Impact of the 3Cs of Batteries on PHEV Value Proposition: Cost, Calendar Life, and Cycle Life

The 9th Advanced Automotive Battery Conference
Long Beach, California

June 10-12, 2009

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NREL/PR-540-45887

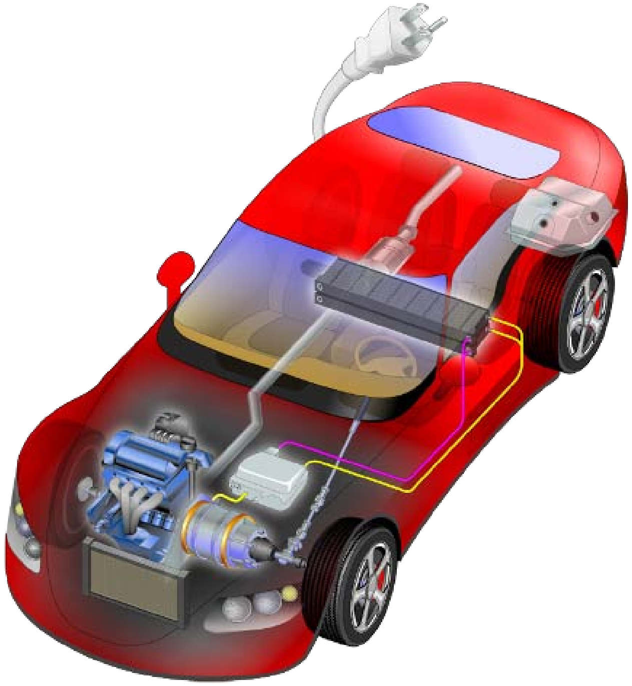
Funded by Energy Storage R&D (David Howell)
Vehicle Technologies Program
U.S. Department of Energy

Overview

- Introduction and background
- Motivation for PHEV battery trade-off analysis
- Battery calendar and cycle life models
- Battery cost model
- Battery life/cost trade-off results
- Impact of temperature on battery life and cost
- Summary

Introduction

- PHEVs have the potential to significantly reduce (imported) petroleum consumption (and GHG emissions) by improving efficiency and use of electricity
- Capacity, c-rate, cost, cycle life, and calendar life are all critical in making batteries for PHEVs commercially viable
- Incremental cost of the long-lasting batteries could be offset with government incentives and high petroleum prices



Introduction

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- Capacity, c-rate, cost, cycle life, and calendar life are all critical in making batteries for PHEVs commercially viable
- Incremental cost of the long-lasting batteries could be offset with government incentives and high petroleum prices
- Cost, calendar life, and cycle life are the least known and have the biggest impact on PHEV value proposition
- Cost, fuel savings, and battery degradation characteristics at beginning of life vs. end of life must be evaluated
- The spectrum of battery degradation rates due to both cycle life and calendar life in various climates and operating states of charge (SOCs) are needed
- NREL has been studying trade-offs between the performance, life, and cost of batteries

Major Battery Requirements (5Cs)

USABC
UNITED STATES ADVANCED BATTERY CONSORTIUM
FreedomCAR & Fuel Partnership

Requirements of End of Life Energy Storage Systems for PHEVs

Characteristics at EOL (End of Life)		High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Reference Equivalent Electric Range	miles	**10**	**40**
Peak Pulse Discharge Power - 2 Sec / 10 Sec	kW	**50 / 45**	**46 / 38**
Peak Regen Pulse Power (10 sec)	kW	**30**	**25**
Available Energy for CD (Charge Depleting) Mode, 10 kW Rate	kWh	**3.4**	**11.6**
Available Energy for CS (Charge Sustaining) Mode	kWh	**0.5**	**0.3**
Minimum Round-trip Energy Efficiency (USABC HEV Cycle)	%	**90**	**90**
Cold cranking power at -30°C, 2 sec - 3 Pulses	kW	**7**	**7**
CD Life / Discharge Throughput	Cycles/MWh	**5,000 / 17**	**5,000 / 58**
CS HEV Cycle Life, 50 Wh Profile	Cycles	**300,000**	**300,000**
Calendar Life, 35°C	year	**15**	**15**
Maximum System Weight	kg	**60**	**120**
Maximum System Volume	Liter	**40**	**80**
Maximum Operating Voltage	Vdc	**400**	**400**
Minimum Operating Voltage	Vdc	**>0.55 x Vmax**	**>0.55 x Vmax**
Maximum Self-discharge	Wh/day	**50**	**50**
System Recharge Rate at 30°C	kW	**1.4 (120V/15A)**	**1.4 (120V/15A)**
Unassisted Operating & Charging Temperature Range	°C	**-30 to +52**	**-30 to +52**
Survival Temperature Range	°C	**-46 to +66**	**-46 to +66**
Maximum System Production Price @ 100k units/yr	$	**$1,700**	**$3,400**

Major Battery Requirements (5Cs)

Requirements of End of Life Energy Storage Systems for PHEVs

Peak Power Discharge (2S/10S) = 46/38 kW

C-rate ~ 10-15 kW

Available Energy = 11.6 kWh (ΔSOC = 70%)

Capacity (EOL) = 16.6 kWh

Cycle Life (depleting) = 3K-5K cycles

Cycle Life (sustaining) =200K-300K cycles

Calendar Life at 35°C = 15 Years

Cost (system) = $3,400

		r/Energy Ratio ttery	High Energy/Power Ratio Battery
Refer			40
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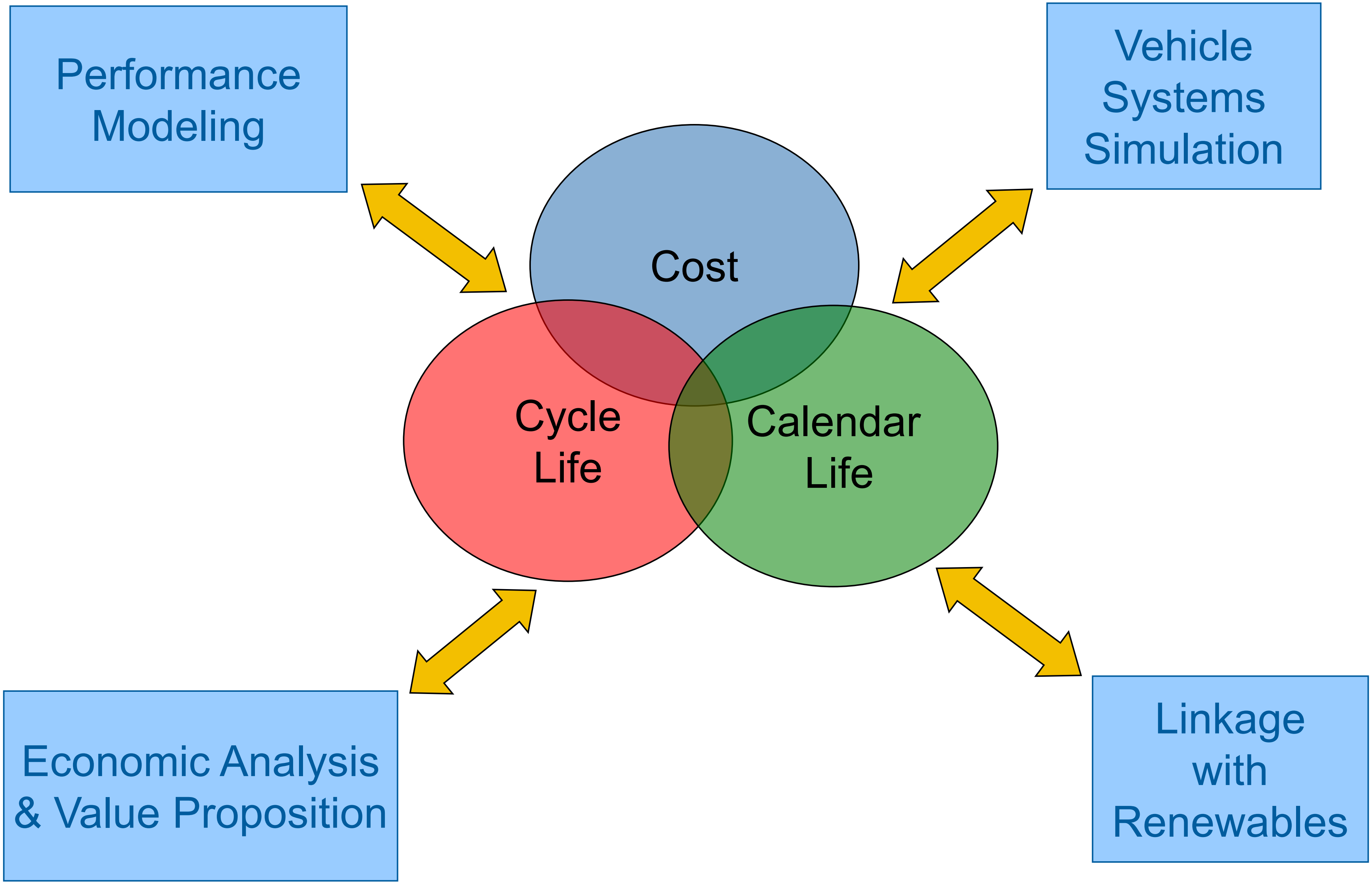
Peak Regen Pulse Power (10 sec)	kW	30	25
Available Energy for CD (Charge Depleting) Mode, 10 kW Rate	kWh	3.4	11.6
Ava		0.5	0.3
Min		90	90
Cold cranking power at -30°C, 2 sec - 3 Pulses	kW	7	7
CD Life / Discharge Throughput	Cycles/MWh	5,000 / 17	5,000 / 58
CS		300,000	300,000
Cal		15	15
Ma		60	120
Maximum System Volume	Liter	40	80
Maximum Operating Voltage	Vdc	400	400
Minimum Opera		>0.55 x Vmax	>0.55 x Vmax
Maximum Self-		50	50
System Recharge Rate at 30°C	kW	1.4 (120V/15A)	1.4 (120V/15A)
Unassisted Operating & Charging Temperature Range	°C	-30 to +52	-30 to +52
Survival Temperature Range		66	-46 to +66
Maximum System Production Price @ 100k units/yr	$	$1,700	$3,400

The Three Important Cs of Batteries

- Cost
- Cycle Life
- Calendar Life

These three attributes vary significantly from supplier to supplier, are not consistently reported, and dramatically affect the market potential of PHEVs and EVs.

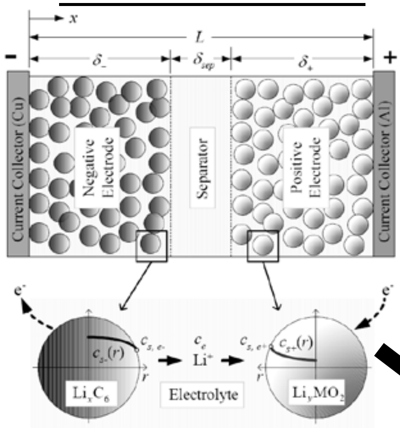
C^3 Data Is Critical to Many Analysis Efforts



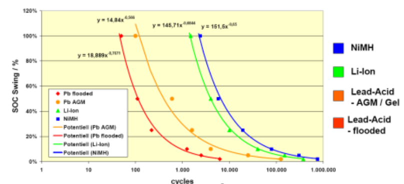
PHEV Battery Design Optimization

Design/size PHEV batteries to meet USABC technical goals/requirements at minimum cost.

Capacity and C-rate Performance



Cycle Life, Calendar Life



Source: VARTA

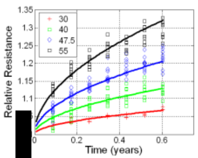
$$\hat{r} = 1 + \exp\left\{\hat{\beta}_0 + \hat{\beta}_1 \cdot \frac{1}{T}\right\} \cdot t^{0.5}$$

t = time (years)

T = temperature (K)

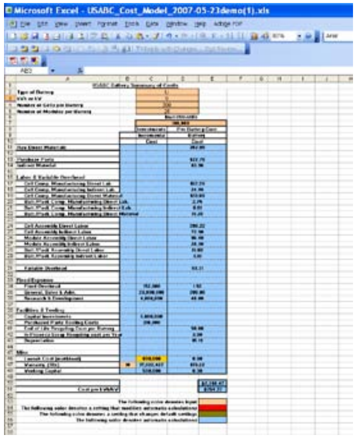
$\hat{\beta}_0 = 18.11$

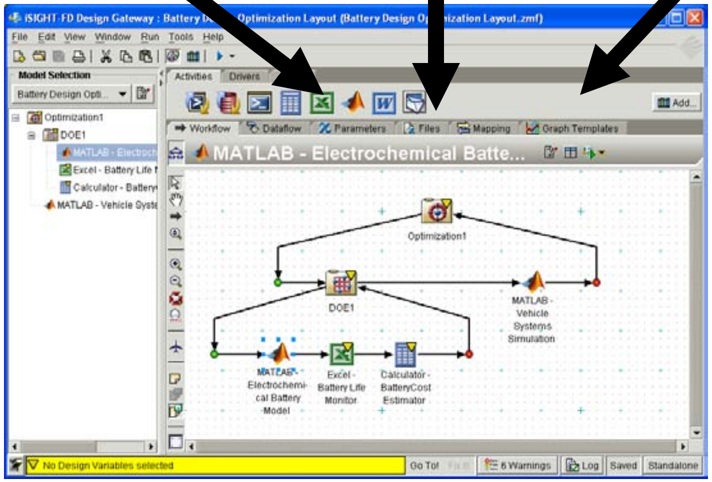
$\hat{\beta}_1 = -6236$



Source: ANL, INL, LBNL, SNL

Cost





Optimization

with vehicle simulations under realistic driving cycles and environments

Life prediction represents greatest uncertainty

Complex dependency on $t^{1/2}$, t, # cycles, T, V, ΔDOD

Motivation: Minimize Battery Cost, Maximize Life

How?

0) Select a high-quality, low-cost cell

1) Size battery appropriately so as not to overstress/overcycle, but with minimum cost and mass

   1) Accelerated calendar and cycle life testing
   2) Accurate life and DOD predictive models

2) Minimize time spent at high temperatures

   1) Standby thermal management (vehicle parked!)
   2) Active thermal management (vehicle being driven)

3) Use proper electrical management, control design

Component design/ selection

System design

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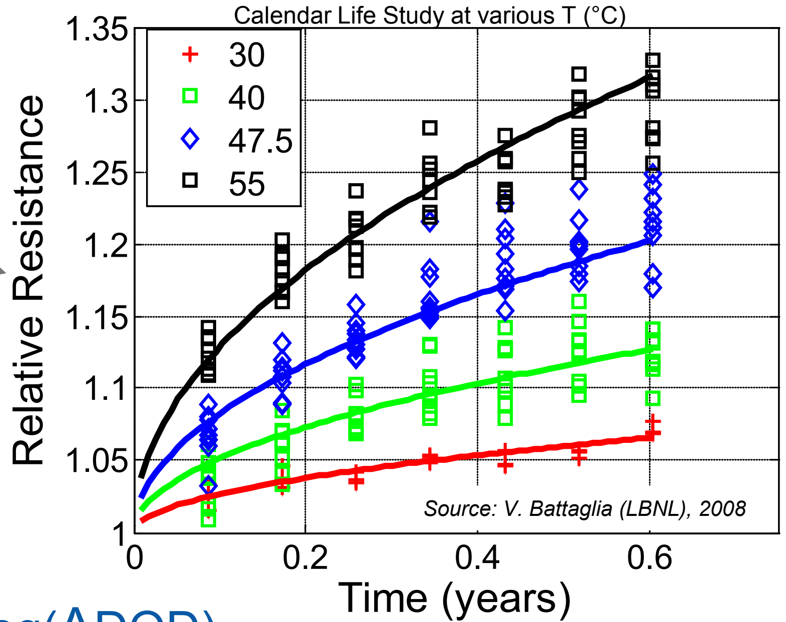
Modeling to Predict Battery Life

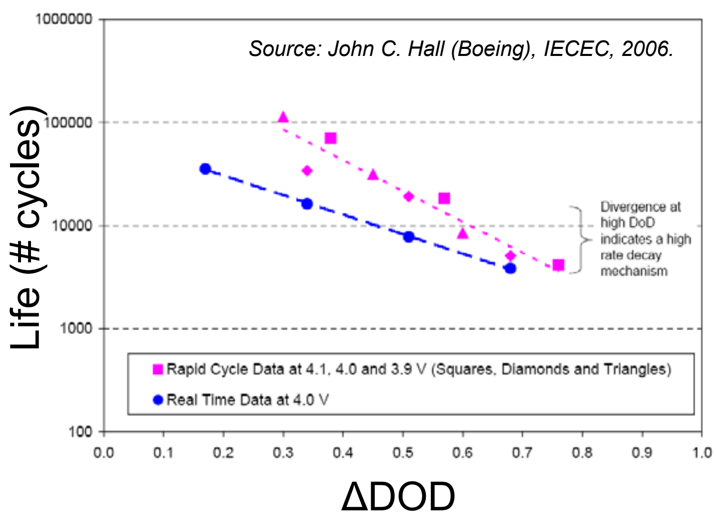
Calendar (Storage) Fade

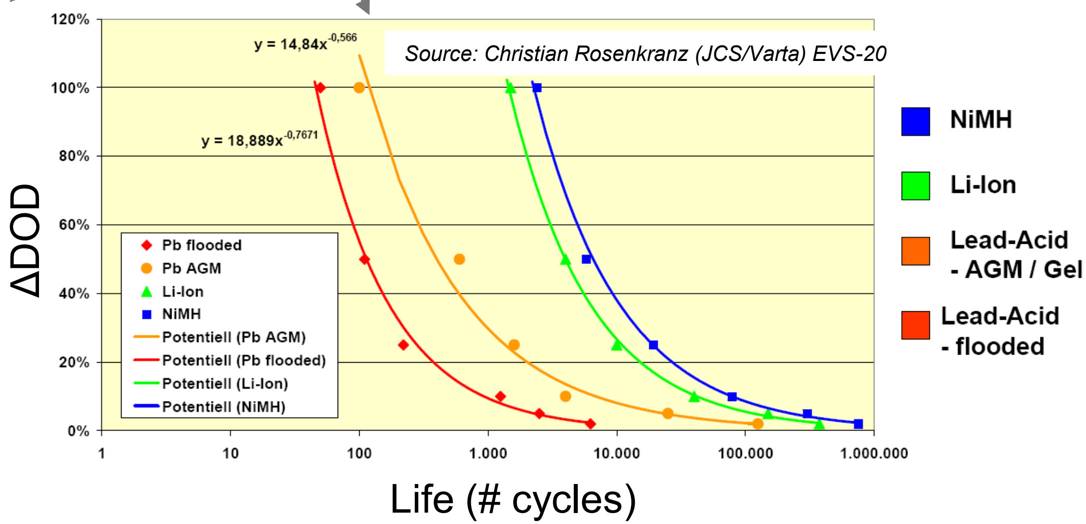
- Relatively well established & understood
- Typical $t^{1/2}$ time dependency
- Arrhenius relation describes T dependency



Cycling Fade

- Poorly understood
- Typical t or N dependency
- Often correlated log(# cycles) with ΔDOD or log(ΔDOD)

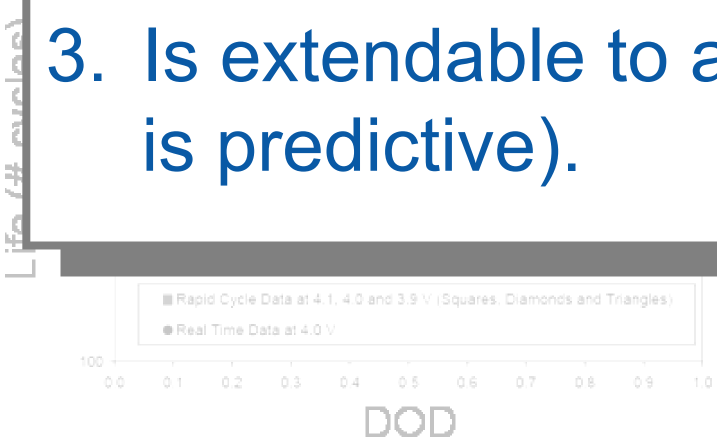


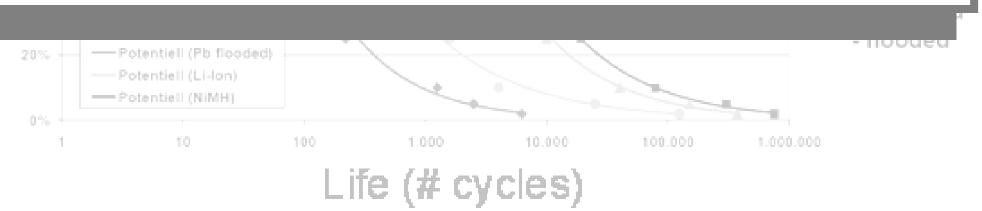


Objectives for Battery Life Modeling

Develop a power and energy degradation model that —

1. Uses both accelerated and real-time calendar and cycle life data as inputs.
2. Is mathematically consistent with all calendar and cycle life empirical data.
3. Is extendable to arbitrary usage scenarios (i.e., it is predictive).





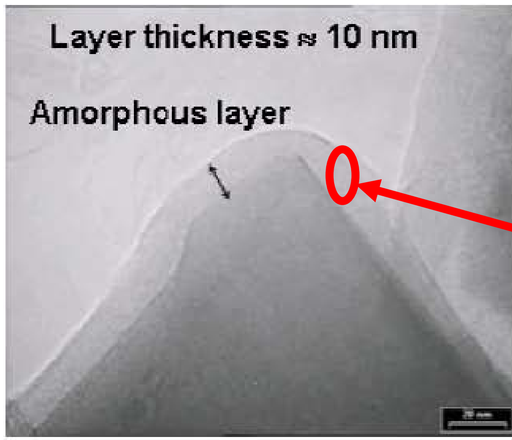
Impedance Growth Mechanisms: Complex Calendar and Cycling Dependency

NCA chemistry: Different types of electrode surface film layers can grow.

(1) “Electrolyte film” or SEI layer (2) “Solid film”

SEM Images: John C. Hall, IECEC, 2006.

Cell stored at 0°C

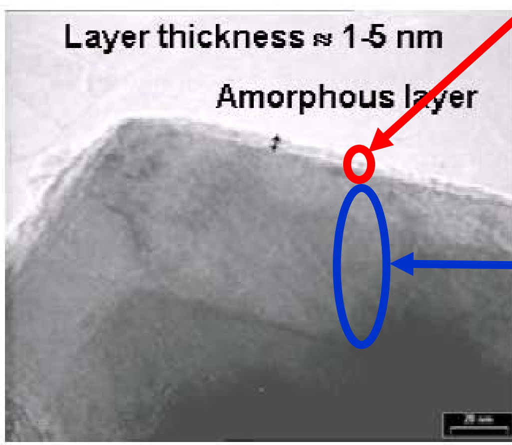


Electrolyte film*

- grows during storage $\alpha\ t^{1/2}$
- suppressed by cycling

*Often called Solid-Electrolyte Inter-phase (SEI) layer

Cell cycled 1 cycle/day at 80% DOD and 0°C



Solid film

- grows only with cycling α t or N

Life Model Summary (equations & coefficients)

Impedance Growth Model

- Temperature
- Voltage
- ΔDOD
- Calendar Storage ($t^{1/2}$ term)
- Cycling (t & N terms)

Capacity Fade Model

- Temperature
- Voltage
- ΔDOD
- Calendar Storage (Li loss)
- Cycling (Site loss)

Life Model Summary (equations & coefficients)

Impedance Growth Model

- Temperature
- Voltage
- ΔDOD
- Calendar Storage ($t^{1/2}$ term)
- Cycling (t & N terms)

$$k_1 = k_{1,ref} \exp\left(-E_{a1} \times (T^{-1} - T_{ref}^{-1}) / R\right)$$
$$k_2 = k_{2,ref} \exp\left(-E_{a2} \times (T^{-1} - T_{ref}^{-1}) / R\right)$$

$$a_1 = a_{1,ref}\, k_1 \exp(\alpha_1 F/RT \times V)$$
$$a_2 = a_{2,ref}\, k_2 \exp(\alpha_2 F/RT \times V)$$

$$a_1 = b_0 + b_1 (1 - \Delta DOD)^{b2}$$
$$a_2 / a_1 = \max[0, c_0 + c_1 (\Delta DOD)]$$

$$a_{2,t} = a_2 (1 - \alpha_N)$$
$$a_{2,N} = a_2 \alpha_N$$

$$R = a_1 t^{1/2} + a_{2,t}\, t + a_{2,N}\, N$$

Capacity Fade Model

- Temperature
- Voltage
- ΔDOD
- Calendar Storage (Li loss)
- Cycling (Site loss)

From impedance growth model

$$Q_{Li} = d_0 + d_1 \times (a_1 t^{1/2})$$

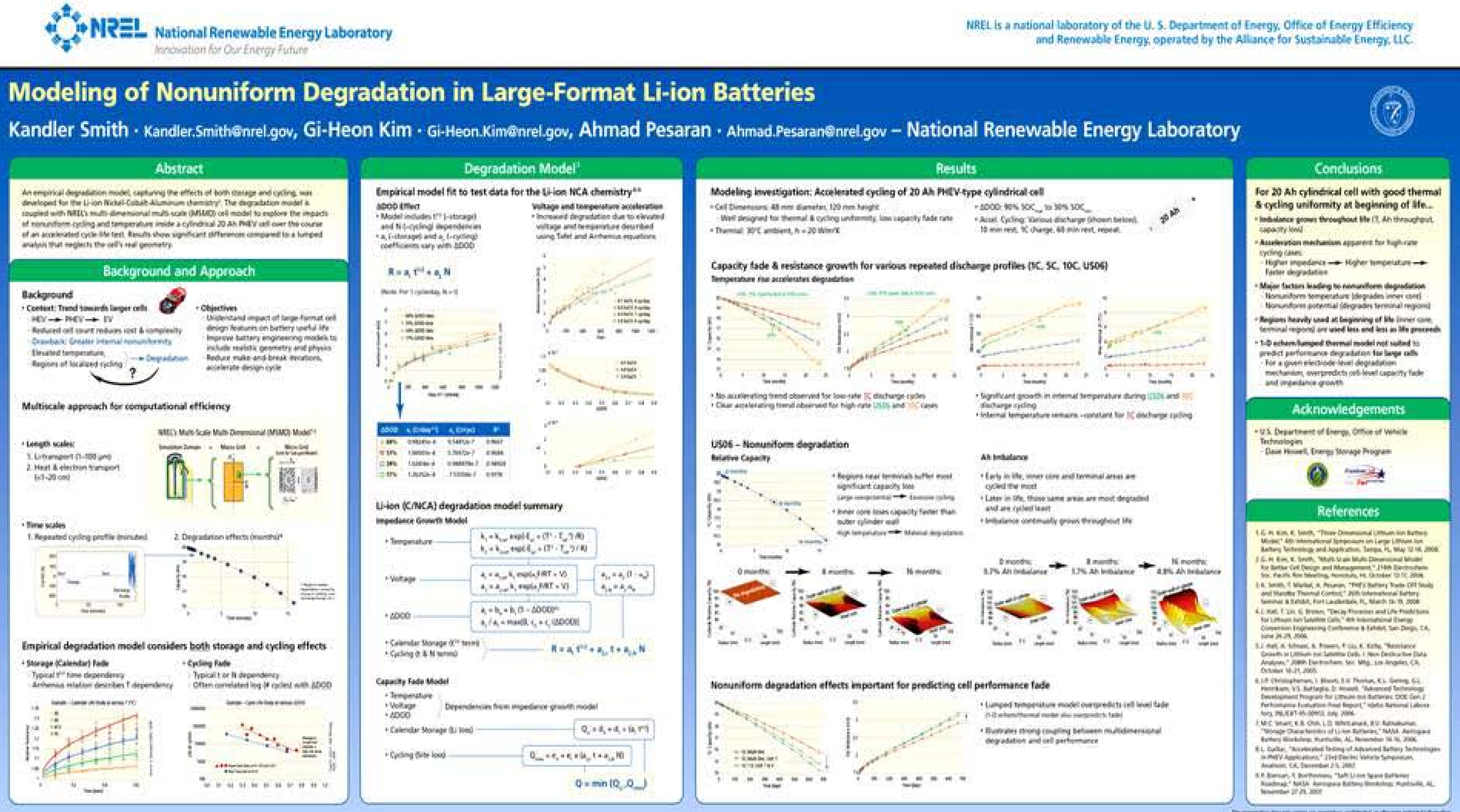
$$Q_{sites} = e_0 + e_1 \times (a_{2,t}\, t + a_{2,N}\, N)$$

$$Q = \min(\, Q_{Li}, Q_{sites}\,)$$

Reasonably fits available data

Actual interactions of degradation mechanisms may be more complex.

Details of Calendar and Cycle Life Models Are Presented by Kandler Smith in the Poster Session forAABC-09



Life Model Summary

- Model structure set by Boeing satellite battery dataset[1,2]
  - Difficult to decouple ΔDOD and voltage degradation effects from cell-level dataset

- Model adjusted to reflect more recent experience with NCA-graphite cells from various Labs [3-6]
  - 4.5 years storage at 40°C, 50% SOC → 10% capacity fade[4]
  - 13.7 years storage at 35°C → 110% resistance growth[5]
  - 2700 PHEV charge depletion cycles at 25°C → 8% capacity fade, 50% resistance growth[6]

- The following analysis illustrates trade-offs for a cell with low capacity fade but high resistance growth over life.

References:
1. J. Hall, T. Lin, G. Brown, "Decay Processes and Life Predictions for Lithium Ion Satellite Cells," 4th International Energy Conversion Engineering Conference & Exhibit, San Diego, CA, June 26-29, 2006.
2. J. Hall, A. Schoen, A. Powers, P. Liu, K. Kirby, "Resistance Growth in Lithium Ion Satellite Cells. I. Non Destructive Data Analyses," 208th Electrochem. Soc. Mtg., Los Angeles, CA, October 16-21, 2005.
3. J.P. Christophersen, I. Bloom, E.V. Thomas, K.L. Gering, G.L. Henriksen, V.S. Battaglia, D. Howell, "Advanced Technology Development Program for Lithium-Ion Batteries: DOE Gen 2 Performance Evaluation Final Report," Idaho National Laboratory, INL/EXT-05-00913, July, 2006.
4. M.C. Smart, K.B. Chin, L.D. Whitcanack, B.V. Ratnakumar, "Storage Characteristics of Li-Ion Batteries," NASA Aerospace Battery Workshop, Huntsville, AL, November 14-16, 2006.
5. P. Biensan, Y. Borthomieu, "Saft Li-Ion Space Batteries Roadmap," NASA Aerospace Battery Workshop, Huntsville, AL, November 27-29, 2007.
6. L. Gaillac, "Accelerated Testing of Advanced Battery Technologies in PHEV Applications," 23rd Electric Vehicle Symposium, Anaheim, CA, December 2-5, 2007.

Life Analysis Conducted Using Simplified Cycling Profiles

Major input parameters that are varied.

ΔDOD

$N_{cycles/day}$

EoCV = 3.9V

(SOCmax = 90%)

Constant current profile generator

Age (Yrs)

T (°C)

V (t)

Li-ion Cell Life Model

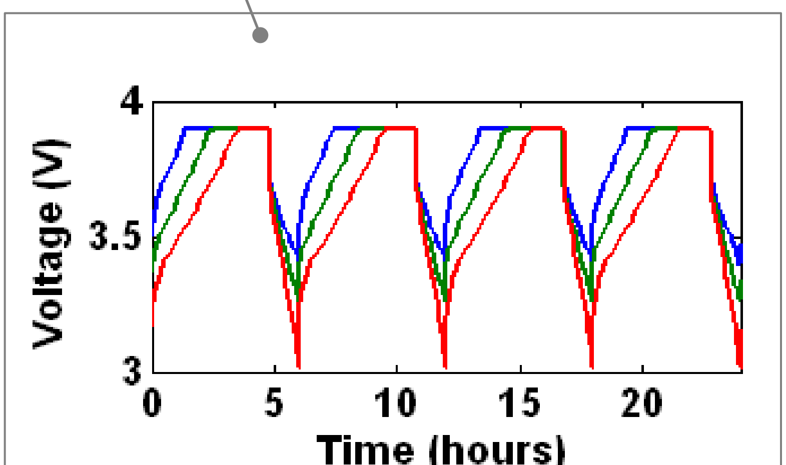
- Capacity (t)
- Resistance (t)

:

- BOL Energy & Power needed to meet EOL requirements

:

- Cost



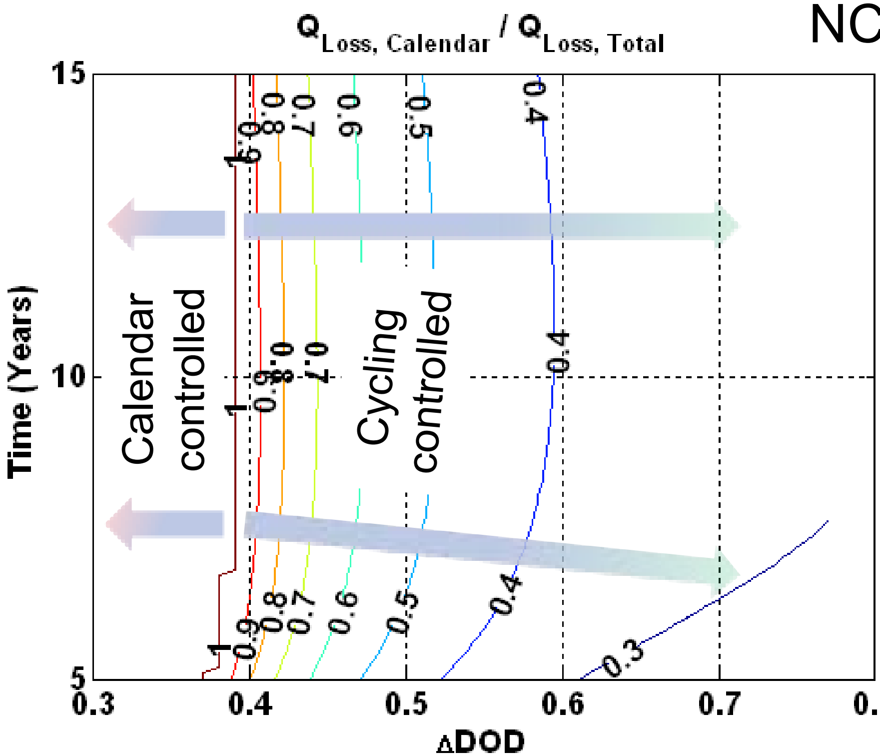
Results: Which Dominates — Calendar or Cycling?
Capacity Fade – Energy

Generally cycling controlled, though it depends on temperature

NCA chemistry

Moderate Climate

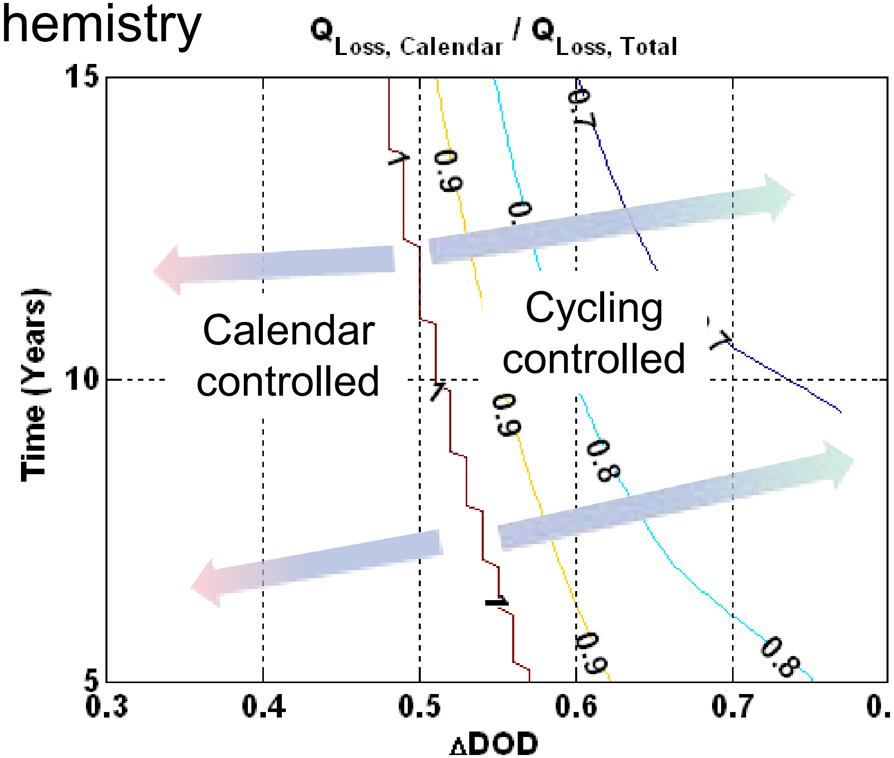
- 20°C, 1 cycle/day, SOC_{max} = 90%



- Predominantly cycling controlled
  (calendar fade just 30% to 40% of cycling fade)

Hot Climate

- 35°C, 1 cycle/day, SOC_{max} = 90%



- Cycling controlled for High ΔDOD
- Calendar controlled for Low ΔDOD

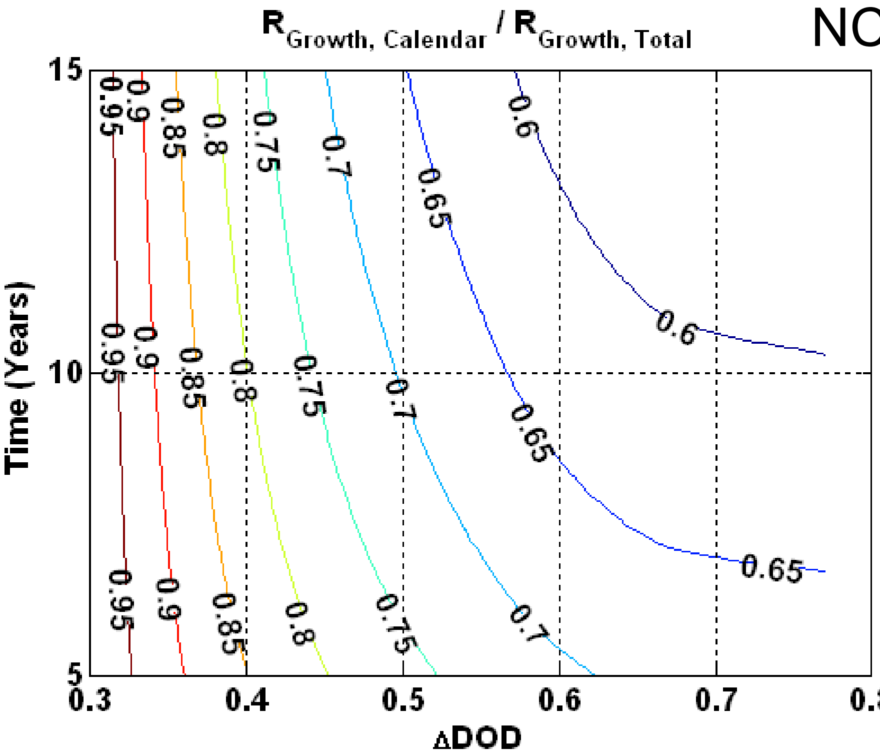
Results: Which Dominates — Calendar or Cycling?
Resistance Growth – Power

Calendar effect dominates, though both are important.

NCA chemistry

Moderate Climate

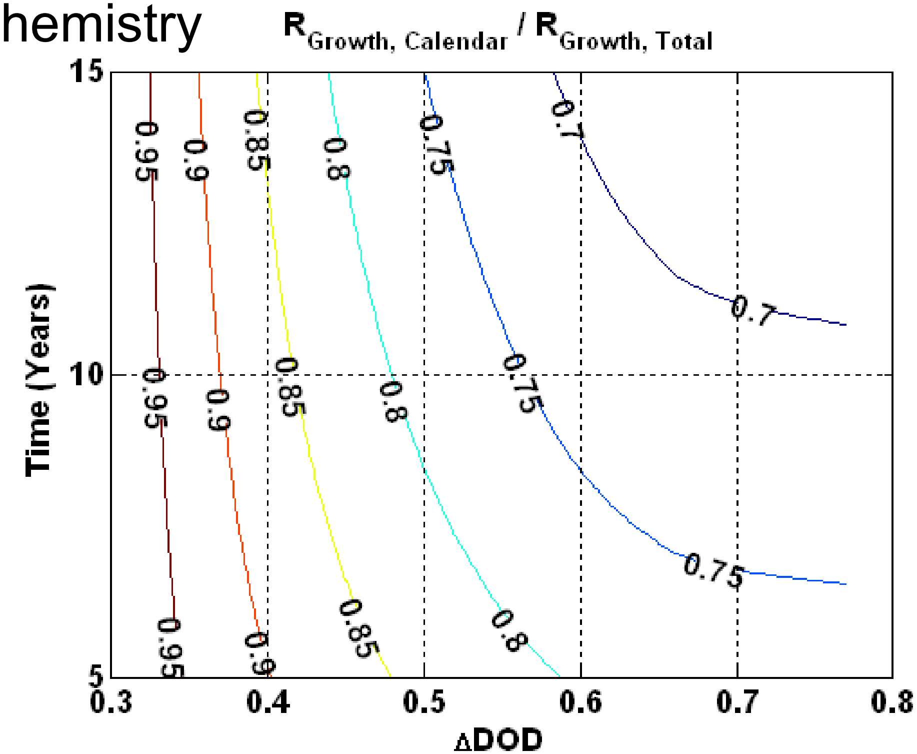
- 20°C, 1 cycle/day, SOC_{max} = 90%



- Calendar degradation:
  > 60% of total resistance growth

Hot Climate

- 35°C, 1 cycle/day, SOC_{max} = 90%



- Calendar degradation:
  > 70% of total resistance growth

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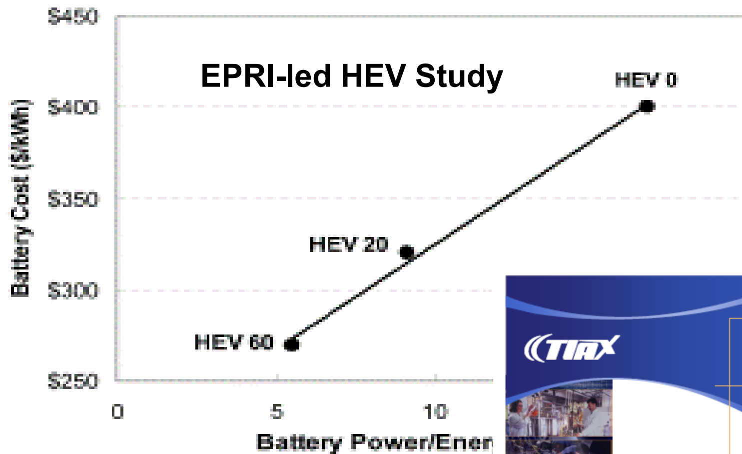
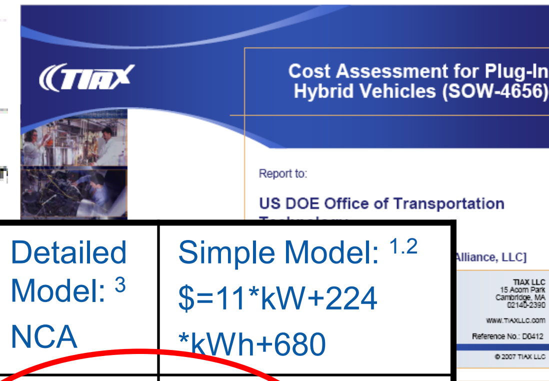
Developing a Simplified Cost Model
Estimating Manufacturer Pack Cost

- Battery cost estimates from EPRI-led HEV study as original source[1]
- EPRI HEV cost model used for NREL's EVS-22 paper on PHEV Cost Benefit Analysis[2]
- DOE-sponsored TIAX study reviewed cost details of two Li-ion cathodes (NCA and NCM) manufacturing[3]
- Modified fixed costs to include a per-cell component based on TIAX estimates (this study)
- Cost at volume manufacturing at 2007 materials' prices





Nominal Energy (kWh)	P/E	Detailed Model: [3] NCM	Detailed Model: [3] NCA	Simple Model: [1,2] $=11*kW+224*kWh+680
6.9	5.8	$3120	**$2600**	**$2660**
8.5	4.7	$3510	**$2860**	**$3020**
11.6	3.5	$4290	**$3500**	**$3680**

NCA - Nickel Cobalt Alumina; NCM- Nickel Cobalt Manganese

Simplified Pack Cost Model

$$\$/pack = 11.1*kW + 224.1*kWh + 4.53*BSF + 340$$

BSF = Battery Size Factor

1. Graham, R. et al. "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options," Electric Power Research Institute (EPRI), 2001.
2. Simpson, A., "Cost Benefit Analysis of Plug-In Hybrid Electric Vehicle Technology," *22nd International Electric Vehicle Symposium*, Yokohama, Japan, Oct. 2006.
3. "Cost Assessment for Plug-In Hybrid Vehicles," *TIAX LLC*, Oct. 2007.

Life-Cost Trade-Off Study: Approach

- Choose a cycle life model and a calendar life model
  - We picked curve fits from slide 13 for NCA chemistry
- Choose a cost model
  - Manufacturing cost of a complete pack at high-volume production
  - We picked the equation on slide 18 for NCA chemistry

- Select the required battery energy and power
  - Energy: 3.4 kWh PHEV10; 11.6 kWh PHEV40 (USABC requirements)
- Select the required battery life
  - Cycles (charge depleting): 5000 CD cycles (USABC requirements)
  - Calendar life: 10 years at 30^{o}C (less aggressive than 15-year USABC)

- Perform analysis to answer the following questions:
  - What ΔDOD & P/E meet life at minimum cost?
  - Which controls life? Calendar or cycle life?
  - What environmental parameters cause greatest life sensitivity?

Life-Cost Trade-Off: Energy and Power Margin to Meet EOL Performance Requirements

Battery Sizing Metrics:

$$\text{BOL Energy Margin} = \left[\frac{\text{BOL Total Energy}}{\text{EOL Available Energy Requirement}} - 1 \right] \times 100\%$$

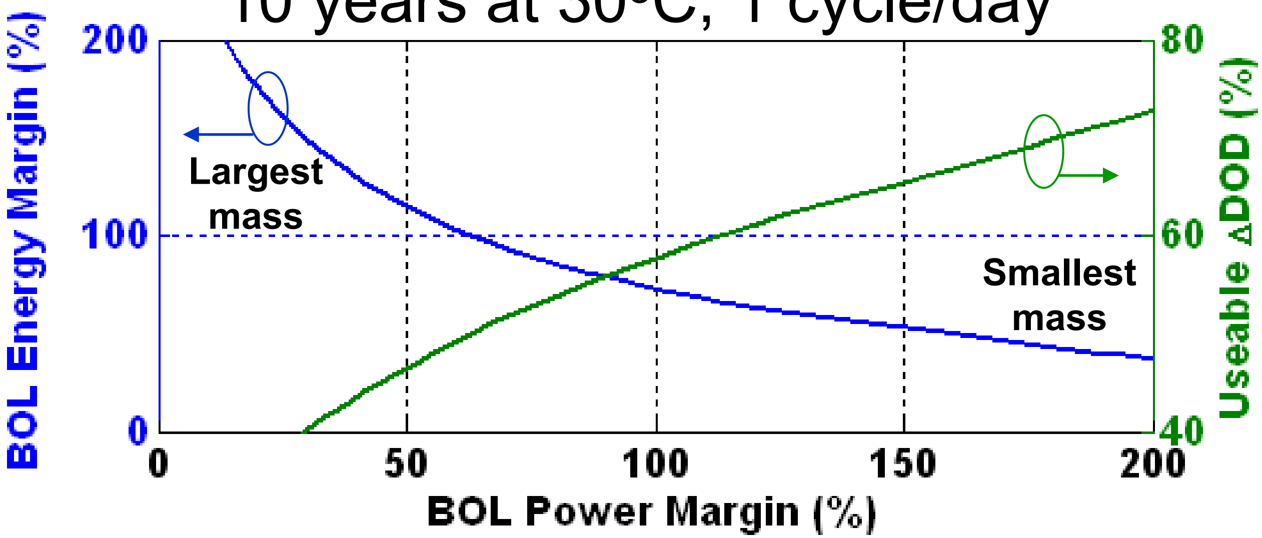
$$\text{BOL Power Margin} = \left[\frac{\text{BOL Total Power}}{\text{EOL Available Power Requirement}} - 1 \right] \times 100\%$$

BOL = Beginning of Life
EOL = End of Life

Next slides give results for **typical** Li-ion NCA chemistry and include fade for a chosen ΔDOD window (1 cycle/day, 30°C).

Example Results: Life-Cost Trade-Off Study
(Energy & Power Margin, Usable ΔDOD)

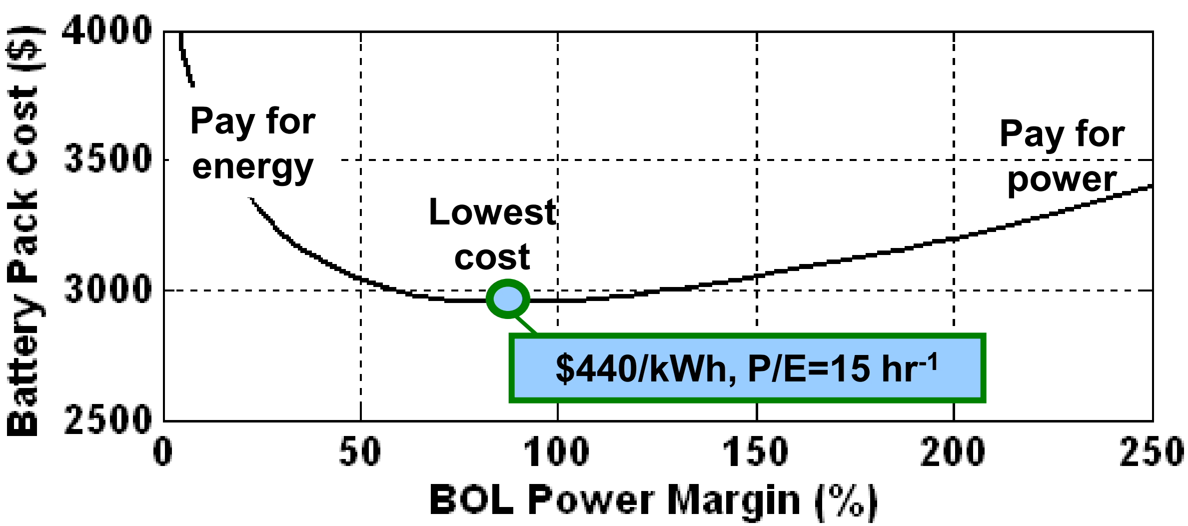
PHEV10 battery sized for
10 years at 30°C, 1 cycle/day*



NCA chemistry

- PHEV10 batteries can require >100% excess power at BOL

  Allows ~60% usable ΔDOD (More useable ΔDOD is possible with even more excess power)



- Too much power is preferable to too little
  - small increase in cost
  - reduces mass

Today's costs at volume production

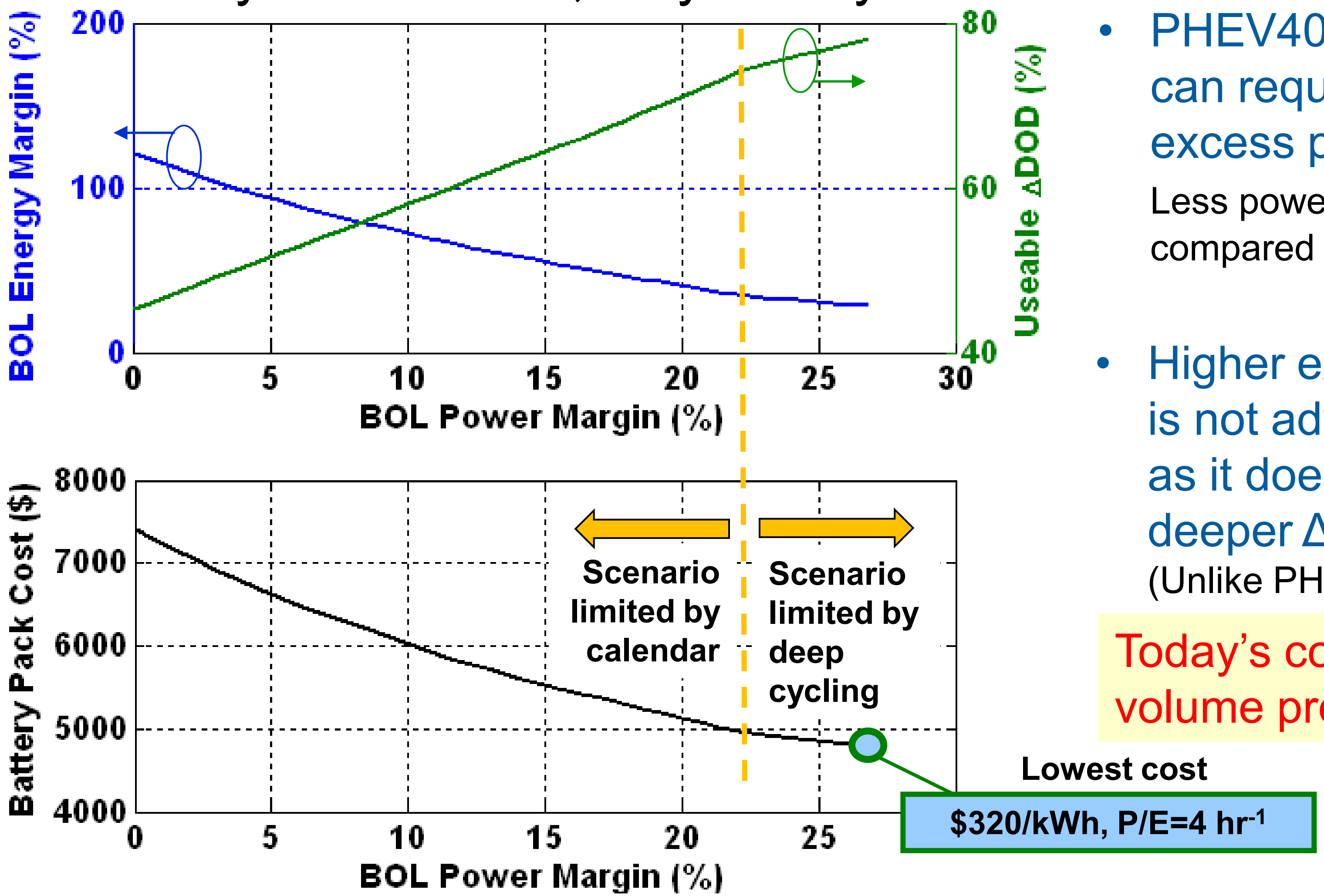
* 3.9 EoCV (90% SOC_{max})

** Excess power and energy relative to 50kW and 3.4 kWh PHEV 10 requirements

Example Results: Life-Cost Trade-Off Study

(Energy & Power Margin, Usable ΔDOD)

PHEV40 battery sized for
10 years at 30°C, 1 cycle/day*



NCA chemistry

- PHEV40 batteries can require ~25% excess power at BOL
  Less power sensitivity compared with PHEV10
- Higher excess power is not advantageous as it does not allow deeper ΔDOD cycling
  (Unlike PHEV10)

Today's costs at volume production

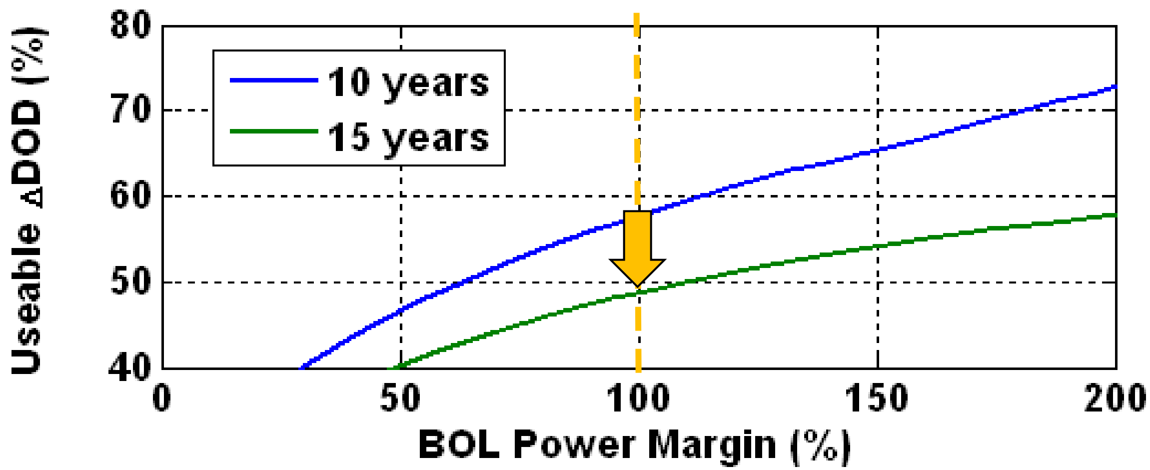
* 3.9 EoCV (90% SOC_{max})

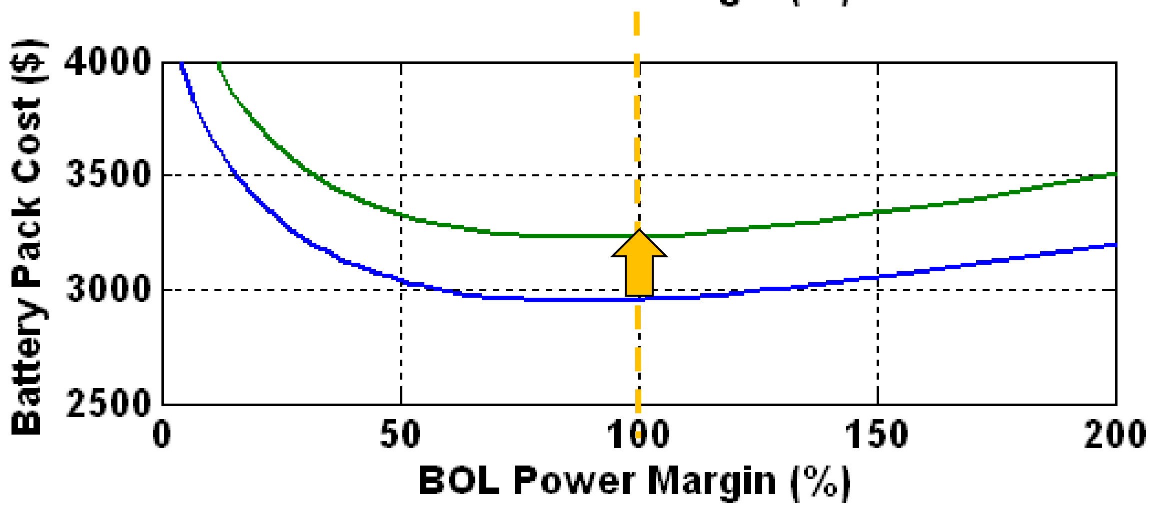
** Excess power and energy relative to 46kW and 11.6 kWh PHEV 40 requirements

Example Results: Life-Cost Trade-off Study
(Sensitivity to Years of Life)

PHEV10 battery sized for
10, 15 years at 30°C*

NCA chemistry





Increasing life requirement from 10 to 15 years means:

- 10% less ΔDOD is usable
- $250 greater cost

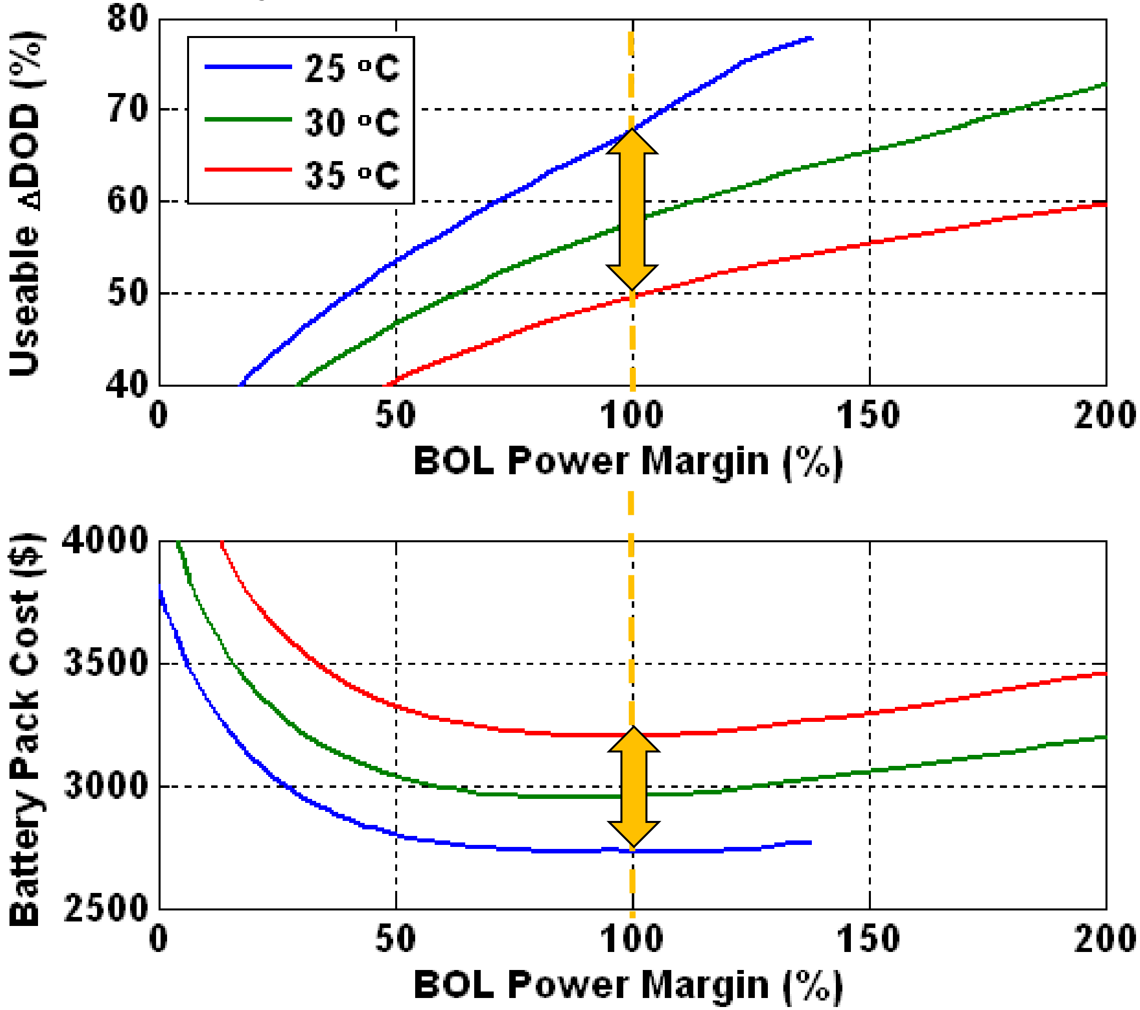
* 1 cycle/day, 3.9 EoCV (90% SOC_{max})

** Excess power relative to 50kW PHEV 10 requirement

Example Results: Life-Cost Trade-Off Study
(Temperature Sensitivity)

PHEV10 battery sized for 10 years at 25°C, 30°C, & 35°C*

NCA chemistry



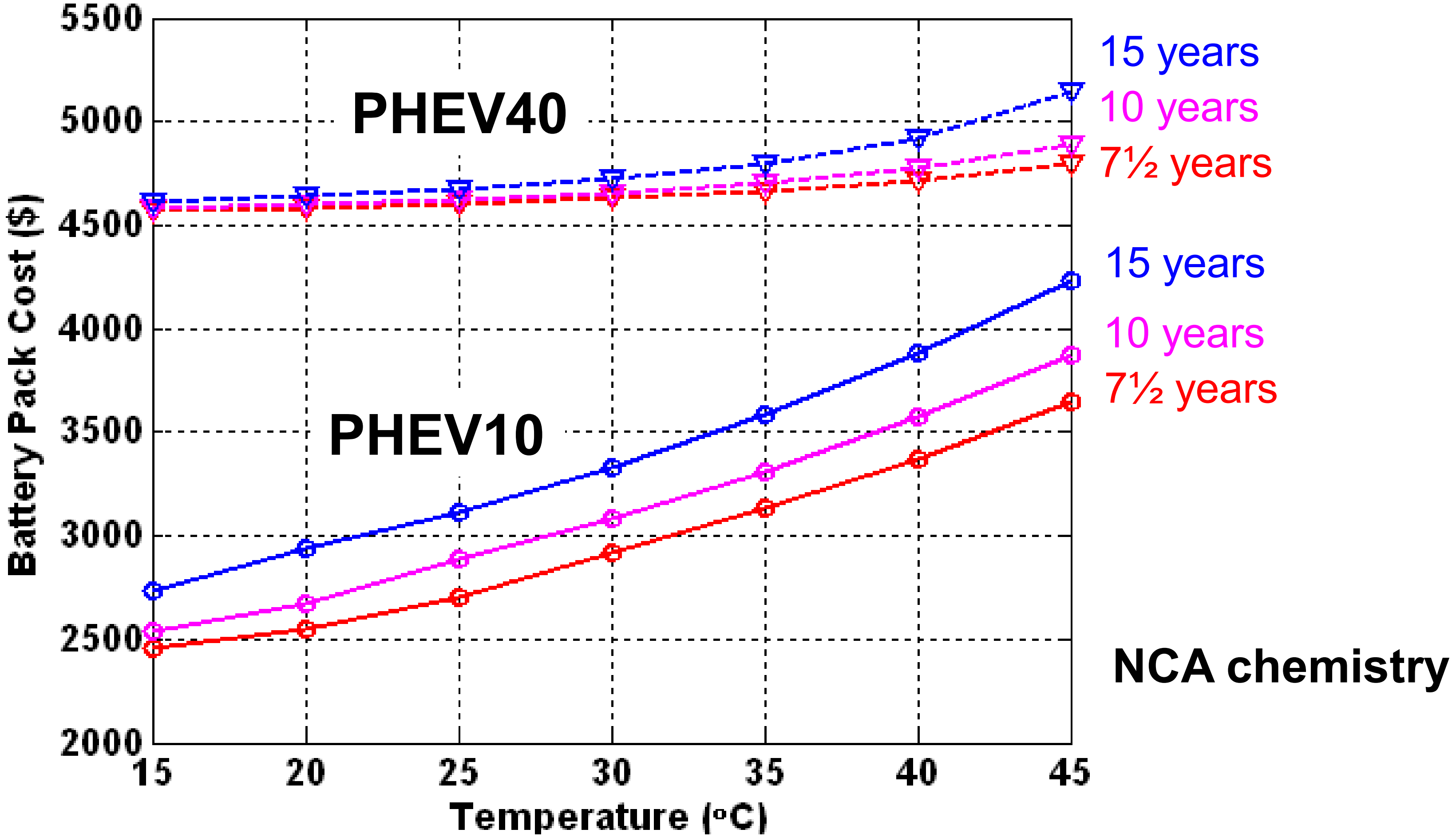
- Temperature exposure drastically impacts system size necessary to meet goals at end of life
  - 25°C: 70% ΔDOD is usable
  - 35°C: 50% ΔDOD is usable
- Modifying life requirements from 10 years at 25°C to 10 years at 35°C increases battery cost by >$500

* 1 cycle/day, 3.9 EoCV (90% SOC_{max}) ** Excess power relative to 50kW PHEV 10 requirement

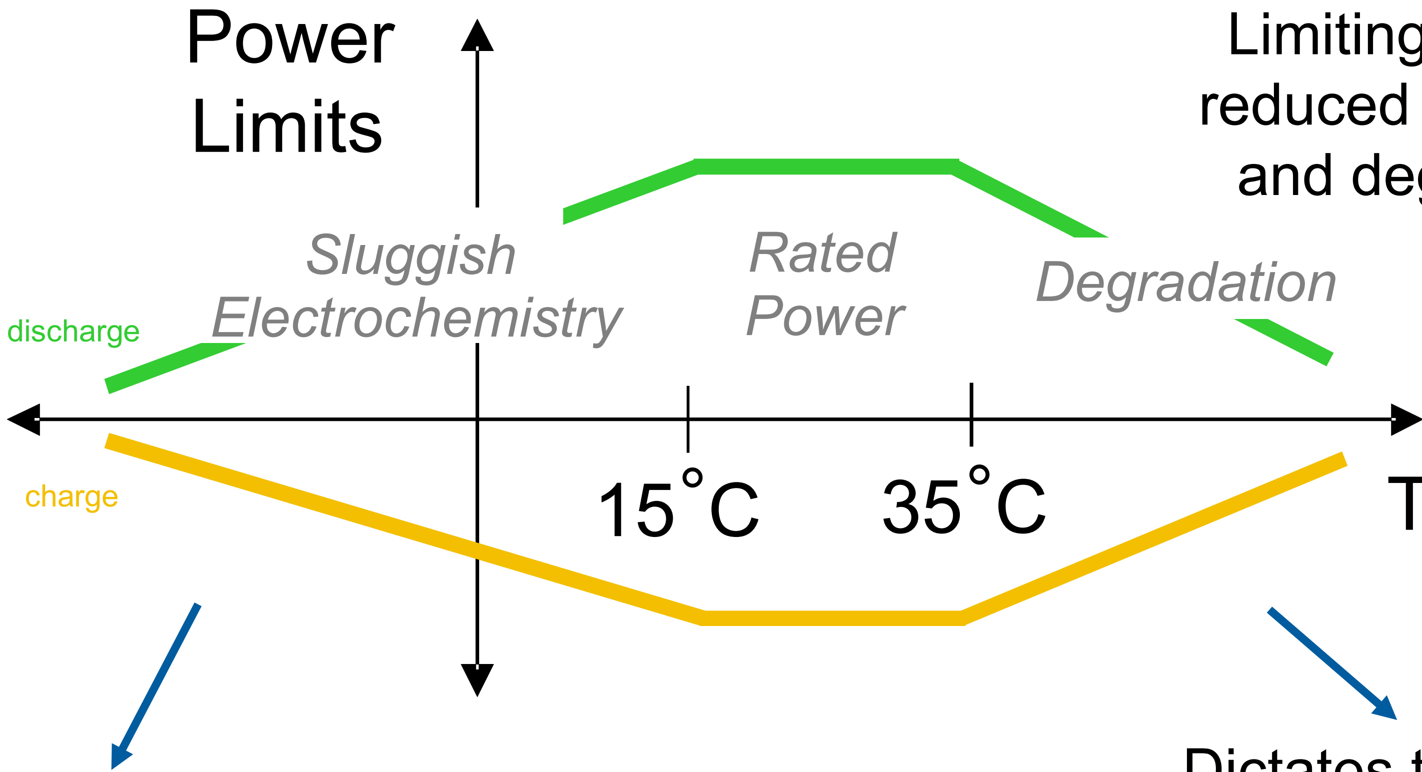
Summary: Comparison of Battery Minimum Cost Designs for Varying Years of Life and Temperature

- Battery replacement not economically justified
- Cost can be ***more sensitive to temperature than years life***

  (Especially true for small PHEV batteries with high power requirement)



Temperature Impacts Cost (Sizing & Life)



Limiting power to reduced T increase and degradation

Dictates power capability through cold cranking

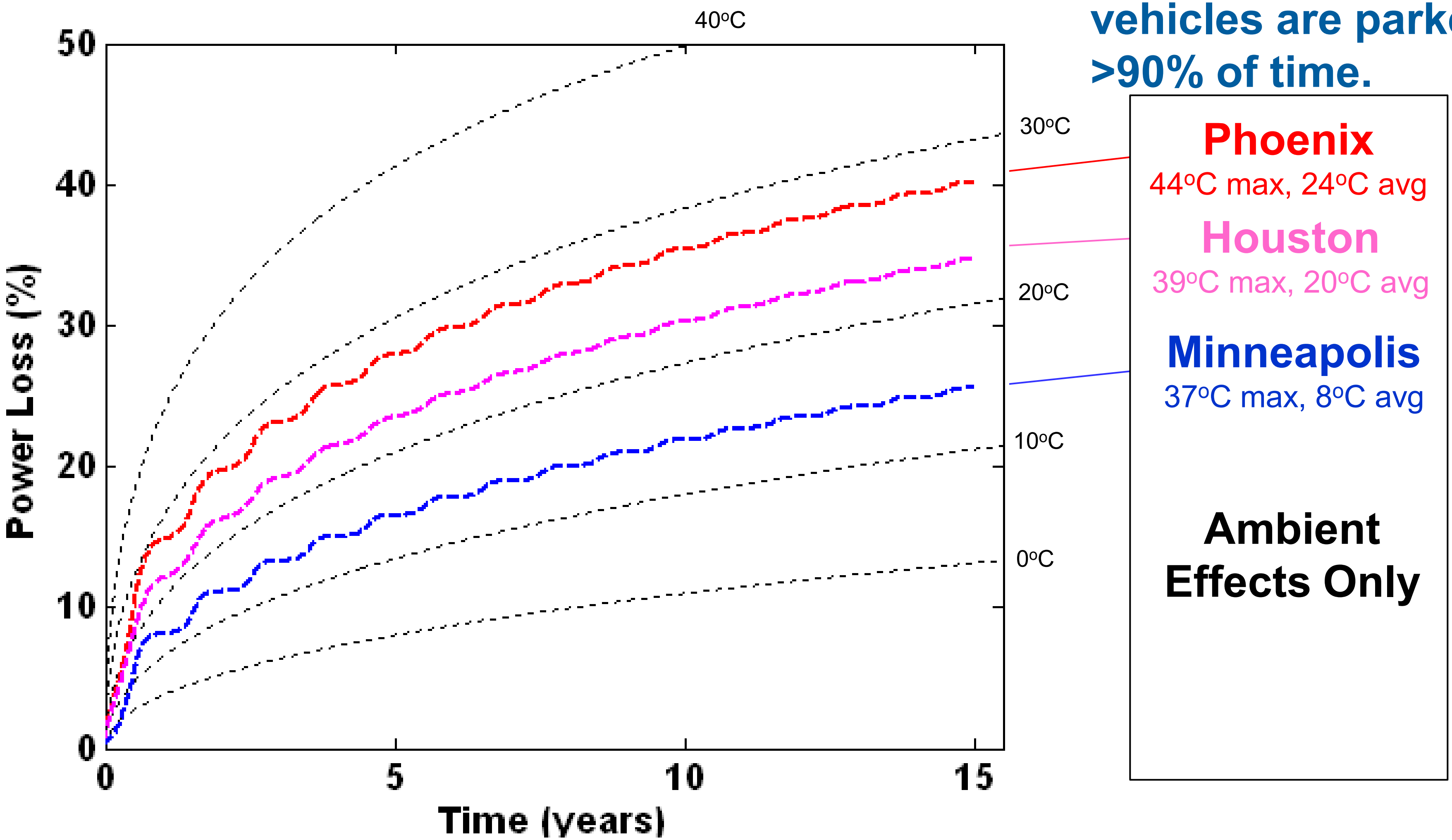
Dictates the size depending on the power and capacity fade rate

Impact of Temperature on Battery in a Parked Car

(Battery T = Ambient T)

- *Used typical metrological year (TMY) as the hourly temperature*
- *Power fade model reformulated as rate law, integrated for temperature profile.*
- *PHEV10 with a typical quality NCA chemistry.*

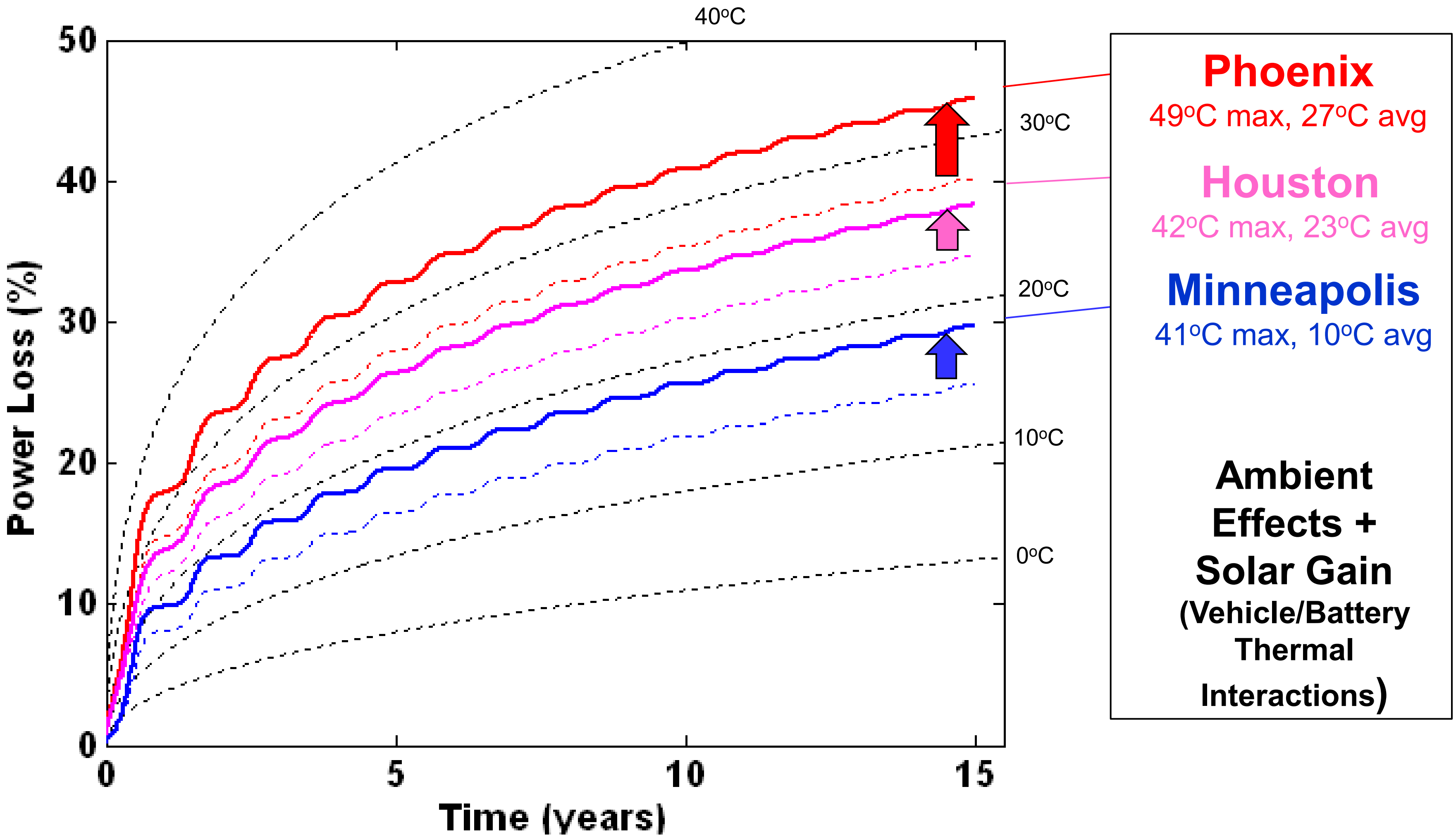
Most passenger vehicles are parked >90% of time.



Impact of Temperature on Battery in a Parked Car

(Battery T = Ambient T + Solar Gain)

- *The same as previous slide (PHEV10, NCA chemistry and TYM weather)*
- *Developed a vehicle-battery-ambient model to predict the battery temperature*
- *Results show significant fade due to the ambient temperature and solar gain*



Ambient Effects + Solar Gain
(Vehicle/Battery Thermal Interactions)

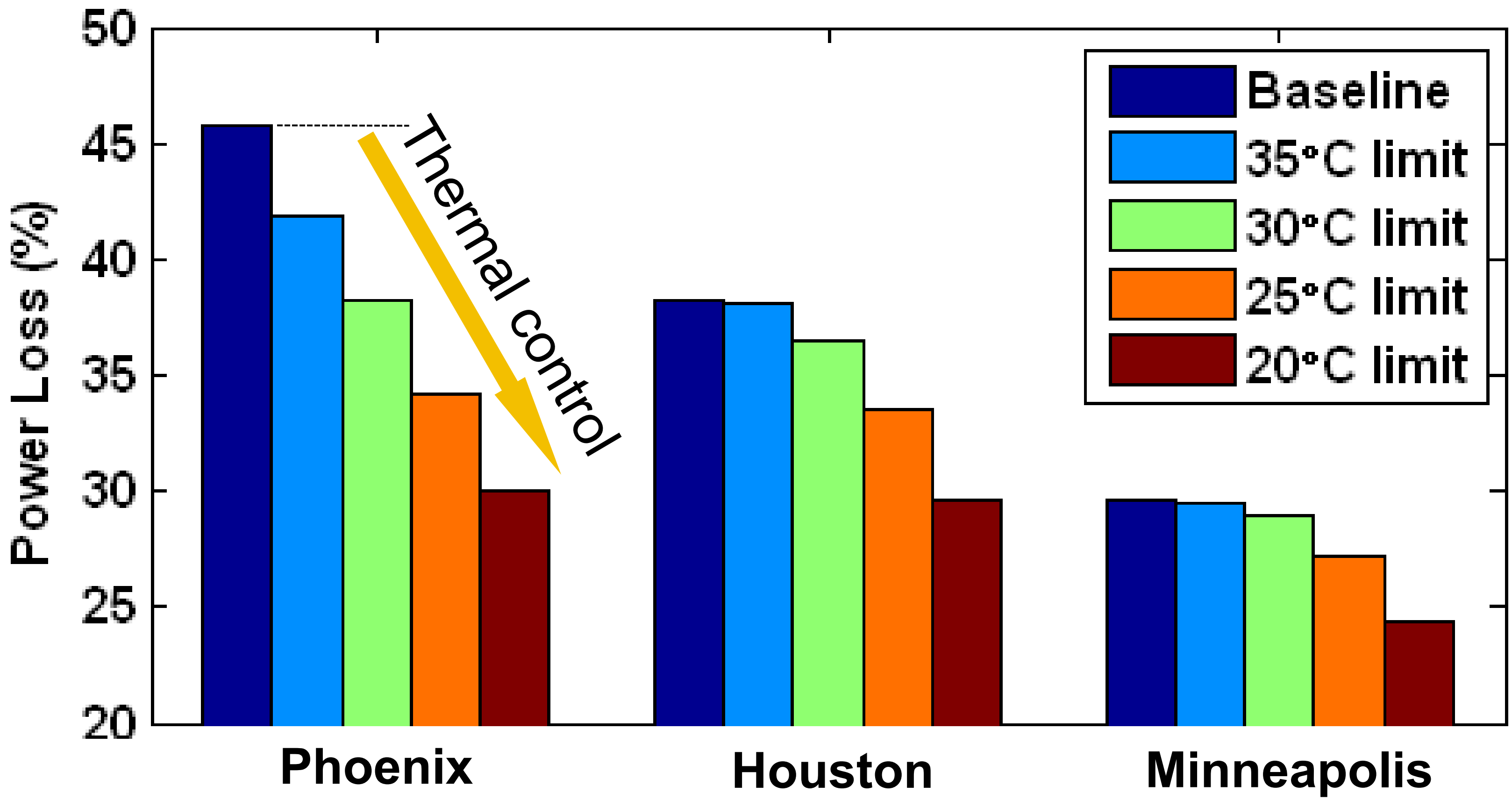
Analysis Shows Keeping Peak Battery Temperature below Extremes Could Greatly Improve Battery Life

PHEV10 – Power loss after 15 years

Ambient temperature & solar radiation climate data input to vehicle/battery thermal model.
Assume peak battery temperatures can be eliminated.

Typical Quality Current NCA Li-ion Technology

How much is it worth to spend on thermal control (parked too)?



Summary

- Battery <u>c</u>ost, <u>c</u>ycle life, and <u>c</u>alendar life must be optimized to achieve maximum value for PHEV commercialization.
  - A process/approach such as the one discussed here is needed.
- Useful life of a given pack design is dictated by complex interaction of parameters ($t^{1/2}$, t, N, T, V, DOD).
  - Different chemistries have different behaviors.
- Battery life is extremely sensitive to temperature exposure; solar loading can cause further battery heating and lower life.
- Thermal control (when parked or driving) could be a cost-effective method to reduce oversizing of battery for the beginning of life.
- PHEV battery "standby" thermal control can reduce power loss, particularly for PHEV10.
- Accurate degradation prediction requires a large experimental matrix (for different chemistries).

www.nrel.gov/vehiclesandfuels/energystorage/