PHEV Battery Cost Assessment

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Objective

In 2012, TIAX's efforts focused on updating the PHEV cost model projections to incorporate changes in materials cost and improvements in manufacturing over the last five years.

Updated Materials Cost Process Equipment Cost And Throughput

Selected Battery Chemistries and Cell Designs

Cost Assessments

- Breakdown of battery costs by material component and process steps highlighting significant changes.
- Investigation of sensitivity of battery cost, using the cost model, to variations in major operating and battery design parameters.

We employed a parametric approach in which TIAX's cost model was applied many times with different sets of input parameters.

INPUTS

Constraints/Assumptions

- Pack energy requirements
- Power input/output
- Battery chemistries and material performance
- Electrode designs
- Fade and SOC range
- Sufficiently high production volume

APPLICATION

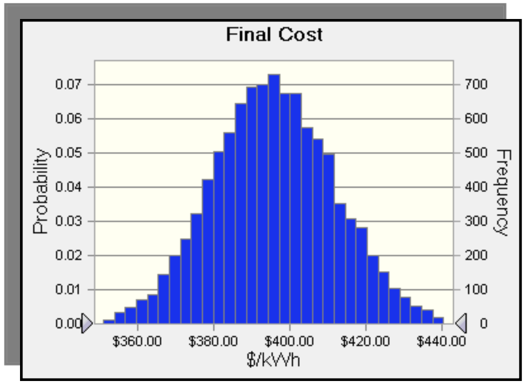
TIAX Cell Design Model

TIAX Cost Model

Outputs

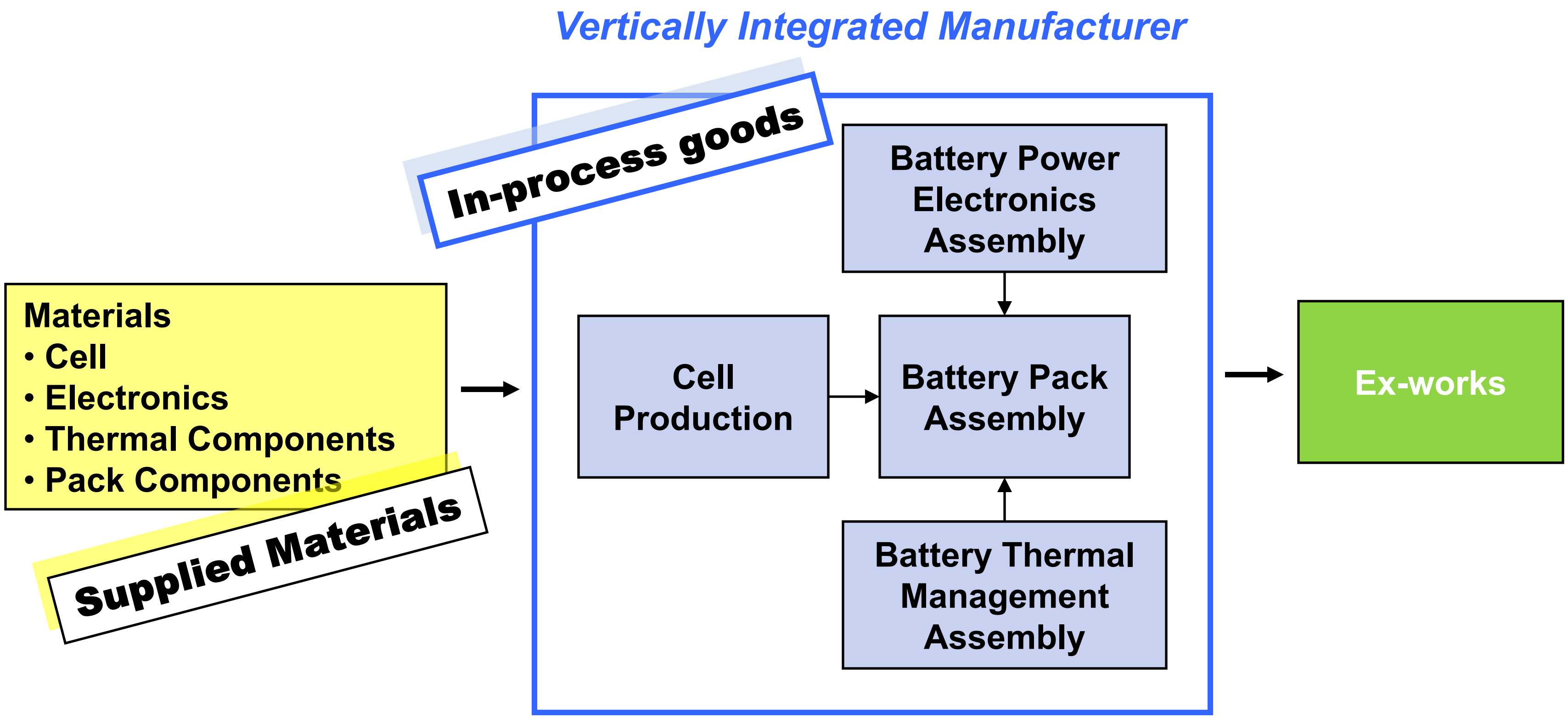
ANALYSIS

- Multi-variable uncertainty



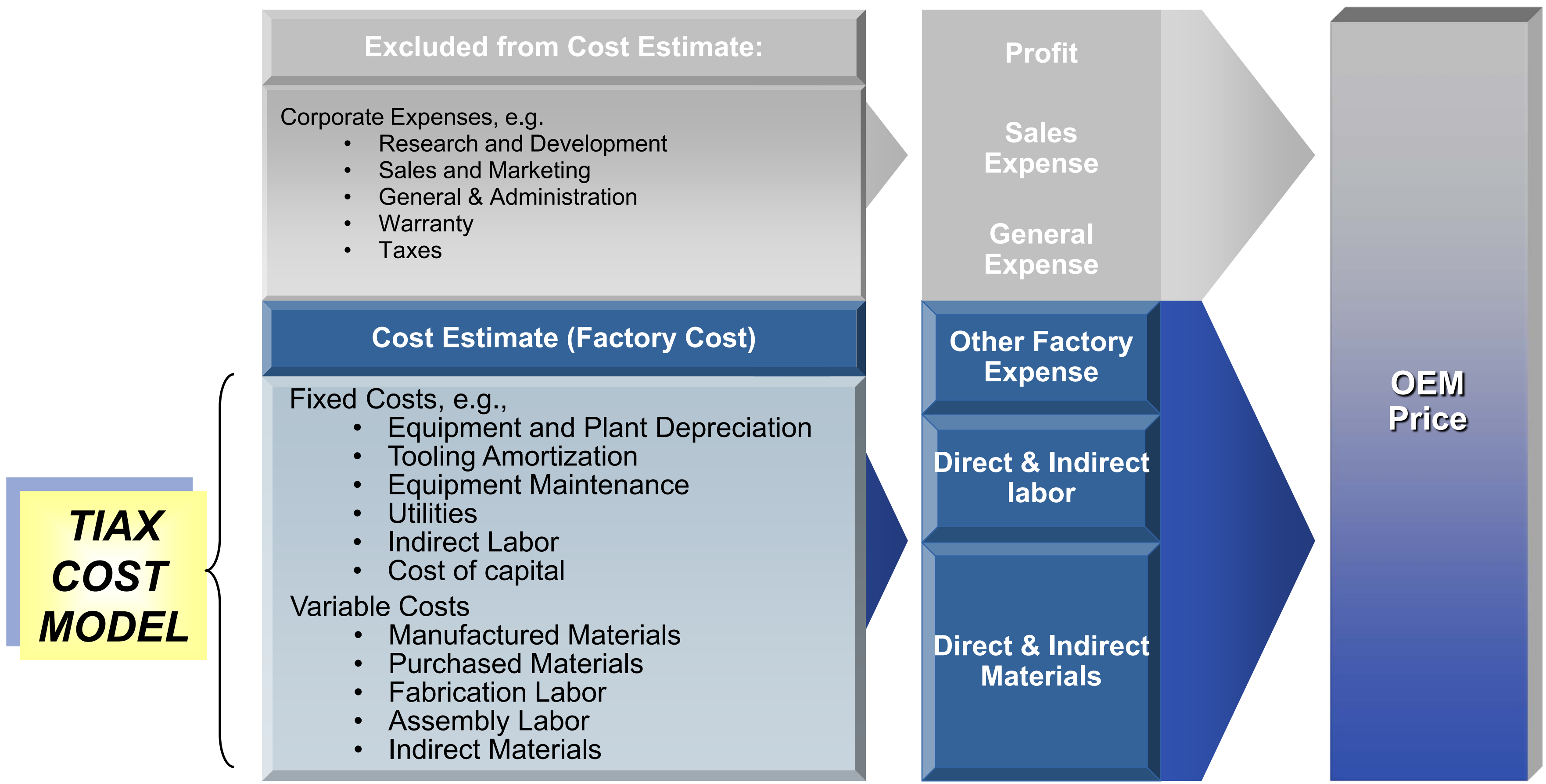
- PHEV battery pack production costs and cost ranges
- Factors with significant influence on battery cost

The cost model assumes a vertically integrated manufacturing process from cell fabrication through completed battery system.



- All supplied materials, e.g., cell materials, packaging components, are treated as outside-purchased and include supplier mark-ups.
- No "supplier" mark-up is included on in-process goods (e.g. cells to be assembled into packs).

The TIAX cost model yields estimates for "COGS" – cost of goods sold (variable plus fixed manufacturing costs).



Undated ranges for key materials inputs, at "high volume", were based on discussions with battery materials producers and battery manufactures.

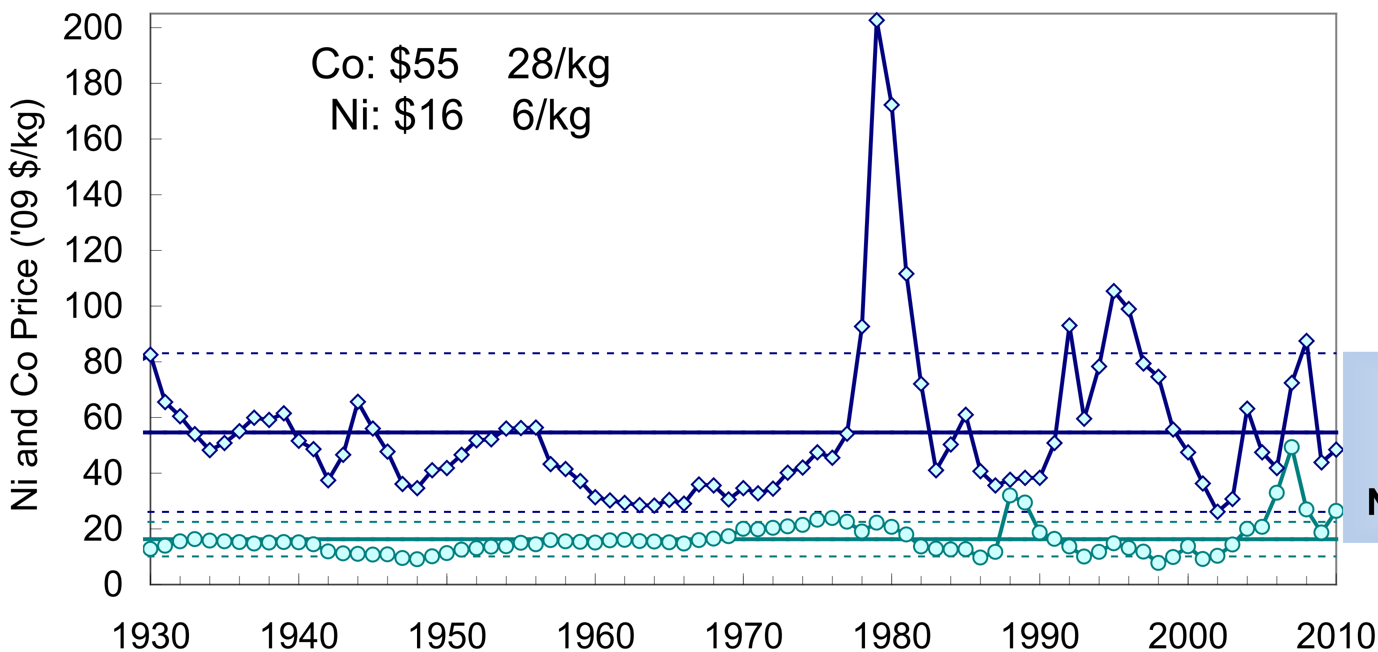
Material	Low Value	Baseline	High Value
Cathode – NCA ($/kg)	36	40	48
Cathode – NCM ($/kg)	33	36	45
Cathode – LFP ($/kg)	15	18	20
Cathode – LMO ($/kg)	12	16	20
Anode - Graphite ($/kg)	15	18	21
Separator ($/m^2)	1.0	1.8	2.2
Electrolyte ($/kg)	17	20	22
Cell components ($/cell)	2.0	2.25	2.50

"Baseline" values were used for *single point* projections of cell costs. Low and high values were used in multi-variable sensitivity analyses to generate *cost probability* curves.

- Cathode materials costs have not changed significantly over the last five years, with an exception of NCM which has been influenced by the recent decline in cobalt prices.
- Separator cost has decreased by ~30% relative to 2007 estimates.

Cobalt, and to a lesser extent nickel, are the most expensive and most volatile constituents of the NCA and NCM cathodes.

Ni and Co price for 1930-2010 (in constant 2009 Dollars)

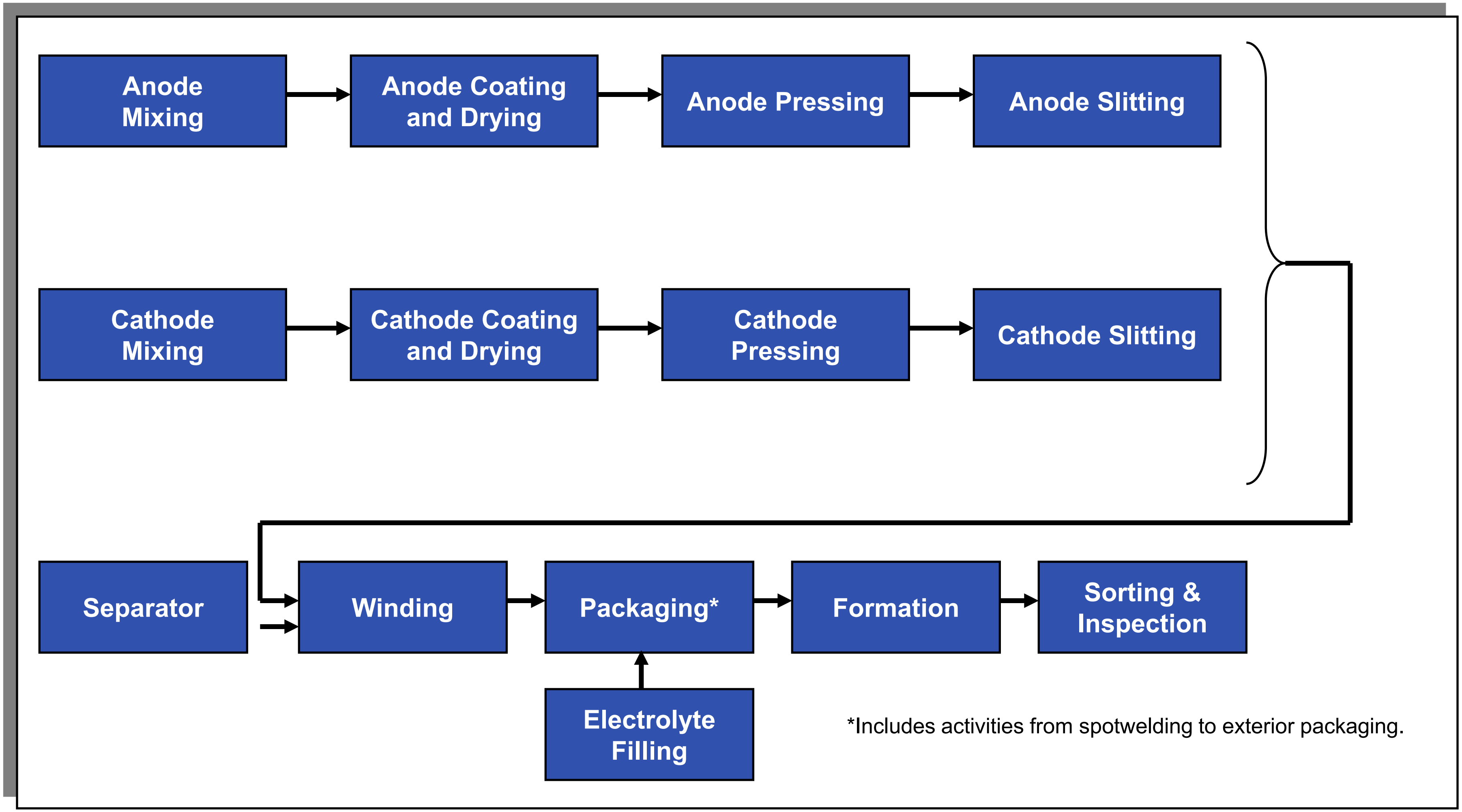


2011-2012:
Co: $26-36/kg
Ni: $16 - $25/kg

Source: USGS, *Historical Statistics for Mineral and Material Commodities in the United States*, 2011.
All data adjusted to 2009 Dollars using Bureau of Labor Statistics' Producer Price Index for *Metals and Metal Products*.

- Cobalt prices have been volatile, ranging from $26 to $202/kg during 1930-2010 period
- Nickel prices have become more volatile in the last decade, ranging from $8 to $49/kg ($15.3, 04/2013)
- In the last year cobalt price has traded near its historical low, ranging from $26 to $36/kg ($25.8, 04/2013)

The cell production line comprises a number of discrete unit operations – *process* steps in fabricating the cell from its component *materials*.



The cell production plant we have modeled is structured to produce 25 million cells (~250 thousand packs) per year.

- Throughput rates for equipment and equipment costs were determined for ***high volume*** manufacturing of PHEV battery cells.
- The number of stations required to meet production demand for each unit operation was determined independently.
  - For example, one mixing station could be used to feed multiple electrode coaters.
  - As a result, equipment utilization was maximized for each unit operation, minimizing production bottlenecks.
  - At this scale, even for cells with the shortest electrodes, 2 anode and 2 cathode coaters are required to meet production demand.

Several major improvements in manufacturing technology occurred between 2007 and 2012, but cost increases were partially offsetting.

Operation	Comments	Throughput	Cost
Slurry Preparation	• No significant changes	-	-
Electrode Coating	• Introduction of slot die and tandem pass double sided coaters • Improvement in web handling leading to increase in width	~10x	~4x
Electrode Pressing	• Significant improvements in throughput	~4x	~3x
Electrode Slitting	• Significant improvements in throughput	~8x	~1.5x
Electrode Winding	• No significant changes	-	-
Cell Assembly	• No significant changes	-	-
Cell Formation, Aging, Inspection	• Implementation of robotic cell handling • Reduction in on-cycler time with RT and high temperature storage to identify faulty cells.	same	~2x

Exchange rates for Japanese and Korean currencies changed significantly between our two forecasts, making Korean equipment more attractive.

2007-2012 Exchange Rate Trends

Materials properties of the four cathodes and the graphite anode were measured at TIAX.

	NCA	NCM	LFP	LMO	Graphite
1st Delithiation to 4.3V vs. Li (mAh/g)	209	189	158	111	-
1st Lithiation to 5mV vs. Li (mAh/g)	-	-	-	-	335
1st Cycle reversibility	92%	88%	95%	95%	91%
Reversible capacity at 1C (mAh/g) (from 4.3V vs. Li for cathodes)	165	152	145	105	305
Average potential vs. Li for 1C discharge (V)	3.8	3.81	3.38	4.02	0.18
Density (g/cc)	4.8	4.6	3.7	4.28	2.2

Lithium Nickel-Colbalt-Aluminum Oxide (NCA)
Lithium Nickel-Colbalt-Manganese Oxide (NCM)
Lithium Iron Phosphate (LFP)
Lithium Manganese Spinel (LMO)

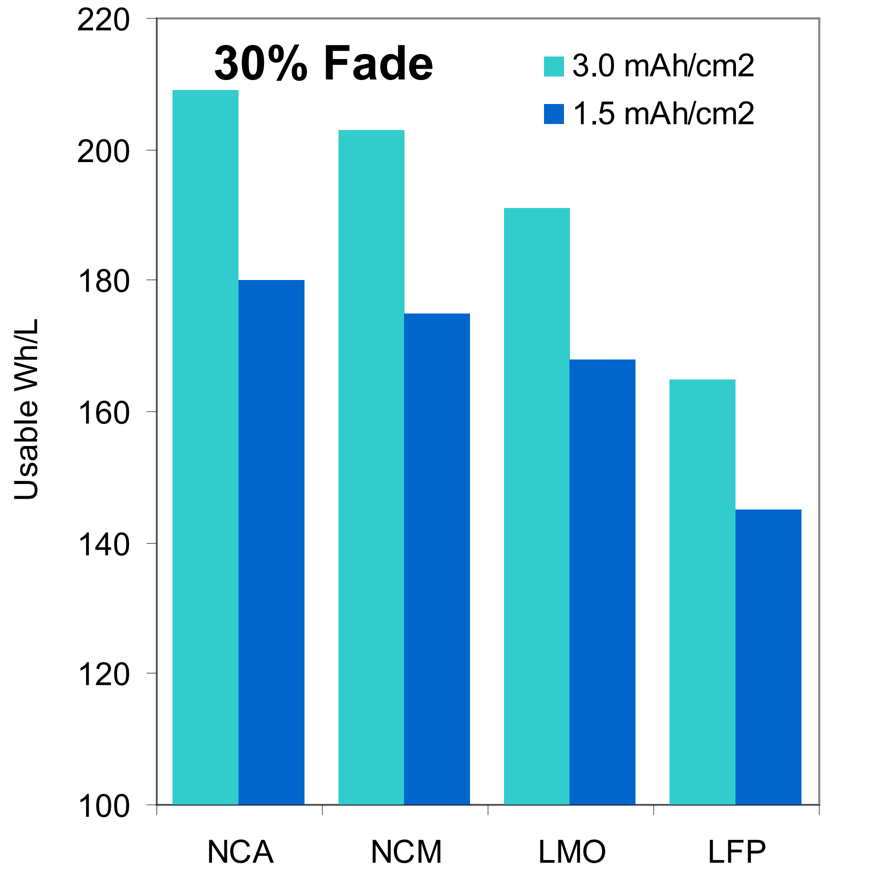
Six different cell design scenarios were considered meeting the 5.5kWh usable energy requirement in a 300V 20-mile PHEV battery pack.

- Costs were modeled for a 300V PHEV battery pack that could provide 5.5kWh of usable energy storage, satisfying AER and BM drive cycle requirements over the 20 mile urban drive cycle.
- Cells were designed for a range of electrode loadings (1.5-3mAh/cm^2) and fade characteristics (0 and 30%).

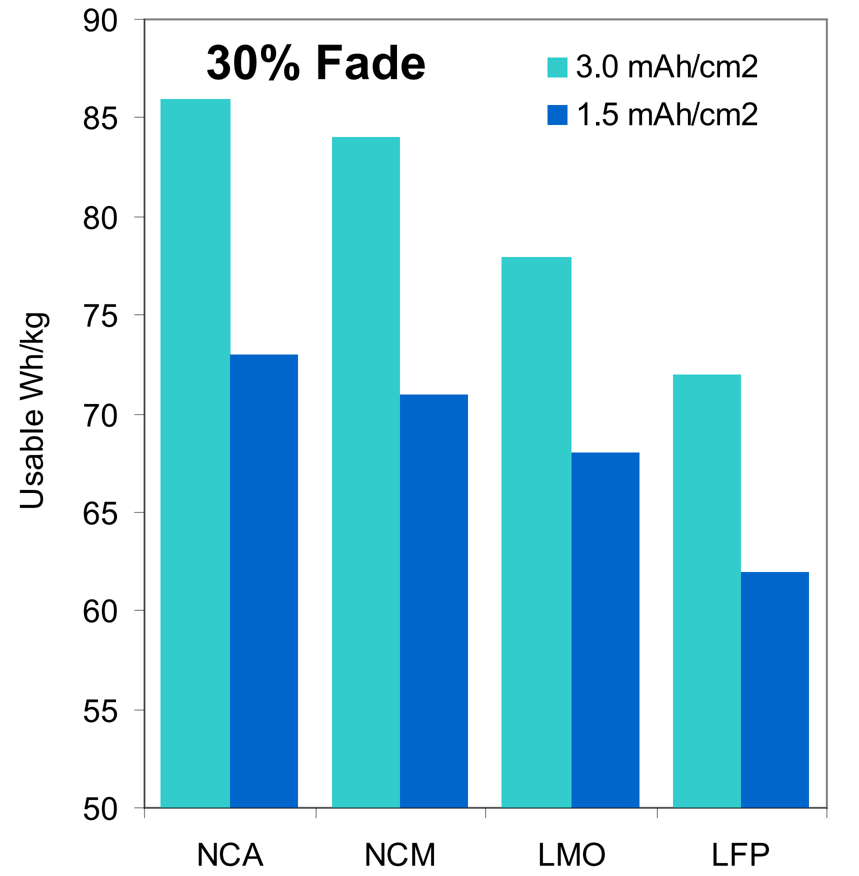
Design Scenario	Cathode Loading (mAh/cm^2)	SOC Range	Fade %	Total Energy (kWh)
A	1.50	80%	0	6.88
B	2.25	80%	0	6.88
C	3.00	80%	0	6.88
D	1.50	80%	30	9.82
E	2.25	80%	30	9.82
F	3.00	80%	30	9.82

While we focused primarily on cost, cell level energy density and specific energy vary significantly across the cell designs considered.

Usable Energy Density (Wh/L)

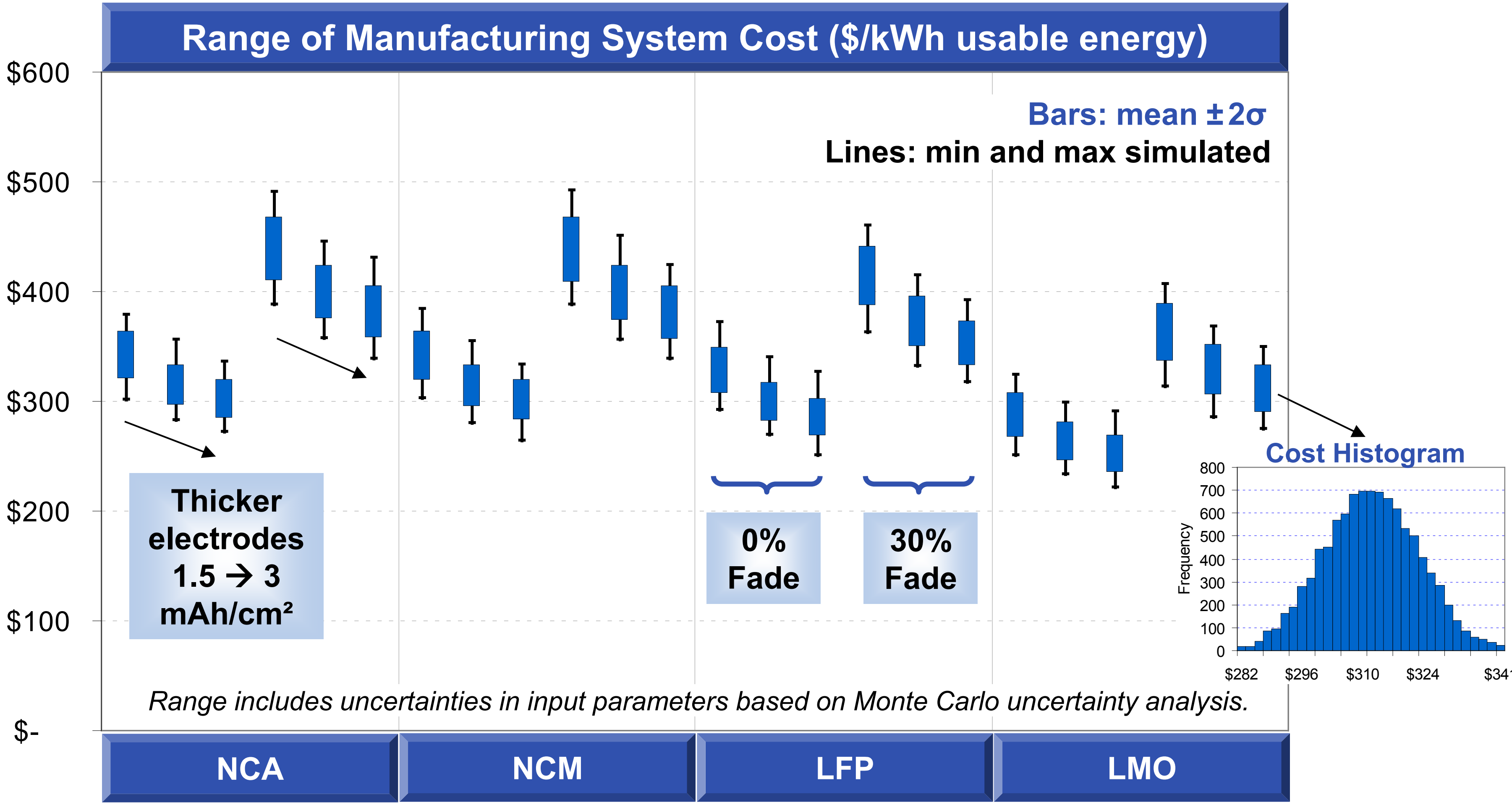


Usable Specific Energy (Wh/kg)

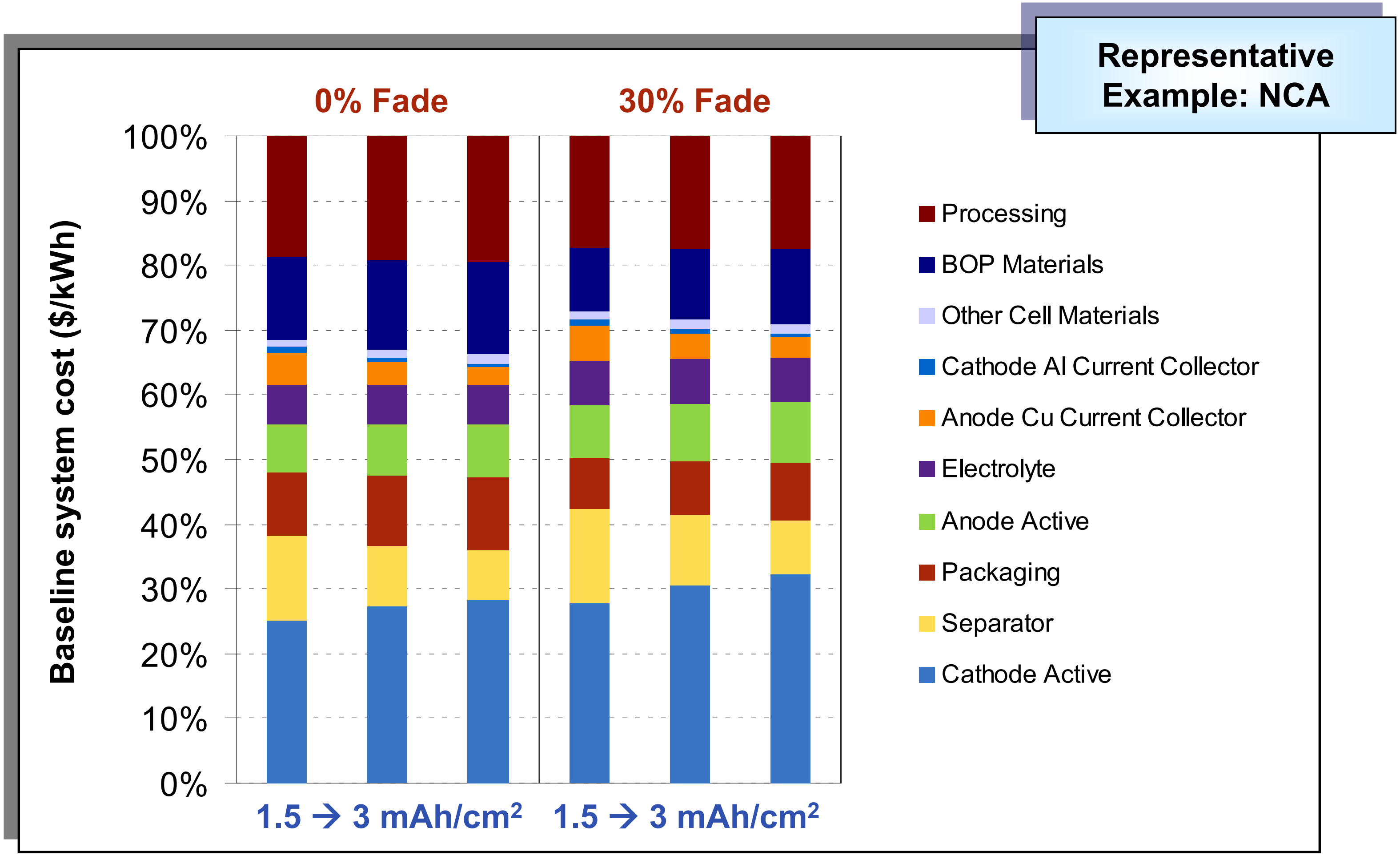


Battery pack designs based on 300V nominal voltage and 5.5kWh available (9.82kWh total) energy.

Given uncertainties in the input cost variables, the battery manufacturing costs are more likely to fall between $220 to $470/kWh usable energy depending on cell chemistry, design, and life.



When batteries are produced "at scale", materials costs are likely to account for ~80% of the final manufacturing costs.

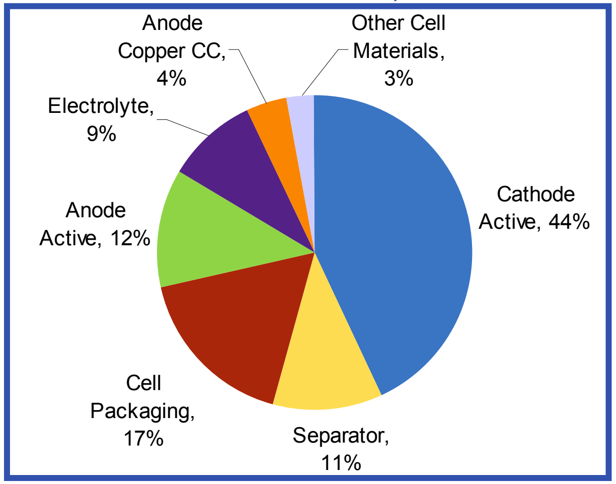


Cathode active material, separator, cell packaging, anode active, and electrolyte account for majority of cell level costs.

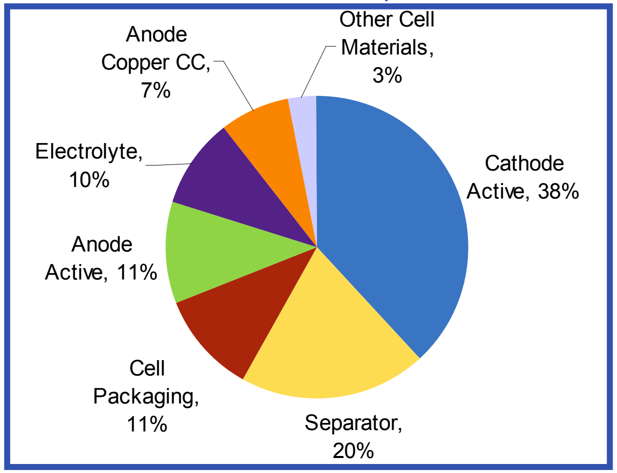
Cell level materials cost ranges among all chemistries and cell designs.

Cell Level Materials Cost	Range
Cathode Active	23 – 45%
Separator	11 – 23%
Cell Packaging	11 – 21%
Anode Active	10 – 14%
Electrolyte	9 – 14%
Anode Copper CC	4 – 9%
Other Cell Materials	3 – 6%

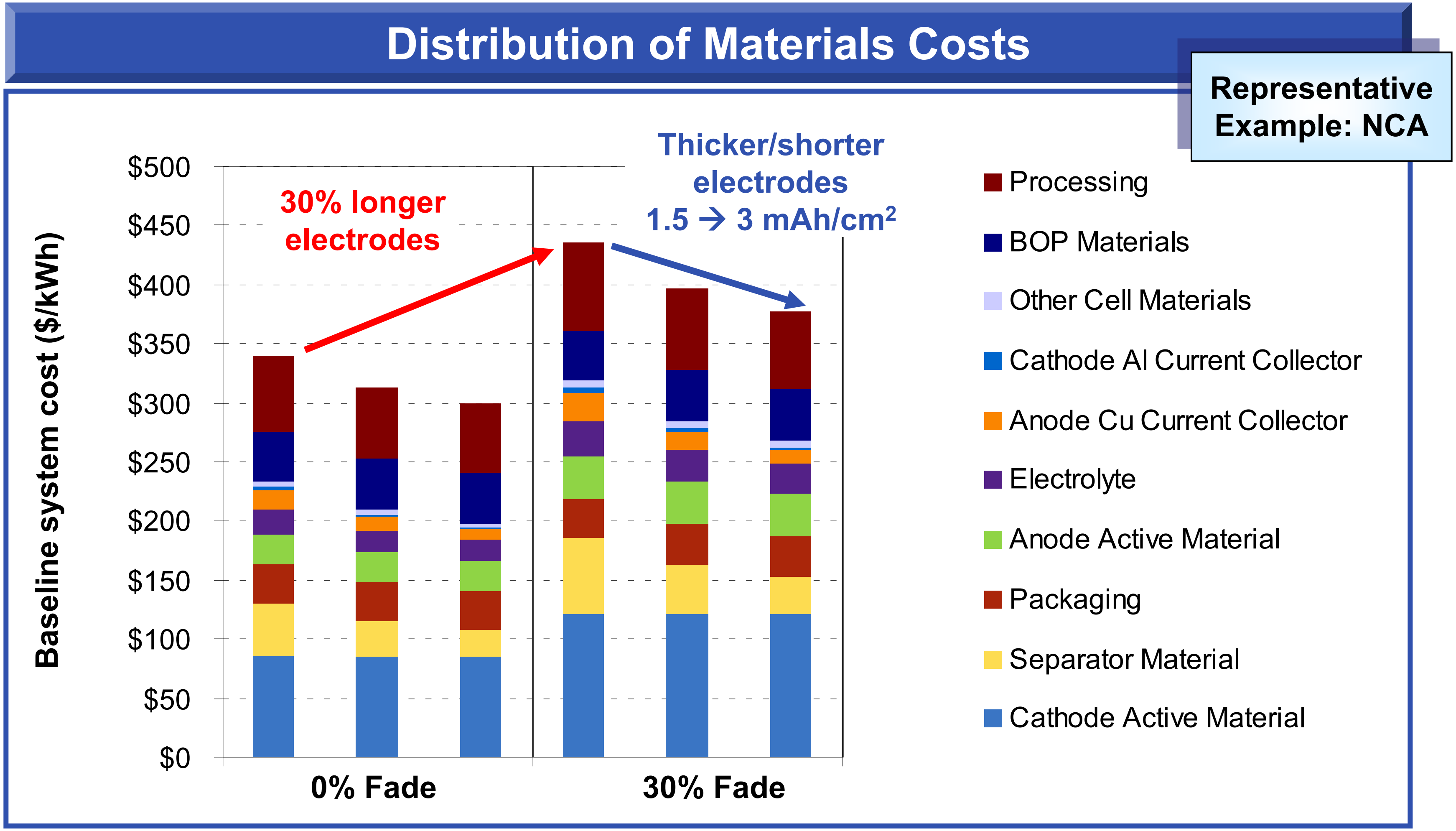
NCA – 3.0 mAh/cm², 0% Fade



NCA – 1.5 mAh/cm², 30% Fade



Ability to use thicker shorter electrodes leads to a lower contribution of inactive materials to the final system cost.



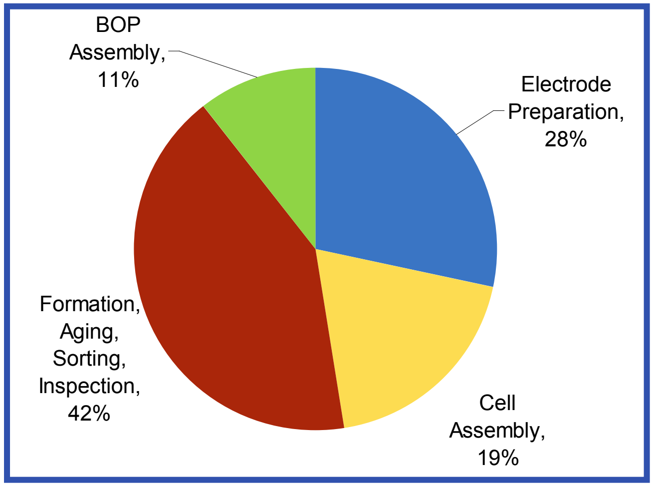
Processing costs are evenly distributed between electrode preparation, cell assembly, and cell formation, aging, and sorting.

Fraction of Process Costs

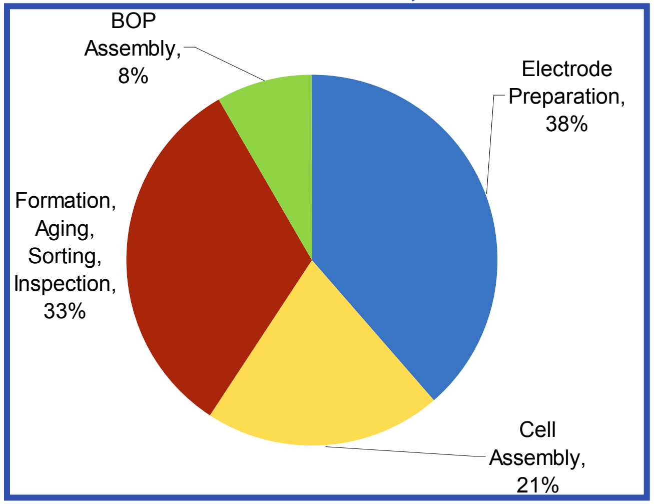
Process	Range
Electrode Preparation	27 – 40%
Cell Assembly	18 – 21%
Formation/Aging/Sorting	32 – 43%
BOP Assembly	8 – 11%

Ranges among all chemistries and cell designs.

NCA – 3.0 mAh/cm², 0% Fade



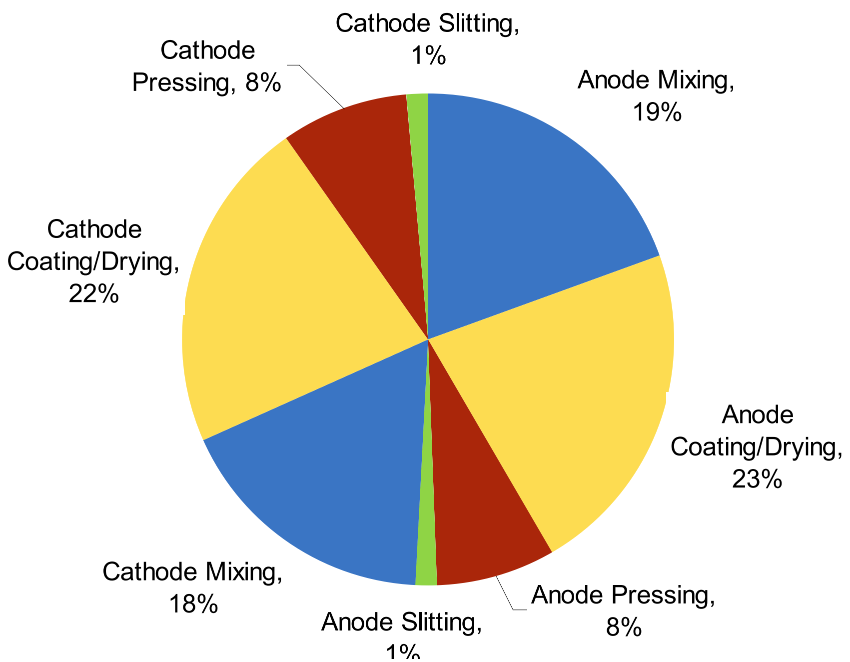
NCA – 1.5 mAh/cm², 30% Fade



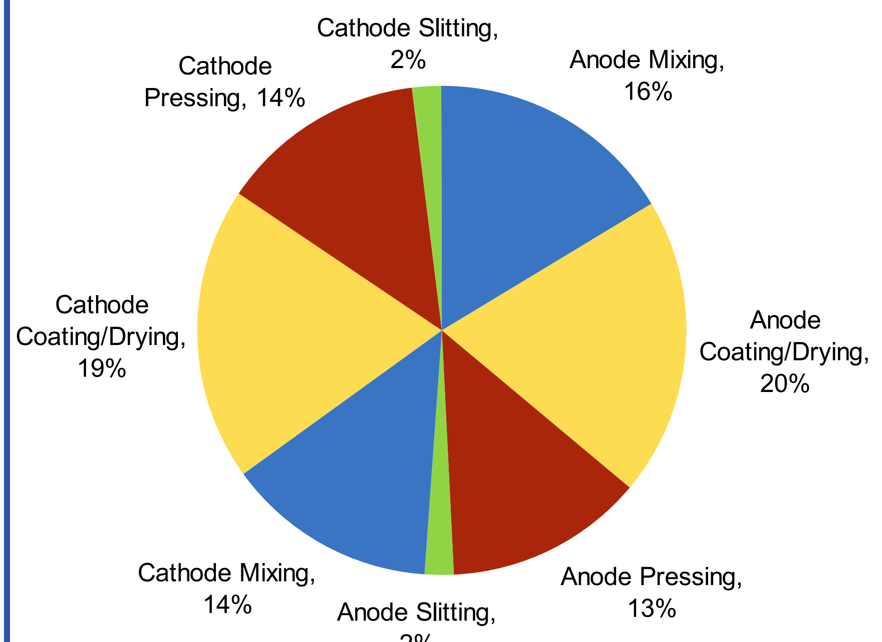
Electrode preparation costs are evenly distributed between slurry mixing, coating and drying, and electrode pressing.

Distribution of Electrode Preparation Costs

NCA – 3.0 mAh/cm², 0% Fade
Thick, short electrodes



NCA – 1.5 mAh/cm², 30% Fade
Thin, long electrodes

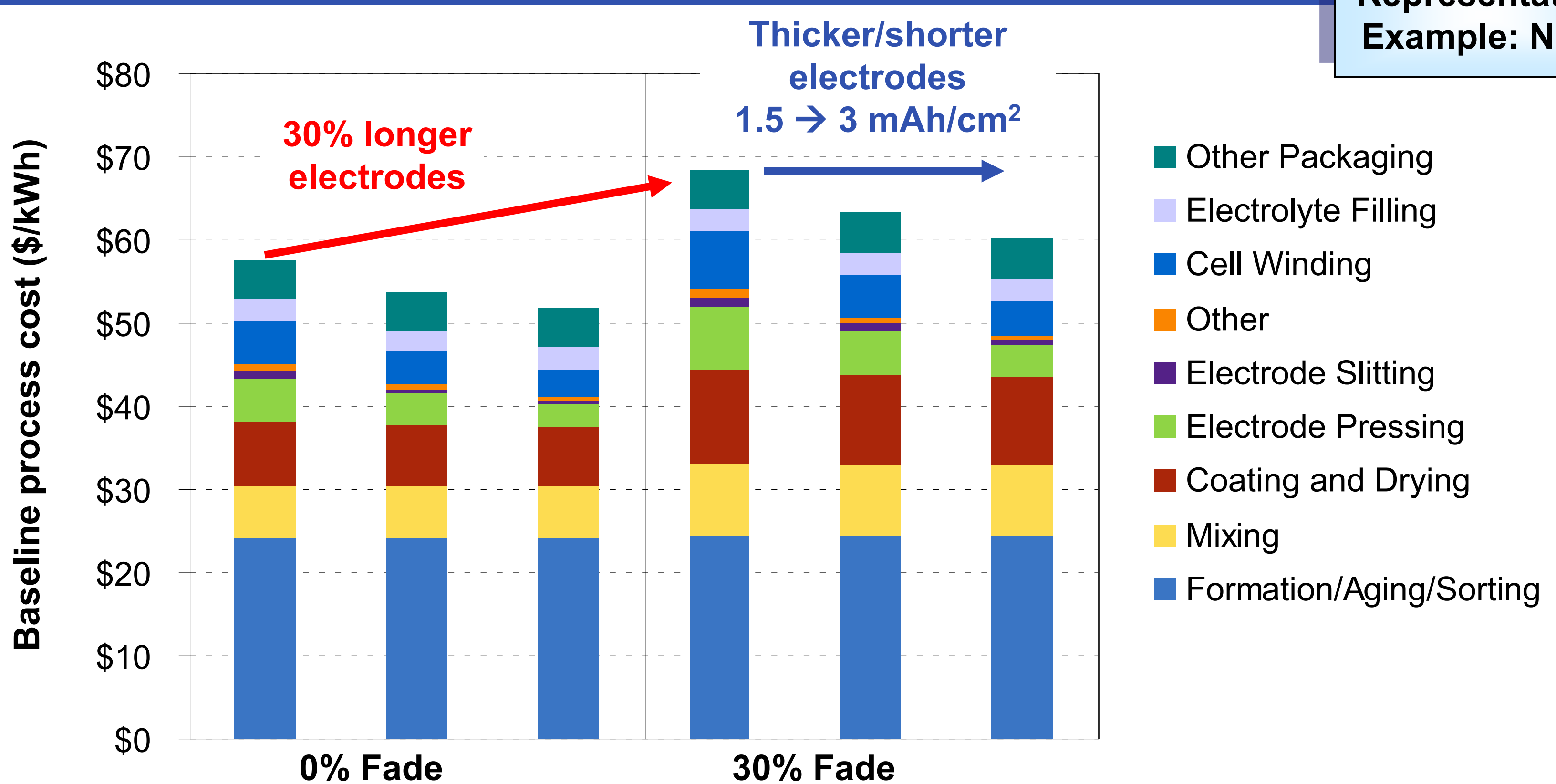


Representative Example: NCA

Ability to use thicker shorter electrodes leads to further reductions in electrode fabrication costs.

Distribution of Processing Costs

Representative Example: NCA



*Process costs: equipment and plant depreciation, tooling amortization, equipment maintenance, utilities, indirect labor, cost of capital, fabrication and assembly labor

Significant improvements in the processing technology and some reduction in materials costs have led to a 17-29% decrease in battery manufacturing cost projections.

Range of costs among all chemistries and cell designs.

2012 vs. 2007	% Cost for 2012/2007
Active Materials	82% - 98%
Inactive Materials	84% - 87%
Total Processing	40% - 56%
• Labor	23% - 35%
• Cost of Operating Capital	59% - 77%
• Capital Expenditures	57% - 80%
Total	**71% - 83%**

Conclusions and Recommendations

- At mass production scale, the PHEV **battery manufacturing costs** are likely to fall between **$220 to $470/kWh** usable energy depending on cell chemistry, design, and life.
- **Materials** costs account for **~80%** of manufacturing costs, with cathode active material, separator and cell packaging accounting for majority of cell level costs.
- **Processing** costs accounts for **~20%** of manufacturing costs, and are evenly distributed between electrode preparation, cell assembly, and cell formation.
- While cost vary among different chemistries, there is a greater variation based on cell designs:
  - Over sizing the batteries to achieve end-of-life energy and power targets leads to significant increase in cost
  - Higher power designs utilizing thinner electrodes are also higher cost.

- Cathode materials costs have not changed significantly over the last five years, with the exception of NCM which has been influenced by the recent decline in cobalt prices, as well as higher production volumes associated with its use in commodity portable product applications.
- Separator cost has decreased by ~30% relative to 2007 estimates.
- Processing speeds have improved significantly in the last five years especially in electrode fabrication operations.
- Significant improvements in processing technology and some reduction in materials costs have led to a **17-30% decrease** in battery manufacturing cost projections **since 2007.**

The cost assessment results point to a three-pronged approach emphasizing specific areas of research with potential for reductions in battery cost…

Materials

- Development of lower cost cathodes on $/Wh basis.
- Active materials with higher specific capacity and/or higher average cell voltage that allow for higher energy density at the cell level.
- Active materials that provide minimal fade, impedance growth and calendar aging and support high power over a wider SOC range.
- Development of lower cost separators.

Cell/Electrode

- New chemistry, electrolytes, and electrode designs permitting shorter, thicker electrodes capable of delivering the same power.
- In general, chemistries and designs that enable lower overall electrode area per battery and minimize battery size will reduce cost.

Manufacturing

- Identification and adoption of advanced technologies allowing for significant reduction of formation and aging time.
- Improvement in electrode processing technology and reduction in equipment cost.