PHEV and LEESS Battery Cost Assessment

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TIAX's objective was to assess high volume manufacturing costs of Li-ion batteries being considered for PHEV and LEESS applications.

Selected Battery Chemistries and Cell Designs

↓

Cost Assessments

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

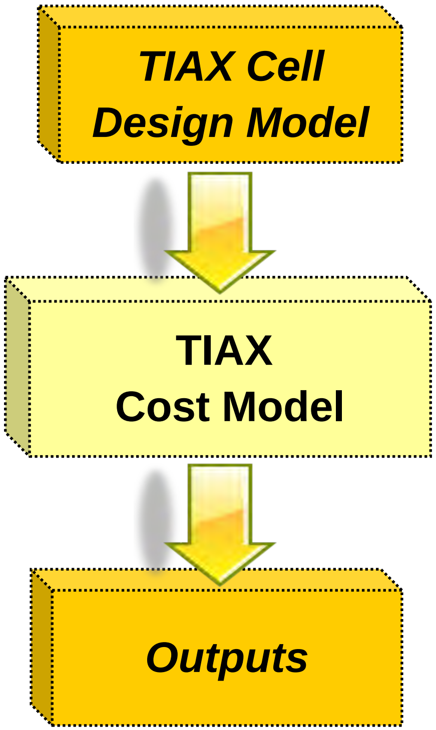
We employed a parametric approach in which TIAX's cost model was applied many times with different sets of input parameters.

INPUTS

Constraints/Assumptions

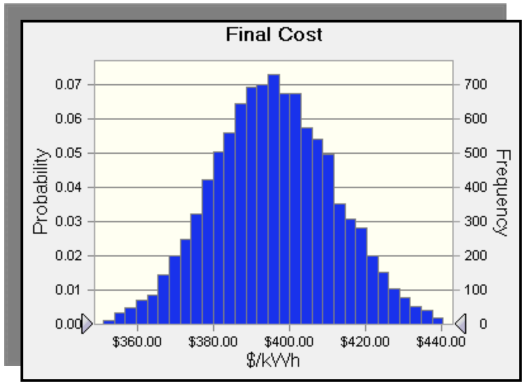
- **Pack energy requirements**
- **Power input/output**
- **Battery chemistries and material performance**
- **Electrode designs**
- **Fade and SOC range**
- **Sufficiently high production volume**

APPLICATION



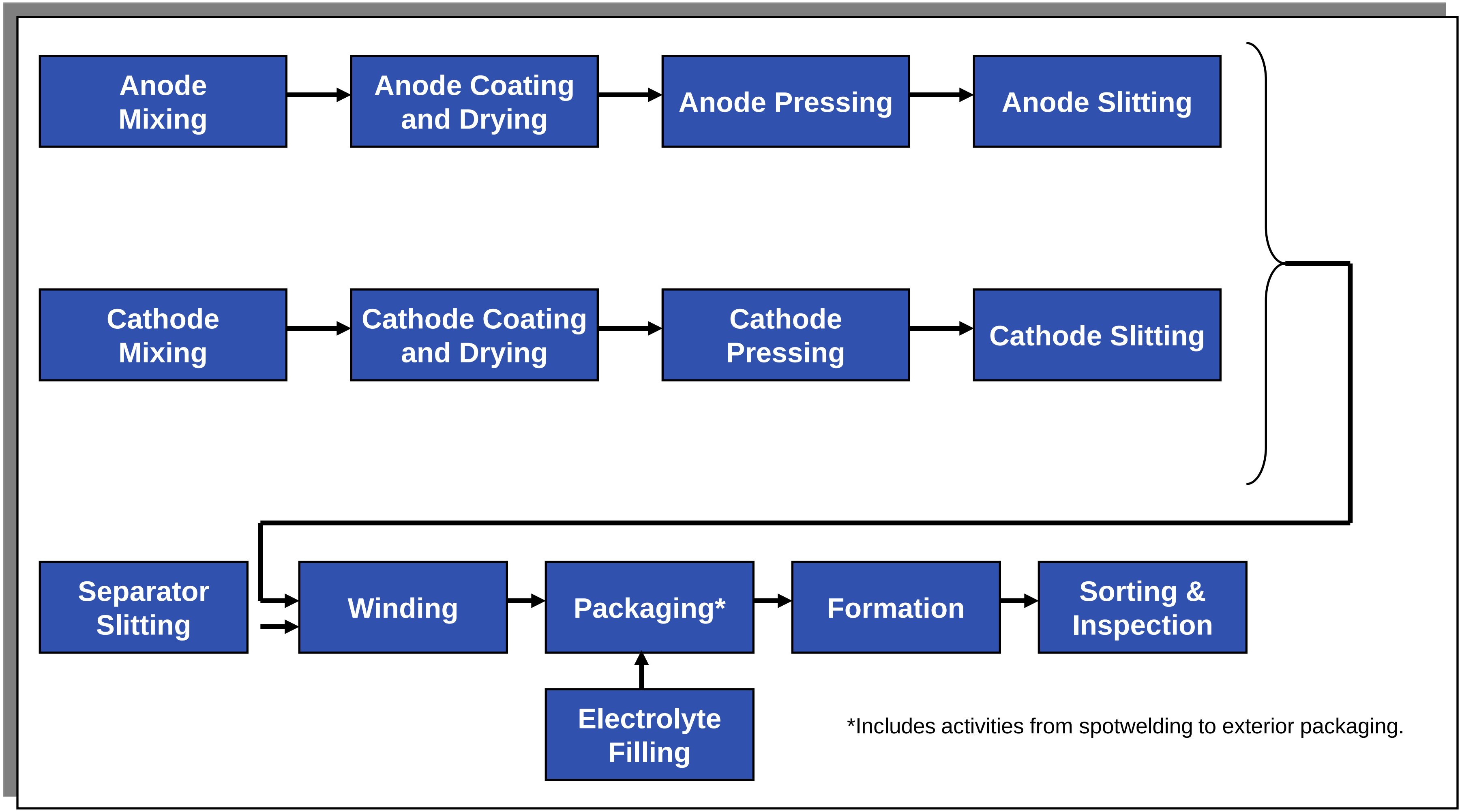
ANALYSES

- **Multi-variable uncertainty**
- **Single variable sensitivity**
- **"What if?"**



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

The TIAX cost model was based on typical process steps currently employed for high volume production of Li-ion cells, using appropriate high volume throughput rates and equipment costs for each unit operation.



PHEV BATTERY COST ASSESSMENT

The program focused on both commercially available and emerging cathode materials aimed for use in a 20-mile PHEV battery pack.

- Costs were modeled for a 300V **PHEV** battery pack that could provide 5.5 kWh 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%), assuming an 80% operating SOC range.

Cathode Materials Considered

NCA: lithium nickel-cobalt-aluminum oxide

NCM: lithium nickel-cobalt-manganese oxide

LMO: lithium manganese spinel

LFP: lithium iron phosphate

LL-NMC: layered-layered lithium nickel manganese cobalt oxide

Material Properties

Cathode 1st delithiation and anode lithiation capacity

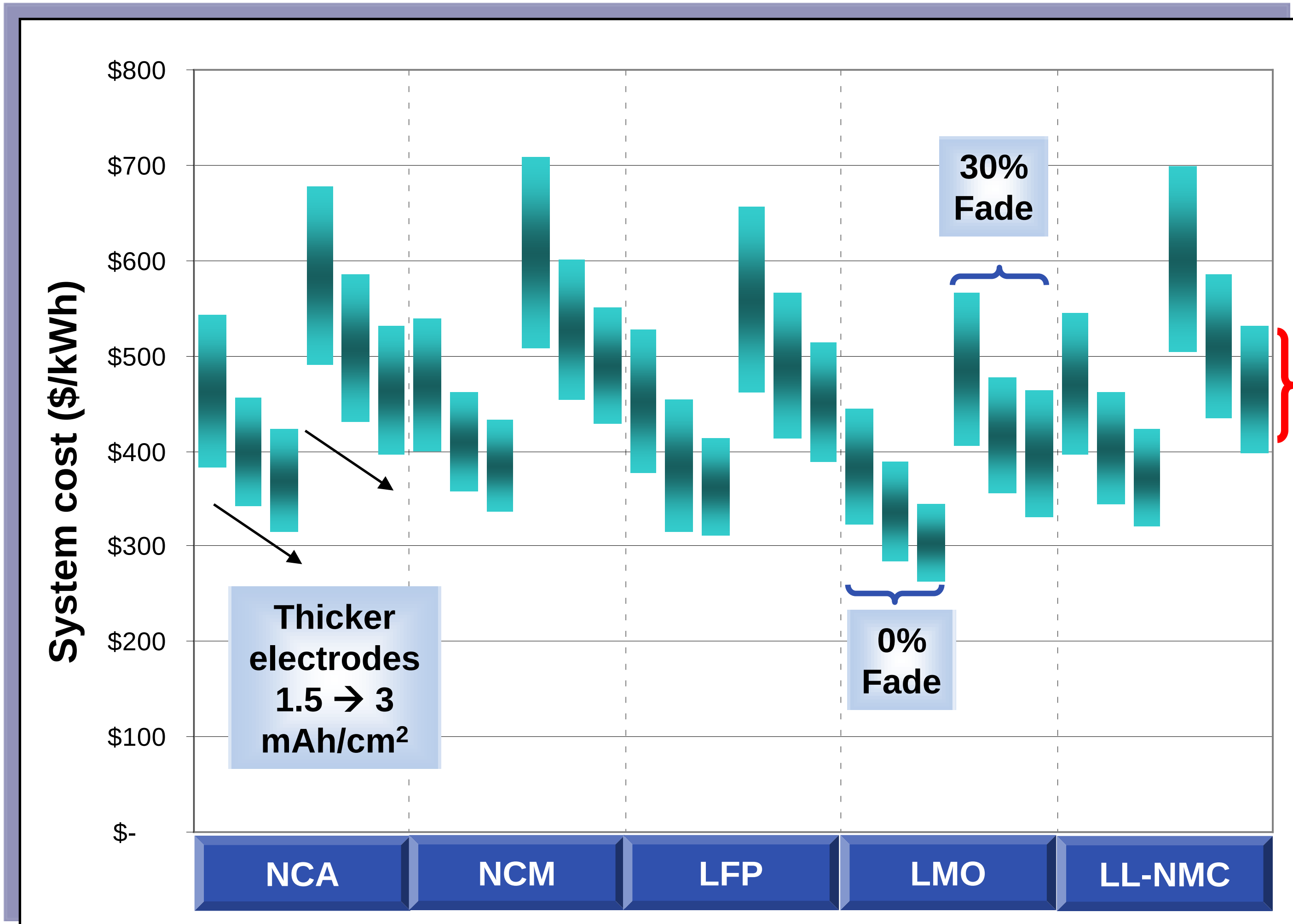
Anode and cathode efficiency

Reversible capacity at 1C

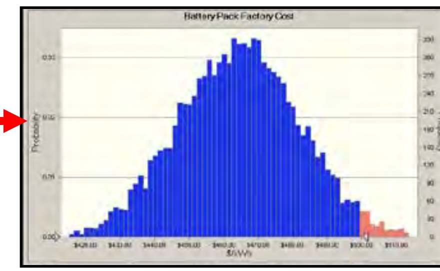
Average potential

Material density and electrode porosity

There is significant overlap in battery costs among the five cathode classes, with wider variation within each chemistry based on the electrode design than between chemistries.



Cost Histogram

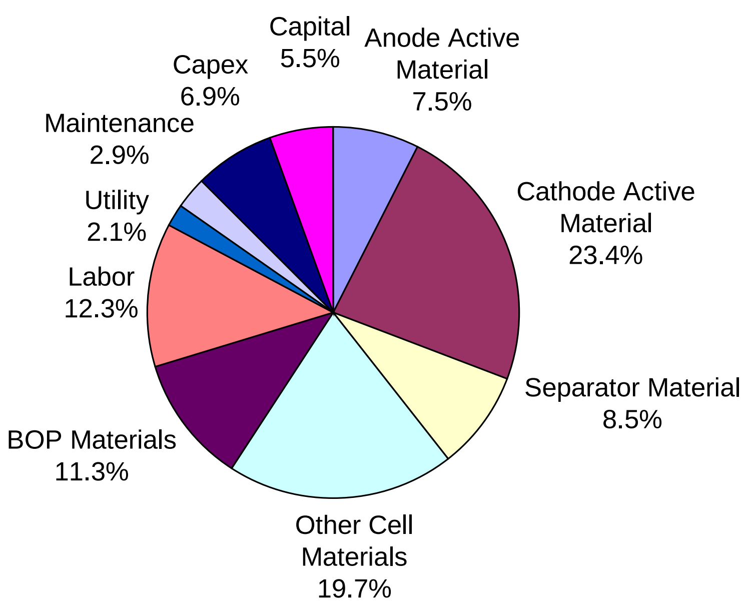


Cost range includes uncertainties in input parameters. Minimum and maximum obtained from multivariable Monte Carlo uncertainty analysis.

The cost model allows us to develop perspective regarding the relative contribution of various material and processing costs, for various scenarios.

Materials account for 60-70% of the final PHEV battery pack cost, with the cathode active material contributing 15-30%

Illustrative Example



Fraction of Process Costs

Process	Range*
Formation and Aging	18 – 32 %
Anode Coating/Drying	13 – 22 %
Cathode Coating/Drying	13 – 22 %
Winding	6 – 10 %
Cathode Mixing	4 – 8 %
Anode Pressing	4 – 5 %
Cathode Pressing	4 – 5 %
BOP Packaging	2 – 4 %
All Others	~12%

*Value depends on cell design

Cell formation and aging, anode and cathode coating and drying, and winding account for as much as 70% of the total processing costs.

The results point to a three-pronged approach in emphasizing 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
- Materials with higher specific capacity and higher average cell voltage

Cell/Electrode

- New chemistry, electrolytes, 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 significantly increase *coater/dryer speed* and/or *other unit operations significantly* (enabled by materials or electrode engineering)
- Fundamentally different electrode preparation processes

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

LEESS BATTERY COST ASSESSMENT

USABC set out new power and energy goals for a power assist HEV battery based on drive cycle simulation results*.

System Characteristics (end of life)	Unit	PA (Lower Energy)	
2s / 10s Discharge Pulse Power	kW	55	20
2s / 10s Regen Pulse Power	kW	40	30
Energy window for vehicle use	Wh	165	
Discharge Requirement Energy (10s x 20kW)	Wh	56	
Regen Requirement Energy (10s x 30kW)	Wh	83	
Energy over which both requirements are met	Wh	26	

*USABC, Development of Advanced Energy Storage Systems for High Power, LEESS for PAHEV Applications, RFPI December 2009.

The major changes in the LEESS requirements resulted in generally higher power, with significant reductions in system weight, volume and energy*.

System Characteristics (end of life)	Unit	PA – Minimum		PA (Lower Energy)	
2s / 10s Discharge Pulse Power	kW	*NA*	25	55	20
2s / 10s Regen Pulse Power	kW	*NA*	**20**	40	**30**
Cold-Cranking Power at -30ºC	kW	5		5	
Energy window for vehicle use	Wh	**425**		**165**	
Energy over which both charge and discharge requirements are met	Wh	300		26	
Maximum System Weight	kg	40		20	
Maximum System Volume	L	32		16	
Selling Price/System @ 100k/yr	$	500		400	

The Lower Energy – Energy Storage System (LEESS) targets added 2 second discharge and regen pulses, and significantly increased the 10 second regen pulse requirement.

*USABC, Development of Advanced Energy Storage Systems for High Power, LEESS for PAHEV Applications, RFPI December 2009.

Noting that the new targets generally involved substantial increases in P/E ratios, we pursued several approaches to defining batteries we could model.

Approach I - Parametric

- Model several candidate energy window ranges over which power requirements can be met and investigate consequences for selected chemistries and electrode designs.

Approach II – Experimental Measurements to Characterize Power/Energy

- Select candidate alternative chemistries and electrode designs and determine appropriate energy window ranges over which power goals can be met.

Approach III – Benchmark/extrapolation of Commercial Systems

- Select candidate commercial systems and use their specifications to size them for LEESS applications.

We pursued and linked all three approaches; highlights from the first two are presented here.

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A major issue for LEESS is the extent to which the battery must be over-sized with respect to *energy* in order to deliver the required *power* (and life).

Energy Window of Nominal	Fade %	Nominal Energy of Battery (Wh)	P/E Ratio				
			10s-20kW Discharge	10s-30kW Regen	2s-55kW Discharge	2s-40kW Regen	3 x 2s-5kW Cold Crank
50%	30	**471**	42	64	117	85	11
40%	30	**589**	34	51	93	68	8
30%	30	**786**	25	38	70	51	6
20%	30	**1179**	17	25	47	34	4

- **Energy:** 165Wh at the end of life
- **Fade:** assume 30% fade over time (i.e. 165Wh end of life translates to 236Wh beginning of life)
- **Operational Energy Window Range:** vary between 20 to 50% of nominal to account for stringent power requirements.
- **Battery Life:** The battery is assumed to be able to achieve the life defined in each of the selected scenarios.

To connect these data to a full size battery, it is necessary to identify electrode loadings at which the power requirements can be met (though such data are generally unavailable).

Several factors must be considered in bracketing electrode thicknesses representative of today's lithium-ion technology.

- Relatively low electrolyte conductivity limits the loadings and thickness of the Li-ion electrodes:
  - Ionic polarization through the separator generally limits the current density at the electrodes. As a result, large electrode area is required to support high current, resulting in long, thin electrodes.
  - Ion transport limitations in porous electrodes create inhomogeneous current distribution and depth-dependant polarization at high current density. As a result, thin electrodes are needed to prevent polarization and enable high interfacial surface area, which in turn reduces current density.
- Thus, high power, high current Li-ion cell designs must have relatively thin, low-loading electrodes.
- Based on our experience, we selected the electrode loadings shown below both for subsequent parametric modeling and for selected experimental measurements.

Electrode loading		
Low	**Medium**	**High**
0.5 mAh/cm^2	1.0 mAh/cm^2	1.5 mAh/cm^2

Two material combinations were selected, representing lower power, higher energy and higher power, lower energy alternatives for LEESS cells.

Material Properties	Higher Energy/ Lower Power		Lower Energy/ Higher Power	
	NCA	Hard Carbon	LMO	LTO
Cathode: 1st delithiation (mAh/g)	209	-	111	-
Anode: 1st lithiation (mAh/g)	-	295	-	171
1st Cycle reversibility	92%	71%	95%	97%
Cathode reversible capacity at 1C (mAh/g)	165	170	105	165
Average potential vs. Li for 1C discharge (V)	3.8	0.53	4.02	1.55
Density (g/cc)	4.8	1.53	4.28	3.43

- NCA/hard carbon represents a higher energy/lower power system with potential to meet high discharge and regen power requirements.
- LMO/LTO represents a lower energy/higher power system with potential to meet high discharge and regen power requirements.

For all cell designs considered, total cell weight ranges between 6 and 25kg and total cell volume ranges between 4 and 14L generally meeting the LEESS weight and volume targets.

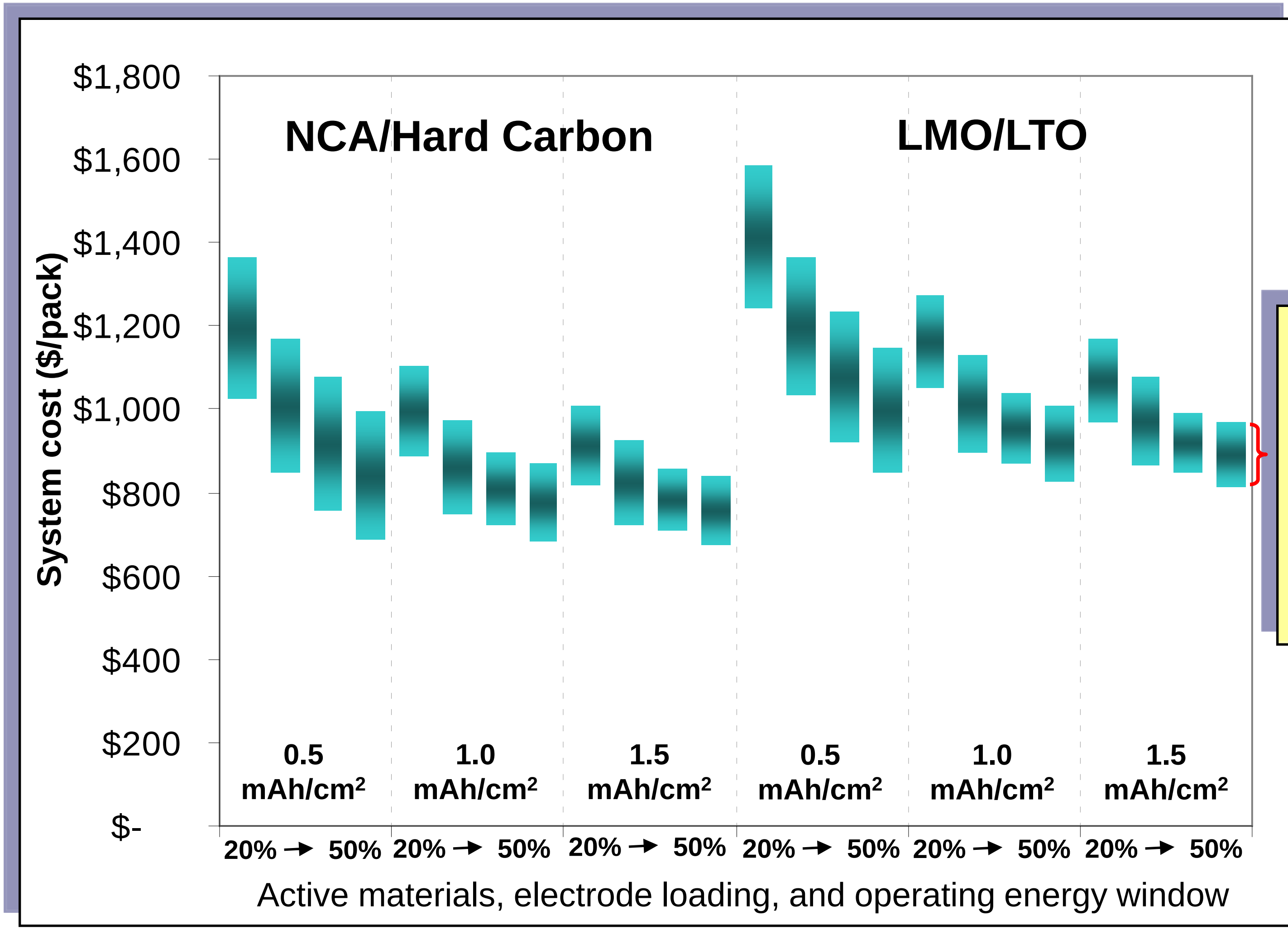
Sample Cell Designs

	NCA/Hard Carbon		LMO/LTO	
	1.5 mAh/cm^2		1.5 mAh/cm^2	
Energy Window Range	20%	50%	20%	50%
Nominal Energy* (Wh)	1179	471	1179	471
Cell diameter (cm)	3.1	2.3	3.3	2.4
Electrode length (cm)	201	80	190	76
# Cells per pack	92	92	121	121
Cell only mass (kg)	11.0	5.5	18.1	8.7
Cell only volume (L)	7.3	4.1	10.5	5.8

* 30% fade assumed for all systems.

…whether these parametric designs actually meet the power and life targets must be experimentally verified.

For cell designs considered, the modeled "high volume" LEESS system costs range between $675 and $1575.



Range includes uncertainties in input parameters. Distribution obtained using Monte Carlo simulations. Minimum and maximum correspond to μ 3σ.

Unlike for PHEV, the cost of the LEESS batteries are dominated by battery management electronics and cell formation and aging operation.

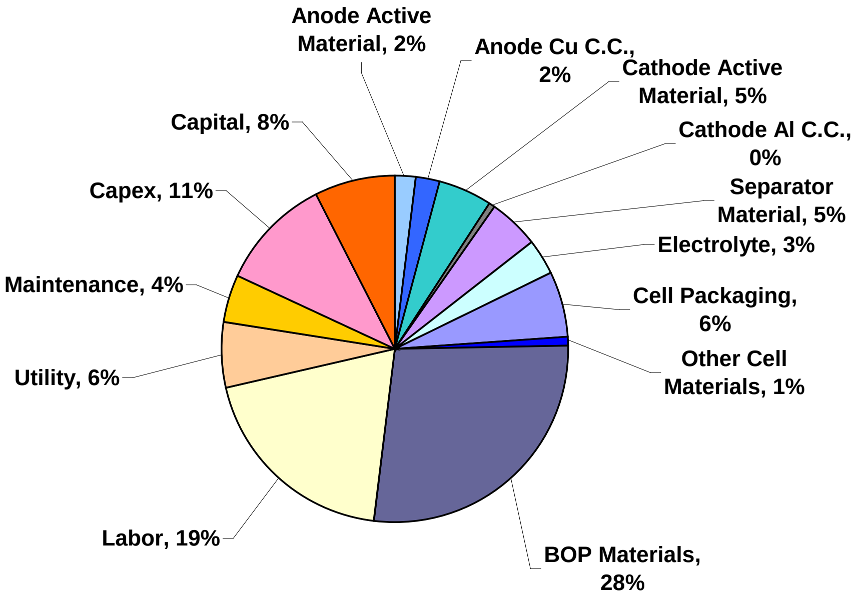
Material costs

- Battery management electronics components account for 30-60% of materials costs.
- Cell packaging, cathode active material, and separator each accounts for 13-39% of materials costs.
- Electrolyte and copper current collector account for 5-15% each.
- Cell packaging is the largest cost contributor for higher loading short electrodes.

Process costs

- Cell formation and aging account for 35-55% of processing costs.
- Cathode and anode coating and drying account for 4-13% of processing costs each.
- Electrode winding contributes 6-9%.

Illustrative Example



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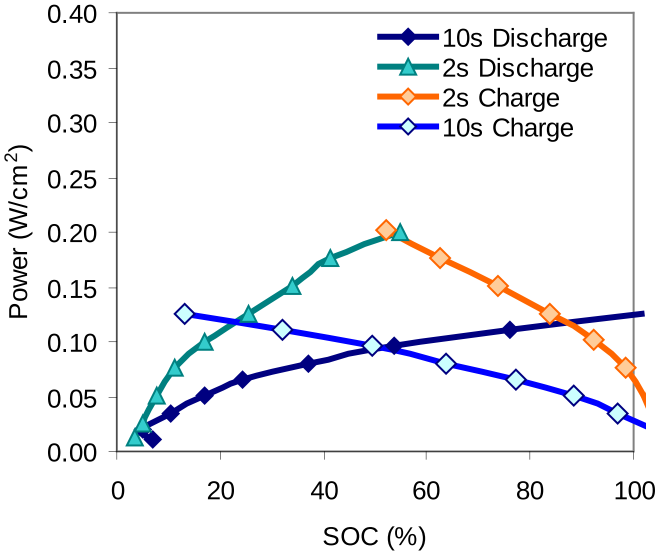
To calibrate the appropriateness of the electrode loadings modeled, we made electrochemical measurements with NCA/hard carbon and LMO/LTO cells.

- Electrode coatings targeting the loadings selected for this study were prepared in the TIAX laboratories.
  - NCA and LMO cathode formulation: 85:10:5 (Active material:Acetylene black:PVDF)
  - Hard carbon anode formulation: 90:3:7 (Active material:Acetylene black:PVDF)
  - LTO anode formulation: 80:10:10 (Active material:Acetylene black:PVDF)

- Coin cells were assembled, targeting anode:cathode ratio of 1.05, and using 1M $LiPF_6$ in 1:1:1 solution of EC:DMC:EMC with 1% VC and Celgard 2500 separator.

- Power capability of each cathode/anode combination was measured by performing constant power pulses
  - Maximum power as a function of SOC was determined for 2s and 10s discharge and charge pulses.
  - Cutoff voltages for the charge and discharge pulses were set at:
    - NCA/Hard carbon – V_{max} = 4.2V; V_{min} = 2.0V
    - LMO/LTO – V_{max} = 3.15V; V_{min} = 1.45V

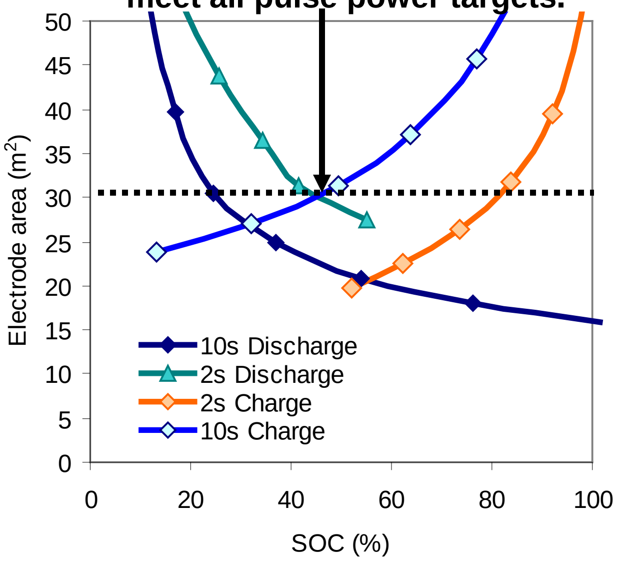
Constant pulse power measurements for 2s and 10s charge and discharge pulses were used to determine the operating SOC range and minimum electrode area required to meet all LEESS pulse power targets.



$$\text{Area} = \frac{\text{Target Power}}{\text{Measured Specific Power}}$$

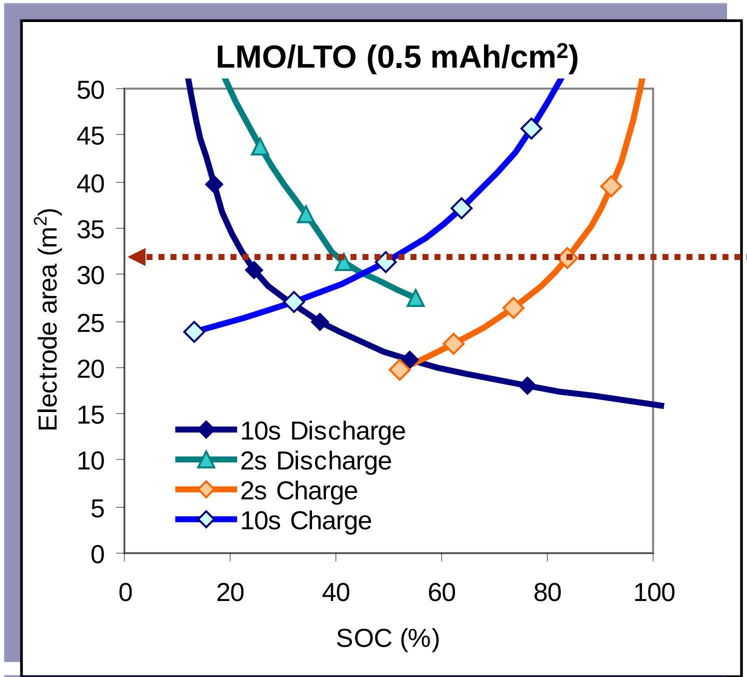
Target Power	2s	10s
Discharge	55 kW	20 kW
Charge	40 kW	30 kW

Minimum electrode area to meet all pulse power targets.

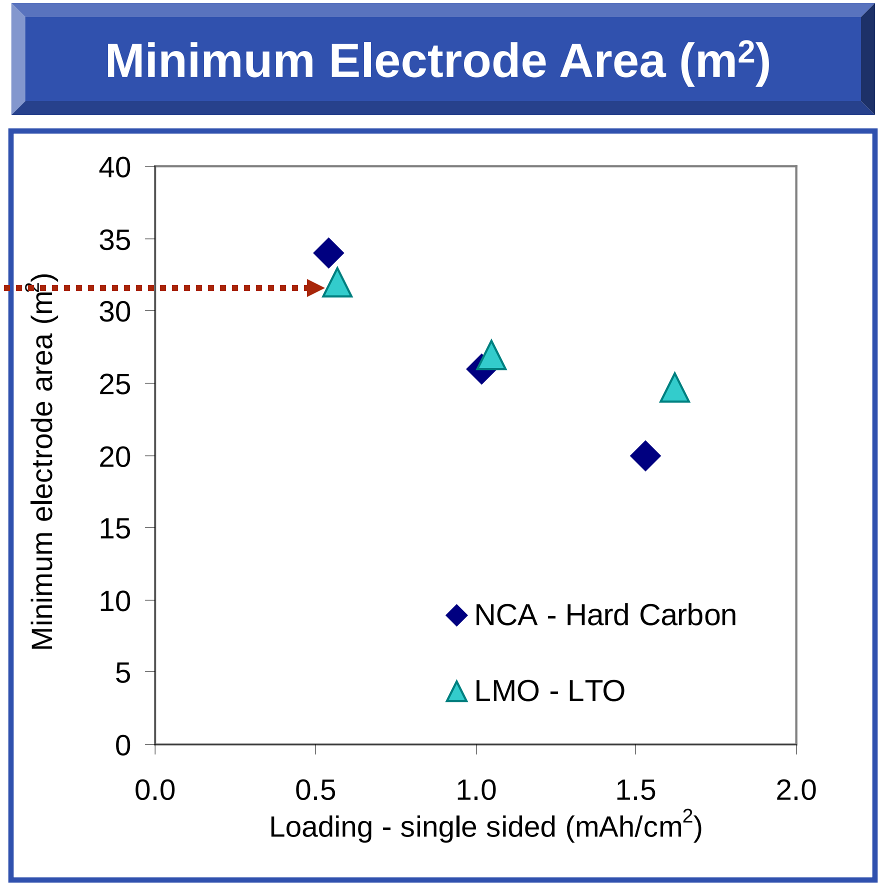


- Measure maximum power as a function of SOC in coin cells using electrode designs selected for the LEESS using 2s and 10s discharge and charge constant power pulses.
- Convert the power to the necessary electrode area for meeting each pulse power target.
- Find the two most strenuous requirements and determine the minimum electrode area for meeting ***all*** of the pulse power targets.

At equivalent mAh/cm² loading, NCA/hard carbon and LMO/LTO cells require similar electrode areas to meet the power requirements for 0.5 and 1.0 mAh/cm² single sided electrodes.

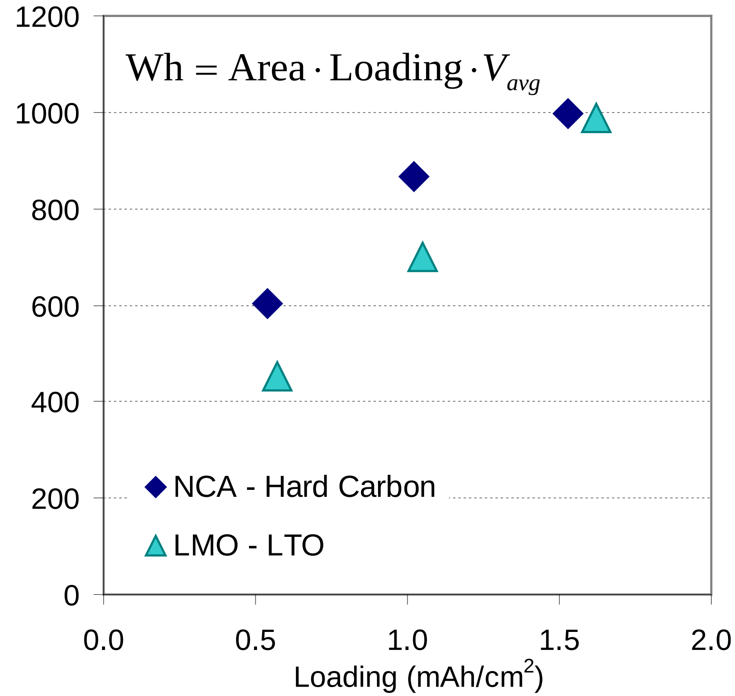


Note that a 3-fold increase in loading, results in only a 20-40% reduction in electrode area.

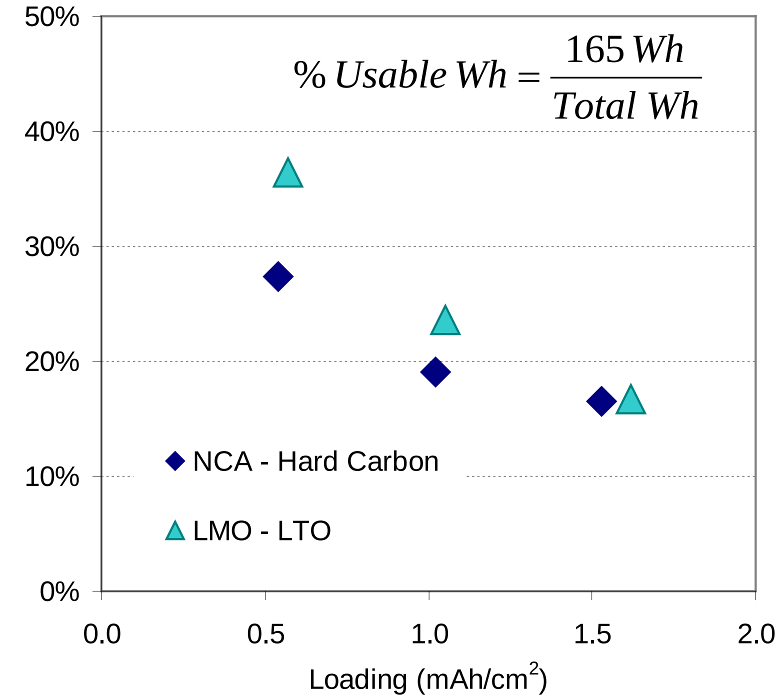


Experimental data show that the likely energy window operating range is between 17% and 36%, necessitating substantial over-sizing of LEESS packs.

Minimum Pack Energy (Wh)

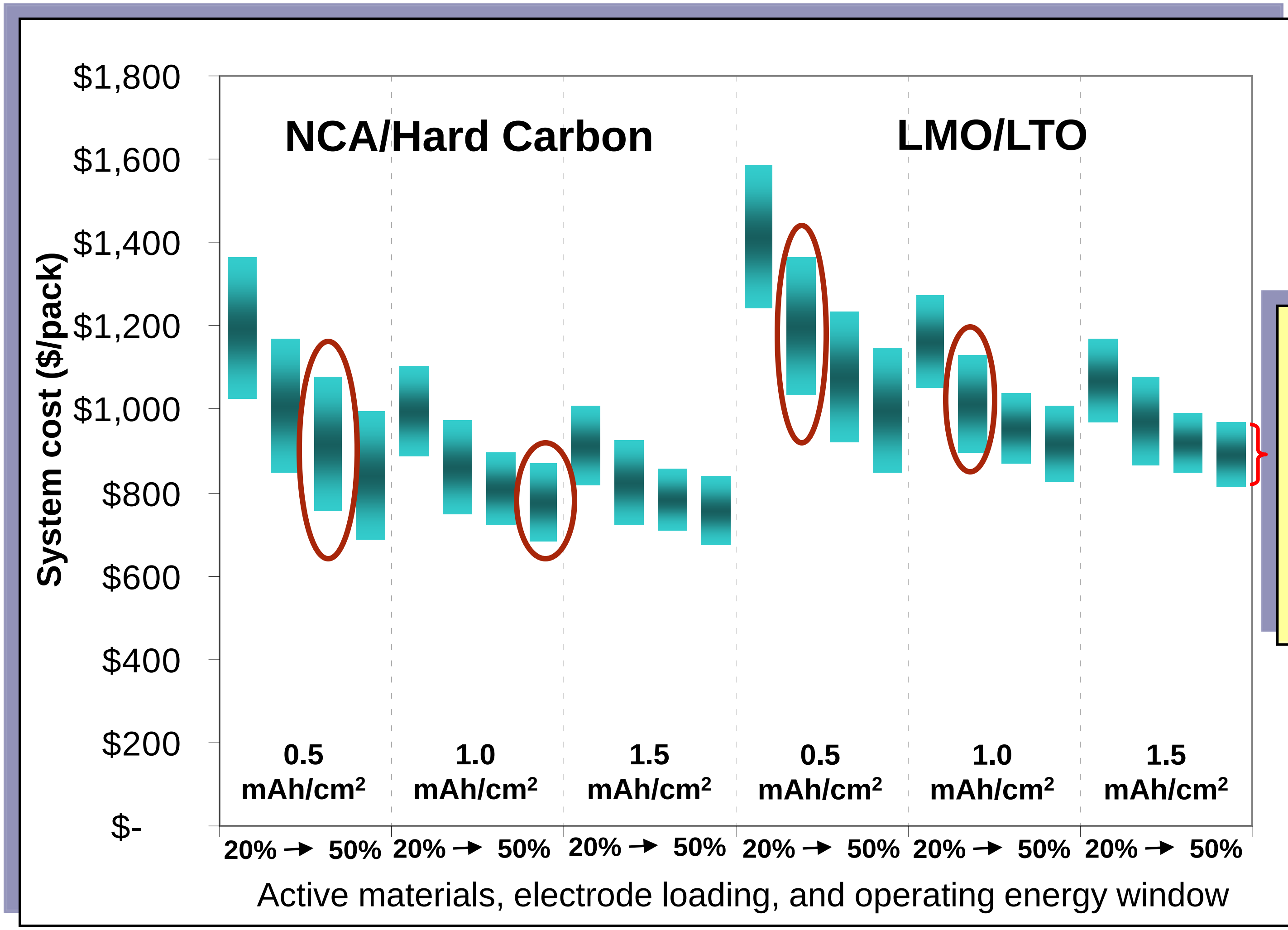


% Maximum Energy Window Range



Whether these cell designs can meet the stringent life requirements is uncertain.

Based on electrode power performance results, the likely range of LEESS pack manufacturing costs would fall in the $650 to $1400 range.



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How realistic are the power targets for today's HEV technology?

	Gen IV Prius NiMH cell (1.2V, 6.5Ah)
Units to meet 30kW, 10s charge	249
Units to meet 20kW, 10s discharge	196
Units to meet 55kW, 2s discharge	**530**
Units to meet all power specs	530
Units assuming 30% power loss at EOL	759
Total Cell Mass, kg	129
Total Cell Volume, L	63

LEESS requires a factor of 3.5 to 4.5 higher number of NiMH cells than are employed in the Gen IV Prius pack. (!!)

LEESS Cost Assessment Summary

- Sizing of LEESS batteries is guided primarily by power requirements, not energy requirements, leading to the need for utilization of very thin electrodes with low active material loadings.
  - The gating requirements are the 2 second discharge and the 10 second charge
- Unlike for PHEVs, active material cost and electrode coating and drying in LEESS batteries account for only a small fraction of the material and process costs.
- The majority of the material cost comes from the BOP components (pack electronics) and cell casing, thus reducing the number of cells can lead to lower overall pack cost.
- Cell formation and aging accounts for majority of process cost, thus reducing the number of cells will also lead to significant reduction in system level cost.

Ongoing Work for FY2011

- Update of models and databases to place all assessments in a common basis pertinent to 2014/2015 timeframe.
- Investigate the tradeoffs between HEV performance, fuel economy and battery cost.