. Thus, $\text{Cost} = C_0(R/R_o)^{0.8}(R_s/R_o)^{0.2}$.
- 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, $(\text{Cap})/40\text{ Ah}$, raised to the 0.3 power. Thus, $\text{Cost} = C_o(R/R_o)^{0.8}(\text{Cap}/40)\times 0.3$.
- 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 ($\text{Mod}$), the cost is multiplied by the ratio of modules, $(\text{Mod})/4$ raised to the 0.3 power. Thus, $\text{Cost} = C_o(R/R_o)^{0.7}(\text{Mod}/4)\times 0.3$.
## Cost Modeling Assumptions

- **Unit cost of battery pack**

<table>
<thead>
<tr>
<th>Variable Costs</th>
<th>Description</th>
<th>Method of Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials and Purchased Items</td>
<td>All materials and purchased items in finished product and lost in processing.</td>
<td>Based on prices of materials, cost equations for purchased items and yields.</td>
</tr>
<tr>
<td>Direct Labor</td>
<td>Labor costs for operations and immediate supervision.</td>
<td>Estimates of costs for each processing step at baseline rates adjusted for actual rates.</td>
</tr>
<tr>
<td>Variable Overhead</td>
<td>Indirect materials, labor, utilities, plant maintenance</td>
<td>60% of direct labor cost.</td>
</tr>
<tr>
<td><strong>Fixed Expenses</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General, Sales, and Administration (GSA)</td>
<td>Plant office, taxes on income and property, cost of sales and insurance expenses.</td>
<td>25% of direct labor and variable overhead plus 35% of depreciation.</td>
</tr>
<tr>
<td>Research and Development</td>
<td>On-going research needed to upgrade product and maintain competitive position.</td>
<td>50% of depreciation</td>
</tr>
<tr>
<td>Depreciation</td>
<td>Provides funds for new investments to replace those in current equipment and plant.</td>
<td>12.5% of capital equipment cost plus 5% of plant floor space cost.</td>
</tr>
<tr>
<td><strong>Profit</strong></td>
<td>Return on invested capital after taxes.</td>
<td>5% of total investment costs.</td>
</tr>
<tr>
<td><strong>Warranty</strong></td>
<td>Funds set aside for reimbursing customers for battery pack failures.</td>
<td>5.6% added to price based on present worth of projected payments.</td>
</tr>
</tbody>
</table>
Materials costs used in calculations

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

Baseline cost, \( C_0 = 16-20 \text{\$/kg}; \ C_{\text{Li}_2\text{CO}_3} = 6\text{\$/kg}; \ C_{\text{NiSO}_4} = 5.5\text{\$/kg}; \ C_{\text{MnSO}_4} = 1\text{\$/kg}; \ C_{\text{CoSO}_4} = 32\text{\$/kg}; \)

- 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)

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemistry</th>
<th>Abbreviation</th>
<th>unit</th>
<th>ANL 2010</th>
<th>TIAAX 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese spinel cathode</td>
<td>( \text{Li}<em>{1.06}\text{Mn}</em>{1.94}\text{O}_4 )</td>
<td>LMO</td>
<td>$/kg</td>
<td>10</td>
<td>12 - 16 - 20</td>
</tr>
<tr>
<td>5V spinel cathode*</td>
<td>( \text{LiNi}<em>{0.5}\text{Mn}</em>{1.5}\text{O}_4 )</td>
<td>LNMO</td>
<td>$/kg</td>
<td>21</td>
<td>-</td>
</tr>
<tr>
<td>Phospholivine cathode</td>
<td>( \text{LiFePO}_4 )</td>
<td>LFP</td>
<td>$/kg</td>
<td>20</td>
<td>15 - 20 -25</td>
</tr>
<tr>
<td>Layered oxide cathode*</td>
<td>( \text{LiNi}<em>{0.8}\text{Co}</em>{0.15}\text{Al}_{0.05}\text{O}_2 )</td>
<td>NCA</td>
<td>$/kg</td>
<td>37</td>
<td>34 - 40 - 54</td>
</tr>
<tr>
<td>Layered oxide cathode*</td>
<td>( \text{Li}<em>{1.05}(\text{Ni}</em>{1/3}\text{Mn}<em>{1/3}\text{Co}</em>{1/3})_{0.95}\text{O}_2 )</td>
<td>NMC-333</td>
<td>$/kg</td>
<td>39</td>
<td>40 - 45 -53</td>
</tr>
<tr>
<td>Layered oxide cathode*</td>
<td>( \text{Li}<em>{1.05}(\text{Ni}</em>{4/9}\text{Mn}<em>{4/9}\text{Co}</em>{1/9})_{0.95}\text{O}_2 )</td>
<td>NMC-441</td>
<td>$/kg</td>
<td>29</td>
<td>-</td>
</tr>
<tr>
<td>Li &amp; Mn rich layered cathode*</td>
<td>( x\text{Li}_2\text{MnO}_3 \cdot (1-x)\text{LiNi}_y\text{Mn}<em>z\text{Co}</em>{1-y-z}\text{O}_2 )</td>
<td>LMR-NMC</td>
<td>$/kg</td>
<td>22-30</td>
<td>24 - 31 - 39</td>
</tr>
<tr>
<td>Graphite anode</td>
<td>( \text{C}_6 )</td>
<td>Gr</td>
<td>$/kg</td>
<td>19</td>
<td>17 - 20 - 23</td>
</tr>
<tr>
<td>Titanate spinel anode</td>
<td>( \text{Li}_4\text{Ti}<em>5\text{O}</em>{12} )</td>
<td>LTO</td>
<td>$/kg</td>
<td>12</td>
<td>9 - 10 - 12</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>1.2 M LiPF(_6) in EC:EMC</td>
<td></td>
<td>$/kg</td>
<td>19</td>
<td>18.5 - 21.5 -24.5</td>
</tr>
<tr>
<td>Separator</td>
<td>PP/PE/PP</td>
<td></td>
<td>$/m^2</td>
<td>2</td>
<td>1 - 2.5 -2.9</td>
</tr>
<tr>
<td>Current collector foil</td>
<td>Copper</td>
<td></td>
<td>$/m^2</td>
<td>3.00</td>
<td>-</td>
</tr>
<tr>
<td>Current collector foil</td>
<td>Aluminum</td>
<td></td>
<td>$/m^2</td>
<td>0.80</td>
<td>-</td>
</tr>
</tbody>
</table>

* 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 $/kWh\text{_{total}}$ & 85-179 Wh/kg

- Advanced Li-ion: 169-178 $/kWh\text{_{total}}$ & 221 Wh/kg

<table>
<thead>
<tr>
<th>Price to OEM ($)</th>
<th>NMC-333 / Gr</th>
<th>NMC-441 / Gr</th>
<th>NCA / Gr</th>
<th>LFP / Gr</th>
<th>LMO / Gr</th>
<th>LMO / LTO</th>
<th>LMR-NMC / Gr</th>
<th>LNMO / Gr</th>
</tr>
</thead>
<tbody>
<tr>
<td>3970</td>
<td>3407</td>
<td>3812</td>
<td>3921</td>
<td>3204</td>
<td>4448</td>
<td>3025</td>
<td>2867</td>
<td></td>
</tr>
<tr>
<td>234</td>
<td>200</td>
<td>224</td>
<td>231</td>
<td>188</td>
<td>262</td>
<td>178</td>
<td>169</td>
<td></td>
</tr>
<tr>
<td>334</td>
<td>286</td>
<td>320</td>
<td>329</td>
<td>269</td>
<td>349</td>
<td>254</td>
<td>241</td>
<td></td>
</tr>
<tr>
<td>102</td>
<td>95</td>
<td>100</td>
<td>128</td>
<td>121</td>
<td>201</td>
<td>77</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>59</td>
<td>61</td>
<td>71</td>
<td>117</td>
<td>117</td>
<td>49</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>167</td>
<td>179</td>
<td>171</td>
<td>133</td>
<td>140</td>
<td>85</td>
<td>221</td>
<td>201</td>
<td></td>
</tr>
<tr>
<td>275</td>
<td>290</td>
<td>280</td>
<td>201</td>
<td>238</td>
<td>146</td>
<td>347</td>
<td>336</td>
<td></td>
</tr>
</tbody>
</table>

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·LiMO_2 / LTO = Li_4Ti_5O_12