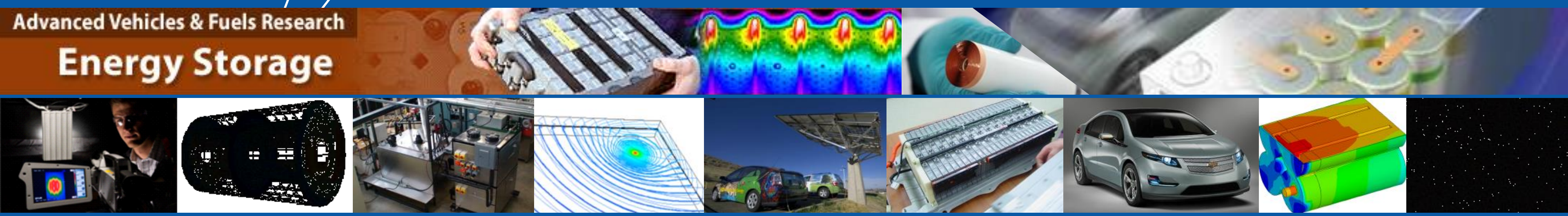
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Battery Technologies for Heavy Duty Electric Vehicles

A Webinar for Members of APTA



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AMERICAN PUBLIC TRANSPORTATION ASSOCIATION

August 19, 2015

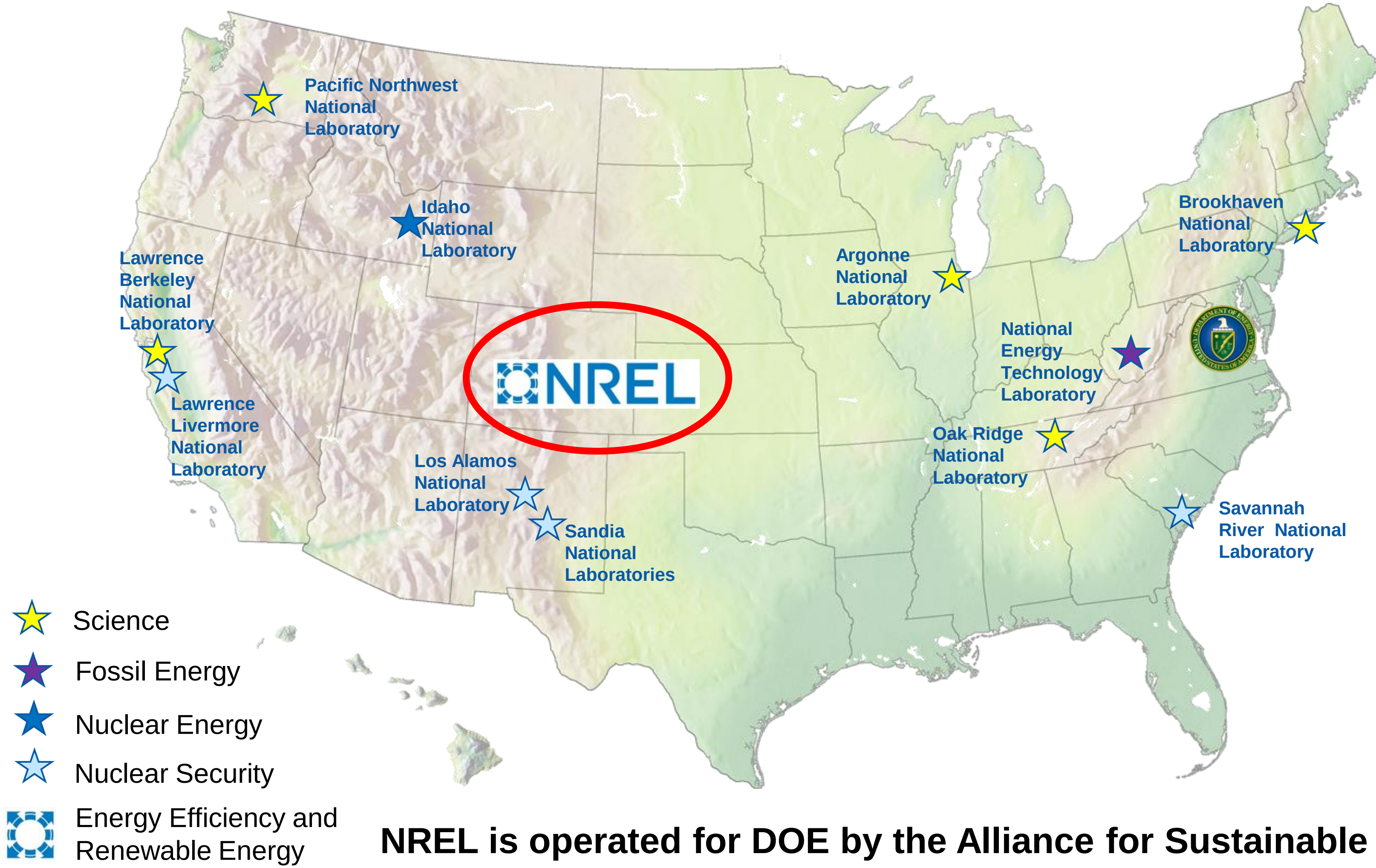
Funding for NREL Battery R&D is Provided by US. Department of Energy, Vehicle Technologies Office

Outline

- Introduction to NREL and Transportation Programs
- General information on Li-Ion technologies/chemistries
- Operational characteristics – power, energy, life, cost
- Battery requirement for heavy duty vehicles
- Battery system integration considerations in vehicles
- NREL research program activities and capabilities
- Battery testing and modeling activities

National Renewable Energy Laboratory

NREL is the only DOE national laboratory dedicated to renewable and energy-efficient technologies



NREL is operated for DOE by the Alliance for Sustainable Energy

(Midwest Research Institute and Battelle)

NREL's Portfolio
Energy Efficiency and Renewable Energy

Electricity

- Renewable Electricity
- Electric Systems Integration
- Net-Zero Energy Buildings

From Concept to Consumer

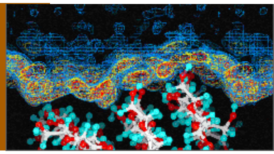
Fuels/Transportation

- Renewable Fuels
- Efficient and Flexible Vehicles

International Programs **Strategic Analysis** **Integrated Programs**

Underpinned with Science

Photoconversion Computational Science Systems Biology



NREL Transportation RD&D Activities & Applications

Vehicle Thermal Management
Integrated Thermal Management
Climate Control/Idle Reduction
Advanced HVAC

Vehicle Deployment/Clean Cities
Guidance & Information for Fleet Decision Makers & Policy Makers
Technical Assistance
Online Data, Tools, Analysis

Regulatory Support
EPAct Compliance
Data & Policy Analysis
Technical Integration
Fleet Assistance

Infrastructure
Vehicle-to-Grid Integration
Integration with Renewables
Charging Equipment & Controls
Fueling Stations & Equipment
Roadway Electrification
Automation

Advanced Combustion/Fuels
Advanced Petroleum and Biofuels
Combustion/Emissions Measurements
Vehicle & Engine Testing

Vehicle and Fleet Testing
MD/HD Dynamometer Testing
MDV & HDV Testing/Analysis
Drive Cycle Analysis/Field Evaluations
Technology Performance Comparisons
Data Collection, Storage, & Analysis
Analysis & Optimization Tools

Advanced Power Electronics and Electric Motors
Thermal Management
Thermal Stress and Reliability

Advanced Energy Storage
Development, Testing, Analysis
Thermal Characterization/Management
Life/Abuse Testing/Modeling
Computer-Aided Engineering
Electrode Material Development

Illustration by NREL

Medium- and Heavy- Vehicle Field Testing Approach

Evaluate the performance of alternative fuels and advanced technologies in medium- and heavy-duty fleet vehicles - in partnership with commercial and government fleets and industry groups vehicles.

Collect, analyze and publicly report data:

- Drive cycle and system duty cycle analysis
- Operating cost/mile
- In-use fuel economy
- Chassis Dynamometer emissions and fuel economy
- Scheduled and unscheduled maintenance
- Warranty issues
- Reliability (% availability, MBRC)
- Implementation issues/barriers
- Subsystem performance data & metrics (ESS, engine, after-treatment, hybrid/EV drive focus)

Data stored in FleetDNA for security and limited public accessibility

Frequent interactions and briefings with stakeholders – fleets, technology providers, researchers, and government agencies

Fleets

UPS, FedEx, Coke, Frito-Lay, Foothill Transit, PG&E, Miami-Dade, Verizon, Walmart, Waste Management

+

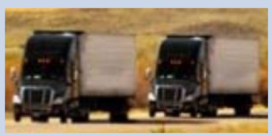
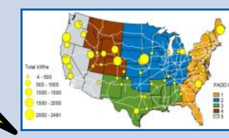
Vehicle & Equip Mfg's

Proterra, Navistar, Smith EV, Eaton, Allison, BAE, EDI, Altec, International, PACCAR, Oshkosh, Odyne, Parker-Hannifin, Cummins

=

Useful Data, Analysis and Published Reports

Current Heavy Vehicle Evaluation Projects

Current DOE Projects		ARRA EV Fleet Data Collection Projects
UPS HHV Solazyme biofuel 	Miami HHV Refuse Trucks 	Smith Newton 
Frito Lay EV 	Natural Gas Refuse Trucks 	Navistar eStar 
Fleet Platooning 	Battery EV Transit Bus 	Truck stop Electrification 
PG&E Electrified Utility Trucks 	EV – V2G School Bus 	Odyne PHEV 
SCAQMD • Fleet DNA • Zero Emissions Cargo Transport 	**CA Air Resources Board (CARB)** • Heavy Hybrid Vehicle Analysis • Aerodynamics Device Testing	**EPA** Heavy-Duty Phase II GHG Drive Cycle Development

Projects that involve electric drives

Commercial and Public EV Applications

Opportunities and Challenges associated with Medium- and Heavy-duty Commercial EV Applications

Electrified Utility Work Trucks

- Utility fleets expanding use of electrified vehicles alternatives
- Ability to provide off-board power for equipment or to power a small community
- Quiet and clean operation in neighborhoods or other noise-sensitive areas

EV and PHEV Delivery Vehicles

- Currently being demonstrated by large commercial fleets such as UPS, FedEx, Coke, Frito-Lay,
- Opportunity to integrate EV with efficient fleet facilities (V2B)
- Large batteries have potential secondary-use applications

Electric Buses

- Clean and quiet operation in urban centers
- Federal funding opportunities promote clean, efficient transit solutions
- Fixed routes and centralized operations allow for innovative solutions such as fast charging, wireless charging, electrified roadways, and integration with transit facilities

Zero Emissions Cargo Transport

- Zero emission cargo transport and major ports, e.g. Port of LA / Long Beach
- Centralized operations – potential for catenary electrification
- Zero idle emissions

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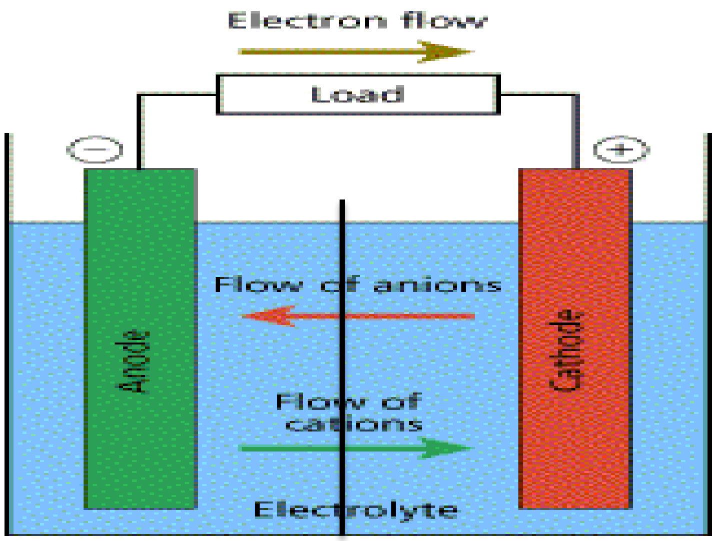
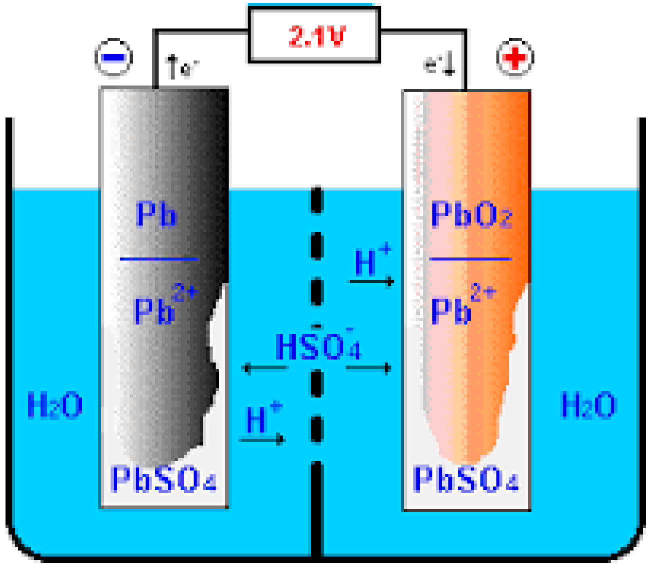
Battery Working Principles

- A battery is a device consisting of two or more electrochemical cells that convert stored chemical energy into electrical energy.
- Current flows between positive terminal (cathode) and a negative terminal (anode), isolated by a separator
- The cathode is at a higher electrical potential energy than anode.
- When a battery is connected to an external circuit, electrolyte allows ions (generated from chemical reactions) to move between cathode and anode.
- It is the movement of those ions within the battery which allows current to flow out of the battery to perform work.

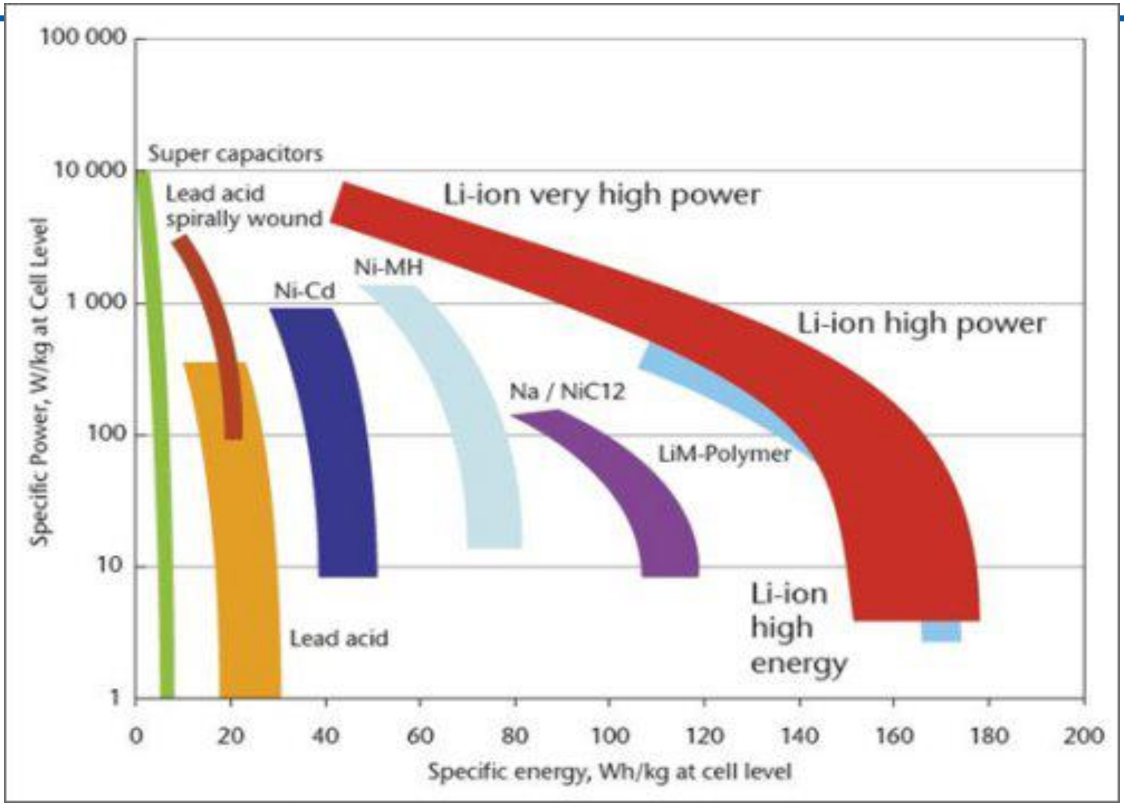


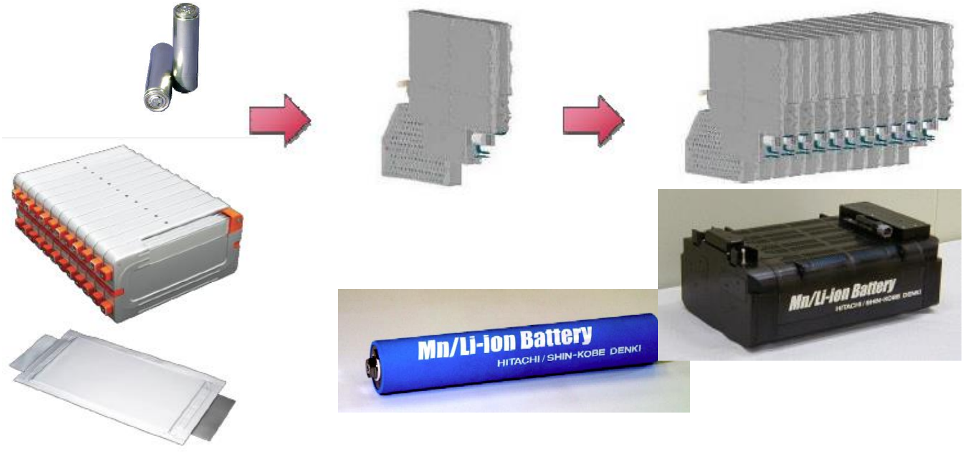


Lead Acid Battery – Conversion Type

Li-Ion Batteries: Choice for xEVs

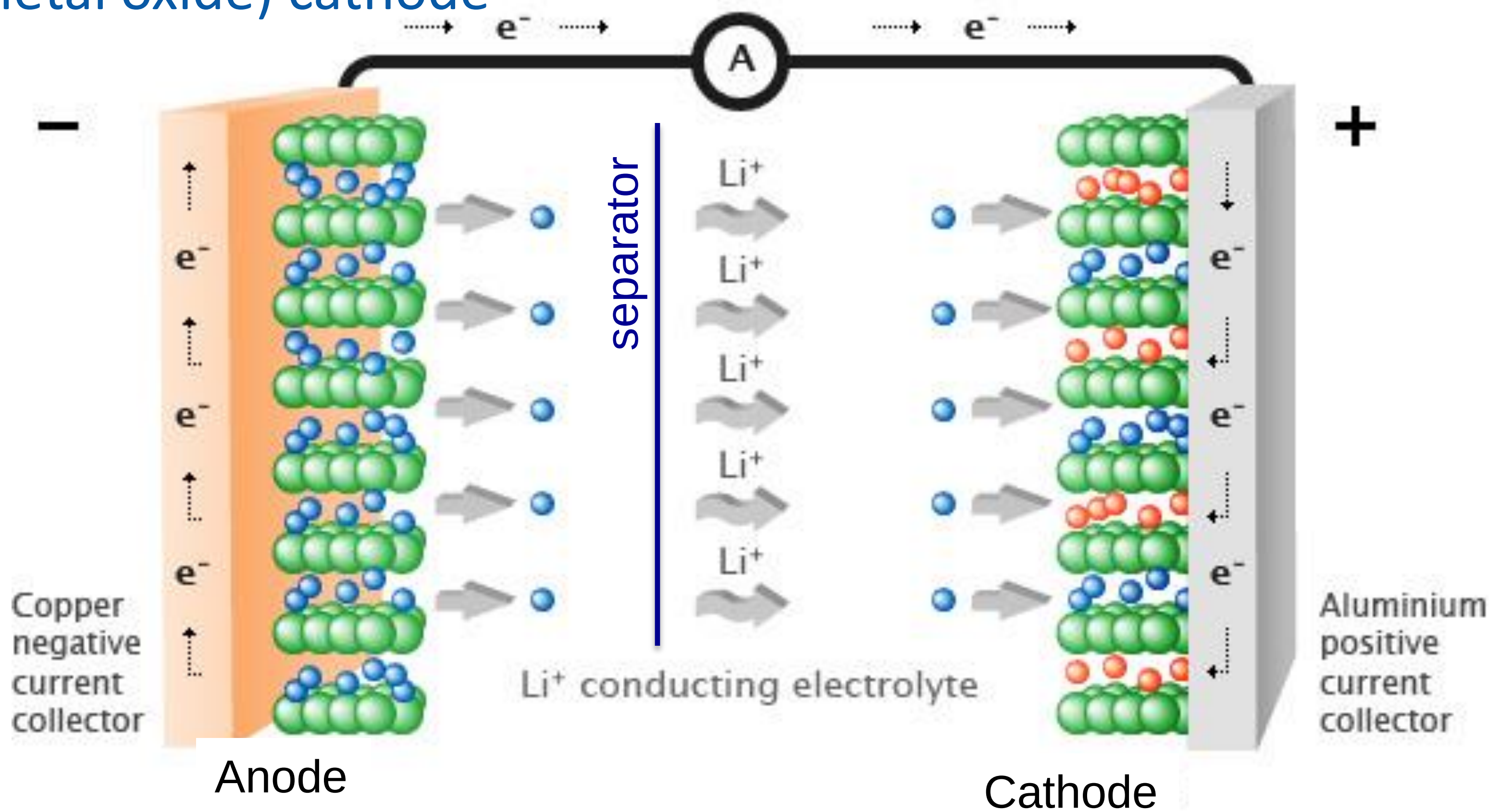
- Lithium-ion battery technology is expected to be the energy storage choice for (xEVs) in the coming years
- Better (energy & power) performance than other existing technologies
- Trends toward large format cells
  - Higher volume &weight efficiencies and packaging
  - Lower # of connections and components
  - Lower system cost



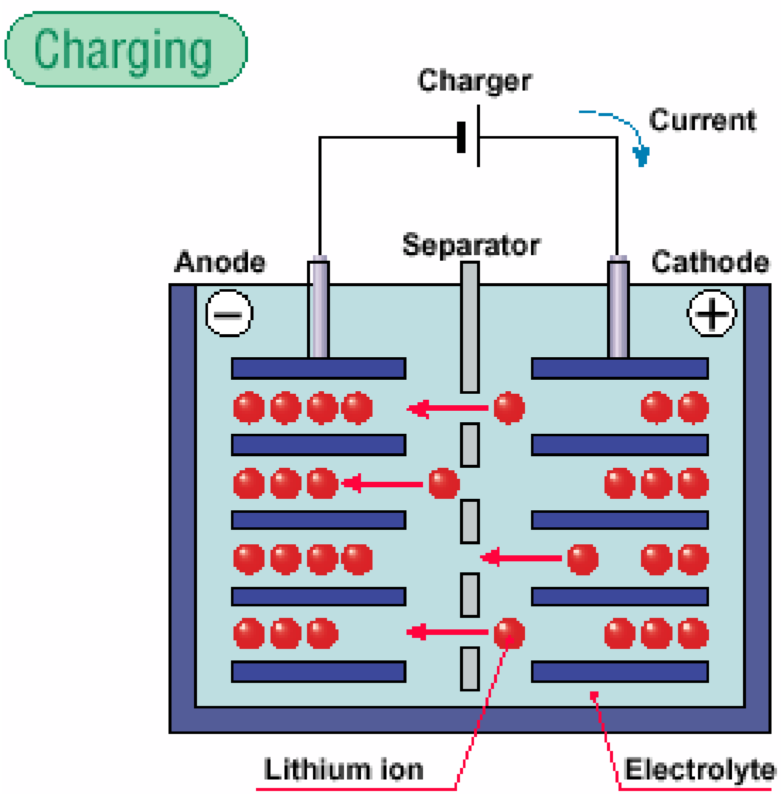


Lithium-Ion Battery Working Principles

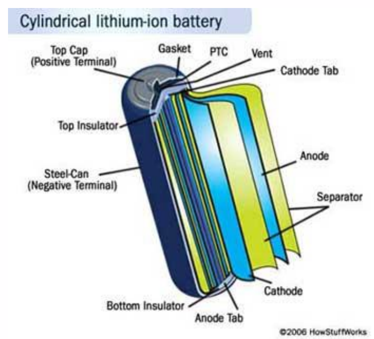
- Li-Ion cell stores energy by intercalation of charged lithium ions in a (graphite) anode
- Li-Ion cell releases energy by transferring these ions through an organic electrolyte to a lower energy intercalated state in a (metal oxide) cathode

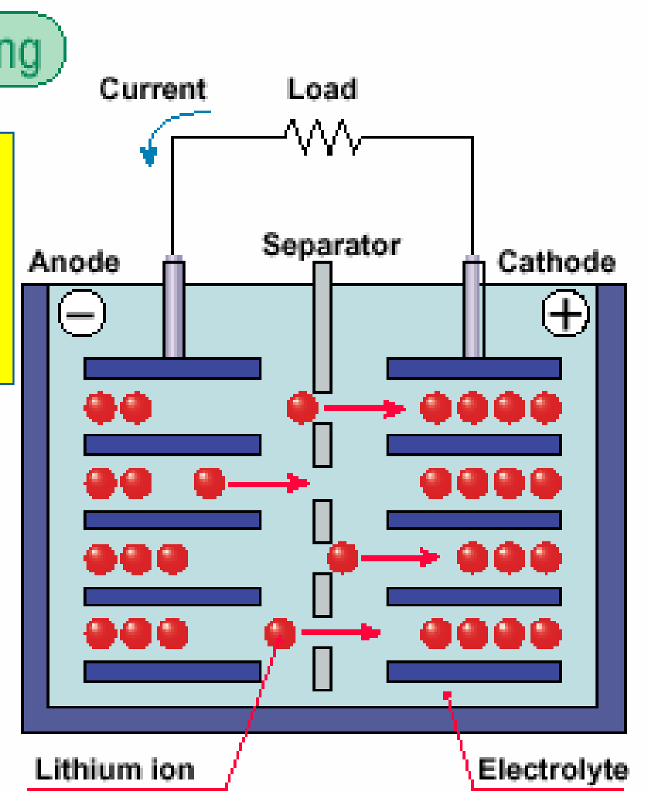


Lithium Ion Battery Technology—Many Chemistries



Voltage ~3.2-3.8 V
Cycle life ~1000-5000
Wh/kg >150
Wh/l >400
Discharge -30 to 60ºC
Shelf life <5%/year





Many anodes are possible
Carbon/Graphite
Titanate ($Li_4Ti_5O_{12}$)
Silicon based
Metal oxides

Many electrolytes are possible
Salts like $LiPF_6$ and $LiBF_4$ added
Dimethyl or ethylene carbonates
Various solid electrolytes
Polymer electrolytes
Ionic liquids

Many cathodes are possible
Cobalt oxide
Manganese oxide
Mixed oxides
Iron phosphate
Rich Li, Mn, or Ni mixed oxides

Source: Robert M. Spotnitz, Battery Design LLC, "Advanced EV and HEV Batteries"

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Li-ion Cell Configurations

- Cylindrical:
  - Jellyroll
  - Hard can

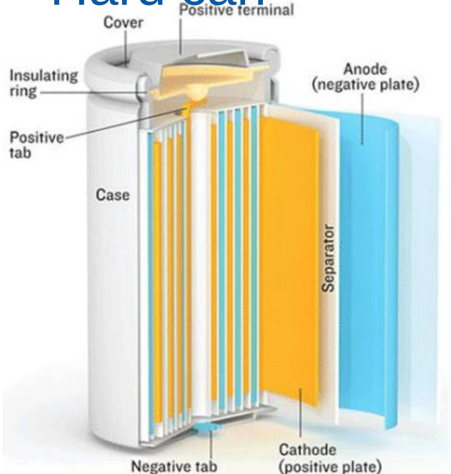


Photo Credit: http://sustainablemfr.com/energy-efficiency/lowering-costs-lithium-ion-batteries-ev-power-trains#lithium

Photo Credit: https://en.wikipedia.org/wiki/List_of_battery_sizes

- Prismatic:
  - Wound or stacked layers
  - Soft pouch or hard can

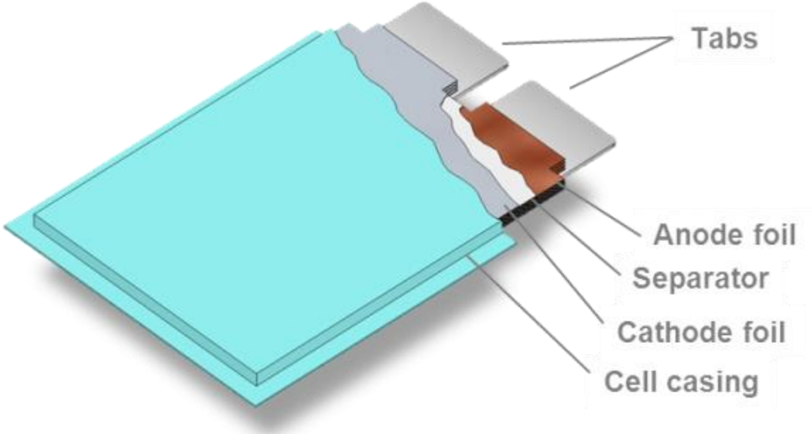
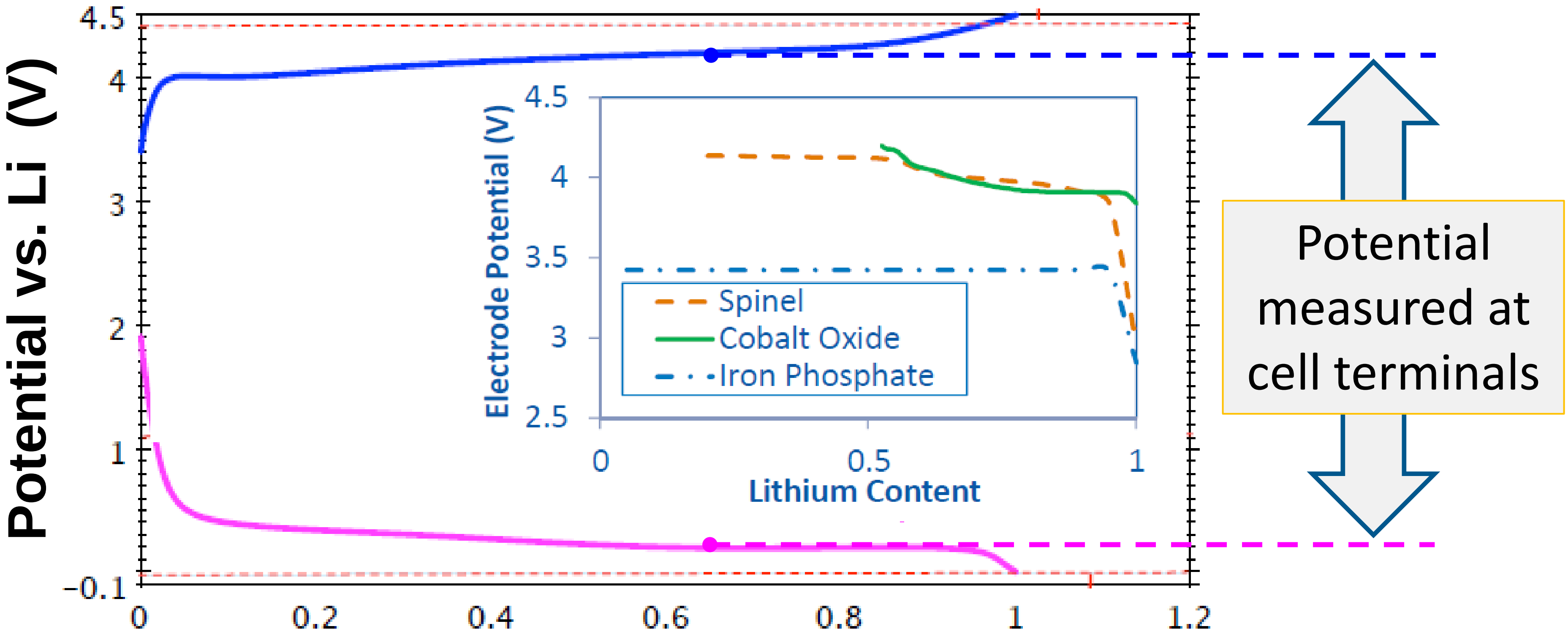


Photo Credit: http://ewi.org/ultrasonic-metal-welding-for-lithium-ion-battery-cells/

Photo Credit: NREL-Dirk Long

Electrochemical Operating Window

0% SOC — charge → / ← discharge — 100% SOC



SOC

(x in Li_xC_6 or y in $Li_{1-0.6y}CoO_2$)

Figure credit: Ilan Gur (ARPA-E) & Venkat Srinivasan (LBNL), 2007

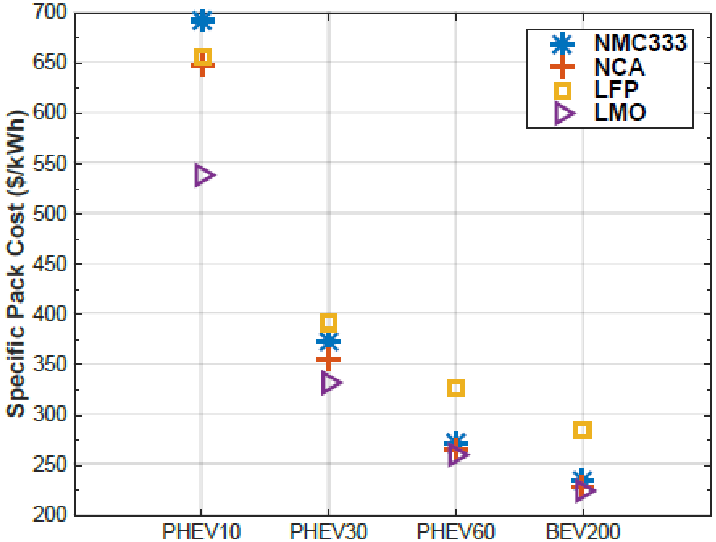
Comparison of Chemistries

Positive electrodes

- Iron phosphate only competitive for power applications
- LMO lowest cost, but life-limited
- NMC is present market-winner. Efforts to reduce Ni content (most expensive metal)
- NCA & LCO have good life, but poor safety and energy density

Negative electrodes

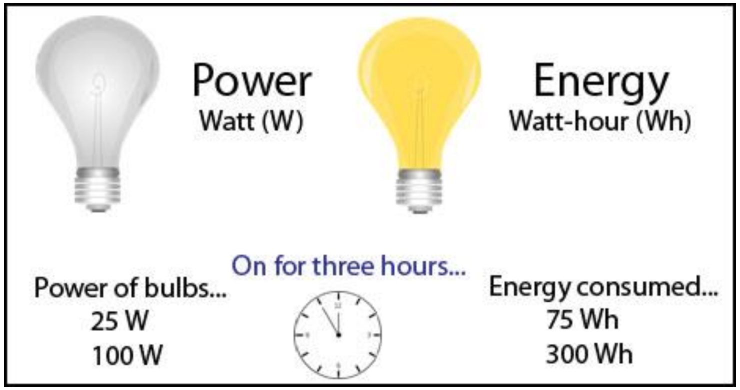
- Graphite inexpensive, used almost exclusively
  - Limited charge rate (Li plating)
  - Calendar life limited (SEI growth)
- Titanate is fast charge alternative
  - Low energy density



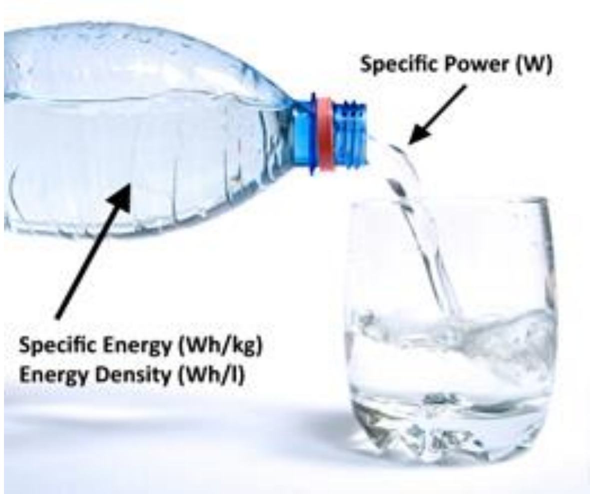
Tuğçe Yüksel, "Quantification of Temperature Implications and Investigation of Battery Design Options for Electrified Vehicles," PhD Dissertation, Carnegie Mellon University, 2015.

Battery Power vs Energy

- Energy: How much Wh or Joule in a battery
  - Energy (Wh) = Capacity (Ah) * Cell Voltage (V)
  - Larger energy means longer run time or electric range
- Power: How fast energy can be drawn from battery W or J/sec
  - Power (W) = Voltage * Current
  - Larger power means a brighter flash or faster acceleration
- A cell delivers less energy at higher powers or current draws
- Cells could be designed to be high energy (for EVs) or higher power (HEVs) by different materials or electrode thicknesses

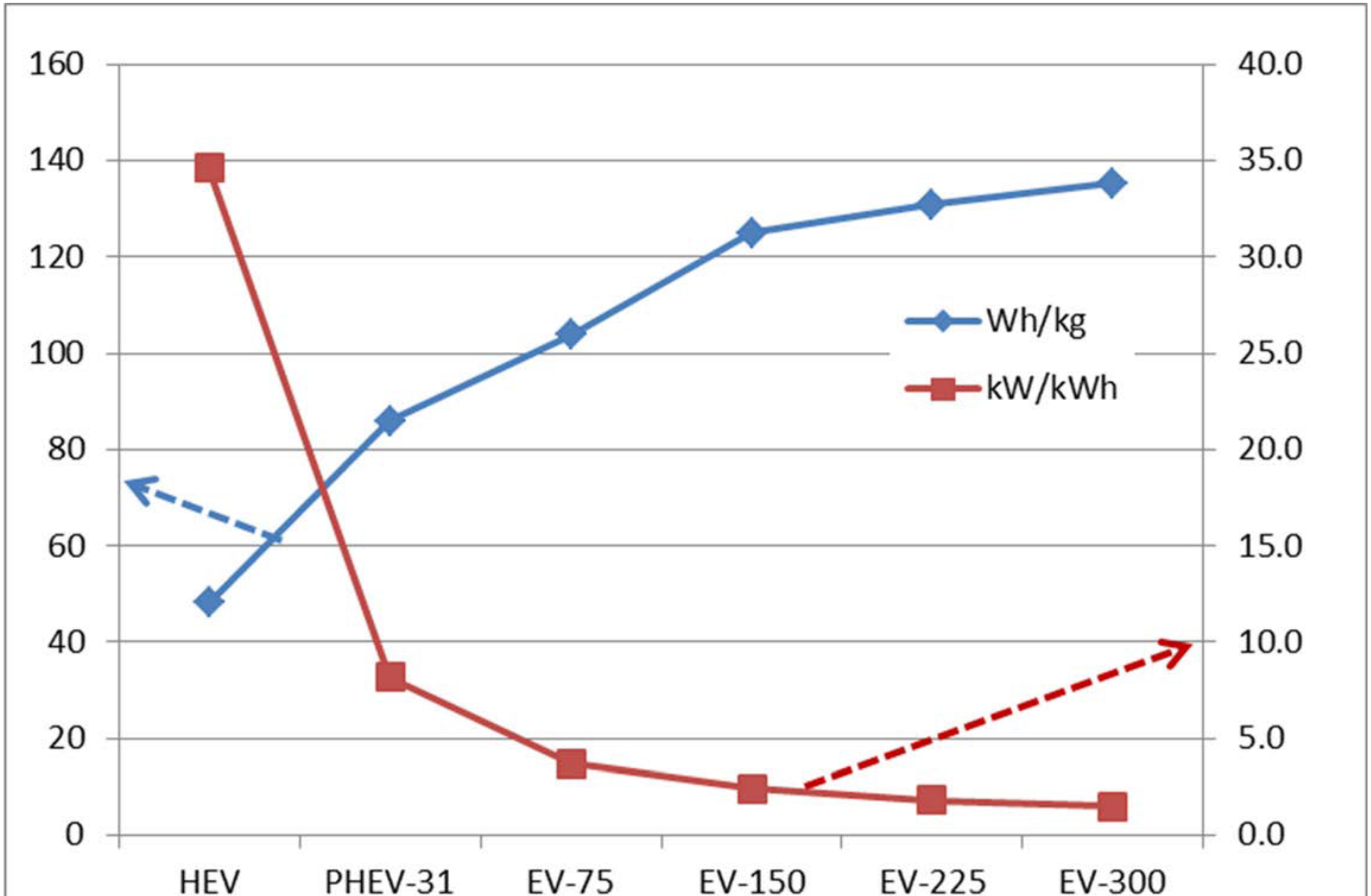


http://www.altenergyshift.com/uploads/60d46aee67b14bba54a99b562f451168.jpg



http://www.batteryuniversity.com/_img/content/energy-density-power2x.jpg

Battery Power vs Energy



M. Anderman, AABC 2015

Automotive Li-Ion Chemistry Characteristics

	Graphite-NCA	Graphite-NMC	Graphite-LMO/Blend	Graphite-LFP	LTO-NMC
Safety	+	++	++	+++	++++
Energy	++++	+++	+++	++	+
Lifetime	+	+++	++	+++	++++
Charging	+++	+++	+++	++	++++
Cost	++++	+++	+++	++++	+
Supply	+++	+++	++	++++	++

Graphite-NCA: Tesla Model S

Graphite-NMC: Seems to be the best compromise German EVs.

Graphite-LMO/Blend: Varying lifetimes depending on blend. Japanese and USA EVs.

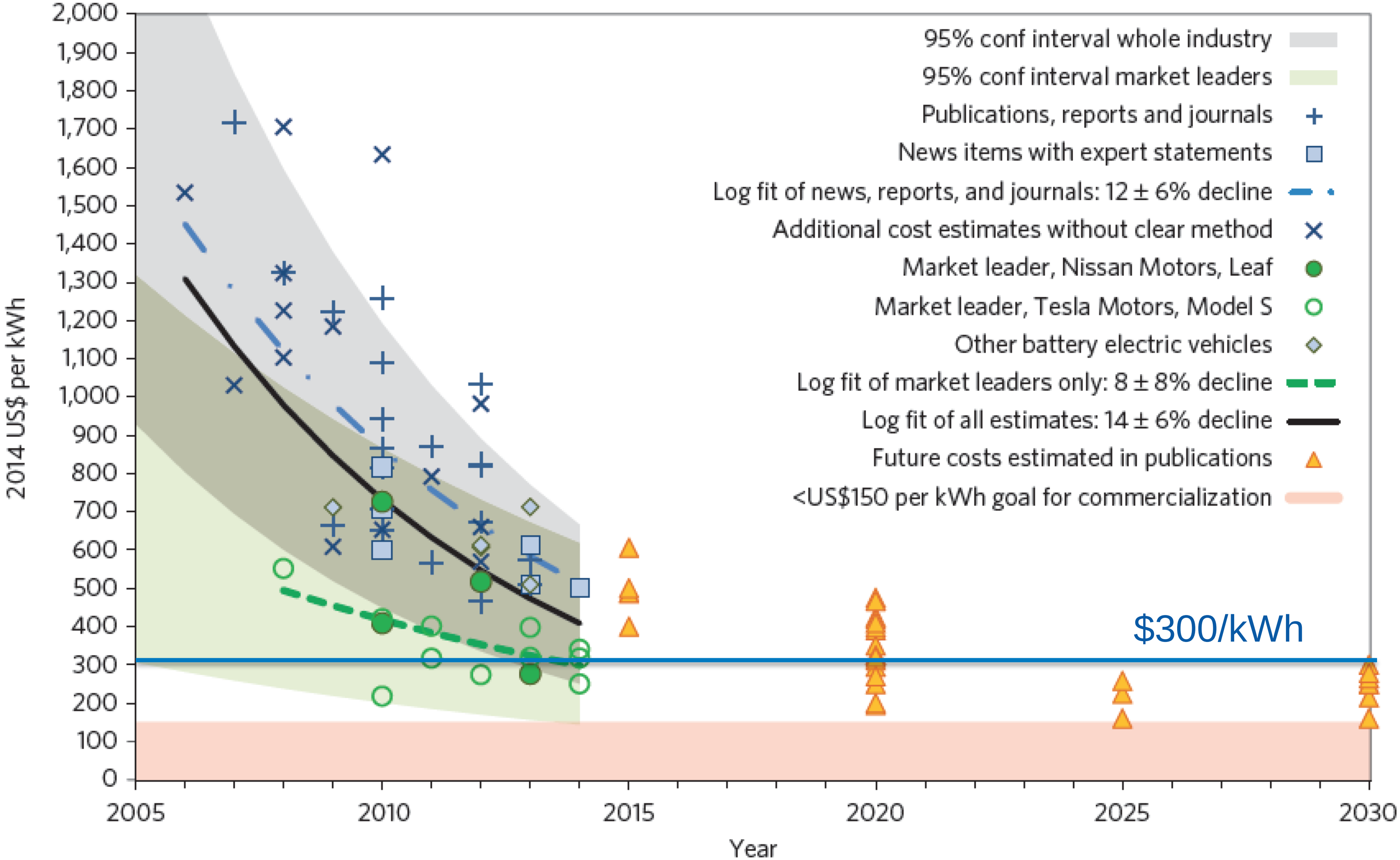
Graphite-LFP: Chinese are flooding the market. Disparities in quality. A real choice for ECVs.

LTO-NMC: Expensive but very durable, and high power. A real choice for ECVs.

07/11/2014

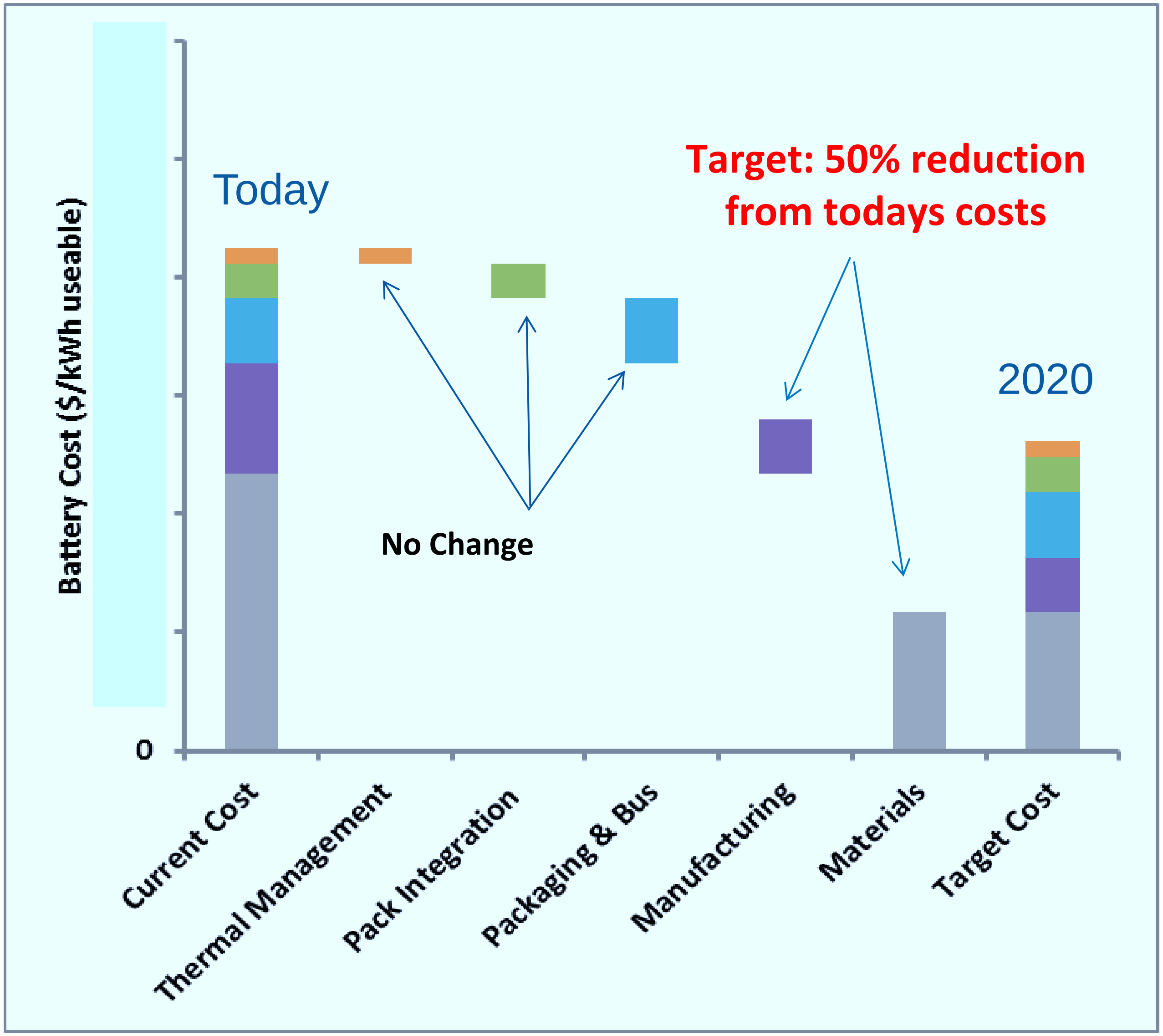
Samu Kukkonen, VTT Technical Research Centre of Finland (2014)

Li-Ion Battery Cost is Falling



Rapidly falling costs of battery packs for electric vehicles
Björn Nykvist and Måns Nilsson (Nature Climate Change, March 2015)

DOE's Vision to Reduce Cost

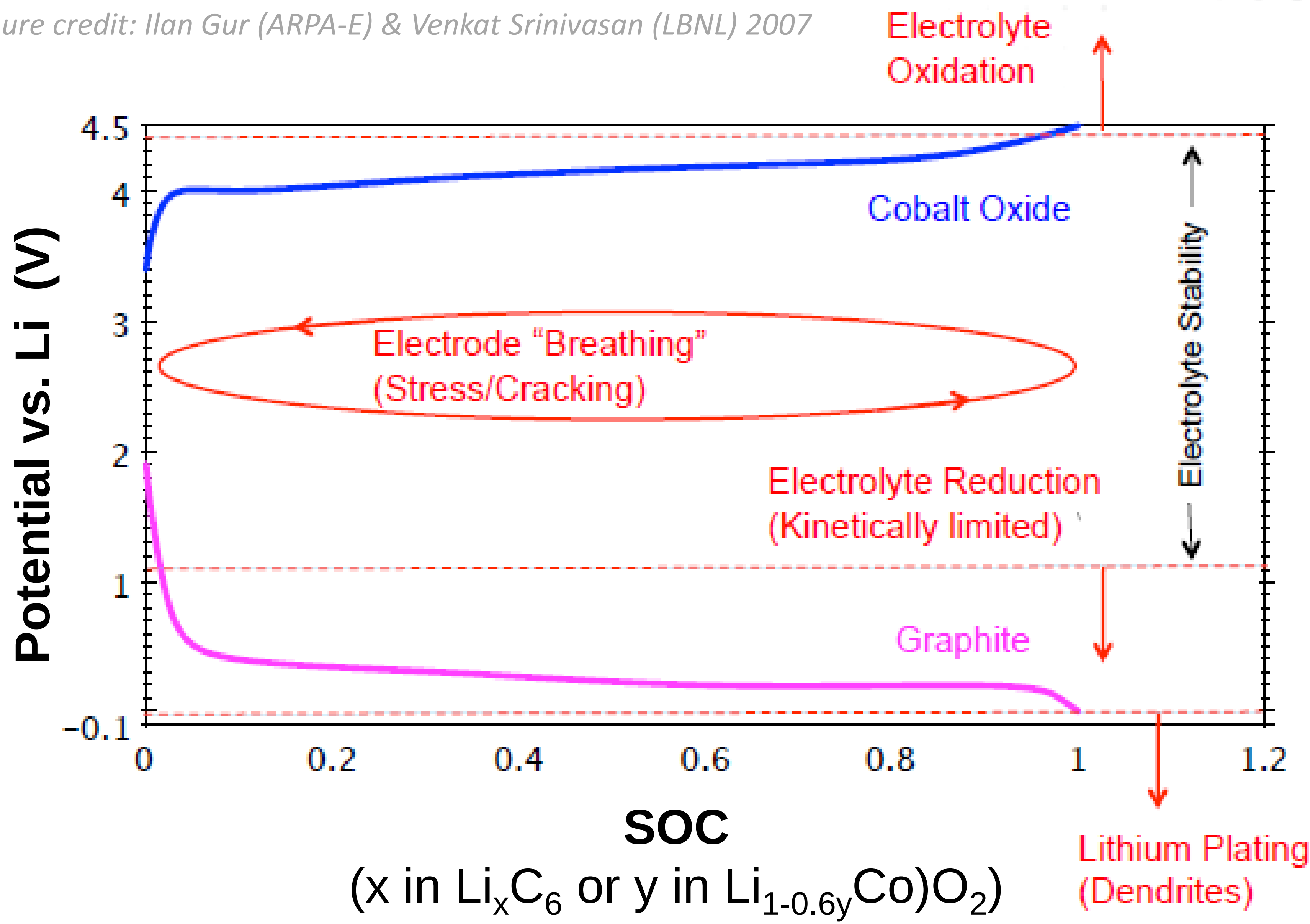


Objective: by 2020, reduce critical material and manufacturing costs by 50%.

- Focus on the energy, water, environmental, and labor costs which, depending on component, can range from ~20% – 60% of the materials cost.
- Reduce energy intensity for producing materials.
- Focus on $/kWh reduction

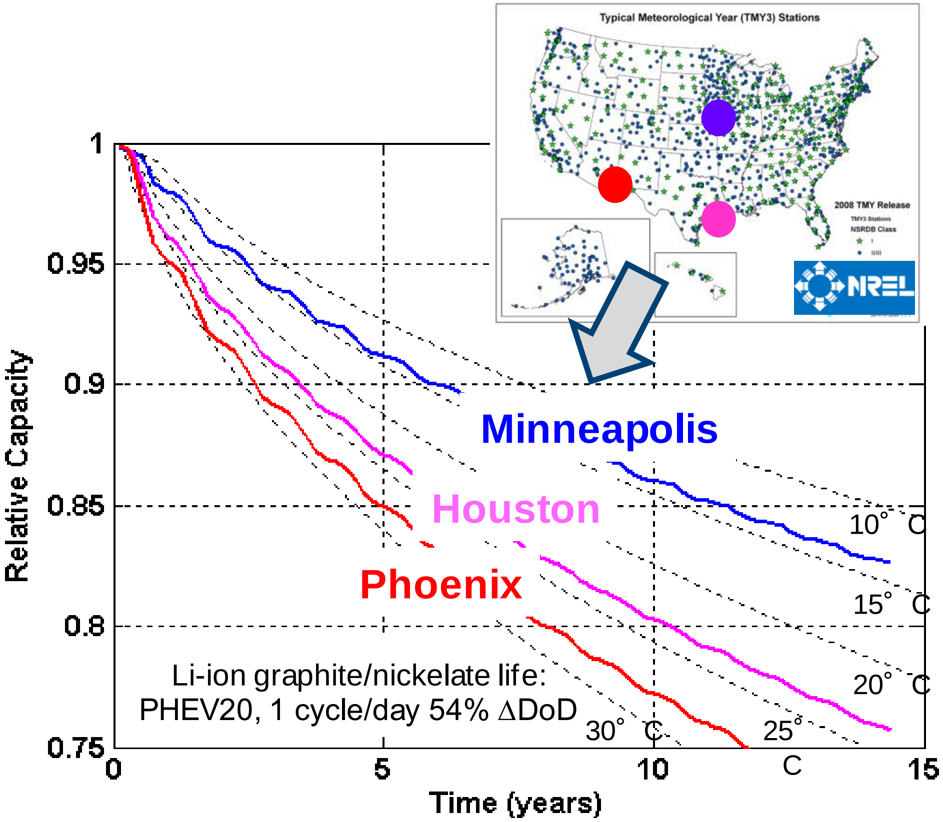
Li-Ion Degradation Mechanisms

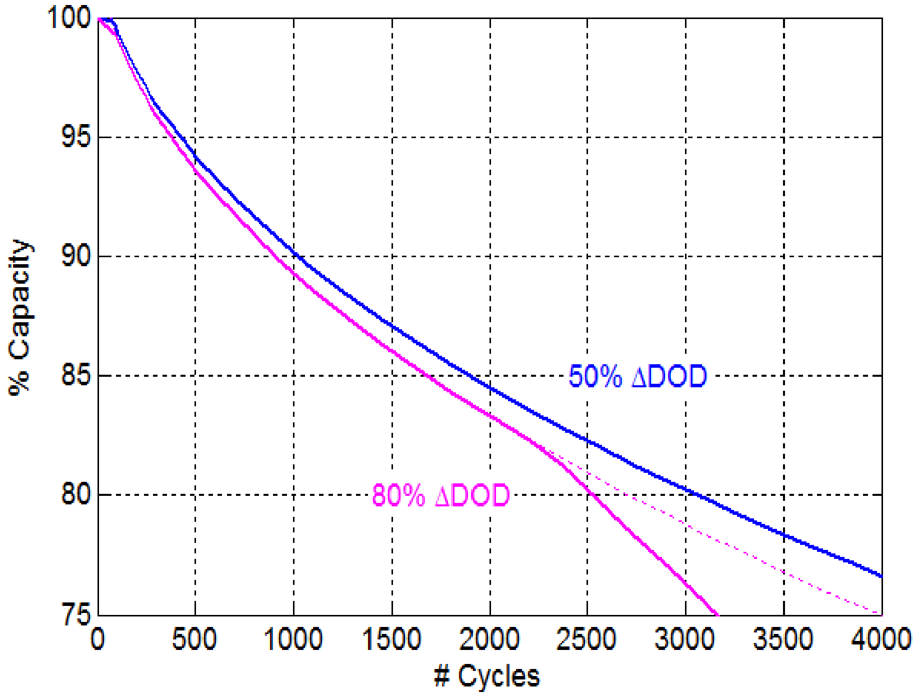
Figure credit: Ilan Gur (ARPA-E) & Venkat Srinivasan (LBNL) 2007



Typical Degradation and Battery Life

- High Temperature
- High DOD





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Technical Targets for Light Duty Vehicles

Battery Technical Targets

DOE Energy Storage Goals	HEV	PHEV (2015)		EV (2020)
		PHEV-10	PHEV-40	
Equivalent Electric Range (miles)	N/A	10	40	200-300
Discharge Pulse Power: 10 sec (kW)	25	45	38	80
Regen Pulse Power: 10 sec (kW)	20	30	25	40
Recharge Rate (kW)	N/A	1.4	2.8	5-10
Cold Crank Power:-30 ºC/2sec (kW)	5	7		N/A
Available Energy (kWh)	0.3	3.4	11.6	40
Calendar Life (year)	15	10+		10
Cycle Life (cycles)	300,000 (shallow)	3,000-5,000 (deep)		1,000 (deep)
Maximum System Weight (kg)	40	60	120	300
Maximum System Volume (l)	32	40	80	133
Operating Temperature Range (ºC)	-30 to +52	-30 to +52		-40 to +85

USDrive Electrochemical Energy Storage Overview, Oct. 2011, Dave Howell and Ron Elder

Requirements for Batteries in HDVs: larger size and more power, more demanding duty cycle, and higher miles, usage, charge-discharge cycles, harsher environment, and more sensitive to total cost of ownership

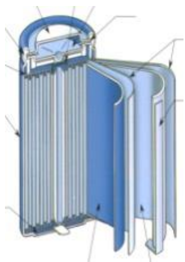
Breakdown of Tech Targets for LDV

Advanced Battery Materials Research	Cell Design & Electrochemistry Optimization	Advanced Battery Development
✓ Capacity Improvement ✓ Failure Mitigation	✓ Power & Capacity Increase ✓ Life Improvement	✓ Performance Optimization ✓ Cost Reduction

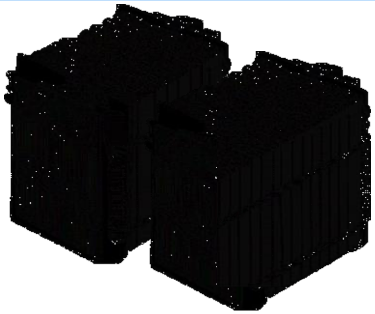
Anodes
(600+ mAh/g)

Cathodes
(300+ mAh/g)

Electrolytes
(5 volt)



Cell Targets
350 Wh/kg
750 Wh/l
1,000 "C/3" cycles

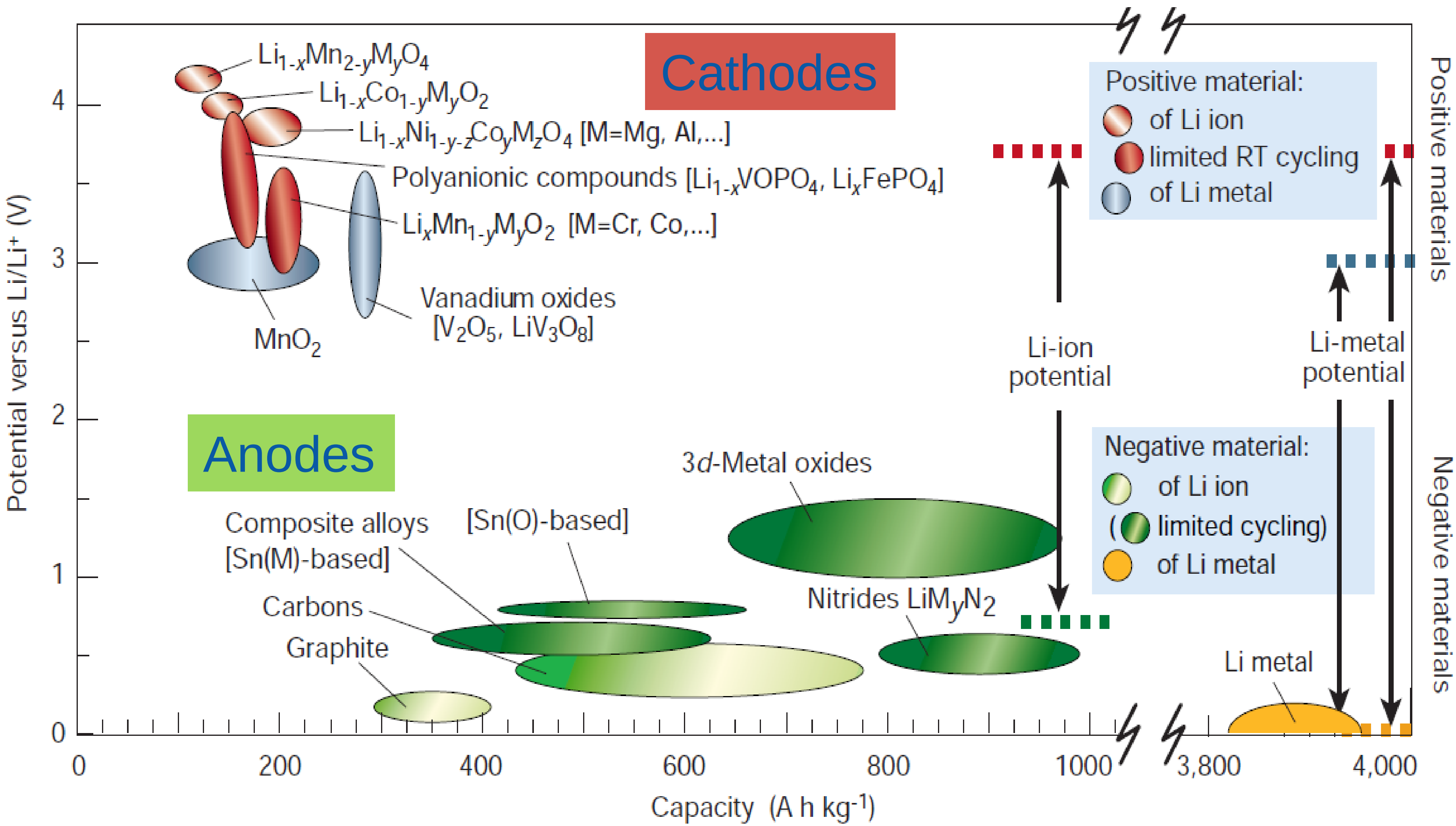


Pack Targets
$125/kWh
250 Wh/kg : 400 Wh/l
2,000 W/kg

10-100 mAh cells	0.5 - 1.0 Ah cells	$5 - 40^{+}$ Ah cells

Energy Storage Overview, DOE Annual Merit Review 2013

Future Battery Chemistries

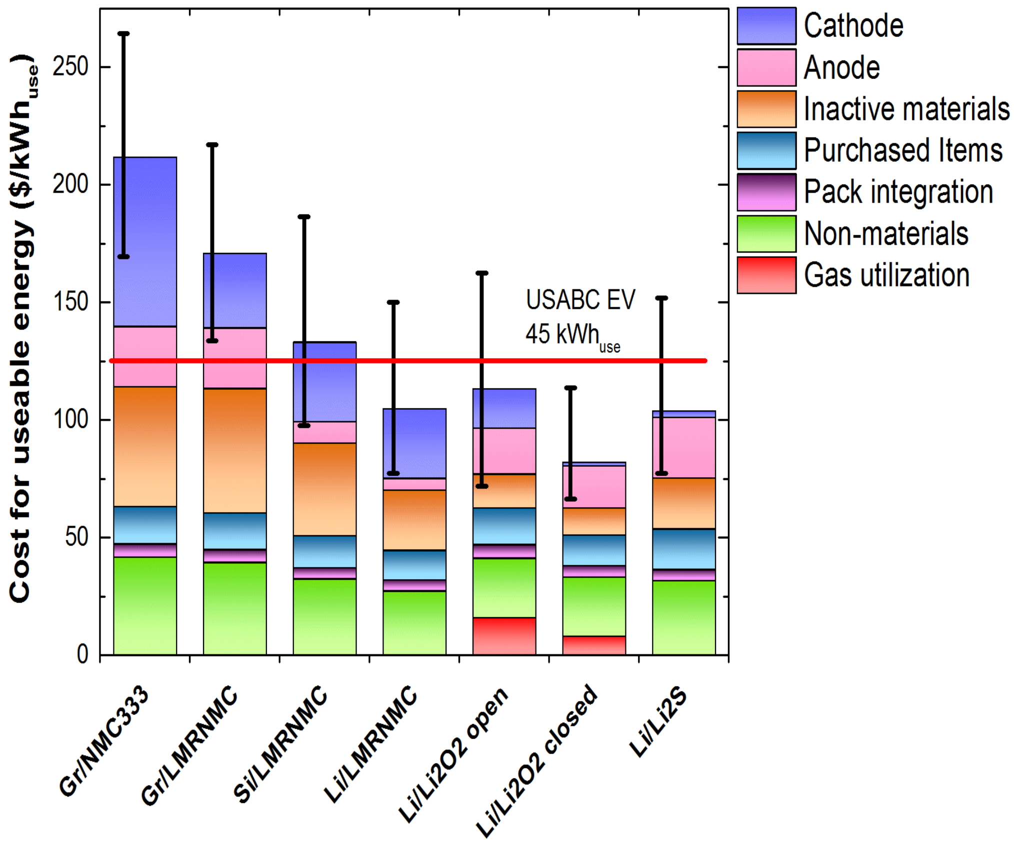


J.-M. Tarascon and M. Armand, Nature Vol. 414, p. 359 (2011)

Potential Cost of Future Batteries Chemistries

- Significant cost reductions are possible using more advanced lithium ion materials (see figure)
  - Lithium Ion: Silicon anode coupled with a high capacity cathode presents moderate risk pathway to less than $125/kWh_{use}$
  - Lithium metal is a higher risk pathway to below $\$100/kWh_{use}$
- Beyond lithium, multi-valent systems are being considered.
- All organic batteries that utilize charge-transfer instead of burning carbon are being developed.

Projected Cost for a 100kWh Battery Pack



Courtesy: JCESR Energy Storage Hub

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

Battery Energy Requirements for Heavy-Duty EDVs

- The energy efficiency of light-duty vehicles is about 200 to 400 Wh/mile
  - 5 to 12 kWh **usable** battery for 30 miles
  - 2-Second power: 30 to 60 kW
  - P/E from 1 to 10
- Heavy-duty vehicles could consume from 1,000 to 2,000 Wh/mile
  - 30 to 60 kWh usable battery for 30-mile range
  - Volume, weight, and cost are concerns
  - Thermal management is a concern
- A 40-ft bus for transit operation could have as much of 320 kWh (total energy) battery system

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Battery Pack Integration Considerations

- Safety (abuse tolerance, one cell will have an event)
- Cost/Value
- Long life/Durable
- Manufacturability
- Recyclability
- Diagnostics
- Maintenance/Repair
- Packaging – Structural and connections
- Thermal Management – life (T), performance (T), safety
  - Impedance change with life – impact on thermal management and design for end of life
- Electrical Management – balancing, performance, life, safety
- Control/Monitoring
  - Gauge (capacity, power, life)

Cylindrical vs. flat/prismatic designs

Many small cells vs. a few large cells

Battery Packaging?

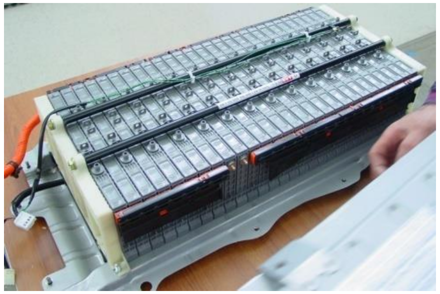
- Many small cells
  - Low cell cost (commodity market)
  - Improved safety (faster heat rejection)
  - Many interconnects
  - Low weight and volume efficiency
  - Reliability (many components, but some redundancy)
  - Higher assembly cost
  - Electrical management (costly)

Source: Valance Technologies

Source: EnergyCS

- Fewer large cells
  - Higher cell cost
  - Increased reliability due lower part count
  - Lower assembly cost for the pack
  - Higher weight and volume efficiency
  - Thermal management (tougher)
  - Safety and degradation in large format cells
  - Better reliability (lower number of components)

Source: Saft America



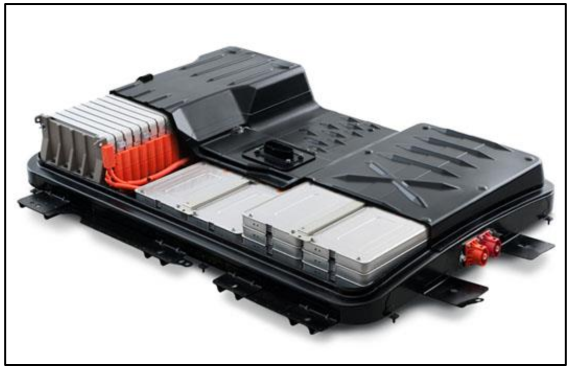
Source: Matt Keyser (NREL)

Battery Packs in Some EVs

Chevy Volt

http://autogreenmag.com/tag/chevroletvolt/page/2/

Nissan Leaf



http://inhabitat.com/will-the-nissan-leaf-battery-deliver-all-it-promises/

Fiat 500 EV

http://www.ibtimes.com/articles/79578/20101108/sb-limotive-samsung-sdi-chrysler-electric-car.htm

i-MiEV

http://www.caranddriver.com/news/car/10q4/2012_mitsubishi_i-miev_u.s.-spec_photos_and_info-auto_shows/gallery/mitsubishi_prototype_i_miev_lithium-ion_batteries_and_electric_drive_system_photo_19

Ford Focus

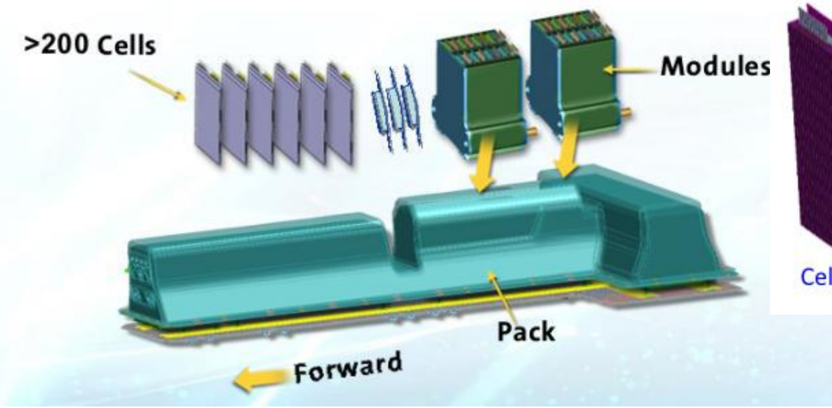
http://www.metaefficient.com/cars/ford-focus-electric-nissan-leaf.html

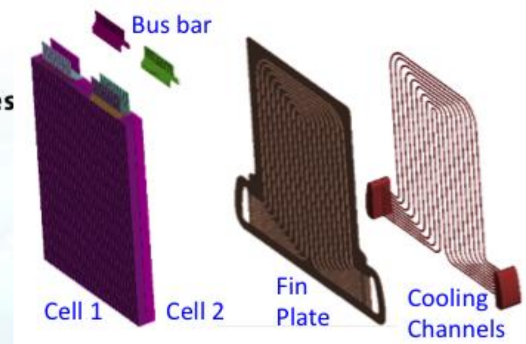
Tesla Model S

https://hackadaycom.files.wordpress.com/2014/09/tesla-batt.jpg?w=800

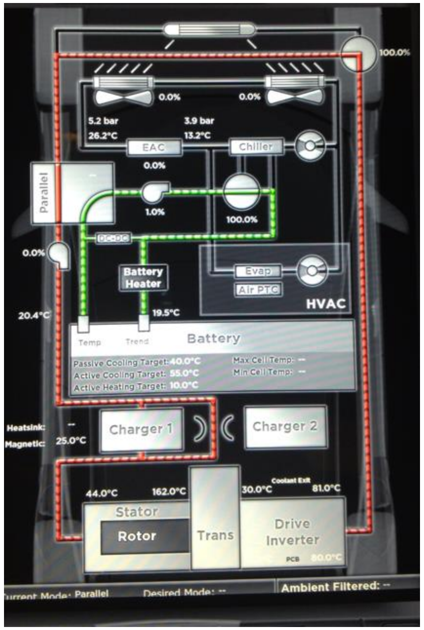
Examples of Liquid-cooled Pack

Chevy Volt liquid cooled battery pack (Courtesy of GM)





Model S liquid cooled battery pack



http://www.coppermotor.com/wp-content/uploads/2014/11/Tesla-Model-S-battery-pack-Ricardo-photo-2_1280.jpg

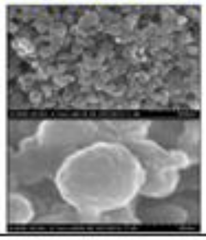
Outline

- Introduction to NREL and Transportation Programs
- General information on Li-Ion technologies/chemistries
- Operational characteristics – power, energy, life, cost
- Battery requirement for heavy duty vehicles
- Battery system integration considerations in vehicles
- NREL research program activities and capabilities
- Battery testing and modeling activities

DOE Energy Storage R&D Programs

Advanced Materials Research → High Energy & High Power Cell R&D → Full System Development & Testing → Commercialization

SEM of Li_2FeSiO_4/C nanospheres



- High energy cathodes
- Alloy, lithium anodes
- High voltage electrolytes
- Lithium metal/ Li-air

- High energy couples
- High rate electrodes
- Fabrication of high E cells
- Cell diagnostics

- Electric Drive Vehicle batteries
- Testing, analysis, and design
- Cost reduction

EERE/VT: BATT, ABR, Development, Testing & Design

BES : Battery and ES HUB & EFRC

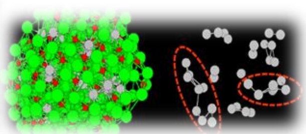
ARPA-E: AMPED, RANGE, GRIDS, etc.

DOE Office of Electricity: Large scale demos for grid

NREL Energy Storage Activities

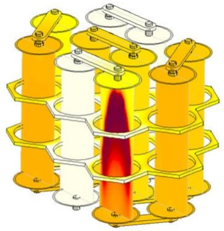
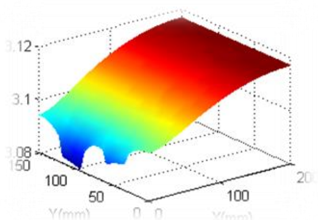
Supporting DOE and industry to achieve energy storage targets for various applications



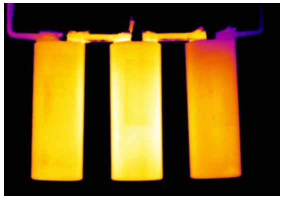
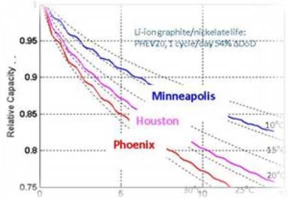


Battery Materials Synthesis and Processing
(Higher energy density and stability)

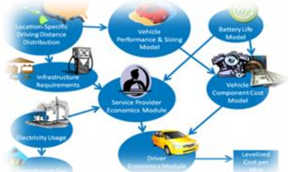

Component Testing and Characterization
(Evaluate performance, life, and safety)

Multi-physics Battery Modeling
(Improve performance, life, and safety)

Battery Management and Control
(Improve utilization and life)



Battery System Evaluation
(Finding cost-effective pathways)

Battery Testing – USABC Standards

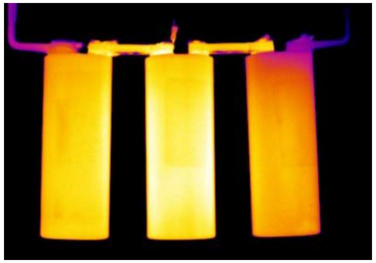
United State Advanced Battery Consortium has established standard battery testing procedures that are widely adopted. They can be used for heavy duty electric vehicle applications.

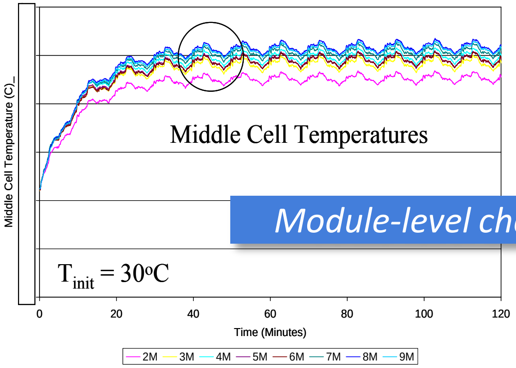
http://www.uscar.org/guest/article_view.php?articles_id=86

- Capacity at C/1 or C/3
- Hybrid Pulse Power Characterization
- Peak Power
- 2-S, 10-s, 20-2 Charge or Discharge
- Cold Cranking
- Calendar life (monthly reference performance test)
- Cycle life (monthly RPT)
- 30-day stand test (self discharge)

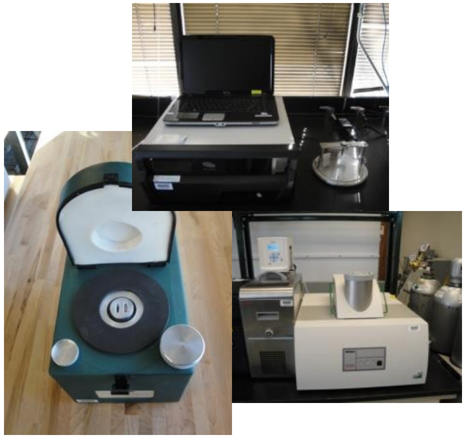
Component Testing and Characterization

- Temperature impacts the performance, life, and safety of batteries
- Thermal management is needed for longevity and safety of batteries, particularly for xEVs
- With unique capabilities, NREL is the lead laboratory for providing data on thermal performance of batteries under electrical loads to the DOE VTO and USABC
  - Calorimetry
  - Infrared thermal imaging
  - Thermal conductivity measurements
  - System thermal evaluation testing





Module-level characterization

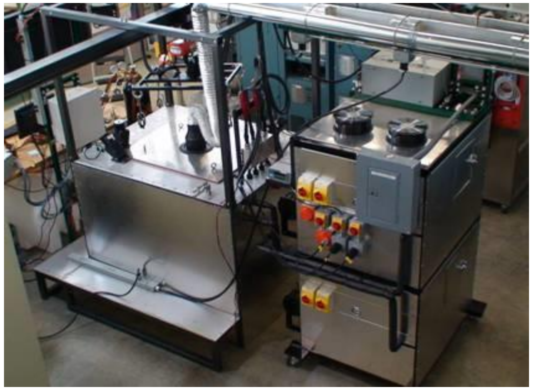


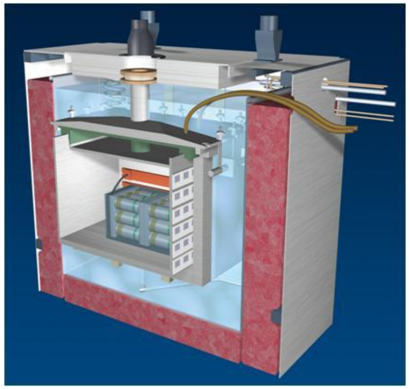
Material thermal characterization

Pack-level characterization

Developed and Commercialized Award-Winning Battery Calorimeter

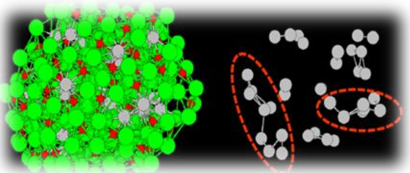
- Battery thermal management systems need to be optimized with the right tools for the lowest cost
- NREL has developed isothermal battery calorimeters to accurately measure battery heat generation and heat capacity under various loads and conditions
- NETZSCH North America is commercializing NREL’s battery calorimeter through a CRADA and licensing agreement
- The NREL isothermal battery calorimeter was selected for a 2012 Colorado Governor’s Research Award and a 2013 R&D 100 Award

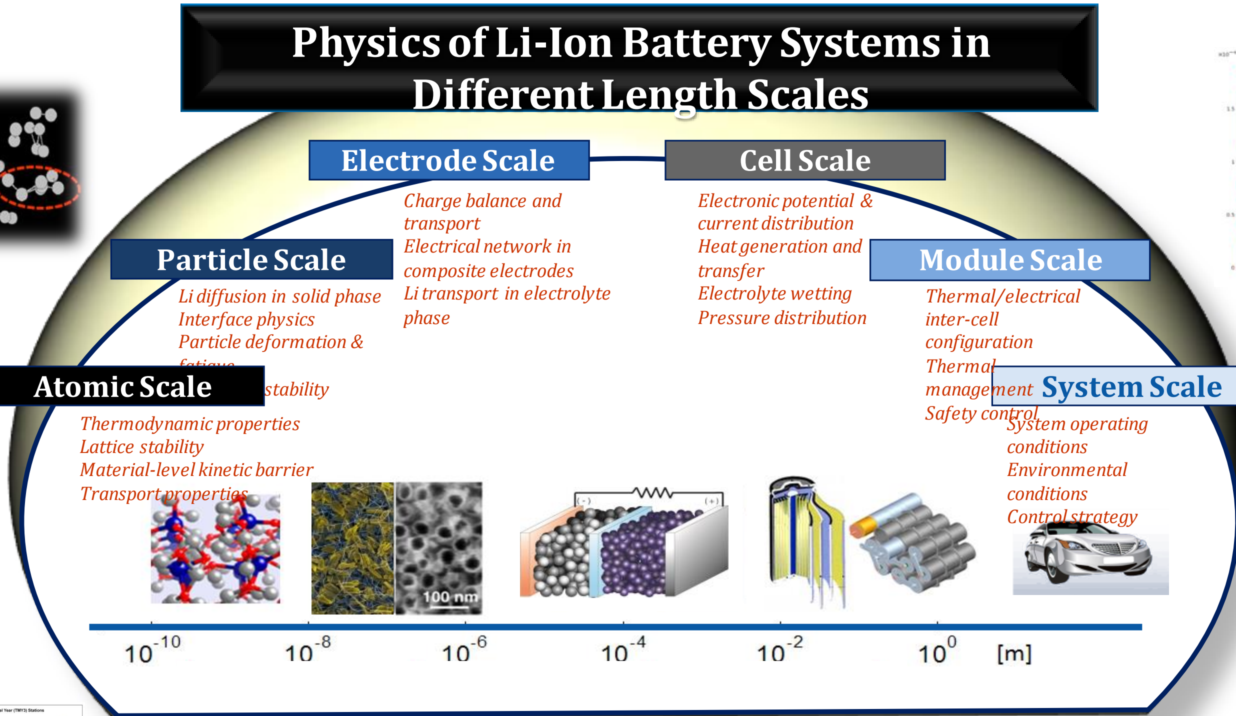


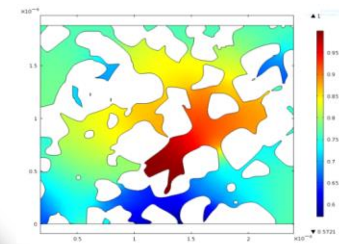


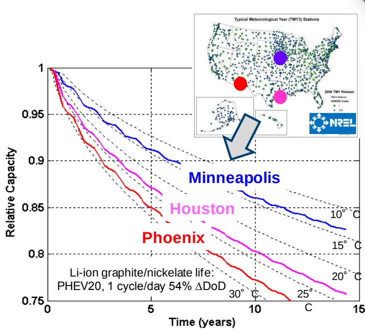
Multi-physics Battery Modeling

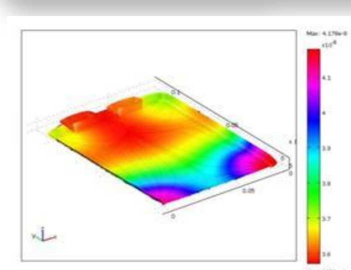
NREL has developed a unique set of multi-physics, multi-scale modeling tools for simulating performance, life, and safety of lithium ion batteries

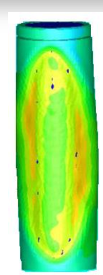


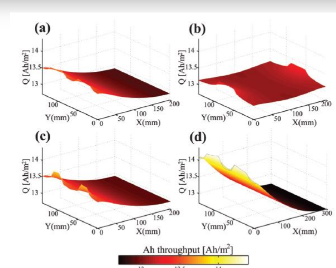


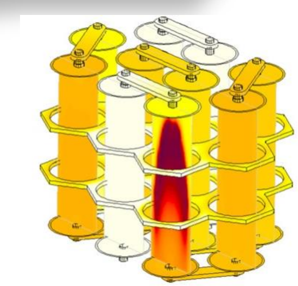


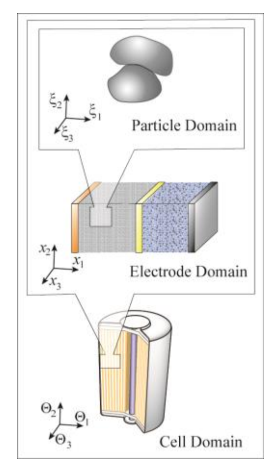




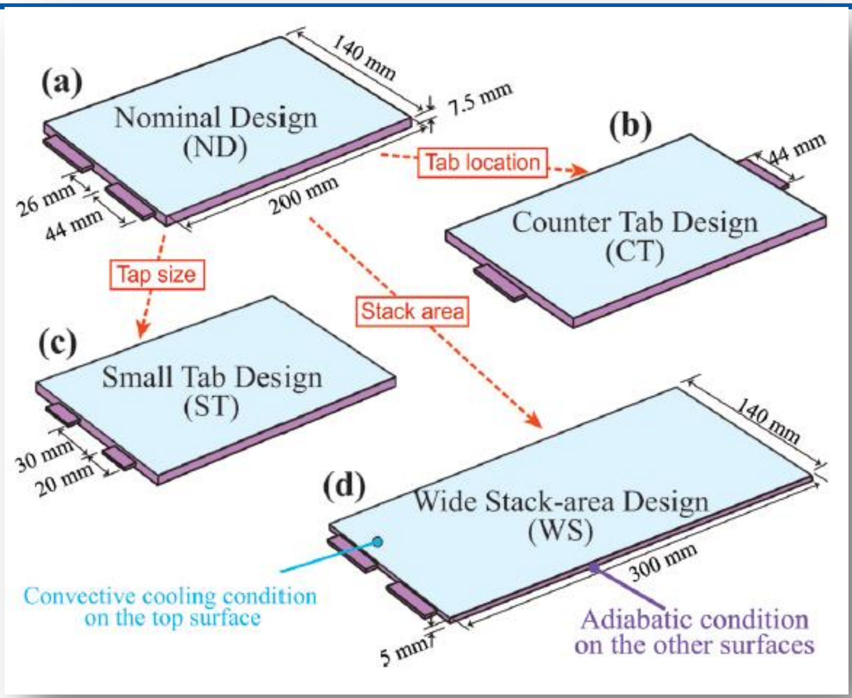




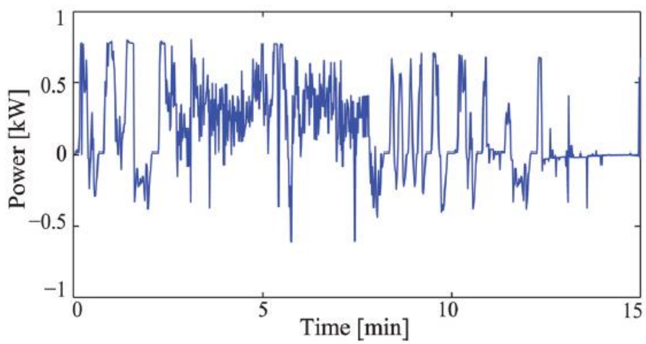


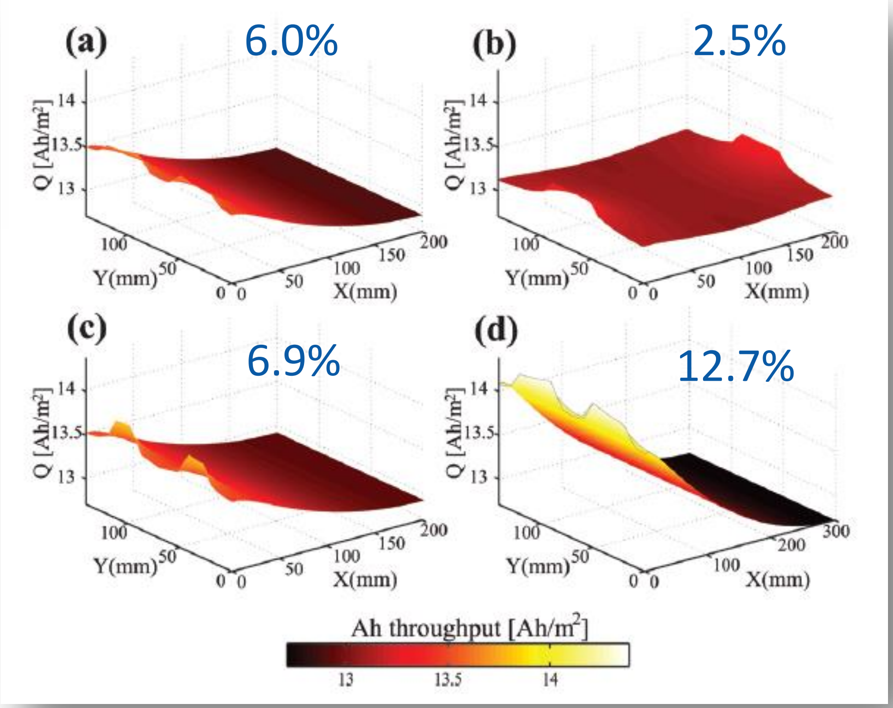


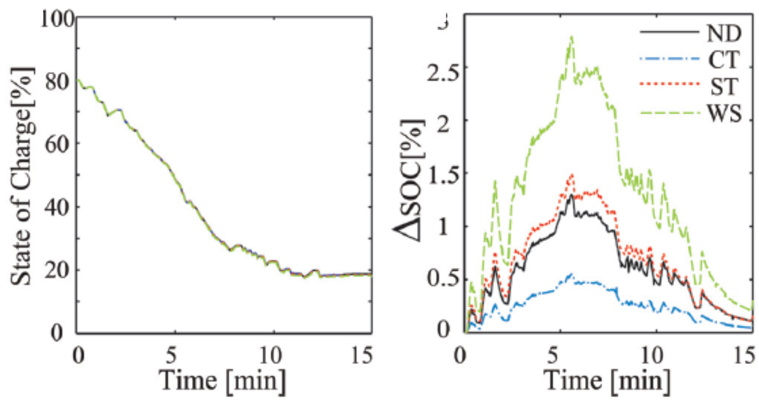
Non-Uniform Utilization Using NREL Model



Mid-sized Sedan PHEV10 US06



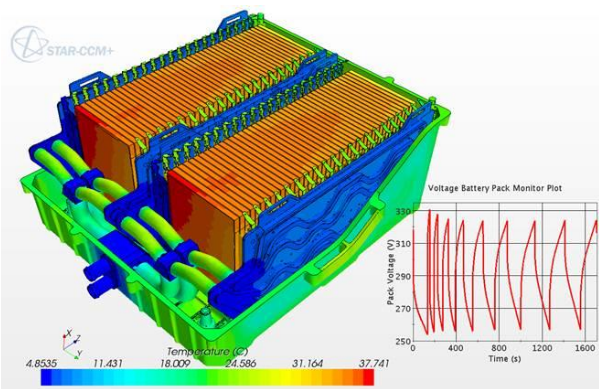


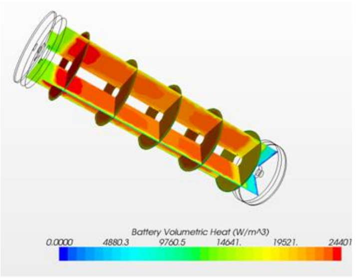


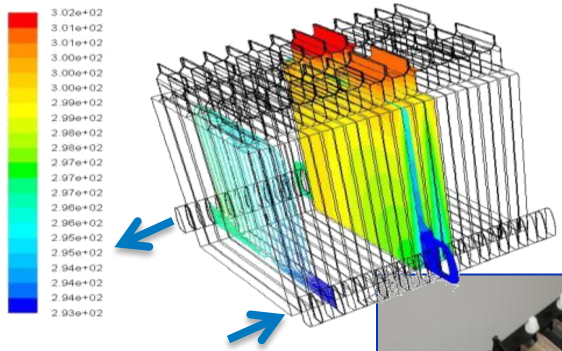
Kim et al., "Multi-Domain Modeling of Lithium-Ion Batteries Encompassing Multi-Physics in Varied Length Scales," *J. of*

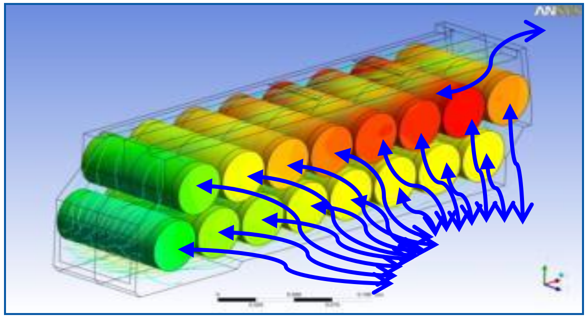
Developed Battery Computer Aided Design Tools

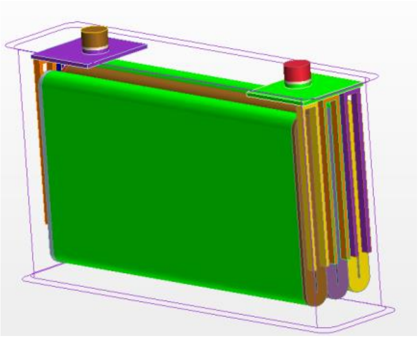
- Supported model developers (ANSYS, CD-adapco, EC Power) to release battery design software tools to accelerate battery development
  - Evaluate configuration and material selection
  - Design battery thermal management
  - Predict electrochemical thermal performance of packs





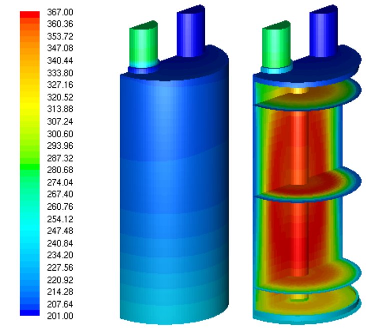


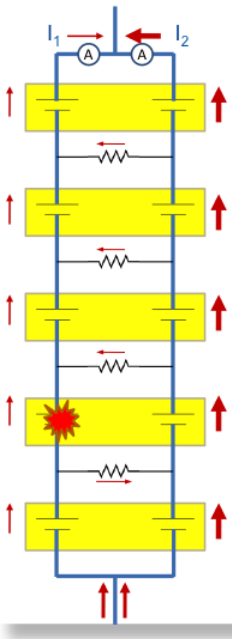


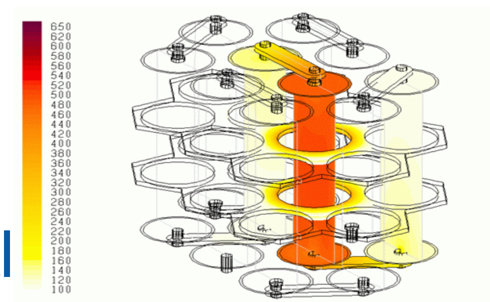


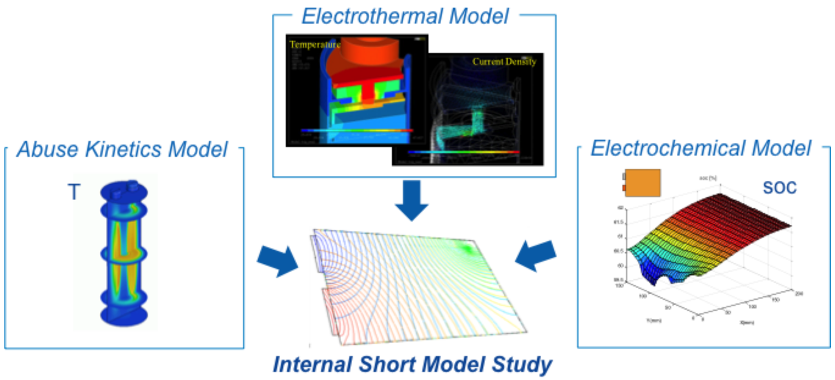
Lithium Ion Battery Safety

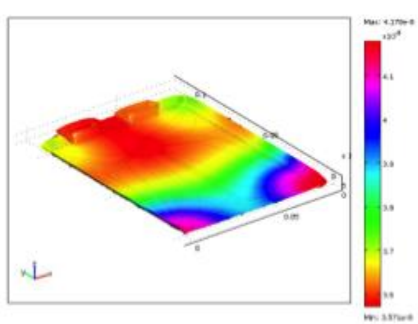
- Chemical Reaction – Thermal Modeling
- Overheating Simulations
- Reaction Propagation in a Module
- Internal Short Circuit (ISC) Modeling
- Internal Short Circuit Sensor Testing
- Overcharge modeling and testing
- Fail Safe Design Architecture
- Mechanical Electrochemical Thermal



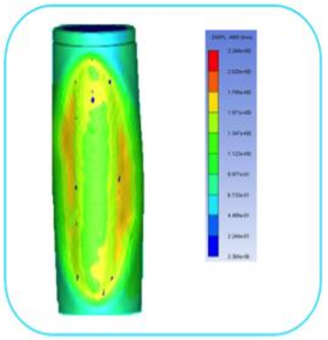








Deformation due to Pressure-Distribution within an 18650 cell



NREL Battery Life Prognostic Model

- Physics-based surrogate models regressed to aging test data
  - Li loss (SEI growth + cycling damage + plating)
  - Site loss (initial damage + continuous fatigue)
  - Electrolyte decomposition
- Typical error across 20-50 lab test conditions
  - Capacity: 3-4%
  - Resistance: 6-12%

  → Similar error for independent validation

Example equations

Calendar fade
- SEI growth
- Loss of cyclable lithium
- Coupled with cycling
- a_1, b_1 = f(ΔDOD,T,V_{oc},…)

Cycling fade
- Active material structure degradation and mechanical fracture
- a_2, c_2 = f(ΔDOD,T,V_{oc} ,…)

Relative Resistance $R = a_1 t^z + a_2 N$

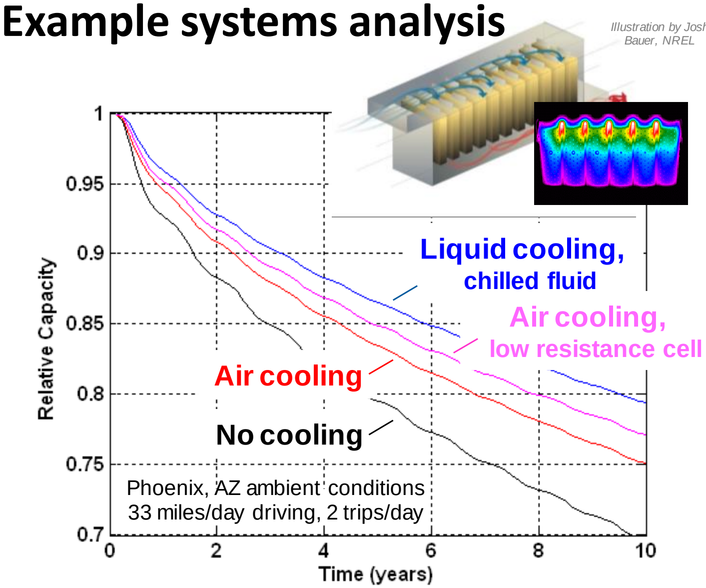
Relative Capacity $Q = \min(Q_{Li}, Q_{sites})$

$Q_{Li} = b_0 + b_1 t^z + \ldots$

$Q_{sites} = c_0 + c_2 N + \ldots$

NCA = Nickel-Cobalt-Aluminum
FeP = Iron Phosphate
NMC = Nickel-Manganese-Cobalt

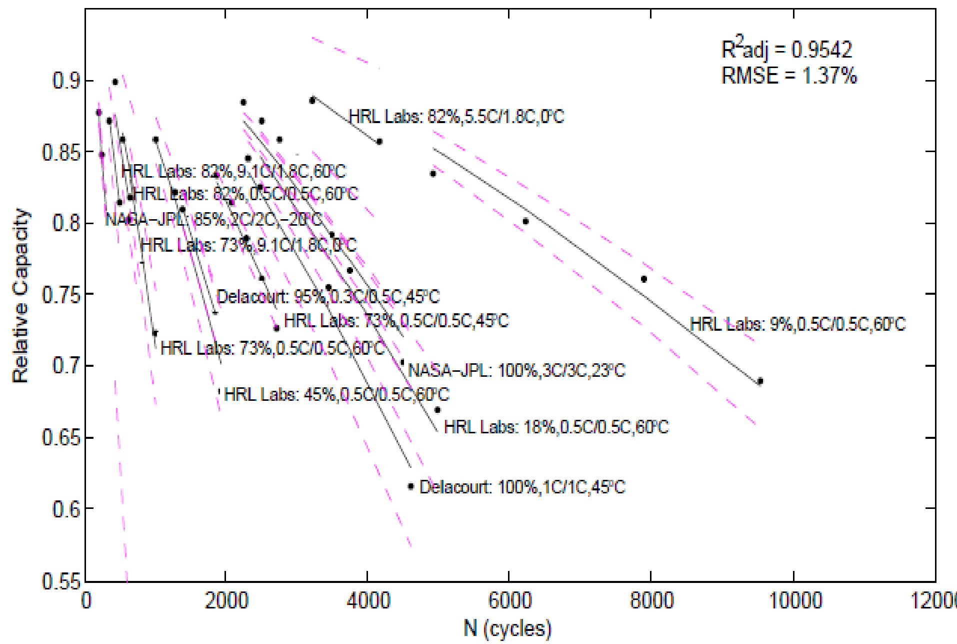
Example systems analysis



Severe cycling causes knee in capacity fade

2.3Ah graphite/FeP cell

- Late in life, capacity fade may transition from graceful decelerating fade to a more sudden accelerating fade
- Likely mechanism is transition from
  - Li-loss / calendar fade
  - Site-loss / cycling fatigue



$$q = \min(q_{Li}, q_{sites}).$$

$$q_{Li} = b_0 + b_1 t^z + b_2 N$$

$$q_{sites} = c_0 + c_2 N$$

Main factors in determining cycle life are temperature, depth-of-discharge (DOD) and C-rate

$$c_2 = c_{2,ref}\left\{ \exp\left(\frac{-E_a^{\text{binder}}}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right)\left[m_1\, DOD + m_2\, \Delta T\right] \;+\; m_3 \exp\left(\frac{-E_a^{\text{intercal.}}}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right)\left(\frac{C_{rate}}{C_{rate,ref}}\right)\left(\sqrt{\frac{t_{pulse}}{t_{pulse,ref}}}\right)\right\}.$$

- $\exp(\ldots)$ term: accelerated binder failure at high T
- $m_1\, DOD$: bulk intercalation strain
- $m_2\, \Delta T$: bulk thermal strain
- $m_3 \exp(\ldots)(\ldots)(\ldots)$: intercalation gradient strain, accelerated by low temperature

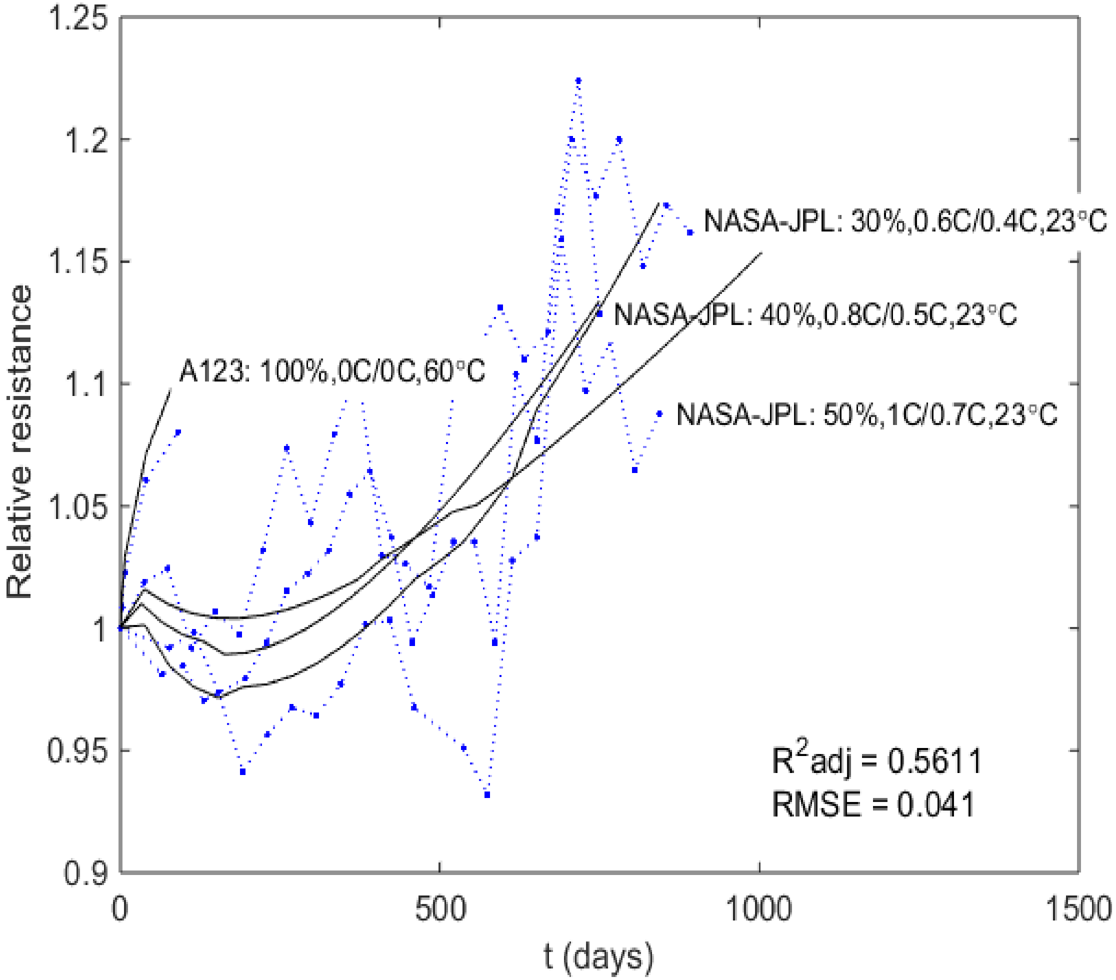
Power Loss/Resistance growth - typical model

2.3Ah graphite/FeP cell

$$R = a_0 + a_1 t^{\frac{1}{2}} + a_2 / q_{sites} - a_3 * (1 - \exp(-\lambda N))$$

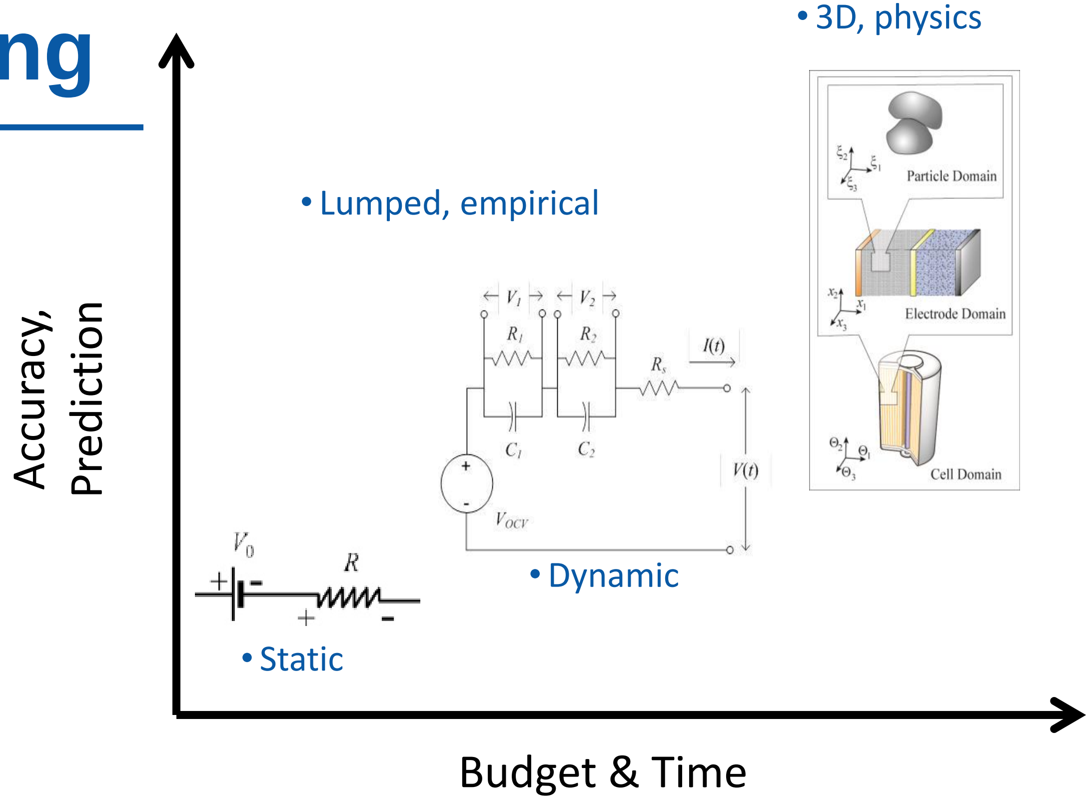
Typical mechanisms

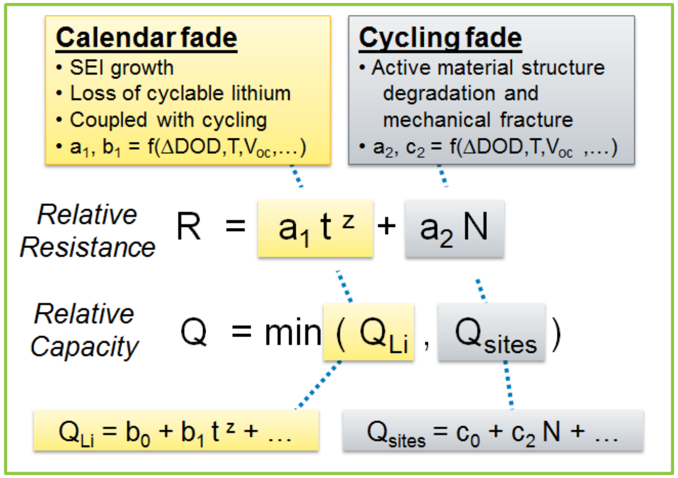
1. SEI growth
2. Site loss
3. Particle fracture
4. Electrolyte decomposition
5. Li plating



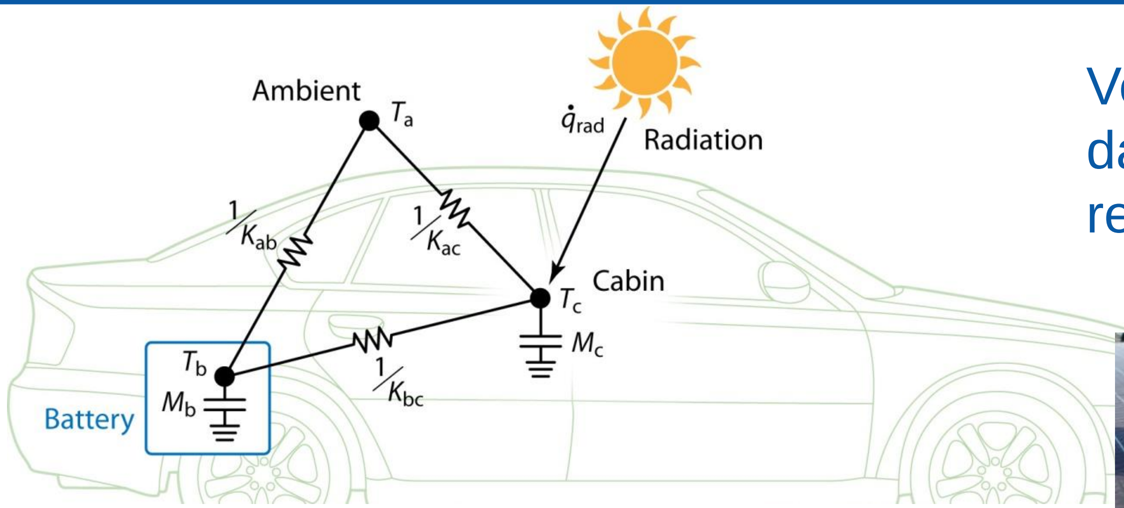
Systems Modeling

- Wide range of performance models
- Life prediction models generally semi-empirical
- Performance and life are both functions of temperature. A thermal model is therefore also needed

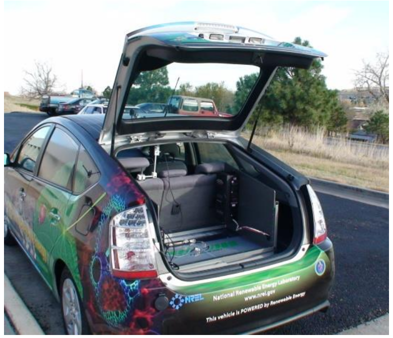


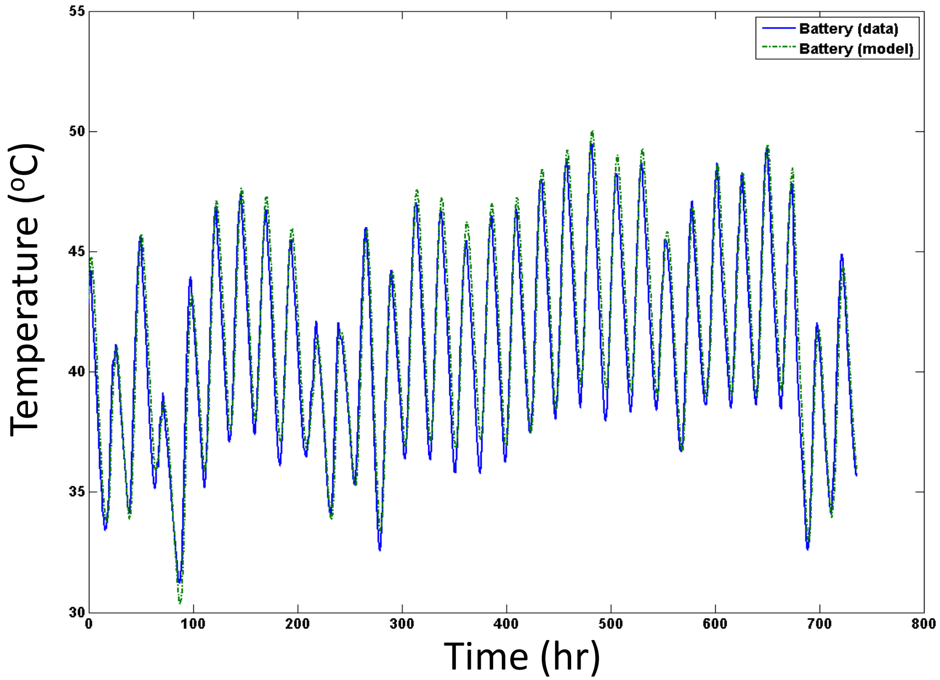


Ambient temperature strongly influences battery life (exception: chilled liquid cooled batteries)



Vehicle thermal model fit to 3 days of Gen II Prius data recorded in Golden, CO in winter



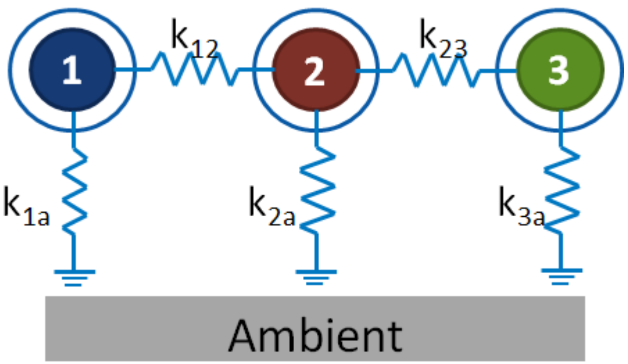


Same model predicts Prius battery temperature fluctuation in Phoenix, AZ

- Winter: within ½ °C
- Summer: within 1°C
  (Passenger cabin fluctuations within 6°C)

Cell-to-cell temperature difference also important to consider for life/warranty prediction

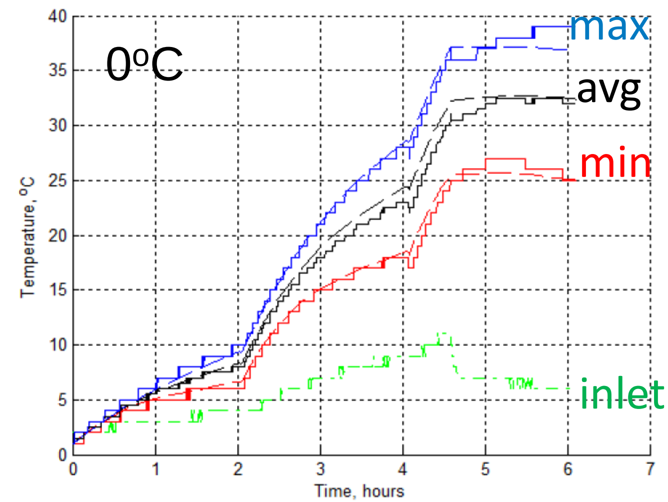
- In a passively balanced series string, total pack capacity is limited by the weakest capacity cell (usually hottest temperature cell)
- Multi-node thermal model easily tuned to pack data; useful for life prediction

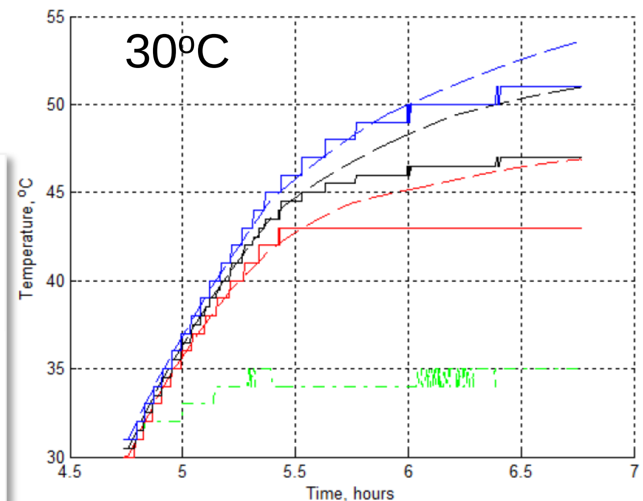


$$\begin{bmatrix}\dot{T}_1\\ \dot{T}_2\\ \dot{T}_3\end{bmatrix} = -\begin{bmatrix} \frac{k_{12}+k_{1a}}{m_1} & -\frac{k_{12}}{m_1} & 0\\ -\frac{k_{12}}{m_2} & \frac{k_{12}+k_{23}+k_{2a}}{m_2} & -\frac{k_{23}}{m_2}\\ 0 & -\frac{k_{23}}{m_3} & \frac{k_{23}+k_{3a}}{m_3}\end{bmatrix}\begin{bmatrix}T_1\\ T_2\\ T_3\end{bmatrix} + \begin{bmatrix} \frac{1}{m_1} & 0 & 0 & \frac{k_{1a}}{m_1}\\ 0 & \frac{1}{m_2} & 0 & \frac{k_{2a}}{m_2}\\ 0 & 0 & \frac{1}{m_3} & \frac{k_{3a}}{m_3}\end{bmatrix}\begin{bmatrix}q_1\\ q_2\\ q_3\\ T_a\end{bmatrix}$$

$$\begin{bmatrix}T_{max}\\ T_{min}\end{bmatrix} = \begin{bmatrix} max(T_1, T_3)\\ min(T_1, T_3)\end{bmatrix}$$

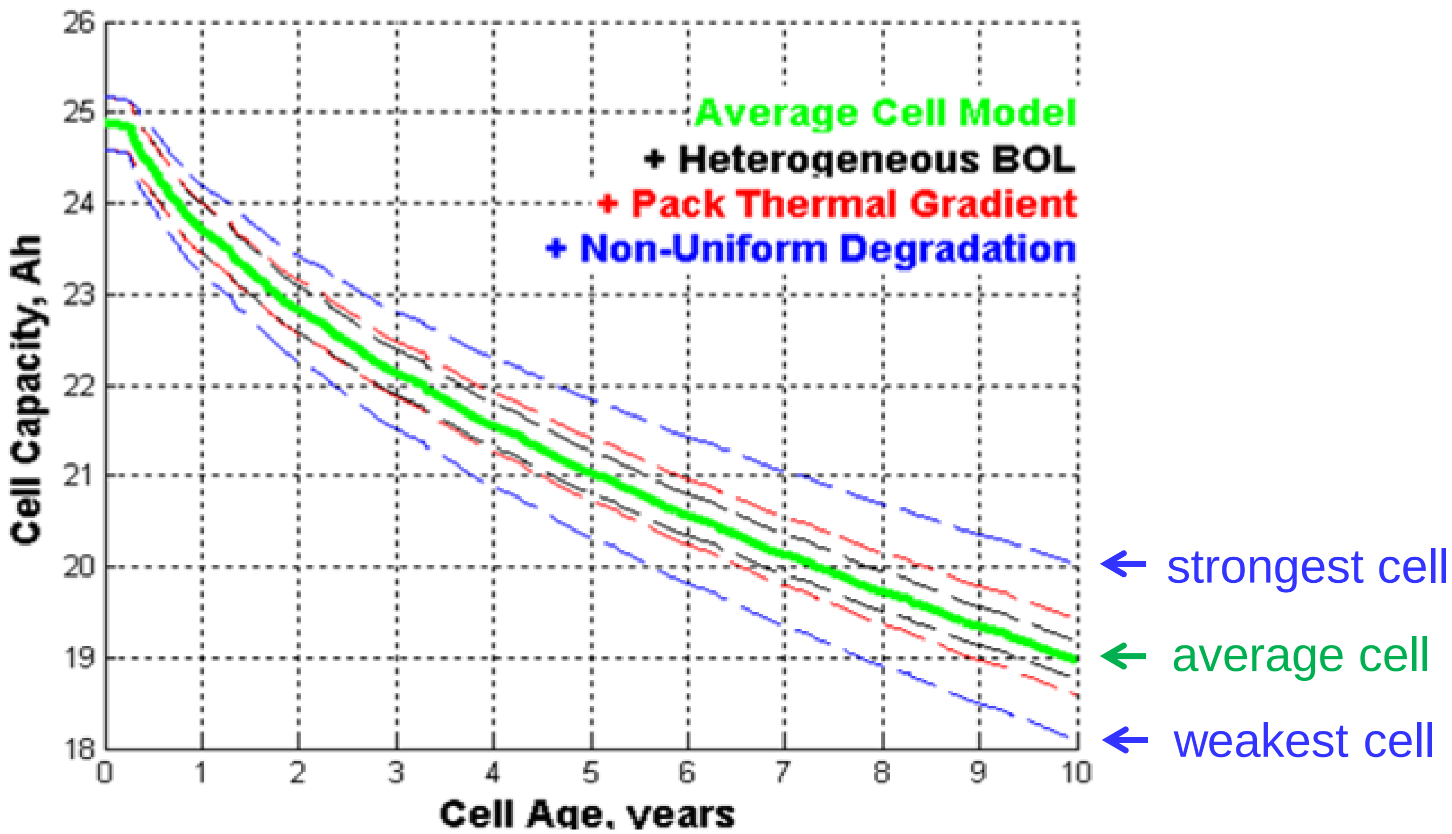
- experiment data (solid lines)
- model prediction (dashed lines)





Cell imbalance growth

- Cells, typically matched to ±0.5% capacity variation at BOL, *may* grow to ±5% at EOL
- With passive cell balancing, capacity is limited by weakest cell



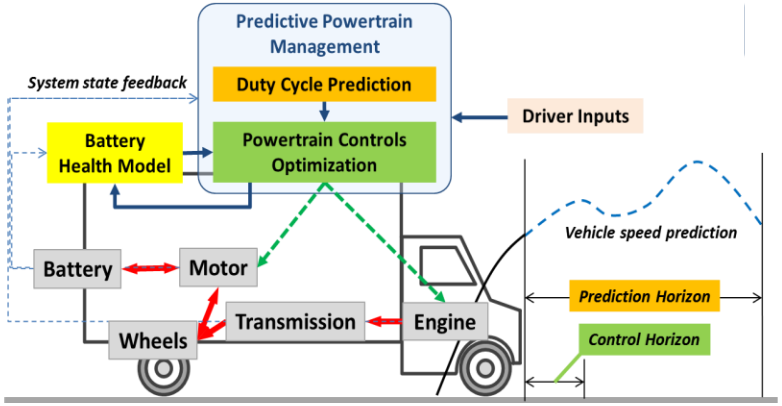
Prognostic-based control (Eaton/NREL ARPA-E AMPED Project)

Team: Eaton Corporation (Chinmaya Patil), NREL (K. Smith)

Medium-duty Commercial HEV
Photo credit: Eaton

Goal: 50% downsized HEV battery

- Meet the driver demand using least amount of fuel,
- …without violating system constraints,
- …while meeting target battery life



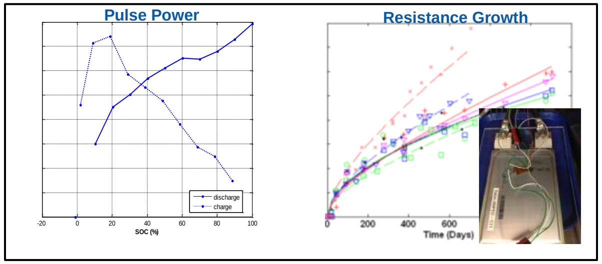
Objective function:

$$J(X,U) = \sum_{t=k}^{k+N_P} w_1 \cdot fuel + w_2 \cdot drivability + w_3 \cdot battery$$

Online Life Prognostic Model Development

1) Cell life test data

- Constant temperature & duty cycle



2) Regress life model parameters

Calendar fade
- SEI growth (partially suppressed by cycling)
- Loss of cyclable lithium
- $a_1, b_1 = f(\Delta DOD, C_{rate}, T, \ldots)$

Cycling fade
- active material structure degradation and mechanical fracture
- $a_2, c_2 = (\Delta DOD, C_{rate}, T, \ldots)$

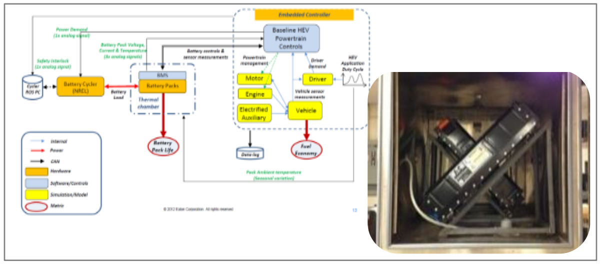
Relative Resistance $R = a_1 t^{1/2} + a_2 N$

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

$Q_{Li} = b_0 + b_1 t^{1/2} + b_2 N$ $Q_{sites} = c_0 + c_2 N$

3) Pack life test data

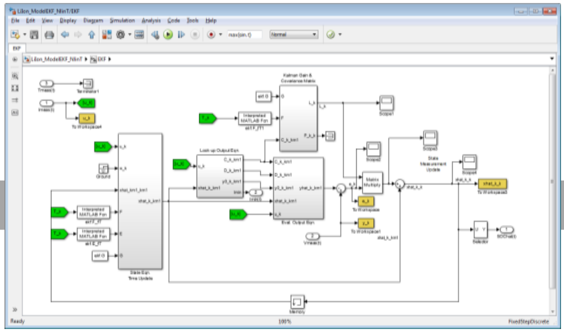
- Variable temperature & duty cycle



4) Validated pack life model

- Forward looking prognosis based on observed I,V,T,SOC,…

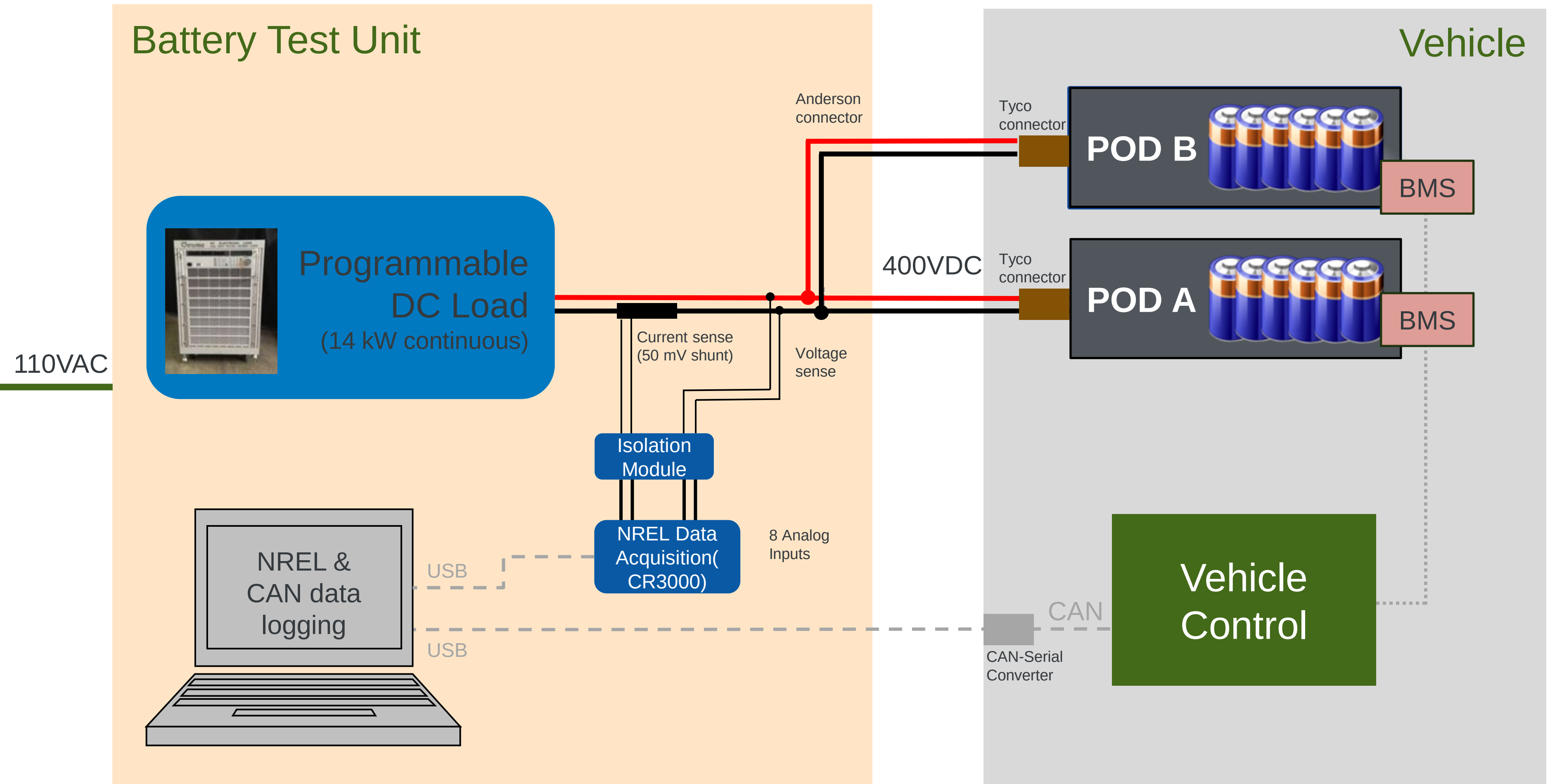
5) Control strategy prototyping



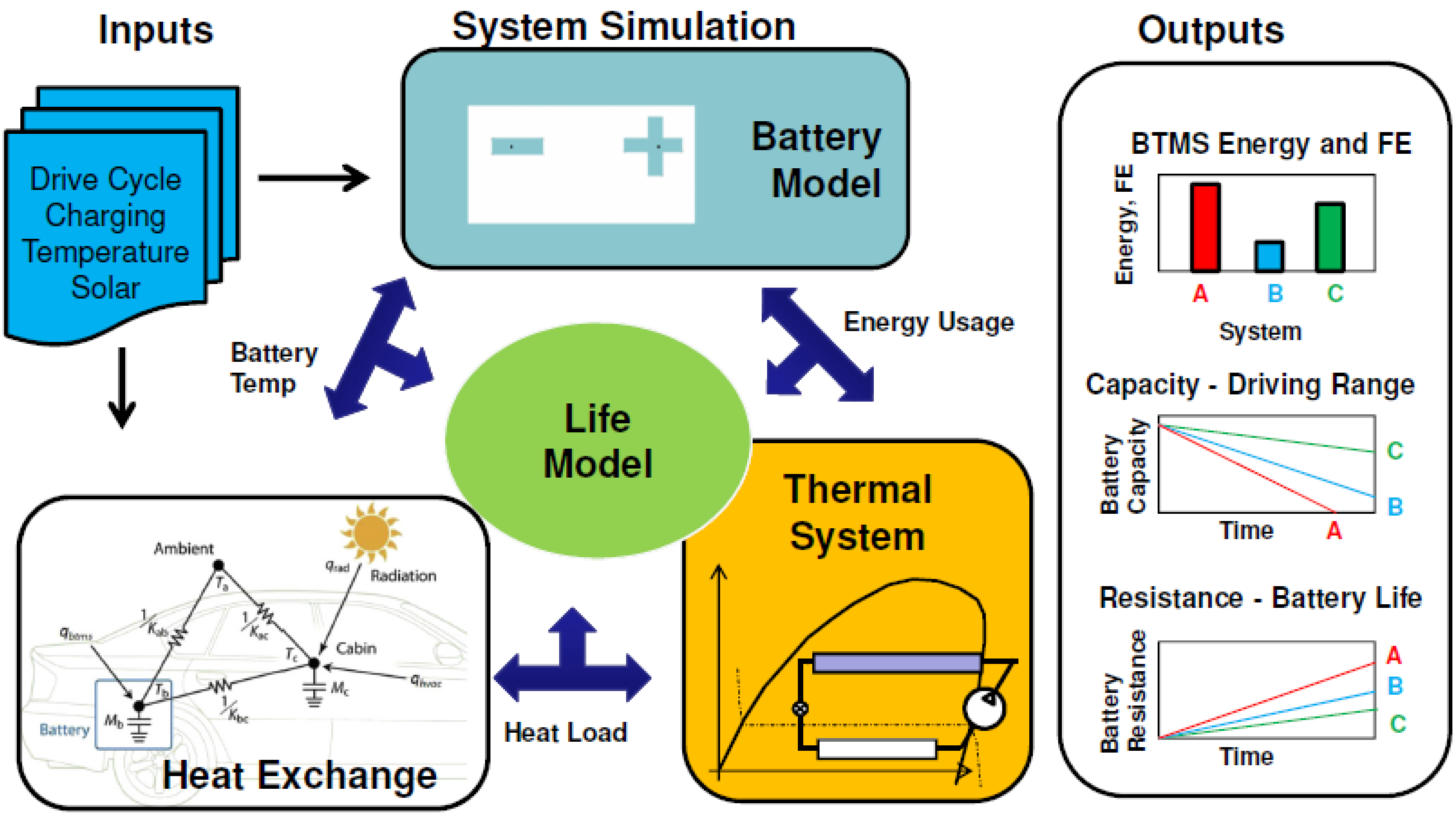
6) Closed-loop HIL testing

Tracking Battery Health of xEV Fleets

- NREL has developed equipment to test battery health in the field
- Presently 2 years into 3-4 year project tracking 8 EV delivery trucks
- Goals are to validate life models, provide feedback on design and route optimization, validate business case for EV adoption



Designing Thermal Management for Batteries

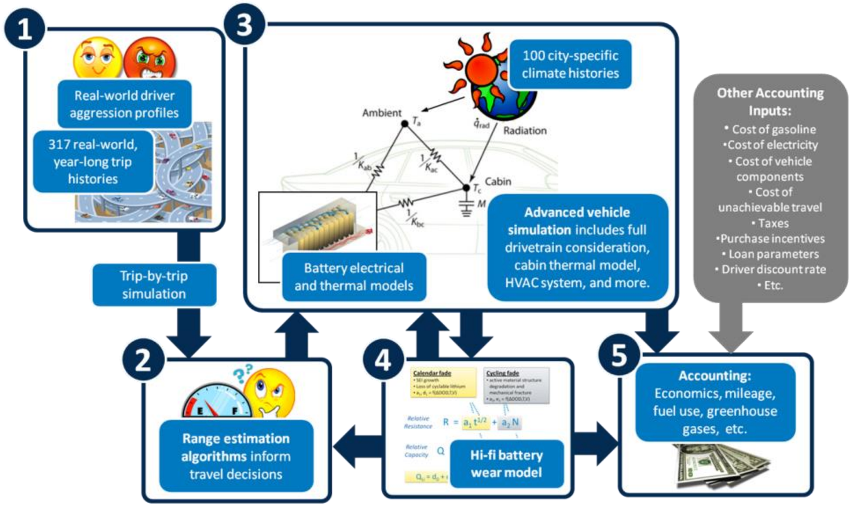


Model vehicle usage and ambient, battery heat generation and thermal system to determine battery life, fuel economy and energy effects of thermal system.

E. Huyge, B. Brodie, K. Santhanagopalan, M. Keyser and A. Pesaran, Presented at the DOE AMR, June 2014.

Battery Second Use Strategies

- NREL developed a Battery Ownership Model, an advanced techno-economic analysis tool
- It evaluates cost-effective pathways and business strategies to increase market adoption of energy storage and electric vehicles
- If EV market adoption is successful, too many battery packs with 60-80% of their initial capacity would become available. NREL used the battery ownership model and utilization of these batteries in various grid services.
- NREL and partners found that **battery second use** won't be a "game-changer" for EVs, but could be a solution to automotive end-of-life battery management if sufficiently large and willing secondary markets evolve



Some Concluding Thoughts

- Li-ion batteries have attributes that make them suitable for both light duty and heavy duty electric drive vehicles
- The cathodes and anodes in Li-ion could be made from various materials which makes them different than other batteries
- In last 5 years, the energy, power, longevity, reliability, and cost of Li-ion batteries has improved significantly
- Li-ion costs have fallen faster than expectations and forecasts as production volume has increased and many battery players have factories that are under-utilized
- As the demand for electric buses are increasing, particularly in China, demand for Li-ion batteries will increase
- Use of batteries in stationary grid applications is rising due to increased penetration of winds and solar energy
- As the commercial targets are still not met, significant R&D is taking place around the world to reduce cost and increase energy
- Some believe we need to go beyond Li-Ion to achieve the targets

Thank You!

http://www.nrel.gov/vehiclesandfuels/energystorage/

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