



PHEV BATTERY COST ASSESSMENT

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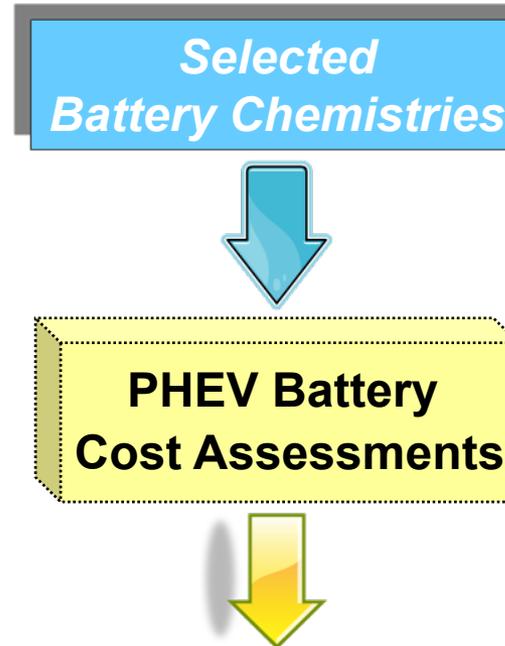
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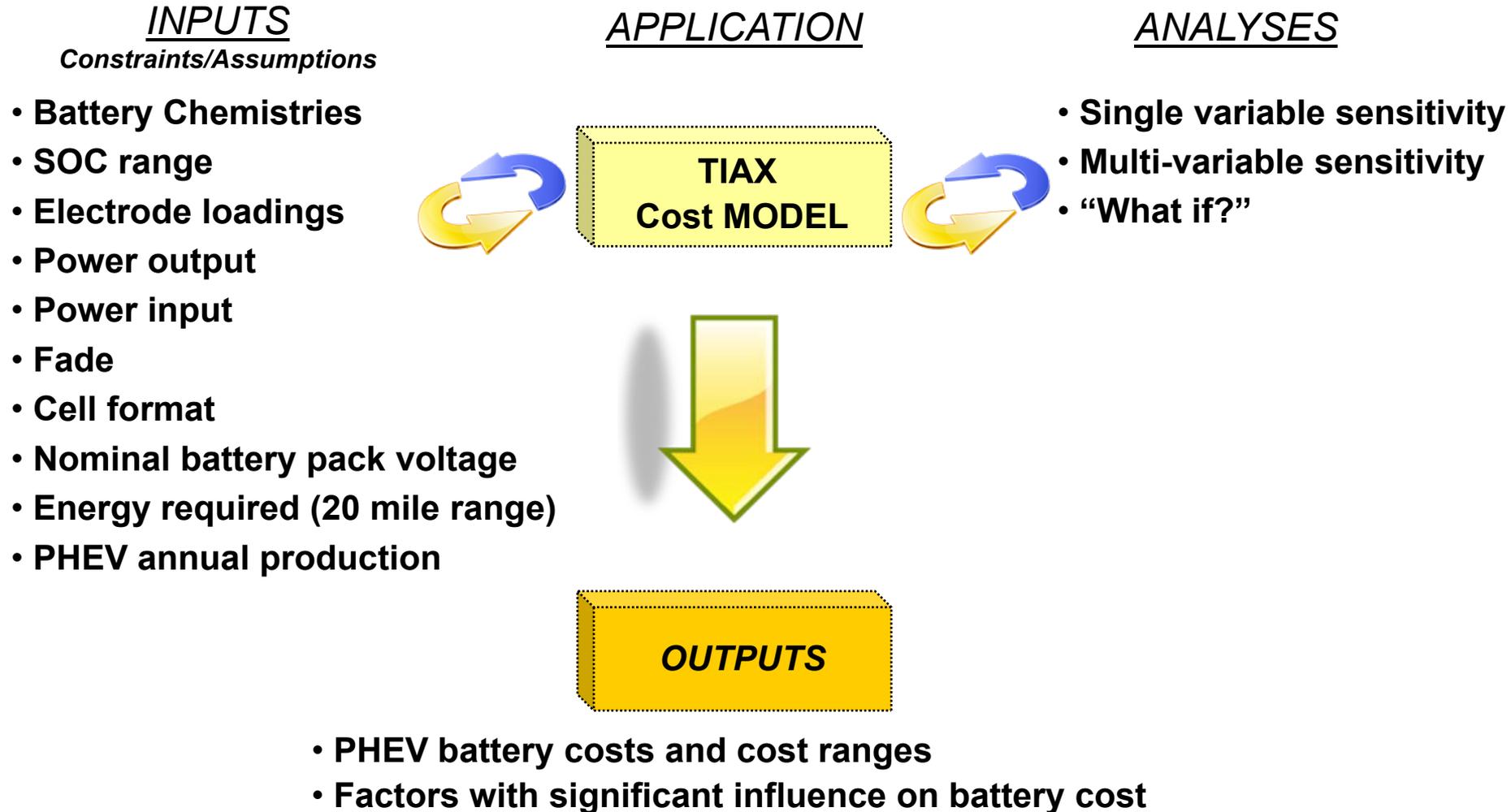
TIAX's objective was to assess cost implications "at a high level" of selected battery chemistries being considered for PHEV applications.



Results:

- ***Insight into the relative benefits of alternative chemistries***
- ***Identification of factors with significant impact on cell pack costs***
- ***Identification of areas where more research could lead to significant reductions in battery cost***

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



The input variables defining the “base case” scenarios were agreed with DOE and included (1) cathode material, (2) electrode loading, and (3) percent fade.

For a 5.5 kWh-usable Li-ion battery pack for PHEV, assessed the implications to the battery cost of using the following cost modeling factors and conditions:

Cathode Material	Anode Material	Electrode Loading	Percent Fade
NCA	Graphite	Low (1.5 mAh/cm ²)	0%
NCM		High (3 mAh/cm ²)	30%
LiFePO ₄			
LiMn ₂ O ₄			

$$4 \times 1 \times 2 \times 2 = 16$$

- The requested cost modeling factors produced 16 different scenarios to be considered.
 - Each scenario based on a state-of-charge (SOC) range of 80% (agreed with DOE)
 - Other cost factors varied as part of a sensitivity analysis of each scenario
 - Costs to be estimated at a production volume corresponding to 500,000 vehicles/yr
- Note that it is not clear whether target power and fade levels can be met at these loadings and over the modeled SOC range for all chemistries.

Since Li-ion batteries of the design and size considered in this study have not been manufactured and tested, several key assumptions were made (and agreed with DOE) about the battery performance.

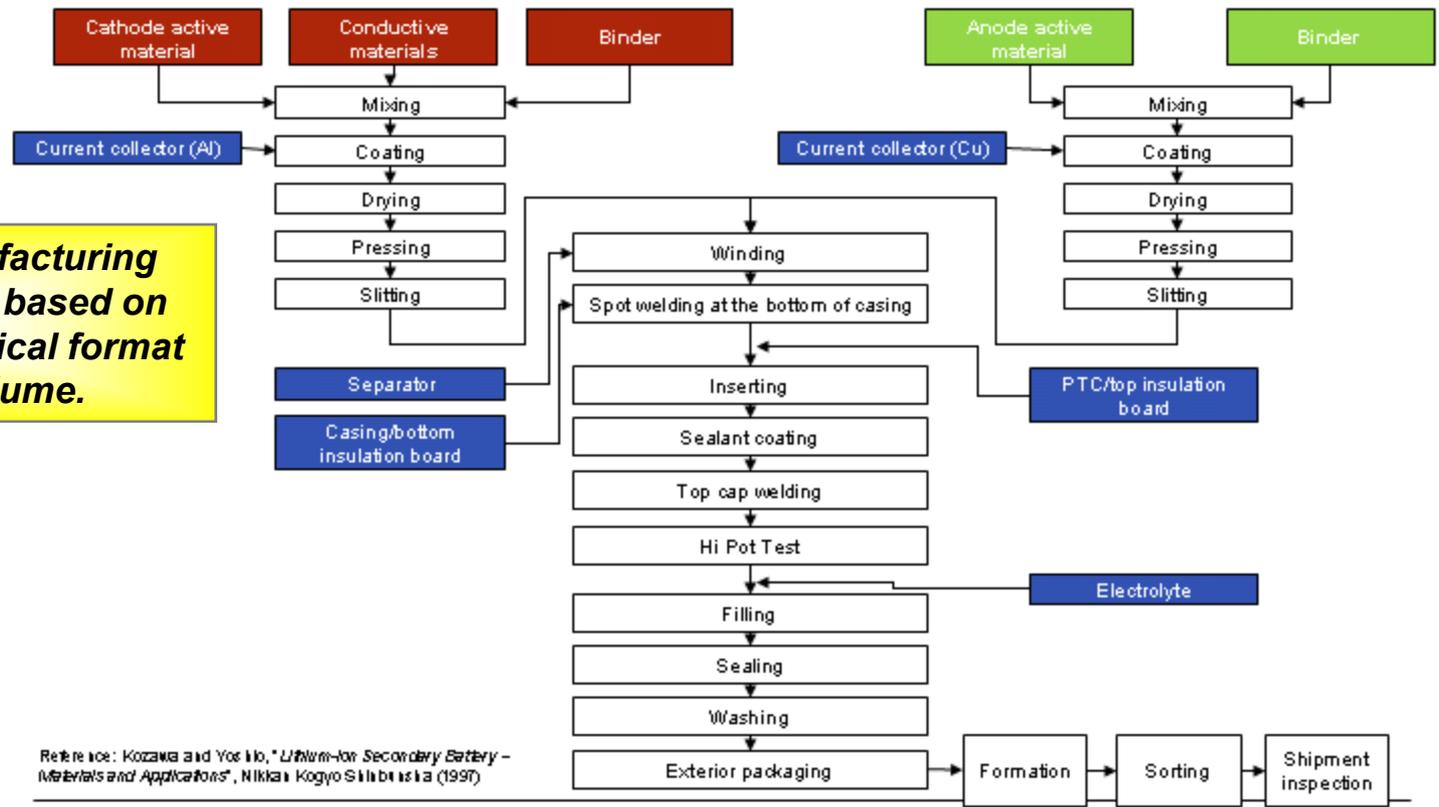
- **Power Output:** Peak power (40 kW for 2 sec., or 20 kW for 100 sec.) is available from the battery even at low battery state of charge (SOC). Low temperature performance was not considered.
- **Power Input:** The battery can be recharged at the peak rate (30 kW) except when the battery is at a high SOC.
- **Battery Life:** The battery is assumed to be able to achieve the life defined in each of the selected scenarios.
 - **5.5 kWh usable:** Each design scenario to yield 5.5 kWh of usable energy (for 1C discharge) at end of life after accounting for assumed SOC limitation and fade
 - **Nominal Li-ion cell energy:** Energy for full discharge at 1C following charging
 - **Fade:**
 - 0% scenarios provide 5.5kWh of usable energy at end of life with 0% fade.
 - 30% scenarios provide 5.5 kWh of usable energy at end of life with 30% fade (i.e., the battery size is 9.8 kWh nominal to deliver 5.5 kWh of usable energy at end of life).
 - **SOC range:**
 - 10-90 % (i.e., battery size is 6.9 kWh nominal to deliver 5.5 kWh usable).
- **Format:** cylindrical cell

For cell production, the TIAX cost model yields estimates for the cost of goods sold (COGS), i.e., *manufacturing cost*, including capital costs.

TIAX Cost Model Assumptions

Cell production begins with receipt of battery materials and concludes with fully assembled and tested cells.

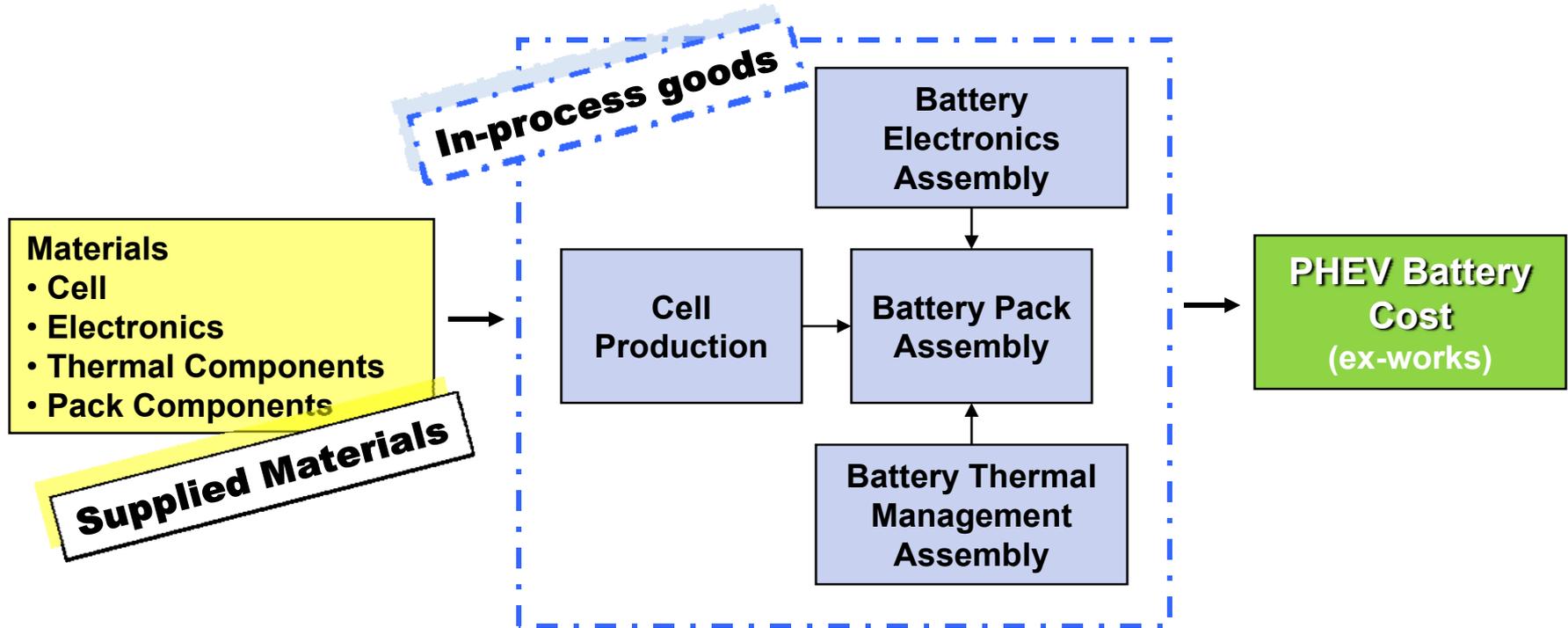
Materials and manufacturing cost estimates were based on production of cylindrical format cells in high volume.



Reference: Kozawa and Yoshio, "Lithium-Ion Secondary Battery - Materials and Applications", Nikkan Kogyo Shinbunsha (1997)

For PHEV battery production, the cost model assumes a vertically integrated manufacturing process from *cell fabrication through completed battery system*.

Vertically Integrated Manufacture



- 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 PHEV battery manufacturing cost analysis assumed use of “current” materials and “current” processing technology in high volume production.

		Materials Technology	
		“Current”	Future
Processing Technology	“Current”	“Current” Materials “Current” Processing Technologies (500k vehicles/year)	Improved Materials Existing Manufacturing Technology
	Future	“Current” Materials Improved Manufacturing Technology	Improved Materials and Manufacturing Technology

Note:

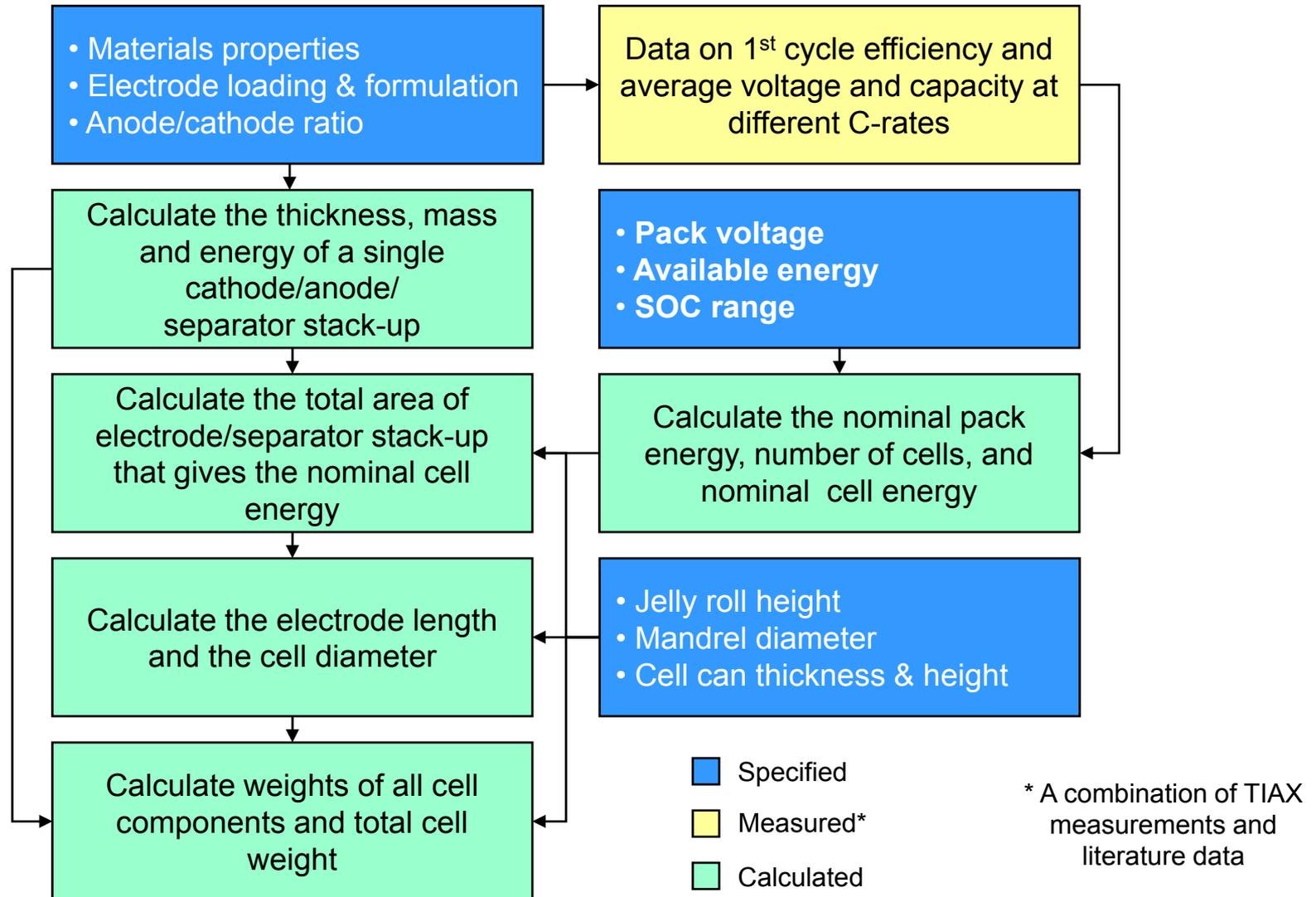
Since these batteries have yet to be developed, the ability of the current battery technologies to meet all performance requirements is untested.

Various materials evaluated were assumed to meet performance requirements within the modeled systems.

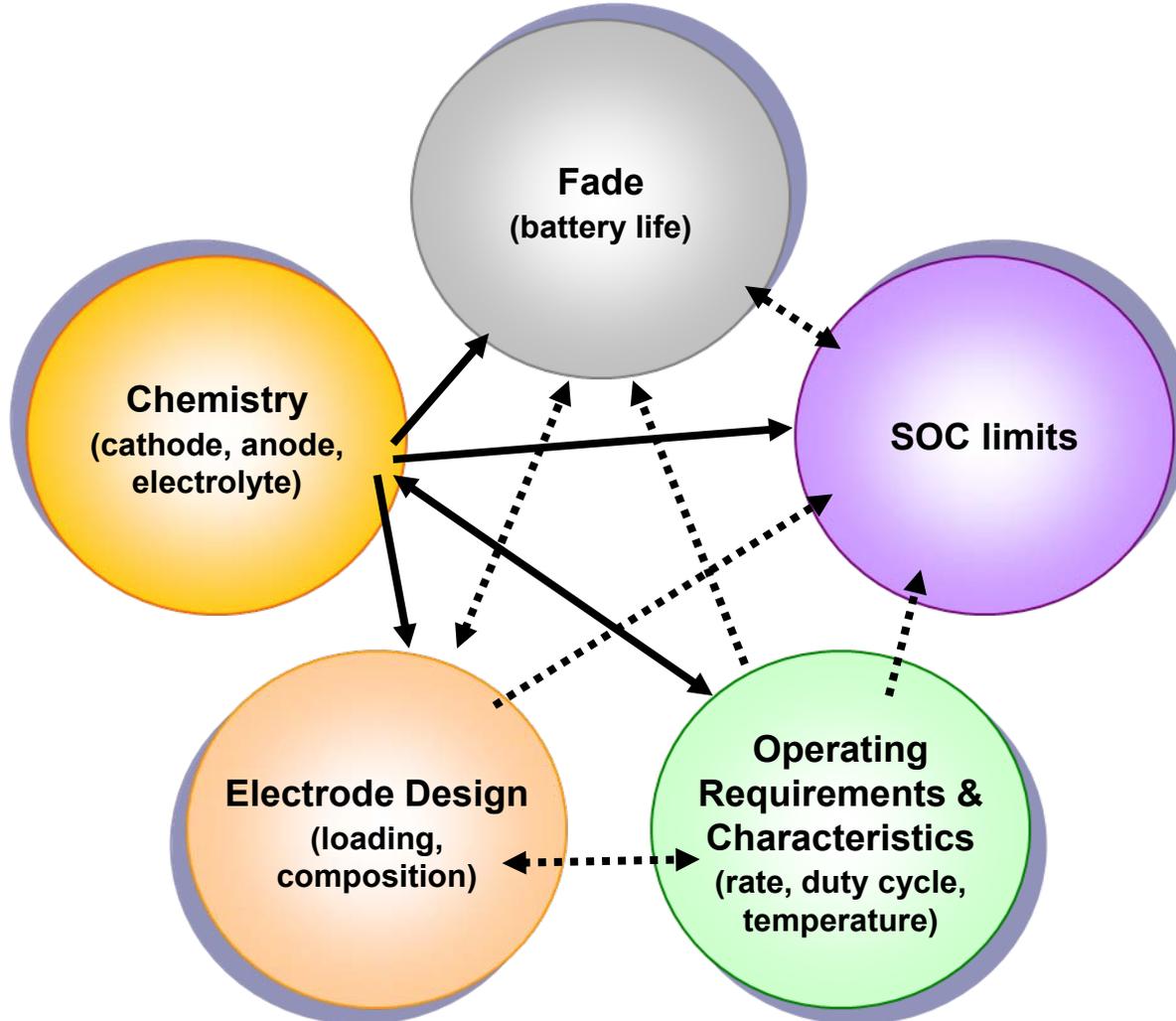
“Current” materials implies currently available materials used in commercial rechargeable battery applications, none of which have yet been used in commercial scale production of PHEV batteries.

“Current” processing technologies implies those adapted from high volume cylindrical cell (18650) production, sold into portable power applications.

Cell designs are built up from specific electrode properties.



Optimized cell designs will inevitably be determined by complex *inter-relationships* between operational requirements/characteristics and design parameters, factors that cannot be integrated into this study at this time.



Key model inputs were identified and a likely range of values established for each.

“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.

Cost Factor	Low Value	Baseline	High Value
Material Cost Inputs (units)			
Cathode – NCA (\$/kg)	34.0	40.0	53.9
Cathode – NCM (\$/kg)	40.0	45.0	52.6
Cathode – LiFePO ₄ (\$/kg)	15.0	20.0	25.0
Cathode – LiMn ₂ O ₄ (\$/kg)	12.0	16.0	20.0
Anode (\$/kg)	17.0	20.0	23.0
Separator (\$/m ²)	1.0	2.5	2.9
Electrolyte (\$/kg)	18.5	21.5	24.5
Cell components (\$/cell)	2.1	2.5	2.9
Process Parameters (units)			
Process Yield (%)	98.0	100.0	100.0
Wage Rate (\$/hr)	21.0	25.0	29.0

Analyses of the sensitivity of battery cost to input parameters were performed in order to determine factors with significant impact on battery cost.

- Single variable sensitivity analyses were carried out using Crystal Ball® risk analysis software/ tornado chart tool*.
- *Single variable* sensitivity analysis manipulates *one input variable* at a time, measuring the impact on the output and displays the results on a “tornado chart”
- A tornado chart ranks input parameters in terms of their impact on the output.
 - Input parameters can be assumptions and/or decision variables
 - Chart provides a convenient way to determine the relative sensitivity of the results to an entire set of input parameters.

* Crystal Ball® is a trademark of Decisioneering, Inc., www.decisioneering.com

Multi-variable analysis allowed us to answer the question “what is the effect on battery cost of a combination of variations (from baseline) in key input parameters?”

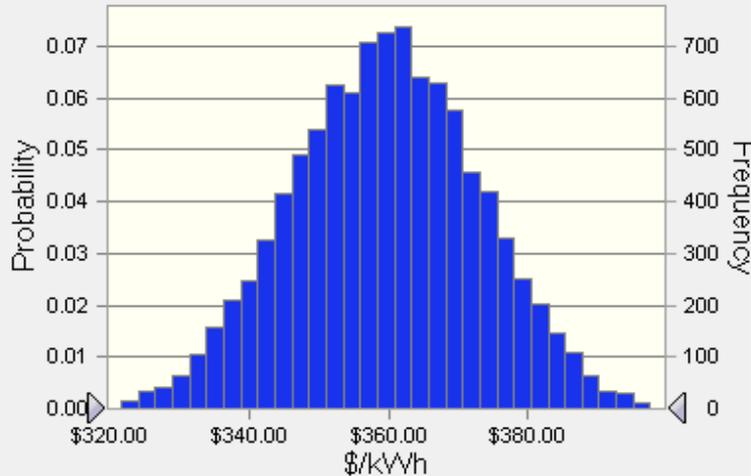
- Multi-variable analysis: all input parameters varied statistically over the identified range for each
- Result of multi-variable analysis: a *plot of battery cost vs. probability (distribution of battery costs)*

Multi-variable Sensitivity Analysis

Example:

LiFePO₄ / 3.0 Loading / 0% Fade (short electrode, zero fade)

Battery Cost



Statistic	Forecast Values \$/kWh
Mean	359.56
Median	359.64
Standard Deviation	13.53
Minimum	313.43
Maximum	414.00
TIAX Baseline*	361.80

* The forecast value using only TIAX “base case” input parameters. This forecast value is a “single point” projection of battery cost.

To help understand if and how battery cost might be driven closer to \$250/kWh, we developed four additional “what if” scenarios to test the impact of extreme values of related input parameters.

“WHAT IF” Scenarios (applied individually to Base Scenarios)

- 1 Increase coater speed by a factor of 10 from 5 m/min to 50 m/min
- 2 Double all manufacturing process speeds
- 3 All cathode and anode active materials cost \$5/kg
- 4 “Made in China”

Assumption Variables	Baseline Cases	Made in China Cases
Labor Rate (\$/hr)	25	0.67*
Equipment Discount Factor (%)	100%	67%**
NCA Cost (\$/kg)	\$40.00	\$28.04
NCM Cost (\$/kg)	\$45.00	\$37.96

* Bureau of Labor Statistics, Department of Labor, " International Comparisons of Hourly Compensation Costs in Manufacturing 2006"; published in 2008

** The Boston Consulting Group white paper, " Made in China: Why Industrial Goods Are Going Next"

Cost of cathode active material is a somewhat less important factor in battery system cost than might have been thought.

- *Upfront cell design is a critical factor in battery cost.*
 - Electrode loading (i.e., electrode length) seems to be more significant than cathode active material cost, within the ranges evaluated
 - *Active materials' influence on cell design has greater impact on battery cost than does the (cathode) active materials' cost itself.*
- *Manufacturing processing speed matters*

PHEV battery configurations modeled in this study resulted in battery costs (COGS) ranging from \$264/kWh to \$710/kWh, or \$1452 to \$3905 for 5.5 kWh usable power.*

* These cost ranges were the output from the statistical, *multi-variable sensitivity analysis*.

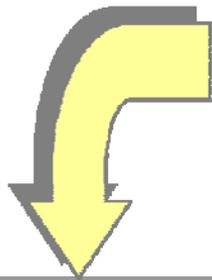
There is significant overlap in battery costs among the four cathode classes, with wider variation within each chemistry than between chemistries.

Material Cost Inputs to TIA X Battery Cost Model for Baseline Cost Outputs and for Sensitivity Analyses (Single & Multivariable)

Cost Factor	Low Value	Baseline	High Value
Material Cost Inputs (units)			
Cathode – NCA (\$/kg)	34.0	40.0	53.9
Cathode – NCM (\$/kg)	40.0	45.0	52.6
Cathode – LiFePO ₄ (\$/kg)	15.0	20.0	25.0
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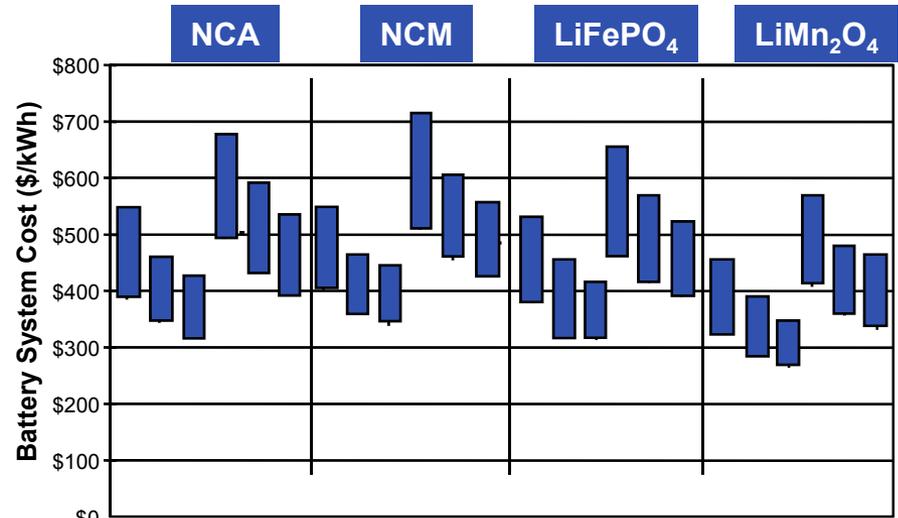
24 scenarios modeled *

* TIA X added a third, intermediate electrode loading to reflect the loading most likely to represent the PHEV battery modeled here, resulting in a total of 24 different scenarios to be analyzed and costed.



Plots of the resulting ranges of battery costs, grouped by cathode active material, show significant cost range overlap between the cathode classes, with battery costs “bottoming” just below \$300/kWh, and show wider variation within each chemistry than between chemistries.

Range of modeled costs as identified in the (multi-variable) sensitivity analyses; each bar represents one scenario.



Modeled Li-ion PHEV Battery Cost (\$/kWh at 5.5 kWh, usable)

The projected costs for PHEV batteries in this study conform with what might be expected from consideration of 18650-based Li-ion battery costs.

- 18650 cells are a standardized Li-ion design currently produced in volumes approaching 1 billion cells/year worldwide, using the most highly automated processes currently available in the industry.
 - This production volume corresponds to about 10GWh/year, or enough volume in terms of materials and electrode area to yield about 1 million PHEVs/year.
- Current Li-ion OEM 18650 *cell costs* are in the \$200-\$250/kWh range, of which about 60% are the materials costs as supplied to battery manufacturers, i.e., powders, metal foils, separators, etc.
- 18650 cells are primarily used in *battery packs* for laptops, for which OEM costs range from \$400/kWh to more than \$700/kWh.

Within the PHEV battery scenarios modeled and evaluated, cathode active material cost by itself is not a major factor in driving system cost changes.

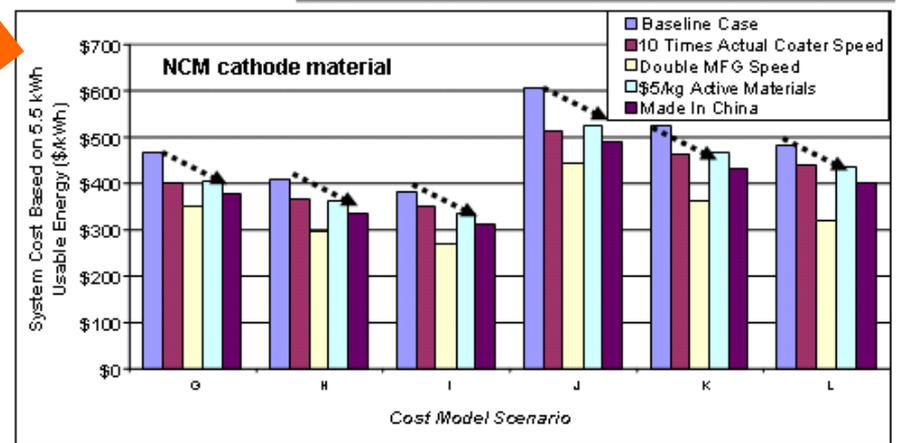
- As expected qualitatively, higher fade leads to higher battery cost; lower cathode capacity loading (i.e., longer electrode length) leads to higher battery cost.
- Our cost model shows quantitatively the influence of fade and electrode length on battery system cost and, by implication, the cost reduction potential of new electrode designs that permit shorter, thicker electrodes.
- The results of an extreme “what if” analysis to test the impact of reducing the cost of active materials by as much as 90% reveals the impact on battery cost to be comparatively modest.

Illustrative Example: NCM, most expensive of the four cathode materials

“WHAT IF” Scenario: All cathode and anode active materials @ \$5/kg

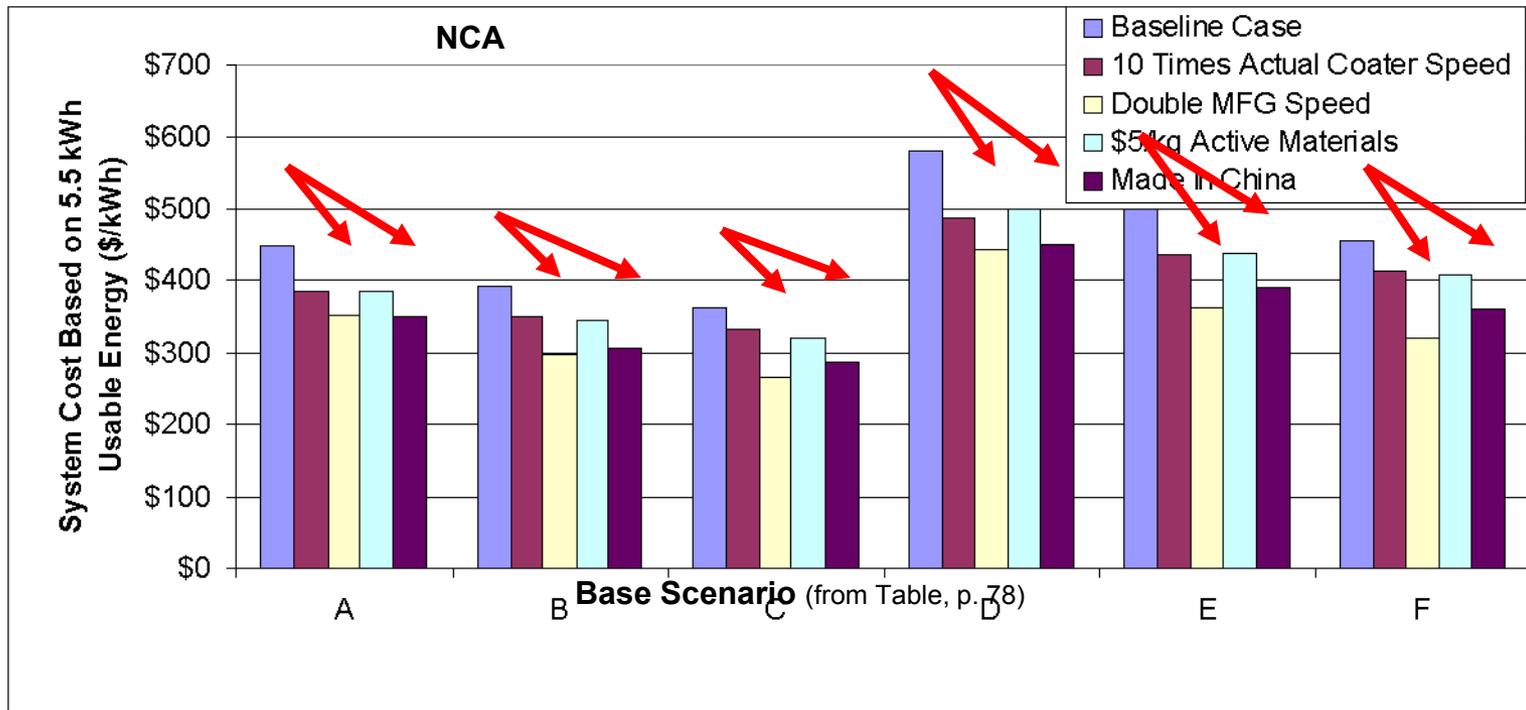
Results:

- Battery cost still above \$300/kWh;
- Cost reductions of 90% in active materials yield battery cost reductions less than 15%



The “made in China” and “doubling speed of all manufacturing processes” scenarios resulted in greater battery cost reductions than “10x coater speed” or “\$5/kg active materials” in the NCA-based scenarios.

Representative Example:

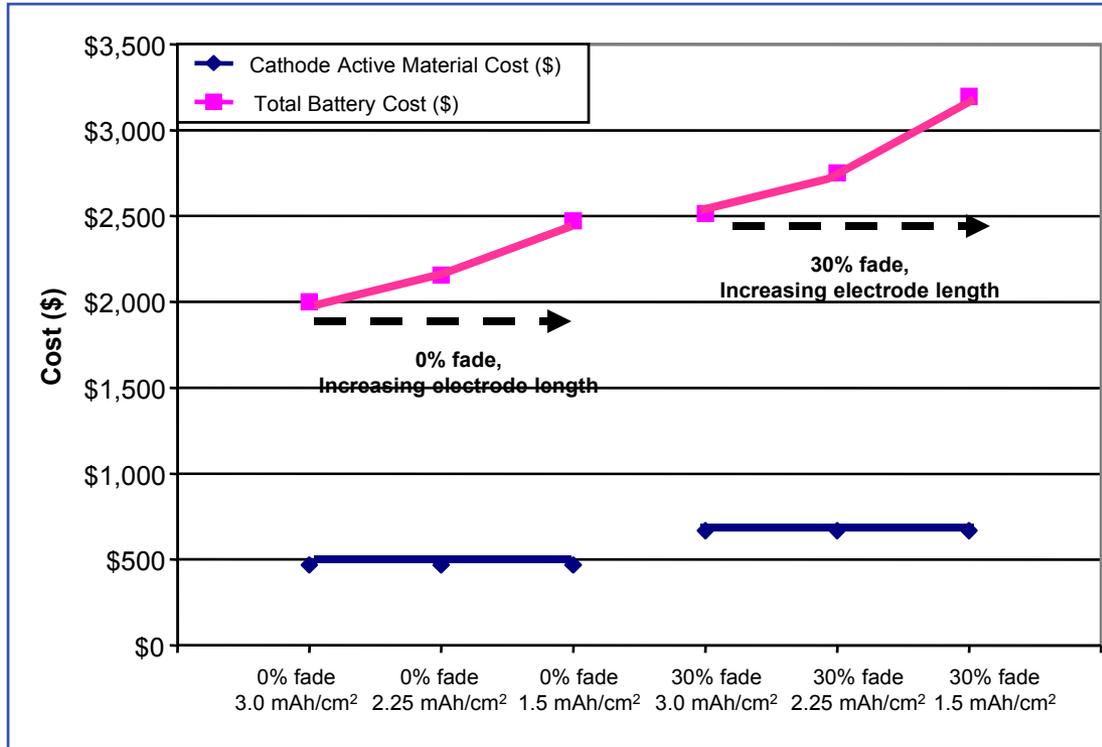


For each of these “what if” scenarios, battery cost is (still) above \$250/kWh.

Generally, battery system cost is a function of fade level and of electrode length, i.e., battery cost increases with increasing % fade and/or increasing electrode length.

Example:

NCA



Battery Cost

Cathode Active Material Cost

Battery cost ranges from a low of about \$2000 to a high of about \$3200 (about \$364/kWh to about \$581/kWh).

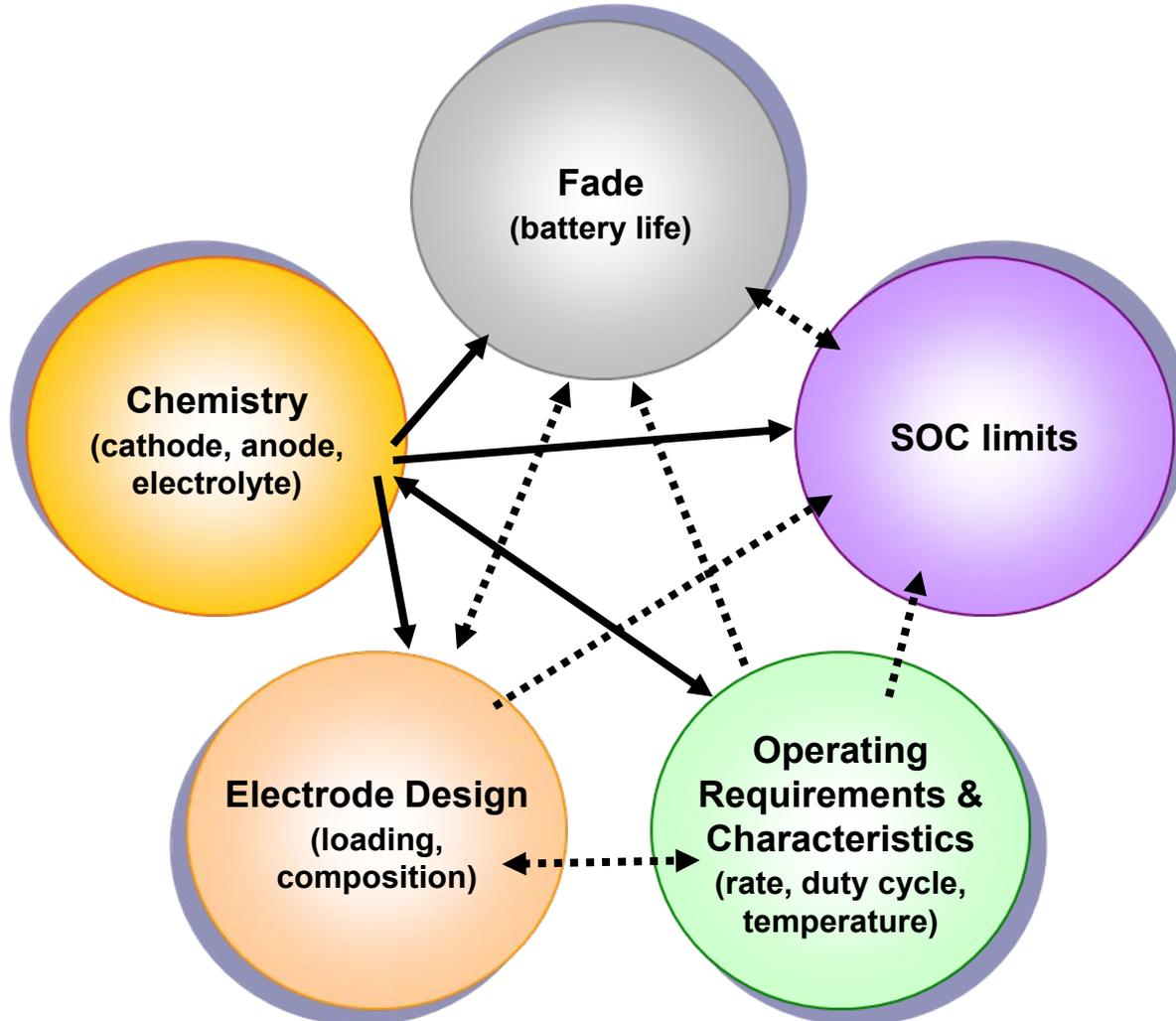
Doubling the speed of all manufacturing processes noticeably decreased battery cost in most cases.

- Analysis of the modeled battery scenarios reveals that *separator cost* and *coater speed* are significant factors in battery system cost.
 - Example: Modeled costs for NCA-based PHEV batteries range from a low of about \$2000 to a high of about \$3200 (about \$364/kWh to about \$581/kWh); *increased separator cost alone* accounts for more than 25% of that difference.
 - Single variable sensitivity analyses of modeled costs show that *separator cost* and *coater speed* are of equal or greater impact on battery system cost than cathode material cost.

The ability to employ a wide SOC range contributes significantly to reducing energy storage costs.

- Lower fade and wider SOC range both reduce cost by resulting in lower required nominal battery energy and smaller battery size.
 - For example, increasing the SOC range from 70% to 80% reduces battery costs by about 12%.
 - Materials that support a wide SOC range, therefore, should help to reduce overall battery costs.

For each candidate battery chemistry, the *inter-relationships* between operational requirements/characteristics and design parameters are factors that should be established experimentally.



These results point to specific areas of research with potential for reductions in battery cost.

Materials

- **Materials that support high power, and a wide SOC range**
- **Materials that provide minimal fade, impedance growth and calendar aging**

Cell/Electrode

- **New chemistry and electrode designs permitting shorter, thicker electrodes**
- **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 processing technologies to increase *coater speed and/or other unit operations significantly***
 - perhaps materials-enabled
- **Fundamentally different electrode preparation processes**

...while meeting target requirements for power and energy.