PHEV Battery Cost Assessment

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May 14-18th, 2012

Vehicle Technologies Program Annual Merit Review
and Peer Evaluation Meeting
Washington D.C.

Project ID# ES111

Overview

Timeline

- Start: August 2010
- Finish: September 2012
- Future: Will continue to support ABR programs
  - Voltage fade
  - Electrochemical couples
  - ABR facilities

Budget

- Total project funding
  - 100% DOE
- FY2011: $300K
- FY2012: $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
  - Implement initial active thermal management into model (complete)
  - Publish documentation as Argonne report (complete)
  - Distribute model openly (complete)
  - Refine cost behavior of some advanced Li-ion couples (complete)
- 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

- Completed and published BatPaC v1.0 with documentation
  - Model and 100+ page report available from www.cse.anl.gov/batpac
  - BatPaC v2.0 and documentation is in progress
- Implemented both liquid (v1.0) and air thermal management (v2.0) in model as well as pack integration components
- Created automatic cost uncertainty calculation (v2.0)
- Continued to support U.S. EPA in their 2017-2025 rule making
- Analyzed benefit and requirements for advanced Li-ion negative electrodes

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 pouch 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)

Battery design calculations

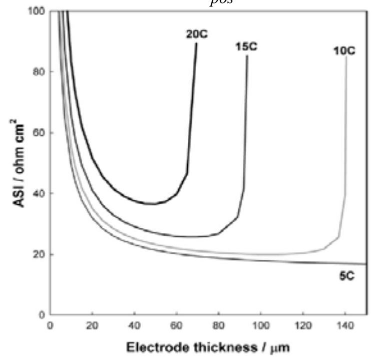
Pack Requirements
- Power
- Energy or range
- # of cells
- Fade over lifetime

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

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

Key Constraints
- Max electrode thickness
- Target cell potential, V, at peak power
- Pouch cell & battery format

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



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

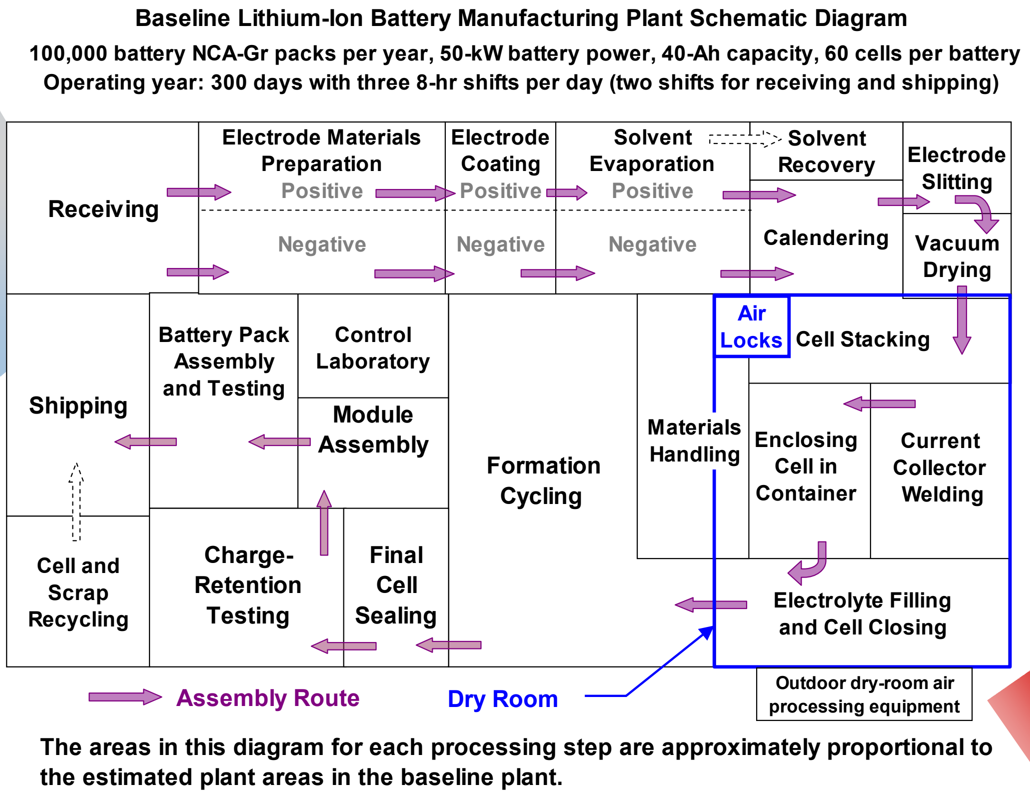
$$L_{pos} = \frac{C}{Q \rho \varepsilon_{act} A_{pos}}$$

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

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

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

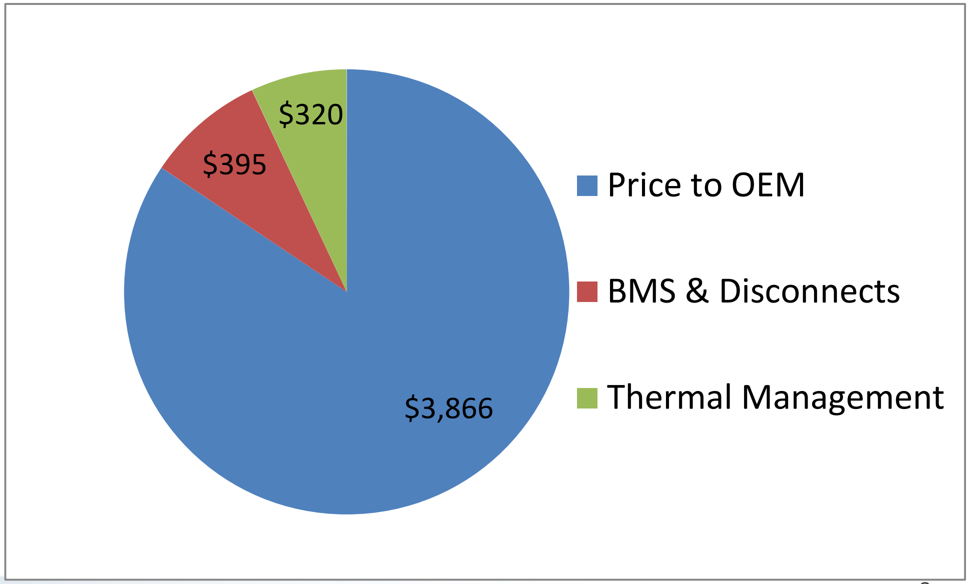
Total cost to OEM
- Materials & purchased items
- Individual process steps
- Overhead, depreciation, etc
- Warranty

Pack Integration Components

- These estimates are derived from conversations with industry for predictions of high volume, year 2020 market
- Battery Management System
  - Auto/Manual Disconnects ~$200
  - Pack voltage & current sensing ~$200
- Thermal Management System
  - Liquid assumed here (EG-W)
  - Includes addition to AC system
- Price to OEM
  - Everything inside the pack
  - SOC controllers: $2.50/cell
  - Aluminum heat sinks
- Total cost to OEM
  - The sum total

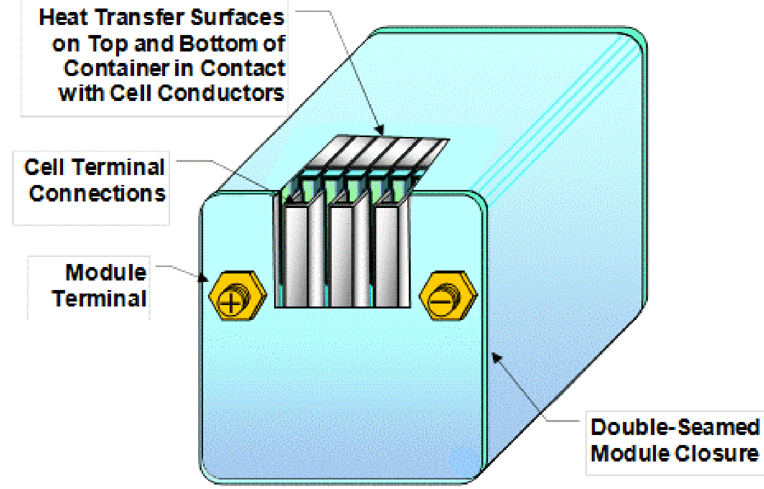
Calculations for a 60 kW, 17 kWh 360V NMC441 - Graphite

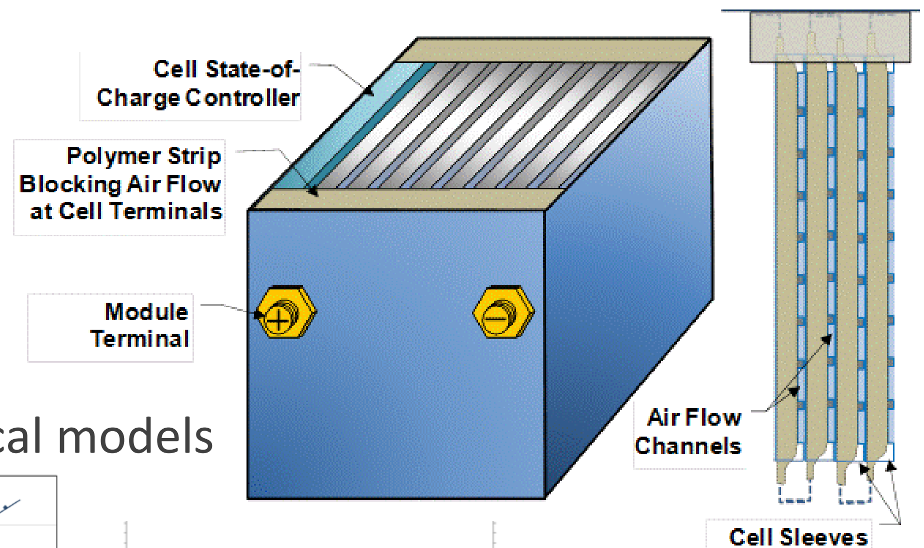
NMC441 = $Li_{1.05}(Ni_{4/9}Mn_{4/9}Co_{1/9})_{0.95}O_2$

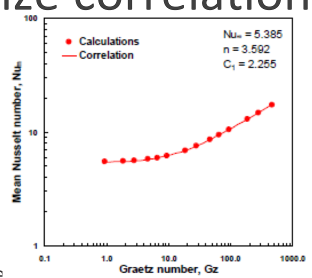


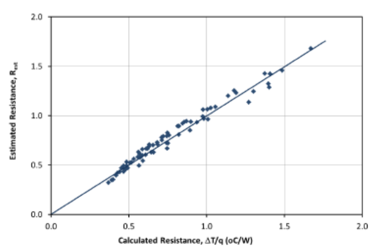
Thermal Management

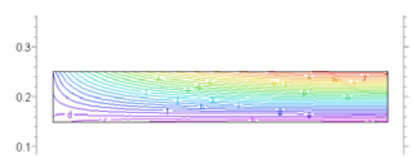
- Liquid heat transfer to/from modules
  - Compact and simple design
  - Maintains high energy density
  - Flow rate and gap height calculated
- Air heat transfer to/from cell walls
  - Higher surface area required
  - Large volumetric penalty
  - Flow passage and manifolds thickness and length calculated
- Heat transfer calculations
  - Utilize correlations from numerical models











Thermal Management

- Using forced cabin-air results in a slightly cheaper PHEV40 battery than using liquid (EG-H_2O) thermal management
- Using cabin-air results in a much larger battery

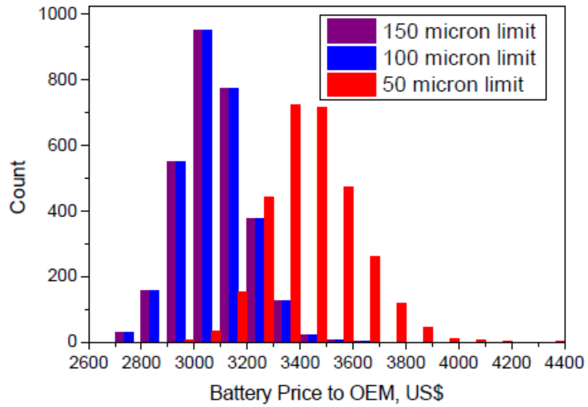
- Liquid thermal management
  - Pack size: 65 L and 104 kg
  - Total cost to OEM: $4580
    - Thermal Mgmt cost: $320
    - Cooling modules enables size efficient packaging
- Cabin-air thermal management
  - Pack size: 130 L and 116 kg (2X the volume)
  - Total cost to OEM: $4500
    - Thermal Mgmt cost: $120 (ducting fan, etc)
    - Increased cost in module assembly and battery jacket decrease savings

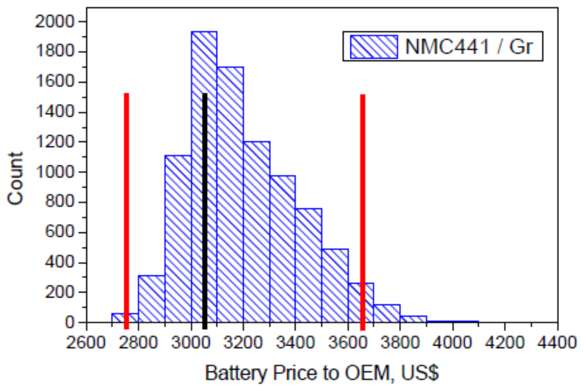
Calculations for a 60 kW, 17 kWh 360V NMC441 - Graphite

Uncertainty calculation

- Varied the top eight high-cost contributors
- Uncertainty in materials cost
  - Active materials, separator, Cu foil
  - State-of-charge electronics
  - Capital cost of coating & formation
- Uncertainty in design limitations
  - Electrode thickness limitation
  - Using parallel cell configurations
  - Cell capacity limitations (adds parallel cells)
- Conclusion
  - Materials cost error is ~±10% regardless of active materials
  - Electrode thickness limitation is often the most significant
    - Use PHEV limits of 50/100/150 microns (min/med/max)
    - Electrode thickness still calculated → thus not always controlled by limit!

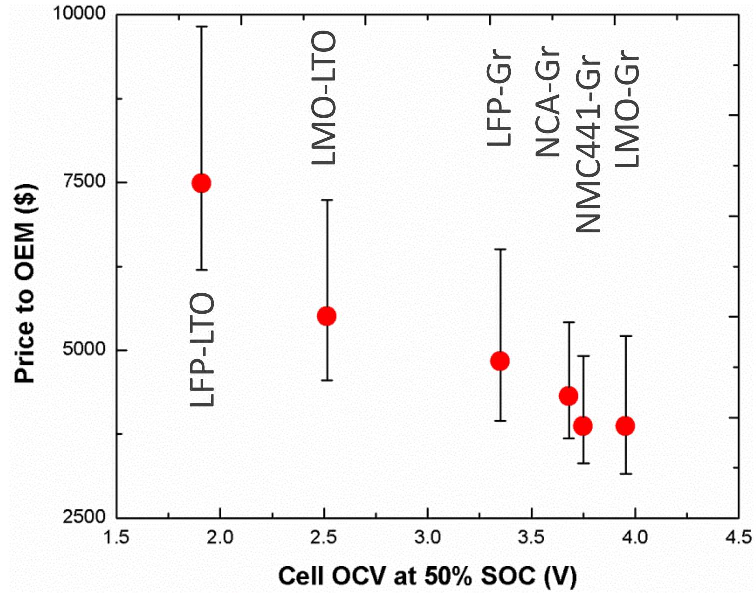
PHEV25: 65 kW, 10.7 kWh 360V

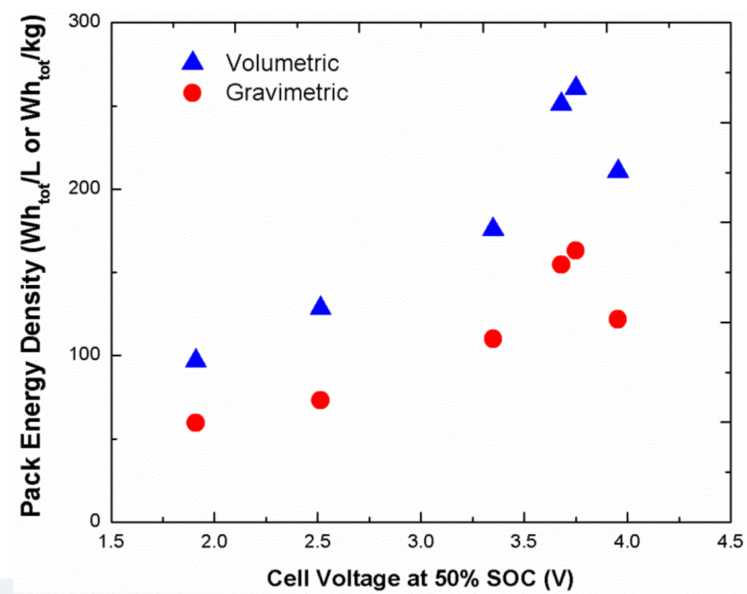




Importance of Cell Voltage in Battery Cost

- Increasing cell voltage usually helps
  - Increases energy density
  - Reduce cell count
    - Thus SOC controllers
  - Less stringent ASI required
    - Higher currents for same efficiency V/U
    - Lowers electrode area required
- Low-voltage, low-impedance cells have lower ASI but still require much higher area
- $A_{cell} \propto ASI/(U_{ocv})^2$



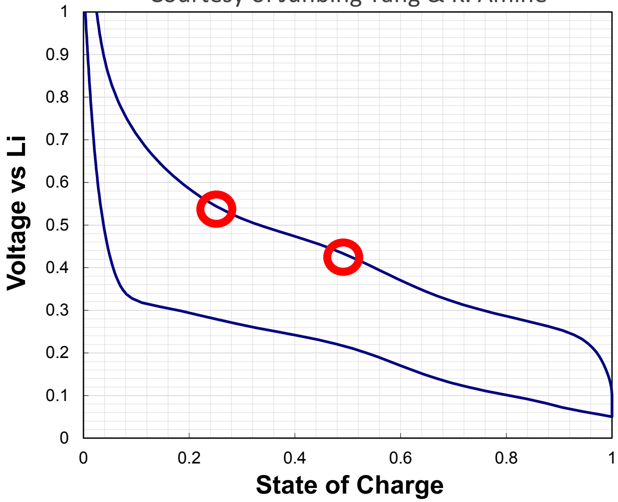


60 kW, 17 kWh 360V

Modeling Advanced Li-ion Couples

- Volumetric specific capacity can also be a controlling factor
- Voltage might not always control, but it is always important
- Analyze possible advanced Li-ion couples
  - Graphite-silicon (GrSi) composite anodes
  - Assume 80% 1st cycle efficiency
  - 50% electrolyte porosity
  - 80:10:10 active:binder:carbon
  - Target V/U = 0.7 for pulse power

Courtesy of Junbing Yang & K. Amine

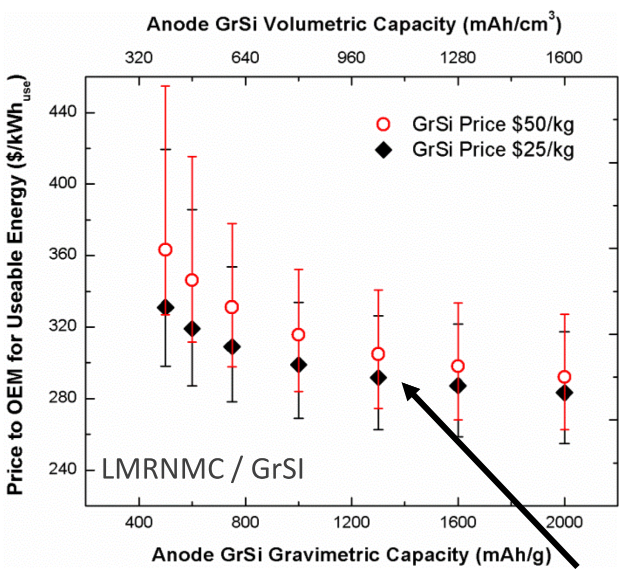


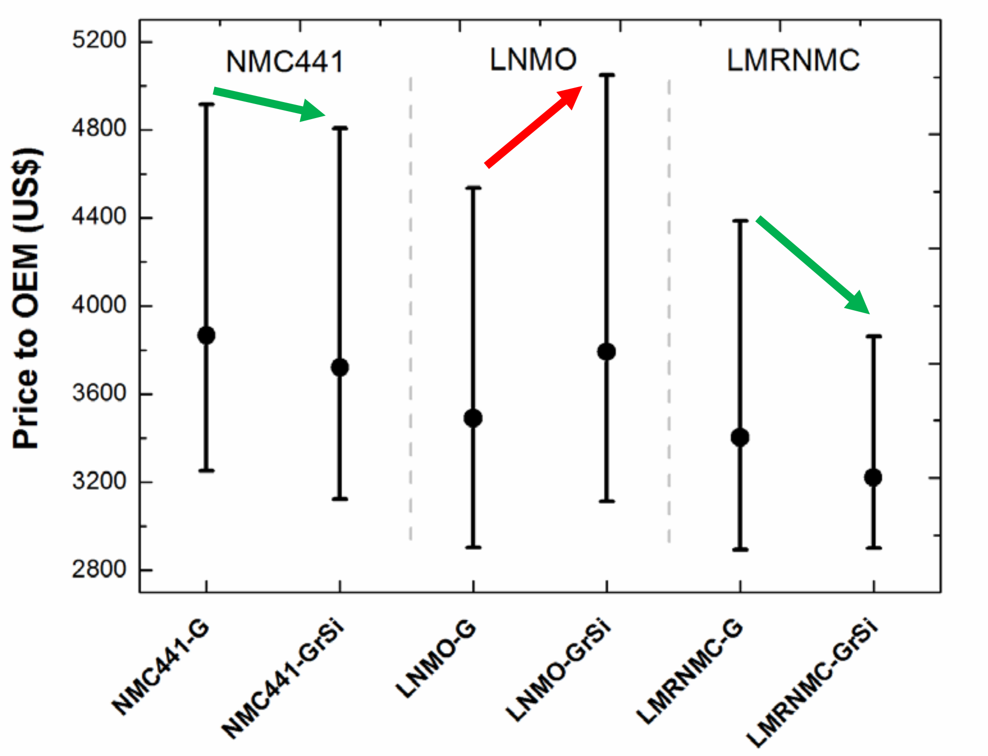
- Cathodes to be analyzed coupled to high capacity anode, GrSi
  - **NMC441**: 175 mAh/g, 420 mAh/cm^3, U_{avg} = 3.82 V vs Li
  - $xLi_2MnO_3(1\text{-}x)LiMO_2$ **LMR-NMC**: 250 mAh/g, 565 mAh/cm^3, U_{avg} = 3.75 V
  - $LiNi_{0.5}Mn_{1.5}O_4$ **LNMO**: 130 mAh/g, 268 mAh/cm^3, U_{avg} = 4.75 V

Advanced Li-ion Couples

- Graphite with LNMO and LMRNMC similar in cost and energy density
- LMRNMC shows synergy with GrSi anode
  - Both have high volumetric capacity, mAh/cm^3
  - Lower cell voltage from GrSi offsets some gains

60 kW, 17 kWh 360V

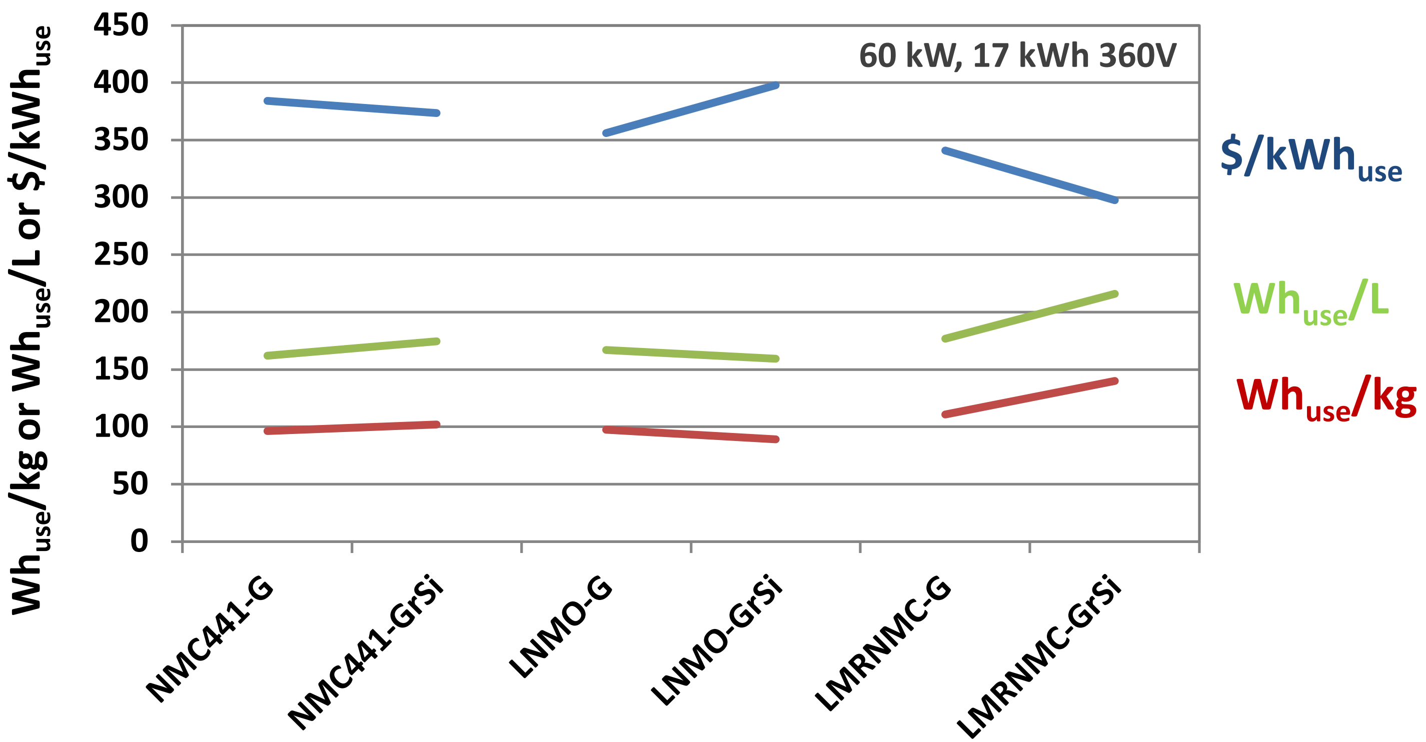




Use this GrSi

Focus on 50-micron Electrode Limited Case

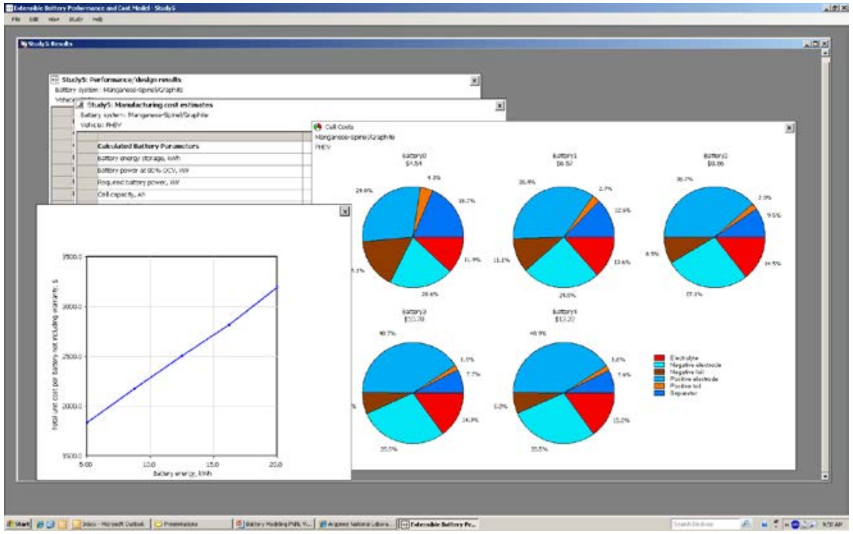
- Most similar electrode thickness to today's transportation batteries
- LMRNMC-GrSi lowers cost and increases energy density
  - LNMO is the limiting electrode (mAh/cm^3), switching the anode penalizes cell voltage more than it decreases anode materials cost



Distribution of BatPaC and BatPro

- BatPaC model (Excel based) and documentation available for free from: **www.cse.anl.gov/BatPaC**

- Battery production and cost model (BatPro)
  - 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
  - Available for a nominal fee



Argonne Software Shop:

- http://www.anl.gov/techtransfer/Software_Shop/index.html

Future Work

- Transitioning project to new ABR format
  - Supporting Voltage Fade project
  - Supporting development of Electrochemical Couples
  - Supporting ABR facilities (CFF, MERF, Post-Test)
- Distribute BatPaC v2.0 to public (targeting September 2012)
- Evaluating new electrochemical couples
- Continuous refinement of model calculations & parameters
- Milestones for next year
  - Distribution of BatPaC v2.0
  - Continued support of U.S. EPA rule-making
  - Develop metrics and targets for ABR voltage fade project

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 battery performance specifications using a selected cell, module, and pack format
- Technical accomplishments
  - Completed and published BatPaC v1.0 with documentation
  - Implemented both liquid (v1.0) and now air thermal management (v2.0)
  - Created automatic cost uncertainty calculation (v2.0)
  - Continued to support the U.S. EPA in their 2017-2025 rule making
  - Analyzed benefits and requirements for advanced Li-ion negative electrodes
- Future plans involve the release of BatPaC v2.0, continued support of U.S. agencies and supporting ABR projects and facilities

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 reviewed our baseline plant in detail
  - EPA: Joe McDonald initiated peer-review
  - EPRI: Fritz Kalhammer, Satish Rajagopalan, Haresh Kamath
  - Multiple domestic cell manufacturers and domestic OEMs
- Argonne National Laboratory
  - Ira Bloom, Dan Santini
  - Junbing Yang, Khalil Amine, Sun-Ho Kang, Wenquan Lu

Technical Back-Up Slides

Adv Li-ion Materials & Purchased Item Cost Contributions for 50 micron case