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The 5th IEEE Vehicle Power & Propulsion Conference

Energy Storage System Technology Challenges facing Strong Hybrid, Plug-in and Battery Electric Vehicles

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Outline

Challenges for Vehicular Energy Storage

Requirements and Technology Status

Power Electronics Facilitated Decoupled Energy and Power

Implementation Challenges

Calendar and Operational Life

Summary

Preface:

What are the challenges facing HEV, PHEV & BEV?

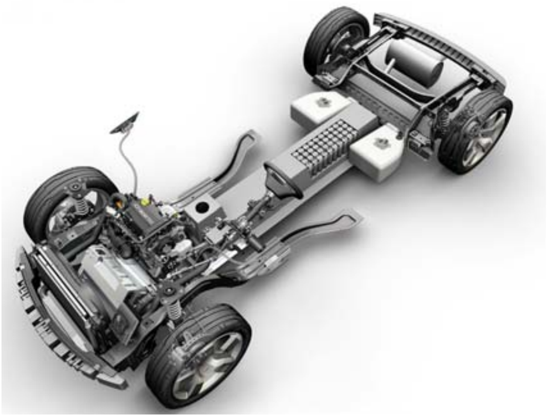
- Energy (Wh/kg, Wh/lit) & Power (kW/kg) metrics of fully packaged ESS
- Highly cyclable useable energy of 50Wh to 150Wh per event for >300,000 such cycles
- Grid connectivity and energy management of both the vehicle ESS and grid regulation activities
- Safety in the automotive environment
- Meeting warranty – mean service life
- Thermal environment
  - Micro, Mild and most Strong HEV's use air cooled energy storage
  - PHEV and Batt-EV(BEV) use liquid cooled ESS

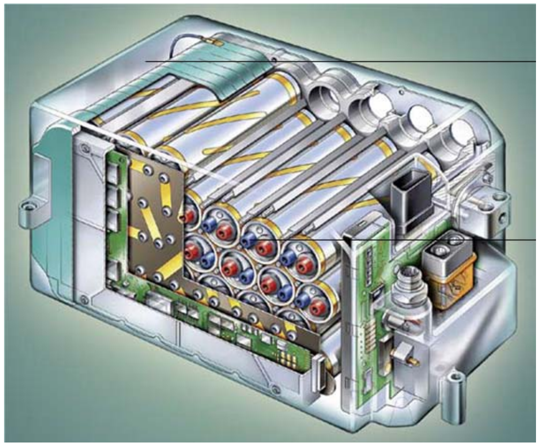
The cost of doing all of the above.

Preface:

What are the challenges facing HEV, PHEV & BEV?

- Thermal environment: Air Cooled
  - Ford Escape (separate air cond loop) & Fusion are air cooled.
  - Prius NiMH pack is air cooled
  - Hymotion 5kWh aftermarket pack is air cooled linked into Prius thermal circuit
  - Focus BEV is air cooled
  - BMW Mini is air cooled
- Thermal environment: Liquid Cooled (WEG)
  - Ford Escape PHEV is liquid cooled
  - Chevy Volt PHEV is liquid cooled
  - Mercedes S Class with Continental ESS using JC-S lithium-ion cells is liquid cooled via conductive gel.





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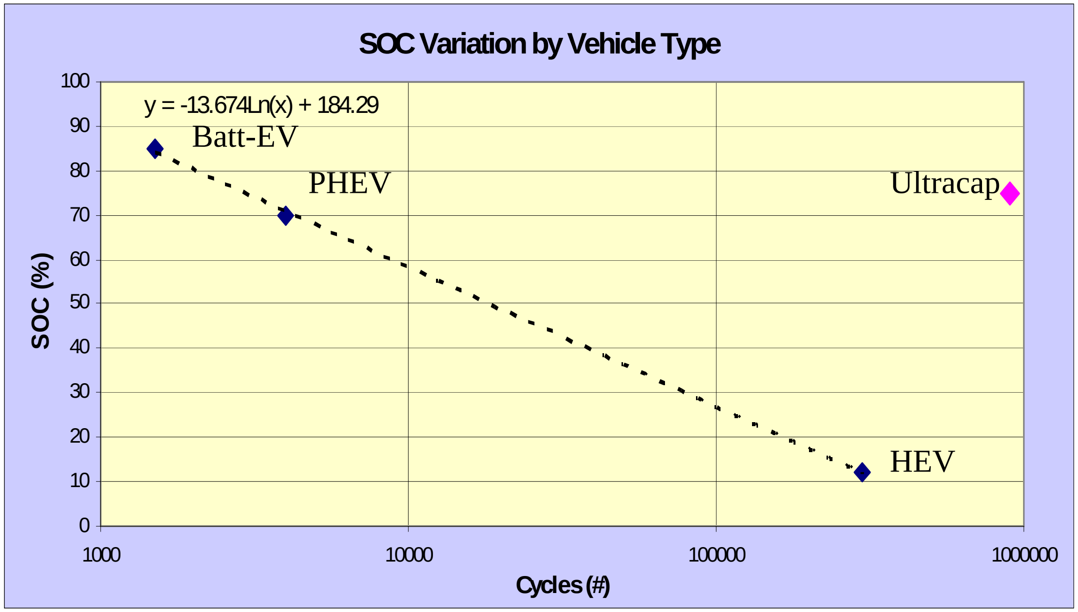
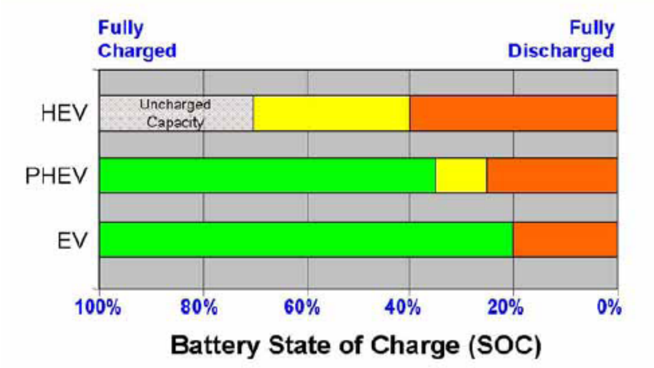
Energy Storage System Cycling Requirements

The higher the cycling requirement:

- The more oversized a battery must be relative to its total stored energy to meet its life target
- Ultracapacitors can cycle 75% or more of their energy well beyond HEV targets





Trends in Lithium-ion Cell Development

Chemistries of interest for automotive applications:

- Plug-in and battery-electric vehicles
- Energy storage system useable capacities of 2kWh (10mi), 8kWh (40mi), >20kWh (>100mi AER) are needed.

Chemistry	Maturity	Thermal	Performance
LiNiCoAlO2 4.xV/cell	Proven	Unstable at high C/x rates	High energy, good power
LiNiCoMnO2 4.xV/cell	Improving	Limited durability experience	High energy, good power
LiMn2O4 3.8V/cell	Improving	Limited life at high temperature	High capacity fade, moderate power
LiFePO4 3.6V/cell	Mature	Very stable	Low energy, rel high power

Lithium-ion versus Ultracapacitor

Performance impairment of lithium-ion below -20C

- This dramatically impacts vehicle performance in cold climates and for large batteries such as used in PHEV and BEV.

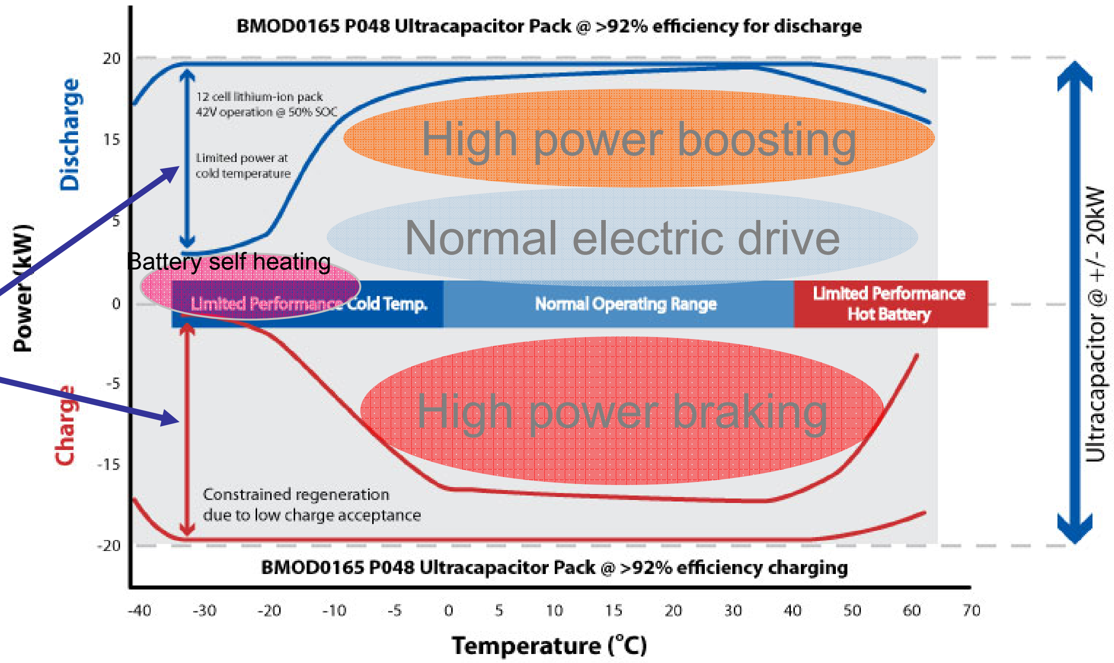
Lithium-ion	*Ultracapacitor*
Resistance of lithium increases dramatically	Resistance increases only moderately.
Consequent dramatic loss of power capability	Power capability is maintained down to -30C and colder.
Charging is major issue and can result in lithium metal plating out on anode	Charge/discharge remains symmetrical and capable of high rates.
Electrolyte begins to gel by -20C	Electrolyte viable to -44C
All of these contribute to loss of useful life of product and its performance	Ultracapacitor use results in long product life without loss of performance.

Strategic Direction in Energy Storage Technology

A value proposition for hybridizing the battery must show a clear positive benefit on each of the attributes of the *hybridized* battery.

Define the value of reduced stress on lithium-ion
Determine how much calendar (storage) and cycle life can be improved
Degree to which reliability is improved at cold temperatures
Value of enhanced energy management & PowerNet stability, and
If overall energy storage system safety is improved, plus
Future goal to have the fully hybridized energy storage system package within the same volume as if lithium-ion alone.

Combination technologies seek to address the performance gaps of battery only implementations through a marriage of strengths.



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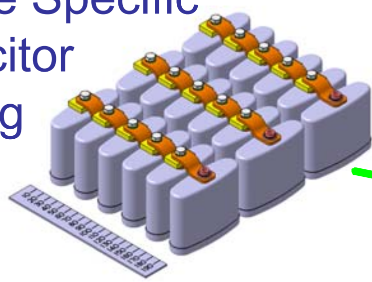
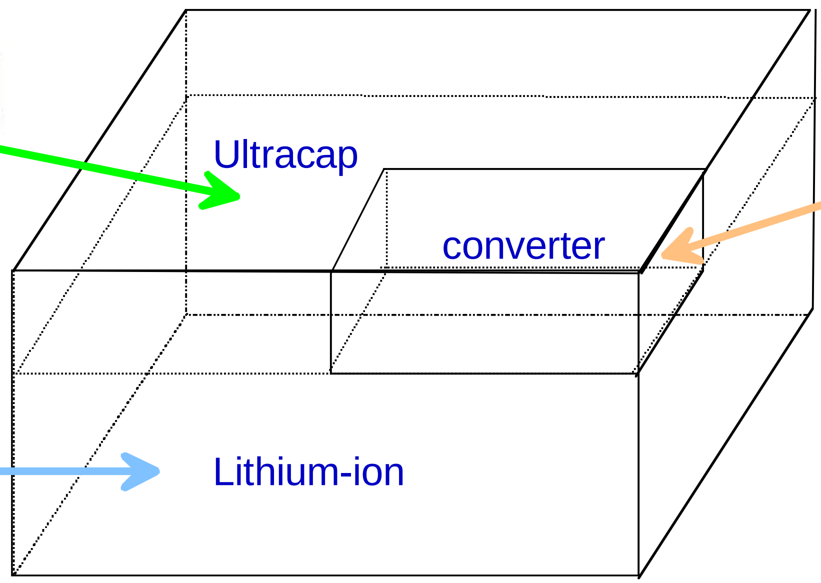
Power Electronics Enabled Electric Energy Storage

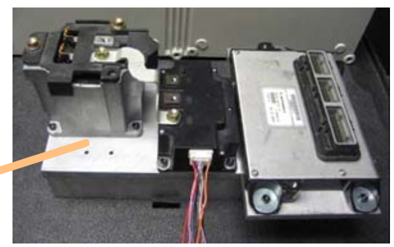
System design targets optimized energy lithium-ion as funding source to defray added cost of ultracapacitors and converter.

- Thick electrode (→ 400um) for true energy battery and cost savings
- High performance ultracapacitors as power element
- Fast converter to manage power flows and overall energy management.

Automotive Specific Ultracapacitor
→ 20kW/kg







Dc-dc converter
→30 kW/liter
→10+ kW/kg
→ ~$25/kW

Long term goal is enhanced ESS performance in same volume package at no additional cost.

Power Electronics Enabled Electric Energy Storage

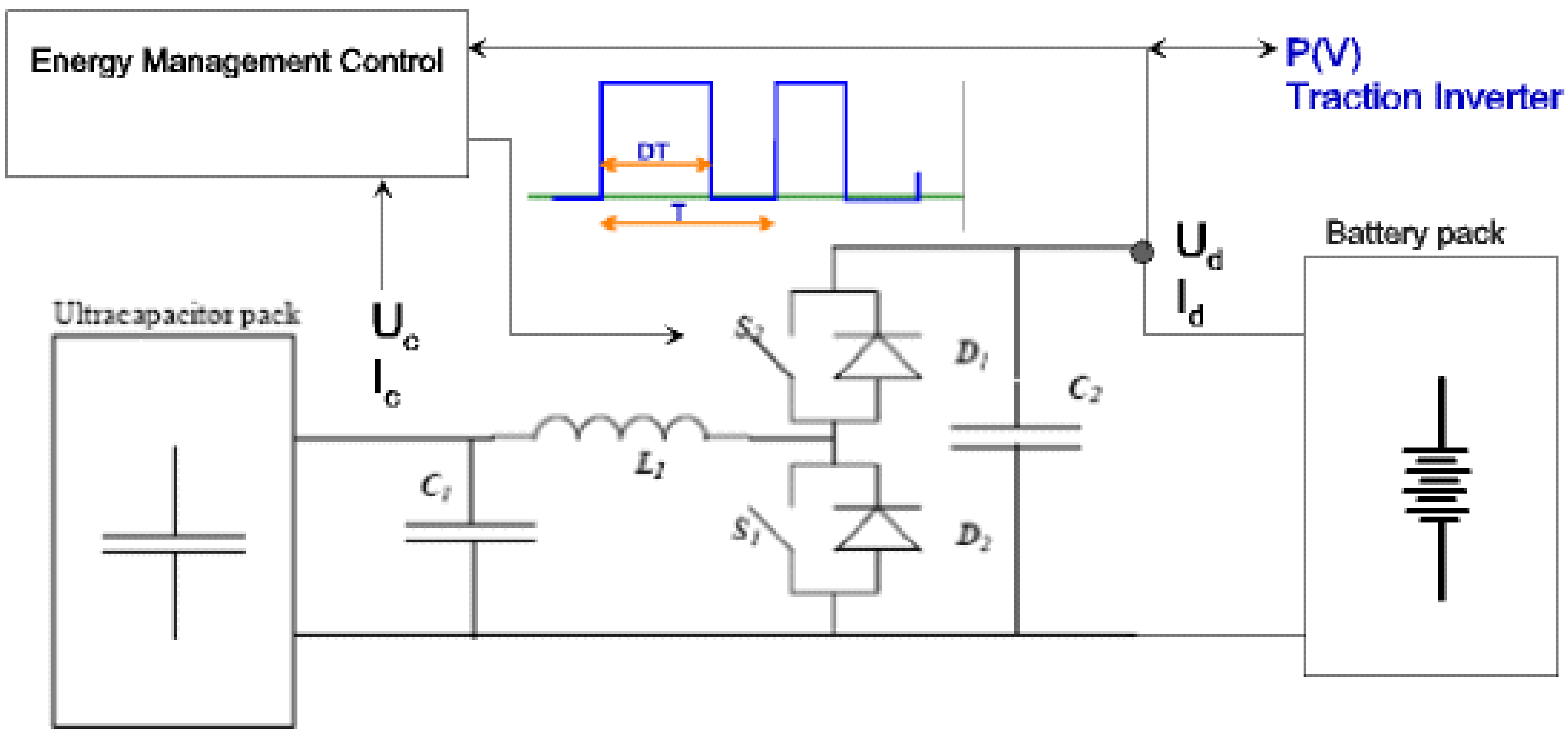
Power electronics is viewed as facilitating next generation energy and power optimized ESS.

- Physical integration at cell electrode level in the form of hybrid-caps, a carbon intercalating electrode with a carbon adsorption electrode are available now:
  - JSR Micro/JM Energy lithium-cap (12Wh/kg, 1kW/kg)
  - Hybrid caps lack peak power and high efficiency needed.

Experimental high performance carbon-carbon ultracap 48V module for system level integration

Power Electronics Enabled Electric Energy Storage

Active parallel combination of ultracapacitor with a battery can be viewed as hybridizing the battery in much the same fashion as vehicle power plants have become hybridized: a base loaded power plant (engine) and a peaking unit (electrical). In this case the hybridized battery becomes an energy optimized electric energy storage unit combined with a power component, the ultracapacitor.

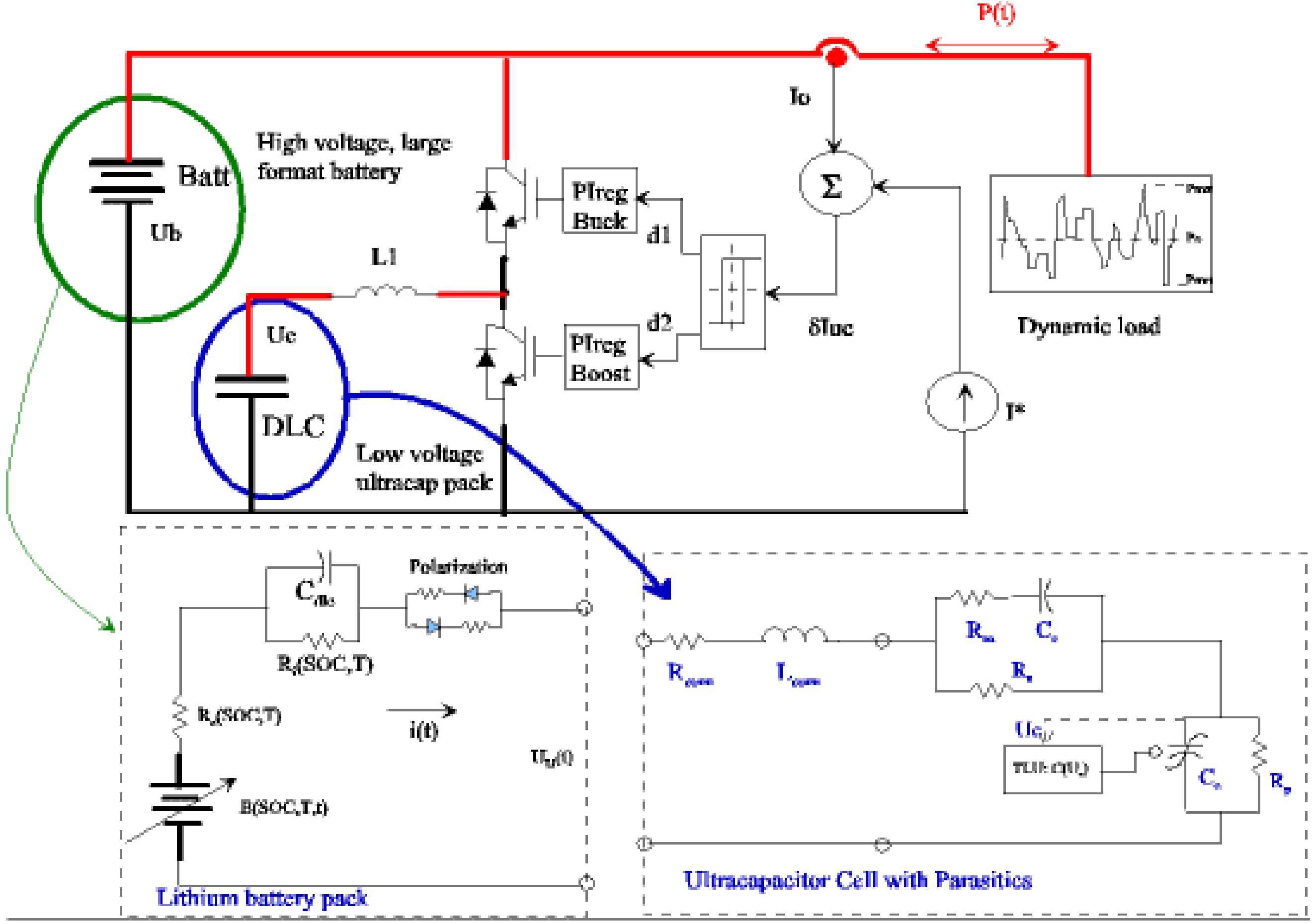


Active Parallel Connection Modeled

Lithium-ion pack thermal system is stressed by load peak current, di/dt, and total rms current

Off setting battery rms current to the ultracapacitor under tight energy management of the converter greatly improves battery life.

Battery thermal performance now limits PHEV and BEV market release.

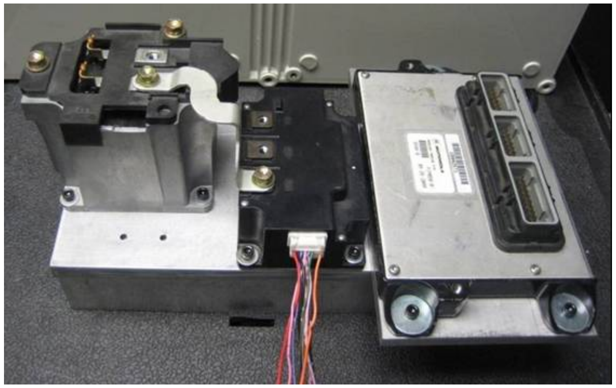


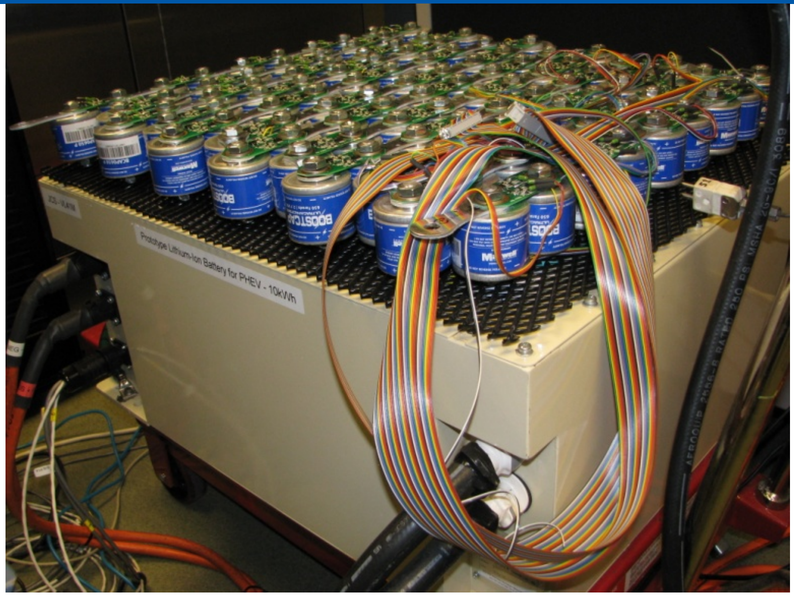
Active parallel connection of ultracapacitors and lithium-ion cells using half-H buck/boost converter and current regulator.

Battery rms current can be arbitrarily reduced according to available ultracapacitor energy and the energy management strategy employed.

Experimental Setup

Ultracapacitor and lithium-ion
Dc-dc converter





Argonne National Laboratory Hardware-in-Loop HIL Facility. Maxwell collaborates with Argonne on combination architectures.

Two programs in progress at ANL's APRF

A. 10kWh lithium-ion plus 70Wh ultracap

B. Small scale 38V lithium-ion and 650F ultracaps

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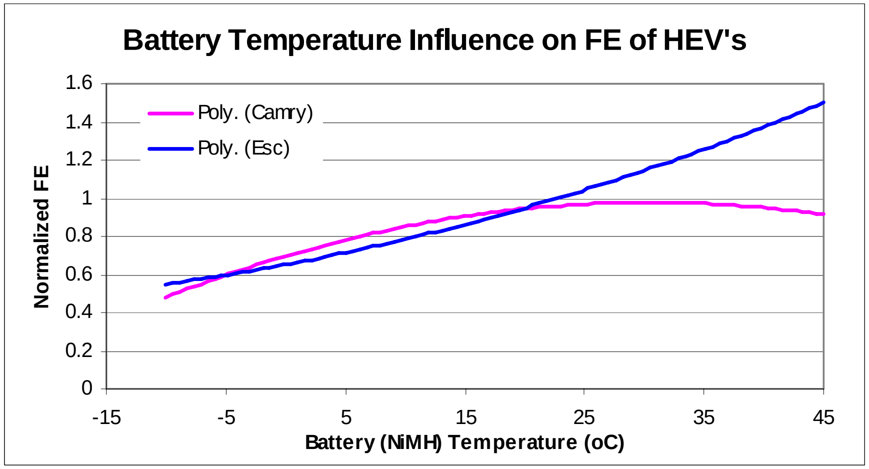
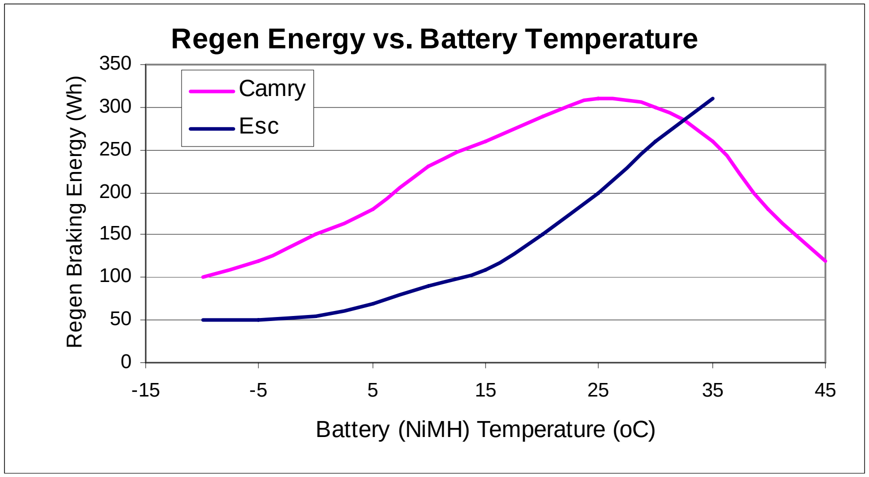
Battery Limitations are Vehicle Performance Limits

- Cold battery limits both vehicle fuel economy and brake regeneration energy recovery.
  - Argonne labs tested two HEV's in cold weather:
    - Ford Escape Hybrid with NiMH pack
    - Toyota Camry Hybrid with NiMH pack
- Vehicles use different climate control and energy management strategies but the result is the same, FE and regenerative energy capture when cold are substantially reduced.
  - In a PHEV the ESS pack thermal time constant is longer leading to extended periods of poor performance when cold.

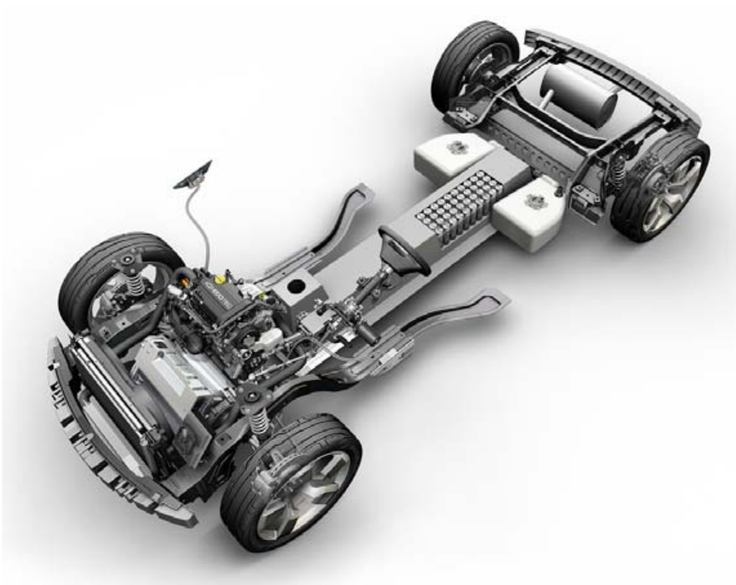




HEV and PHEV and BEV

- Practical benefits of separating the energy storage system for a PHEV into two sections is that *the Joule (I^2R) losses can be relocated into the high current capability ultracapacitors which have much lower impedance than batteries and possess reciprocal charge-discharge behavior*.
- The actively coupled capacitor ESS relocates the heat outside of the battery, allowing the battery to be more densely packaged, with thicker electrode material for higher energy capacity and AER.

Range extended EV, series configuration.



Parallel configuration

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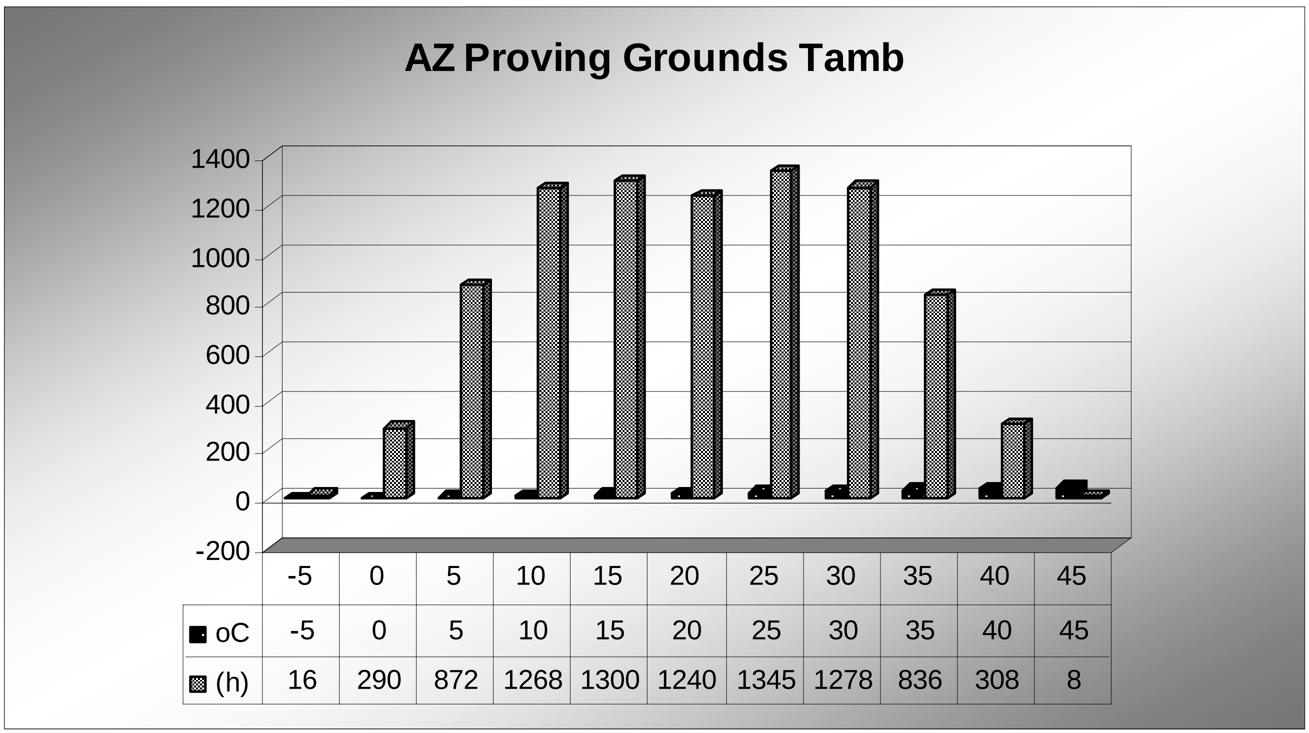
Temperature is the Major Stress Factor for ESS

Temperature statistics of various geographical areas are available and necessary to characterize the vehicle ESS environment.

Time at temperature along with voltage (and current) stress factors are essential to better estimate ESS operational life.



oC	-5	0	5	10	15	20	25	30	35	40	45
(h)	16	290	872	1268	1300	1240	1345	1278	836	308	8

Mean Service Life to Quantify Operational Life

Electrochemical energy storage systems follow an Arrhenius type response to temperature stress factor.

This basic relationship of component life with temperature is extended to include additional stress due to voltage and its cross-coupled influence with temperature.

As an illustration, the mean life at 40C is modeled as follows. “A” is the nominal life component, “B” is the Arrhenius factor, “C” a voltage only factor and “D” the coefficient on the cross terms.

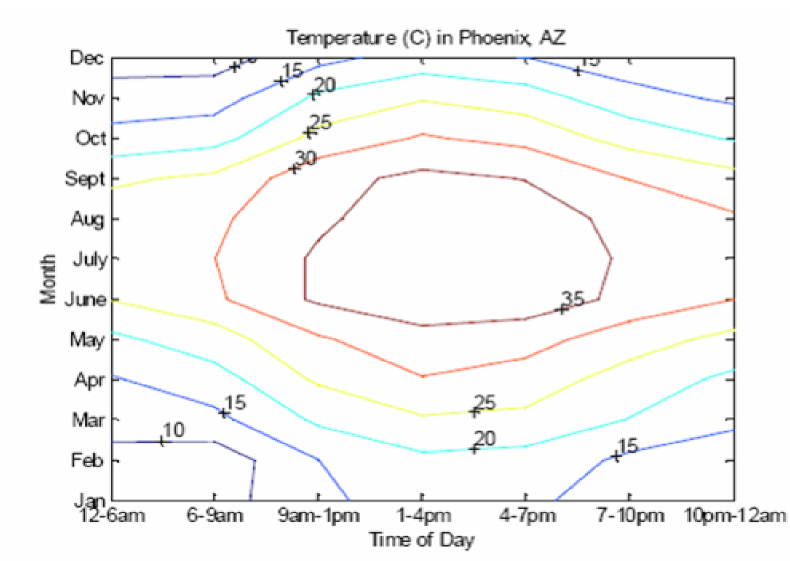
$$ML_{.40} := A + B \cdot \left(\frac{1}{T_{.0}} - \frac{1}{T_{.2}} \right) + C + D \cdot U_{.c}{}^{\alpha} \cdot \left(\frac{T_{.2}}{T_{.0}} \right)^{\beta}$$

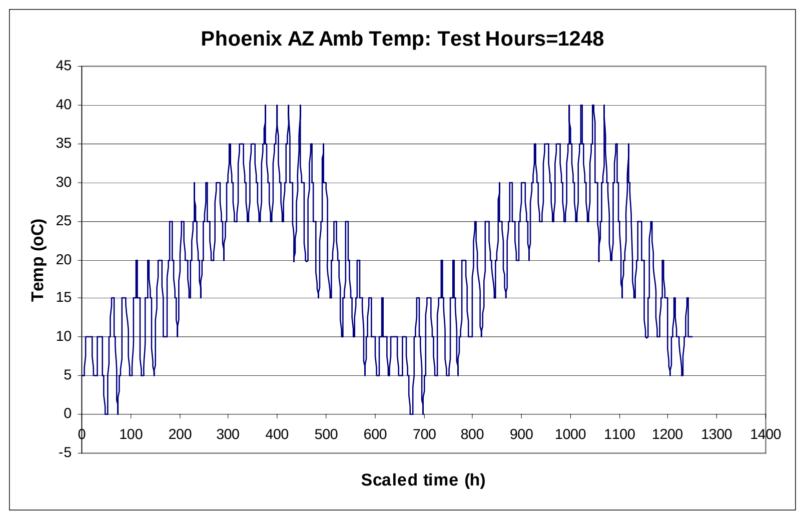
Mean Service Life to Quantify Operational Life

The vehicle package environment imposes additional temperature (and perhaps voltage) stress on the ESS.

The challenge is to characterize the package space thermal environment, size the thermal management system, and insure the design meets all electrical, mechanical, and thermal requirements.

Illustration of compressed annualized temperature environment.

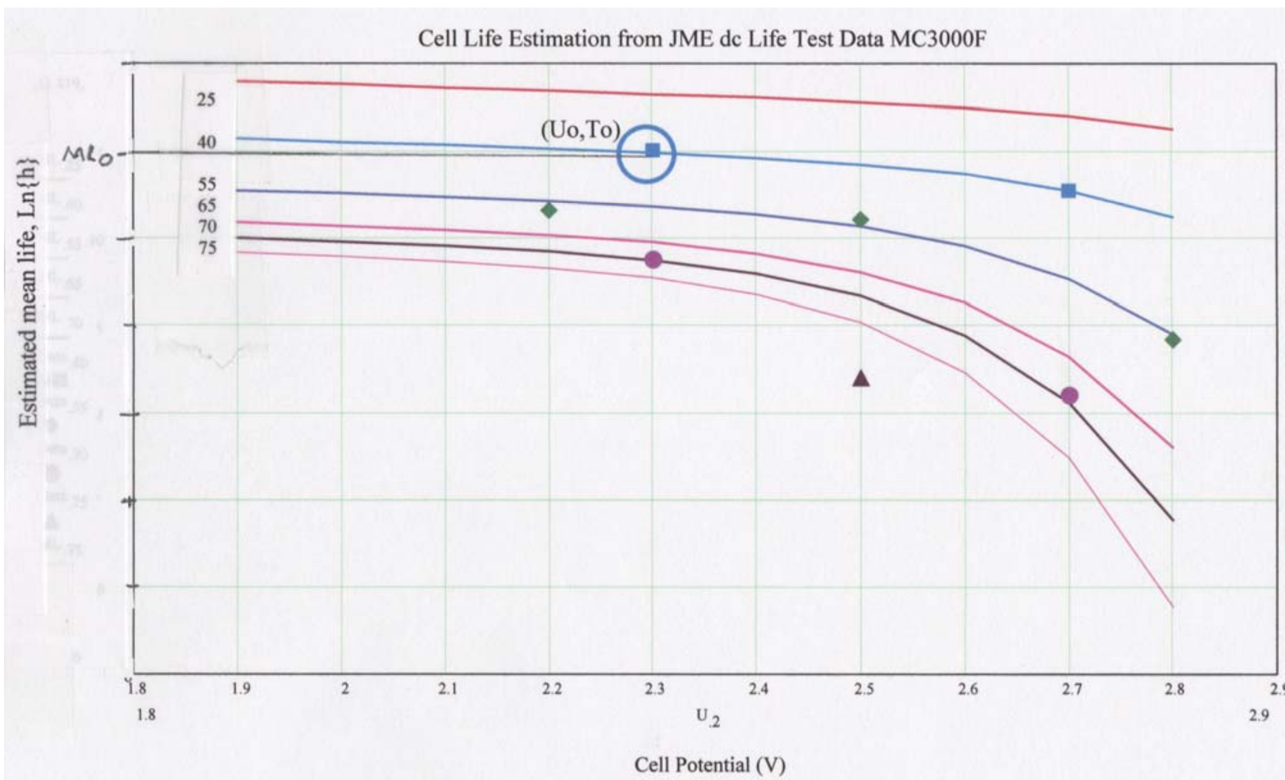




Mean Service Life to Quantify Operational Life

Meeting service life requirements is primarily a thermal design exercise and the challenge remains that of finding an appropriate system level thermal management design.

The following illustrates a validated MSL characterization of a 3000F cell.



Summary: Commercialization Challenges

For a hybridized battery to become commercial two technical and two business objectives must be met:

Business

Development of an automotive specific ultracapacitor

Development of a "true" energy lithium pack (>200Wh/kg)

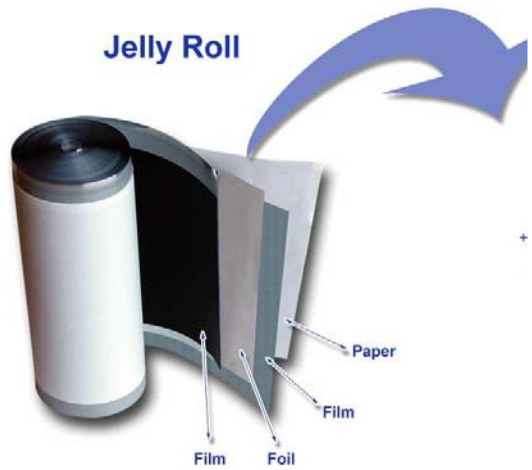
Technical

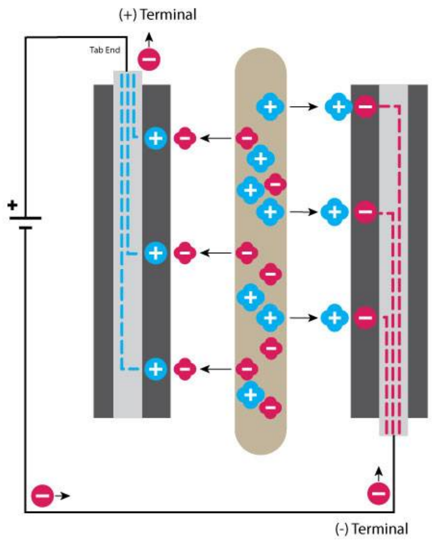
Availability of a high power, bi-directional, dc-dc converter having >30kW/liter PD and <$25/kW SC.

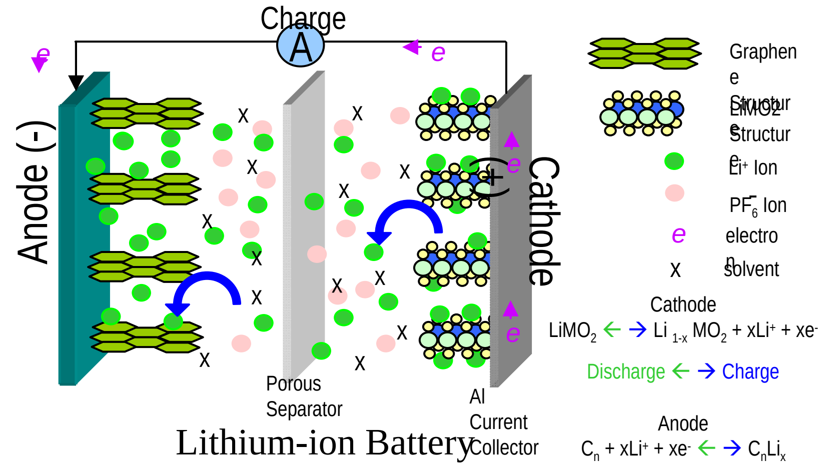
Energy management strategy capable of seamless power and energy decoupling without loss of SOC window.

Appendix

Ultracapacitor & Lithium-ion Chemistry







EC – <u>Physical</u> energy storage
Charge contained in electrolyte
Adsorption of ion
Solvated ions
Conductivity, σ(SOC)
E = f(electrode surface)

Battery – <u>chemical energy storage</u>
Charge contained in electrode mass
Orbital electron exchange REDOX
ion intercalation
σ=constant
E=f(electrode mass)

EC = electrochemical capacitor
SOC= state-of-charge

REDOX = reduction-oxidation reaction

Bio

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John M. Miller joined Maxwell in December 2005, assuming primary responsibility for world wide applications engineering that includes development of Maxwell University training for field application engineers. He remains active in the development and promotion of ultracapacitor-based solutions for the automotive and heavy vehicle industries. Previously, he spent almost 20 years in a series of engineering and research and development positions with the Ford Motor Company, where he led several Ford automotive electronics and electric and hybrid drive train development programs before taking early retirement in 2002. Immediately prior to joining Maxwell, he spent three years as an industry consultant, author and guest lecturer. He holds 53 patents and has written more than 160 scientific and technical papers and three books, including Hybrid Vehicle Propulsion Systems, which was published in 2003. He holds a BS degree from the University of Arkansas, an MS degree from Southern Methodist University and a doctorate from Michigan State University, all in electrical engineering. He has nearly 30 years experience as a registered professional engineer.