HTTP://WWW.CSE.ANL.GOV/BATPAC/

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Automotive Battery Cost Using BatPaC

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BatPaC is a spreadsheet tool for designing automotive Li-ion battery packs

- Designs the cells and the pack for a given set of specifications
  - Electrode Chemistry
  - Energy storage capacity
  - Pulse power requirement
  - And many others (voltage, fast charge requirement, …)

- The results include
  - Battery pack metrics (size/dimensions, weight, energy density, etc.)
  - Cost of battery packs when manufactured in large volume

- The design and cost calculations are performed by using
  - algorithms and correlations derived from other results in other models
  - material properties generated in the laboratory

BATPAC DESIGNS THE BATTERY AND CALCULATES ITS MASS, VOLUME, MATERIALS, HEAT TRANSFER NEEDS, AND COST

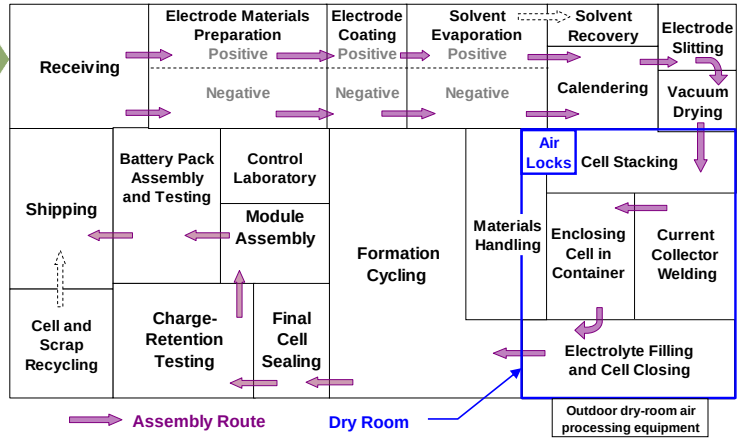
Iterate Over Governing Eqs. & Key Design Constraints

- Cell, module, & pack format
- Maximum electrode thickness
- Fraction of OCV at rated power

Battery Pack Components

- Volume
- Mass
- Materials
- Heat generation

$$Process\ cost = Baseline\ cost \cdot \left(\frac{Processing\ rate}{Baseline\ processing\ rate}\right)^{p}$$



- **Pack specifications**
  - Power and energy (range)
  - Number of cells
- **Cell Chemistry**
  - Area-specific impedance (ASI)
  - Reversible capacity C/3
  - OCV as function of SOC
  - Physical properties

Governing Equations

$$E = N \cdot C \cdot \left(U_E - \frac{C}{3}\frac{ASI_E}{A}\right)$$

$$L = \frac{C}{Q \cdot \rho \cdot \varepsilon \cdot A}$$

$$I = \frac{P}{A \cdot N \cdot U_P\left[\frac{V}{U}\right]}$$

$$A = \frac{ASI_P \cdot P}{N \cdot (U_P)^2\left[\frac{V}{U}\right]\left(1-\left[\frac{V}{U}\right]\right)}$$

$$ASI = \frac{\alpha + f(I)}{L} + \beta$$

Total Cost to OEM

- Materials & purchased items
- Individual process steps
- Overhead, depreciation, etc.
- Warranty

http://www.cse.anl.gov/batpac/

P.A. Nelson, K.G. Gallagher, I. Bloom, D.W. Dees, Modeling the Performance and Cost of Lithium-ion Batteries for Electric Vehicles, second ed., Chemical Sciences and Engineering Division, Argonne National Laboratory, Argonne, IL USA, 2011. ANL-12/55.

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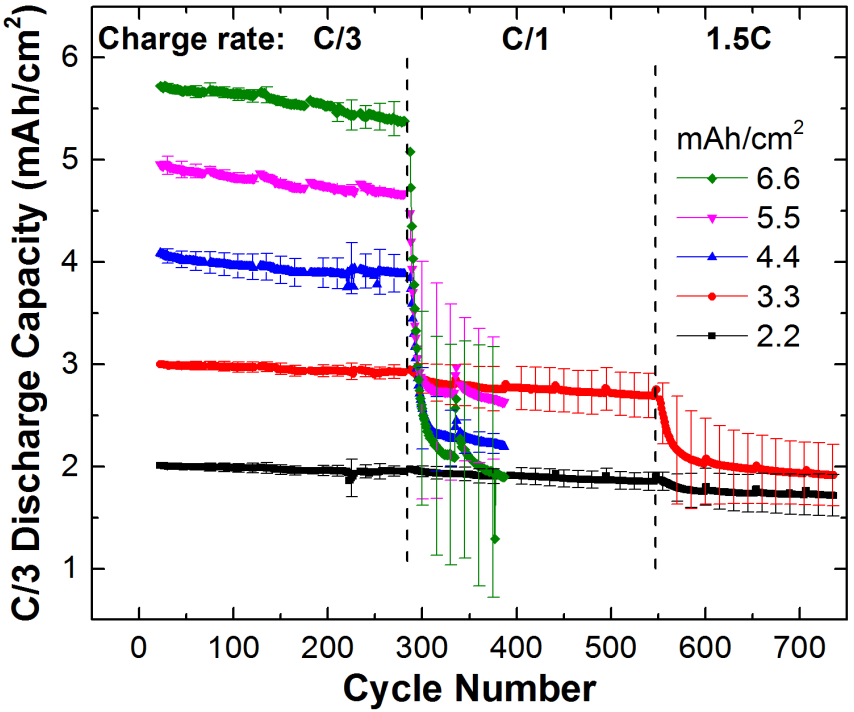
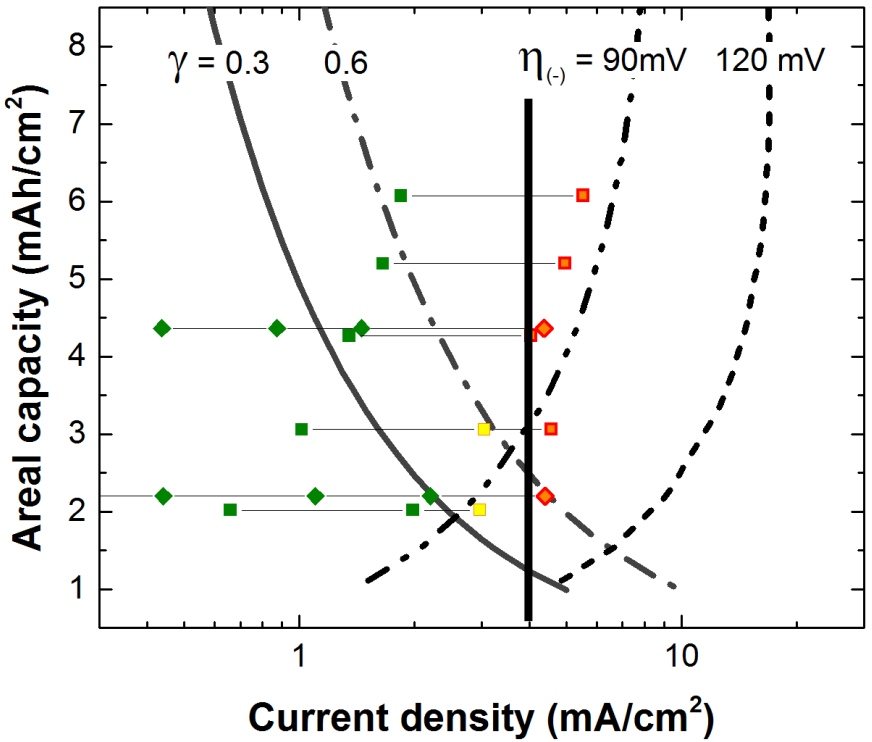
Transport models are used to define correlations for electrode thickness

Analytical expression for limitations on both discharge & charge

NMC622/Gr 14 cm^2 pouch cells
C/3 discharge rate; charge varied

$$Q_A = \sqrt{\frac{\gamma Q_v \left(\frac{\varepsilon}{\tau}\right) DcFt_d}{\left(1 - t_+^o\right)}}$$





4 mA/cm^2 is a critical current density to be avoided during charge

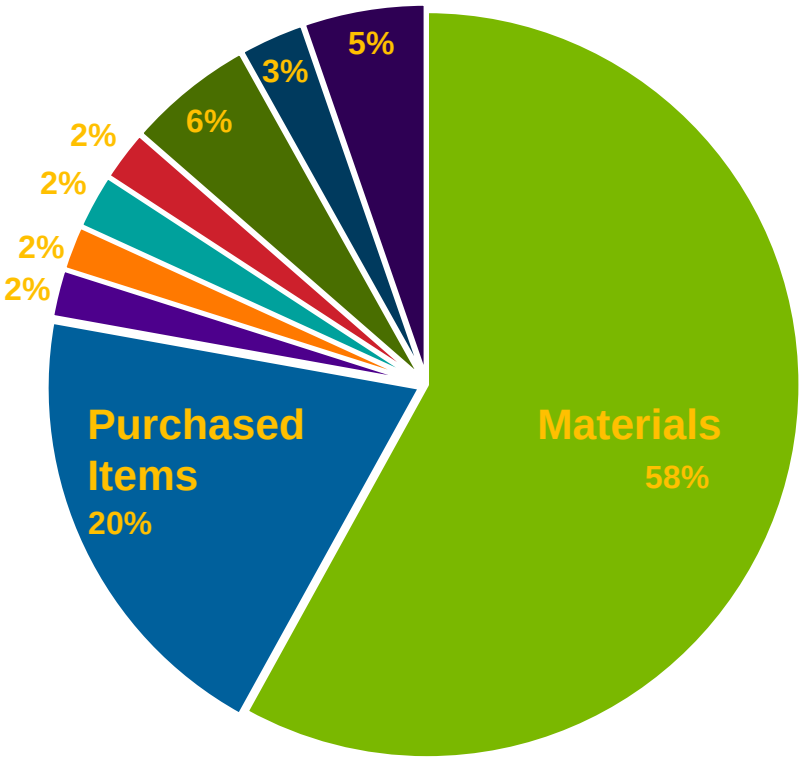
Comparing 3 EV batteries (Cost based on 100 K packs produced per year)

NMC622-Graphite	Case 1	Case 2	Case 3
Energy, kWh	60	80	100
Power, kW	150	200	300
Charging Time (ΔSOC=80%), min	30	30	30
Cathode Thickness, µm	76	88	98
No. of Cells	240	240	240
No. of Modules	6	6	6
Cell and Pack Capacity*, Ah	67	89	111
Price of Cells to OEM, $	$6,596	$8,074	$9,477
$/kWh	$110	$101	$95
Price of Pack to OEM, $	$8,646	$10,240	$11,761

*Same since all the cells are in series

The electrode materials represent a significant fraction of the pack cost

60 kWh, NMC622-G, 100K packs/year



Materials and Purchased Items	%
Positive Active Material	29
Negative Active Material	15
Carbon and Binders	2
Positive Current Collector	2
Negative Current Collector	6
Separators	11
Electrolyte	10
Cell Hardware	4
Module Hardware	13
Battery Jacket	8

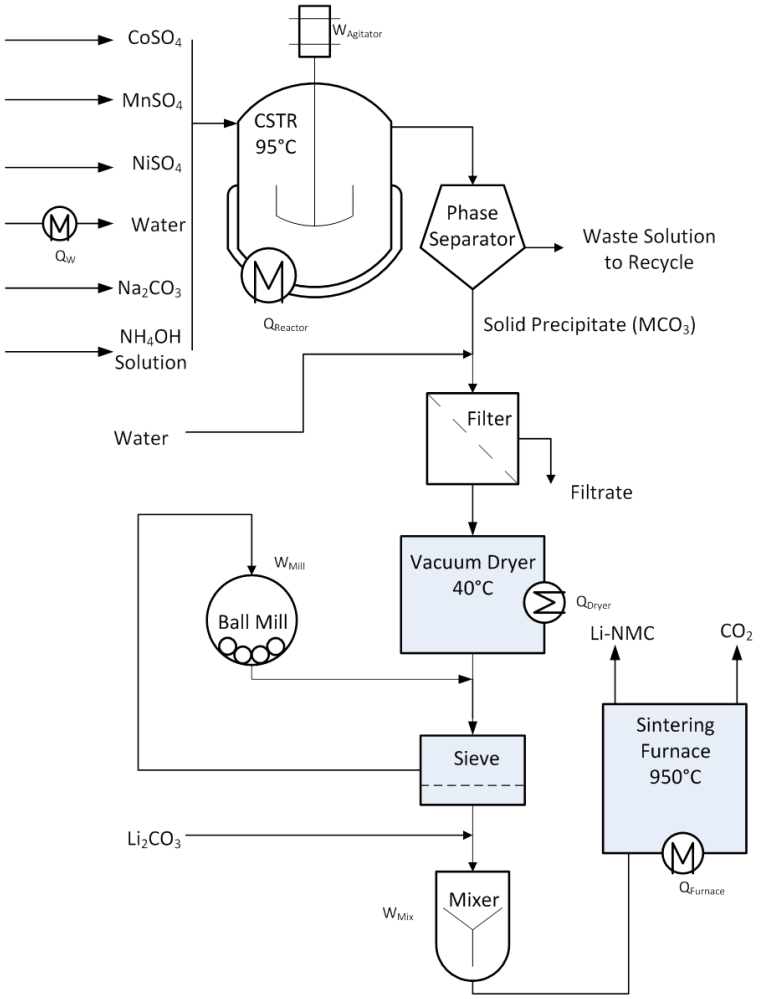
Batpac is updated with results from a number of supporting models

- Other models used to generate input parameters for BatPaC include
  - Baseline plant production cost model
  - Transport model of electrode layer
  - Heat transfer modeling within the cell
  - Production of the NMC cathode material
  - Cathode drying and solvent (NMP) recovery
  - Model of Cell-Formation protocol
  - Mass and heat transfer model for drying of the cathode layer
    - *Journal of Power Sources* 378 (2018) 660–670
  - Dry room operations
    - *Journal of Power Sources* 326 (2016) 490-497

NMC PRODUCTION PROCESS

Estimated production cost of NMC333 is approximately $20 per kg

- $MSO_4 + Na_2CO_3 = MCO_3\downarrow + Na_2SO_4$
  - The energy demand is ~ 2 kWh/kg
    - Thermal/Electrical = 3
  - Raw materials contribute 50+% to cost of final product
- $MSO_4 + 2NaOH = M(OH)_2\downarrow + Na_2SO_4$
  - Requires more water, costs 40 ¢/kg more



Results based on 6500 kg/day plant

- 4 kWh per kg_{NMC333}
- $23[1] per kg_{NMC333}
- $22[1] per kg_{NMC622}

BatPaC 3.1 includes a correlation for cost of NMCxxx
= f(metal prices)

[1]Co metal price $26/$kg_{Co}$, $8/$kg_{Li2CO3}$

Journal of Power Sources 342 (2017) 733-740

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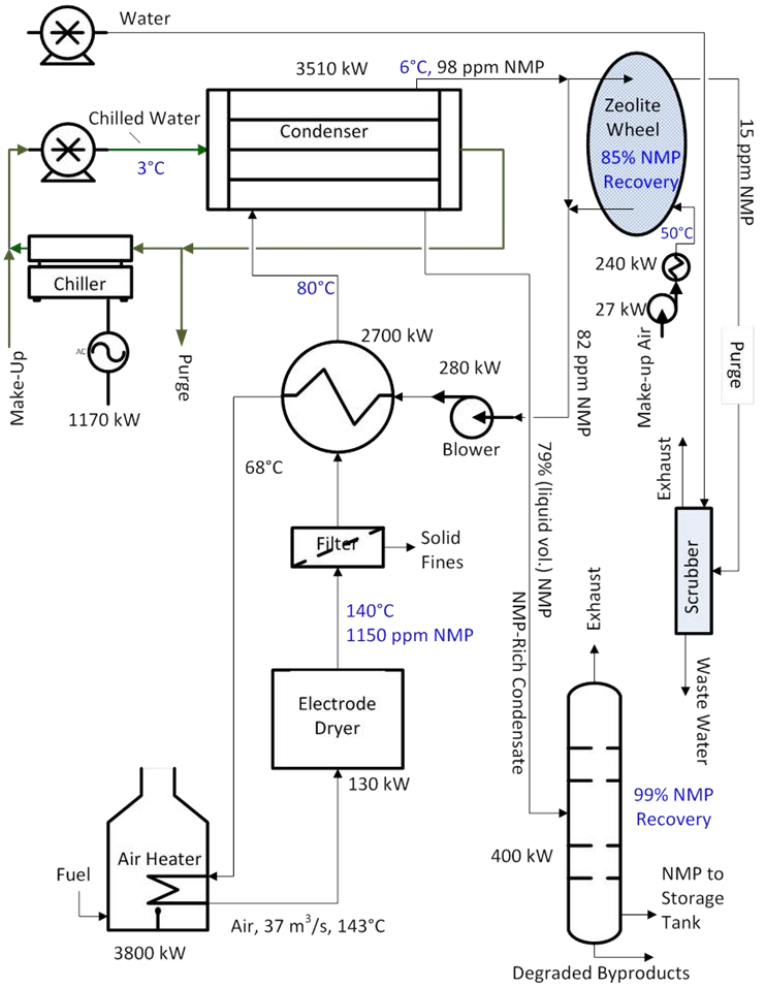
Modeled the cathode drying and NMP recovery process

Cathode drying and recovery contributes ~$10 / kWh (3%) to the cost of a PHEV battery pack

- The process requires ~420 kWh per kWh battery pack*
  - 5800 kW, 580 kW/kWh
- Energy demand is 45 times the energy needed for NMP vaporization
- Large energy demand is constrained by safety
  - Large excess air is needed to limit NMP concentration in hot air
- The air heater for the coating line ovens (dryer) is the largest contributor with 60+% of total demand
- Cost of energy is ~10% of process, with opportunities to reduce energy demand (CO2-equivalent emissions)



Process for evaporation and recovery of 4M kg/yr of NMP

*Plant producing 100K packs/yr of 60 kW, 10 kWh PHEV batteries

Ahmed *et.al.*, Journal of Power Sources **322** (2016) 169-178

Effect of production volume and cathode price on cell level prices

- For 60 kWh batteries
  - Effect of production Volume, packs per year

Packs per year	Cell-Level Prices $/kWh
500 K	93
100 K	109
50 K	118
25 K	130

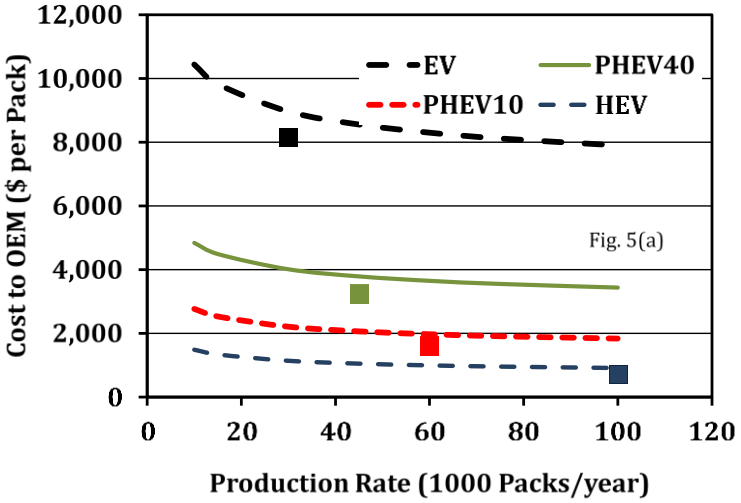
  - Effect of cathode price, $/kg

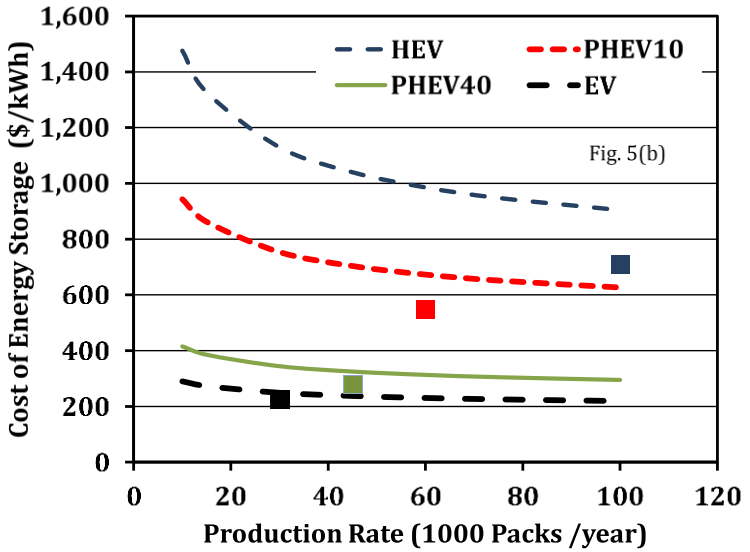
NMC622 Price, $/kg	Cell-Level Prices $/kWh (100K pk/yr)
17.00	106
18.00	109
19.00	113

  - Combined effect of $20/kg and 25K packs per year
    - Cell Price = $134 / kWh

A study reported on the economies of scale derived from a flex plant

- Unit cost per battery pack and cost of energy storage (including the BMS) for LMO batteries manufactured at the indicated rates in plants dedicated to a single battery type producing at 100% capacity (lines) and in a flex plant producing all of the batteries at 100% of the 235,000 packs per year capacity (markers); all positive electrodes measure 100-mm by 300-mm.

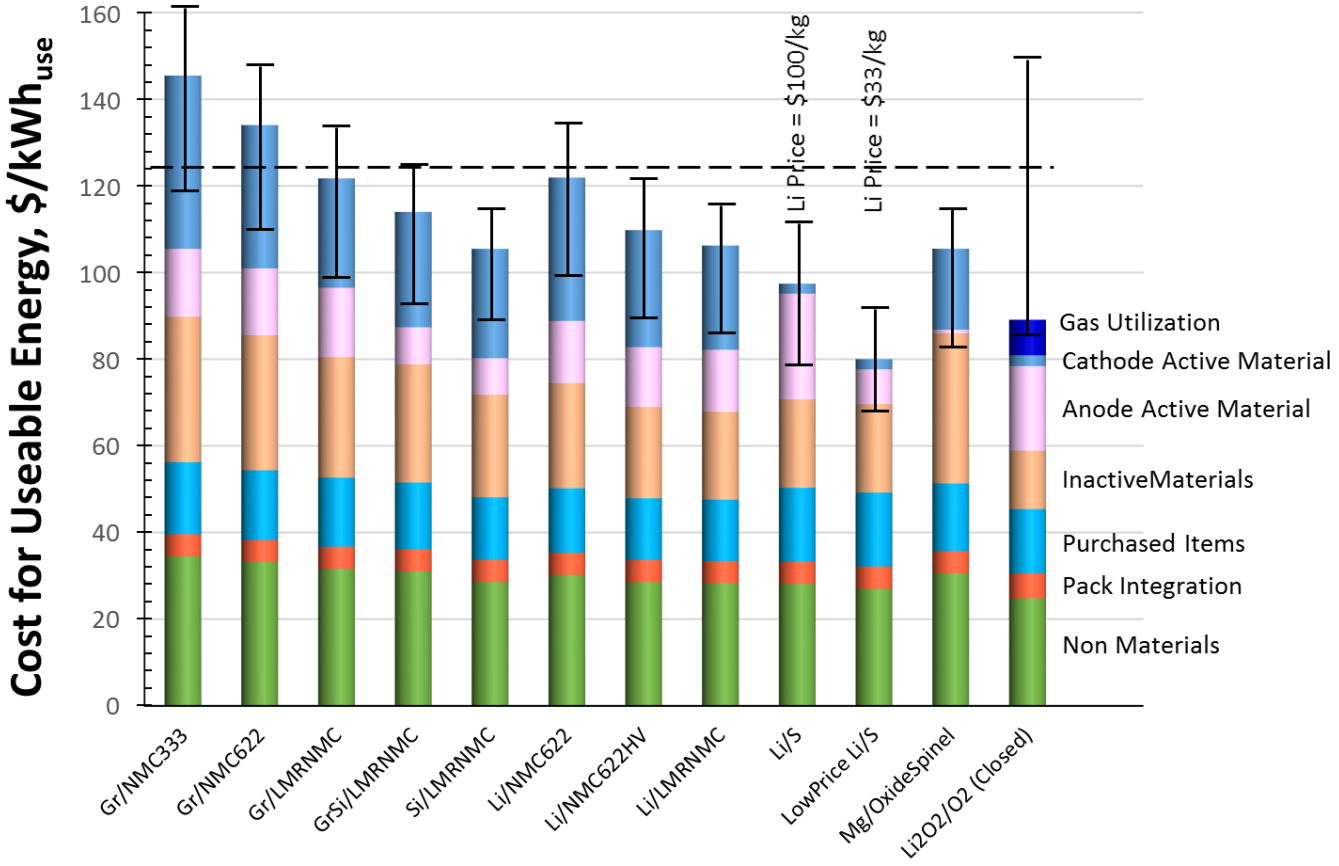




Nelson, P.A., Journal of Power Sources 283 (2015) 506-516

BatPaC was used to project and compare pack costs with different electrode combinations

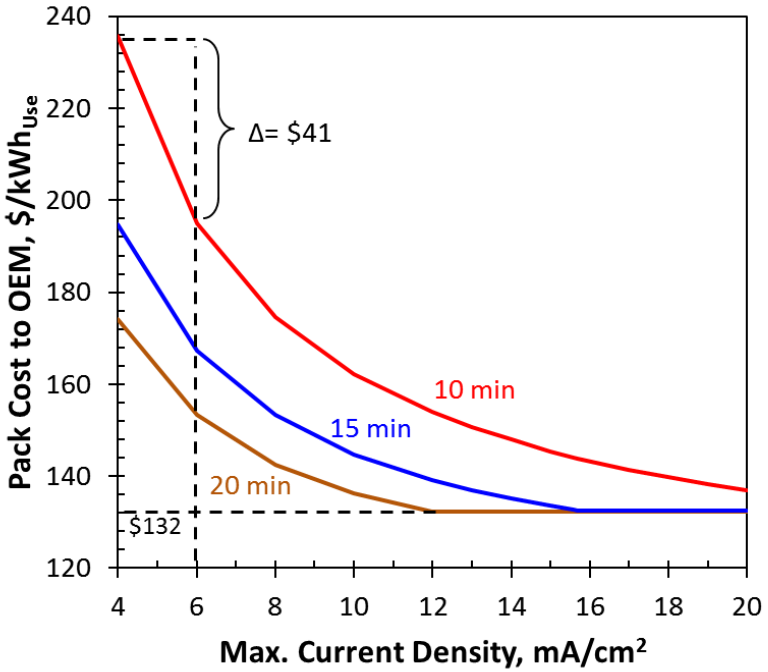
Projected costs for 100kWh$_{Total}$, 85 kWh$_{use}$, 80kW battery packs

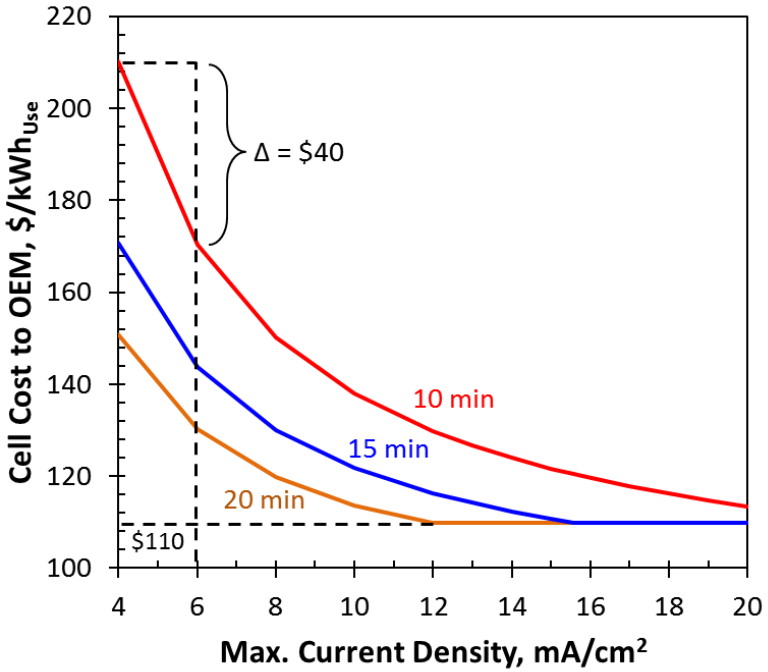


These are best case projections: all chemistry problems solved, performance is not limiting, favorable system engineering assumptions, high volume manufacturing

Fast charge capability increases the cost of batteries

100 kWhTotal, 85 kWhUseable, 300 kW, Gr-NMC622, 168 cells, 315V





For Δ80% SOC (4 mA/cm²)	Cells $/kWh$_{Use}$	Pack $/kWh$_{Use}$
60 min	110	132
20 min	128	151
15 min	145	171
10 min	179	210

Journal of Power Sources 367 (2017) 250-262

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SUMMARY

The cost of the battery pack is affected by many factors

- Upstream supply chain
- Pack production steps
- Downstream
  - Second life
  - Recovery and/or recycle of used cells
  - Waste
- Technology advances

- Price will be balanced between the cost and what the market will bear

This project is funded by the US Department of Energy's Vehicle Technologies Office.

QUESTIONS / COMMENTS ?

BatPaC was used to project performance metrics with different electrode combinations

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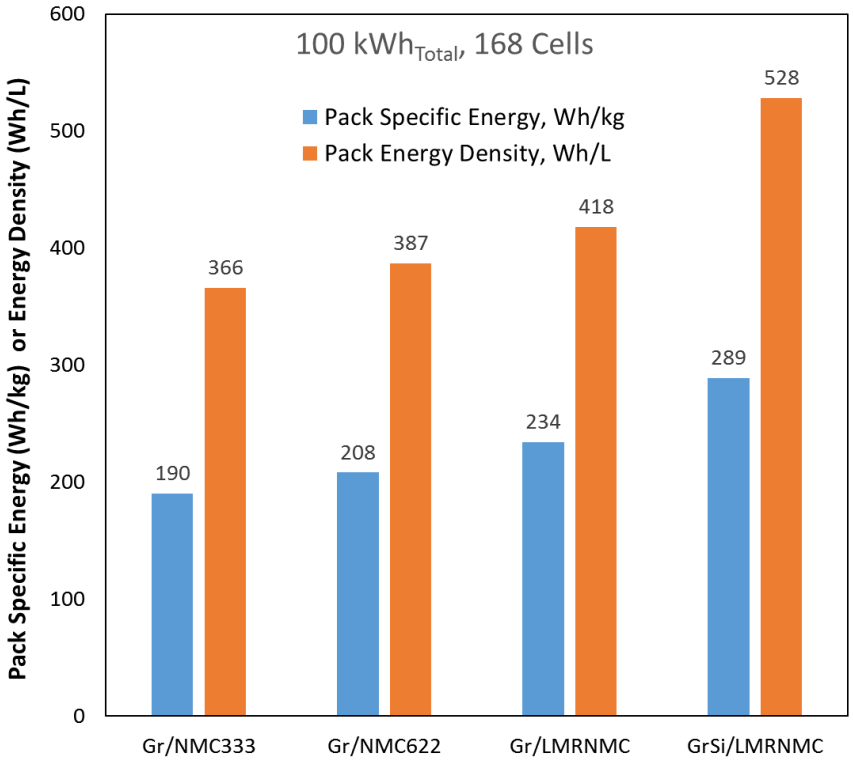

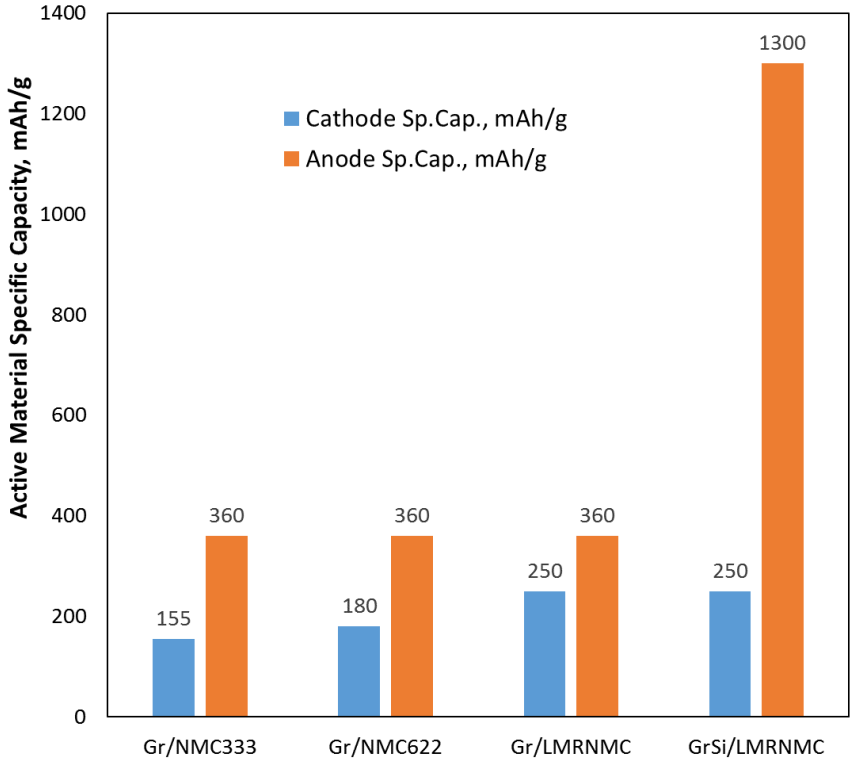

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