# Battery Choices and Potential Requirements for Plug-In Hybrids

*Plug-In Hybrid Electric Truck Workshop*
*Hybrid Truck Users Forum*
*Los Angeles, CA*

February 13, 2007

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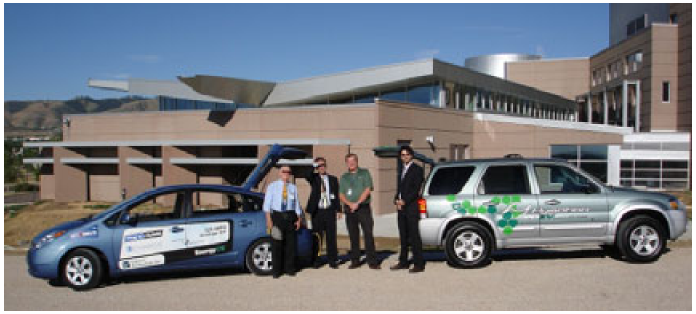
**National Renewable Energy Laboratory**

With support from
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
FreedomCAR and Vehicle Technologies Program

NREL/PR-540-41328

# NREL's Plug-in Hybrid R&D Activities

- Battery Level
  - R&D support to developers
  - Testing and evaluation – Sprinter PHEV testing
  - Thermal characterization and design
  - Requirement analysis in support of EES Tech Team
- Vehicle Level
  - Simulated real-world PHEV fuel economy
  - Support development of test procedures and MPG reporting
  - Route-based control
  - PHEV design cost-benefit analysis
- Utility Level
  - Assessment of PHEV impacts on utilities
  - Exploring synergies between PHEVs and wind power
  - V2G opportunities for PHEVs in regulation services
- National Level
  - Benefits assessment - oil use and emissions
  - Renewable community – linking PHEV to homes/communities
- Analysis support to DOE, OEMs, and others
  - Working to identify and overcome barriers to PHEV adoption

# NREL's Heavy Hybrid Vehicle Activities

- Technical Monitor of DOE's Advanced Heavy Hybrid Propulsion System Program
  - **GM – Allison Transmission** (Heavy hybrid transit bus application & orototype validation) – parallel hybrid
  - **Eaton/International** (Class 4-6 vehicle applications & prototype validations) – parallel hybrid
  - **Oshkosh** (Class 7-8 vehicle application & prototype validation) – Series hybrid; extremely demanding duty-cycle
  - **Caterpillar** (Focus on thermoelectric waste heat recovery)
- Technical Contributions
  - ReFUEL Lab (Chassis and engine dynamometers)
    - » Vehicle fuel economy and emissions testing
    - » Vehicle drive cycle characterization and analysis
  - Thermal testing, analysis, and management
    - » Power electronics
    - » Batteries and ultracapacitors

# Topics of This Presentation

- **Battery Technologies for PHEVs**
  - — State-of-the-art
  - — Advances
- **Impact of Vehicle Attributes on Battery**
  - — EV Range
  - — System Architecture
  - — Driving cycles and profiles
- **Concluding Remarks**

# Key Messages

- There is a broad spectrum of PHEV designs leading to different battery requirements

- Batteries are available that could meet the energy and power demands for PHEVs, but cost and limited cycle/calendar life are major barriers for affordable PHEV introduction:
  - NiMH could do the job – volume and weight are concerns
  - Li-ion are potentially best candidates
  - All li-ions are not "created equal"

- For heavy-duty PHEV, combining low-cost, high-energy batteries (such as NaNiCl or ZnAir) with high power ultracapacitors may have potential

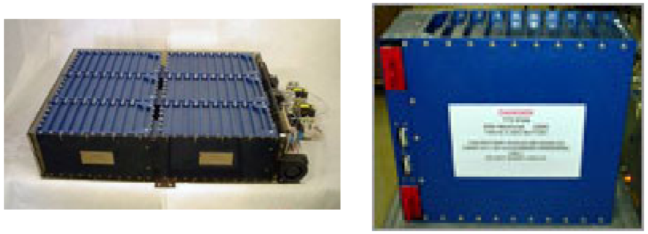
- There is a trade of between high fuel economy and emissions benefits
  - Engine-off during EV operation reduces the petroleum consumption
  - Too many engine-off cycles lead to cold starts and higher emissions

- PHEVs are the most-cost-effective choice in a scenario of projected low battery costs and high fuel costs.

# Batteries in Current PHEVs

**NiMH**

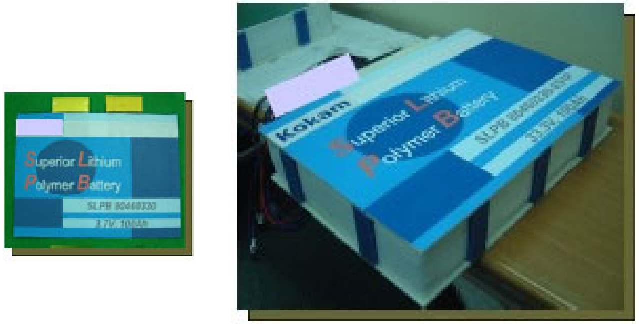
Johnson Controls / Varta



Electro Energy Inc.

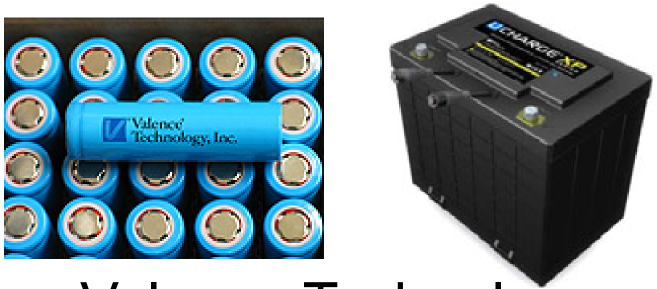
**Co/Ni based Li-Ion**


Johnson Controls / SAFT




Kokam

**Iron phosphate based Li-Ion**




Valence Technology


A123 Systems

# High Power Battery and Ultracapacitor Characteristics

| Parameter | VRLA | NiMH | Li Ion | Ultracap |
|---|---|---|---|---|
| **Cell configuration** | Parallel plates; spirally wound cylindrical | Spirally wound cylindrical; parallel plates | Spirally wound cylindrical & elliptic | Spirally wound cylindrical & elliptic |
| **Nominal cell voltage (V)** | 2 | 1.2 | 3.6 | 1.8 |
| **Battery electrolyte** | Acid | Alkaline | Organic | Organic |
| **Specific energy, Wh/kg** | 25 | 40 | 60 to 80 | 5 |
| **Battery/Module specific power, 10 sec, W/kg** | | | | |
| **23°C, 50% SOC** | 400 | 1300 | 3000 | >3000 |
| **-20°C, 50% SOC** | 250 | 250 | 400 | >500 |
| **Charge acceptance, 10 sec. W/kg** | | | | |
| **23°C, 50% SOC** | 200 | 1200 | 2000 | >3000 |
| **2010 Projected Cost >100,000 per year** | | | | |
| **$/kWh, Module** | 100.00 | 500.00 | 700.00 | 20,000.00 |
| **$/kWh, Full pack** | 140 | 600 | 1100 | 25000 |
| **$/kW, pack** | 9.00 | 18.00 | 22.00 | 40.00 |
| **Energy efficiency** | Good | Moderate | Good | Very Good |
| **Thermal managements requirements** | Moderate | High | Moderate | Light |
| **Electrical control** | Light | Light | Tight | Tight |

Source: M. Anderman, AABC-04 Tutorial, San Francisco, CA June 2004

# Qualitative Comparison of Existing Energy Battery Technologies for PHEVs

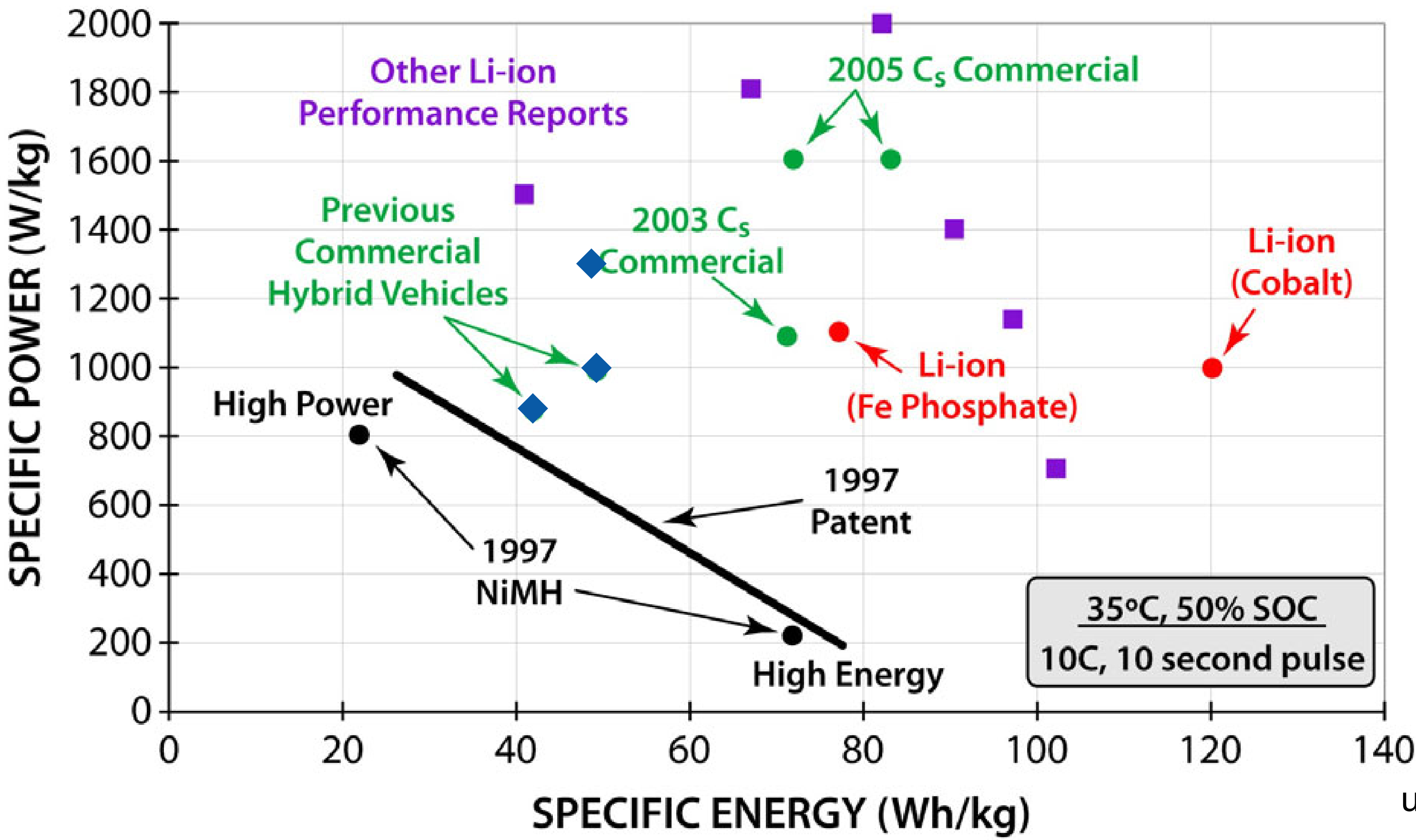
Key

| Key |
|---|
| Poor |
| Fair |
| Good |

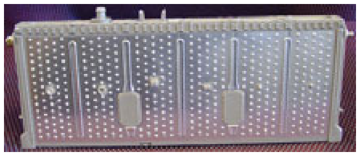
| Attribute | Lead Acid | NiMH | Li-Ion |
|---|---|---|---|
| Weight (kg) | Poor | Fair | Good |
| Volume (lit) | Poor | Good | Good |
| Capacity/Energy (kWh) | Poor | Fair | Good |
| Discharge Power (kW) | Good | Fair | Good |
| Regen Power (kW) | Good | Good | Good |
| Cold-Temperature (kWh & kW) | Good | Fair | Poor |
| Shallow Cycle Life (number) | Good | Good | Good |
| Deep Cycle Life (number) | Poor | Good | Fair |
| Calendar Life (years) | Poor | Fair | Fair |
| Cost ($/kW or $/kWh) | Good | Poor | Poor |
| Safety- Abuse Tolerance | Good | Good | Fair |
| Maturity - Technology | Good | Good | Fair |
| Maturity - Manufacturing | Good | Fair | Poor |

# NiMH has Matured in Power and Energy

Specific energy ranging from 45 Wh/kg to 80 Wh/kg depending on the power capability.




● Ovonic



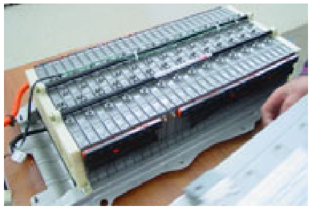
◆ Panasonic EV


95 Ah EV module used in Toyota RAV 4

Source: Reproduced from A. Fetcenko (Ovonic Battery Company) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

# NiMH technology is forecasted to have a major market share in hybrid market until Li-Ion takes off

## Panasonic



6.5 Ah Battery for Toyota Prius

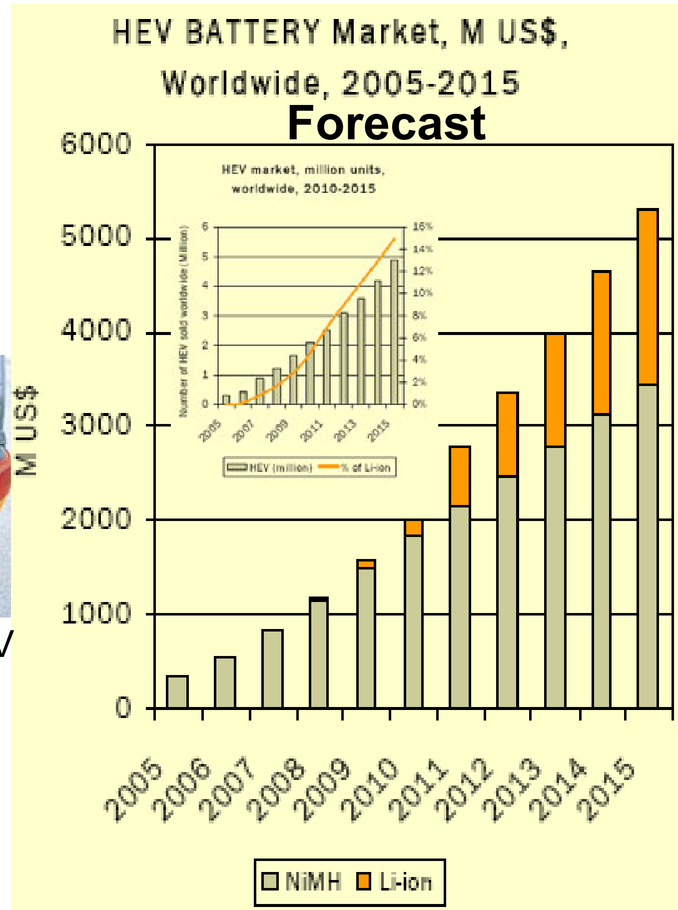
## Sanyo

6.5 Ah HEV cells in Ford Escape HEV

Source: Sanyo website news

## Cobasys


EV module (left) and 42V HEV batteries




Source: C. Pillot (Avicenne) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

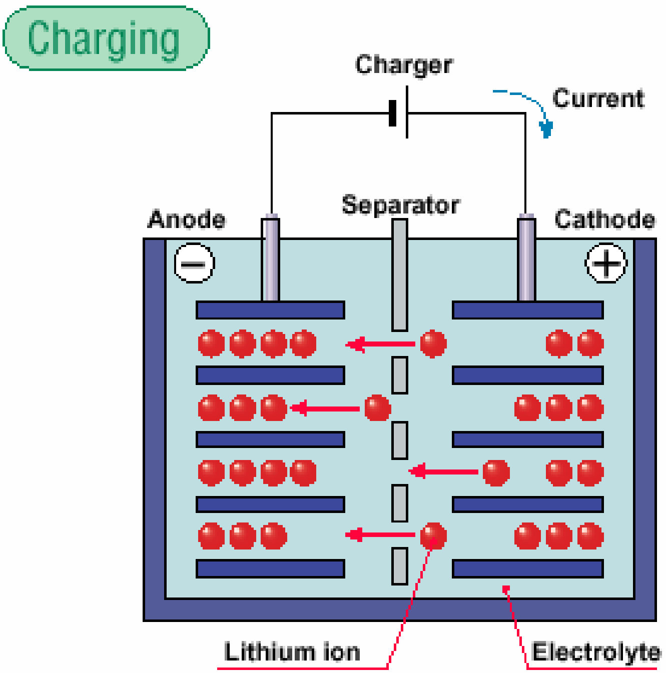
## Electro Energy

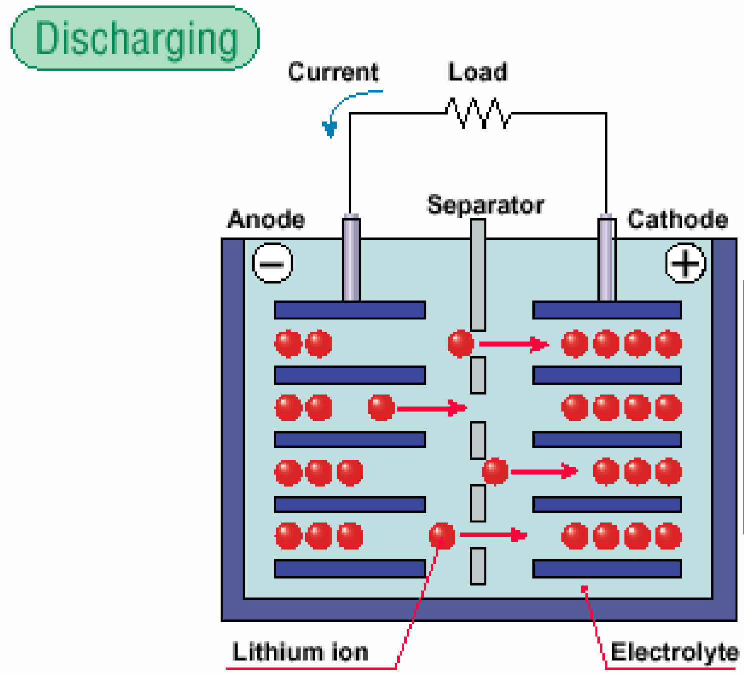
Pack with bipolar Cells/Modules

Bipolar pack in a Plug-In Prius

Source: Images provided by James Landi of Electro Energy Inc.

# Li-Ion Technology – Diverse Chemistry & Opportunity




**Voltage ~3.2-3.8 V**
**Cycle life ~1000-3000**
**Wh/kg >150**
**Wh/l >400**
**Discharge -30 to 60°C**
**Shelf life <10%/year**

| **Many anodes are possible** | **Many electrolytes are possible** | **Many cathodes are possible** |
|---|---|---|
| Carbon/Graphite | $LiPF_6$ based | Cobalt oxide |
| Titanate ($Li_4Ti_5O_{12}$) | $LiBF_4$ based | Manganese oxide |
| Titanium oxide based | Various solid state electrolytes | Mixed oxides with Nickel |
| Tin Oxide based | Polymer electrolytes | Iron phosphate |
| Tungsten oxide | (+ some salts) | Vanadium oxide based |

Source: Robert M. Spotnitz, Battery Design LLC, "Advanced EV and HEV Batteries," 2005 IEEE Vehicle Power and Propulsion Conference, September 7-9, 2005, IIT, Chicago, IL

# Characteristics of Cathode Materials

**Theoretical values** for a battery system relative to graphite anode and $LiPF_6$ electrolyte

| Material | Δx | mAh/g | avg V | Wh/kg | Wh/l |
|---|---|---|---|---|---|
| $LiCoO_2$ | 0.55 | 151 | 4.00 | 602 | 3073 |
| $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ | 0.7 | 195 | 3.80 | 742 | 3784 |
| $LiMn_2O_4$ | 0.8 | 119 | 4.05 | 480 | 2065 |
| $LiMn_{1/3}Co_{1/3}Ni_{1/3}O_2$ | 0.55 | 153 | 3.85 | 588 | 2912 |
| $LiFePO_4$* | 0.95 | 161 | 3.40 | 549 | 1976 |

*Typically diluted with 10% carbon for electronic conductivity

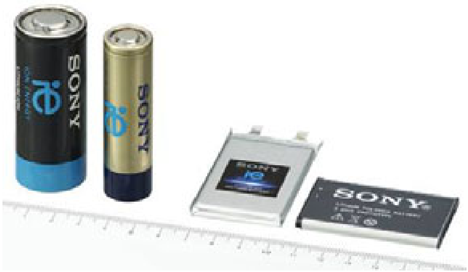
- Cobalt oxide most widely used in consumer cells but recently too expensive
- $LiMn_{1/3}Co_{1/3}Ni_{1/3}O_2$ newer than $LiNiCoO_2$
- $Mn_2O_4$ around for many years – not competitive for consumer – good for high power
- Oxide cathodes with cobalt are more energetic
- $LiFePO_4$ – very new – too low energy density for consumer electronics
  - safe on overcharge but need electronics to prevent under-voltage
  - may require larger number of cells due to lower cell voltage

Source: Robert M. Spotnitz, Battery Design LLC, "Advanced EV and HEV Batteries," 2005 IEEE Vehicle Power and Propulsion Conference, September 7-9, 2005, IIT, Chicago, IL

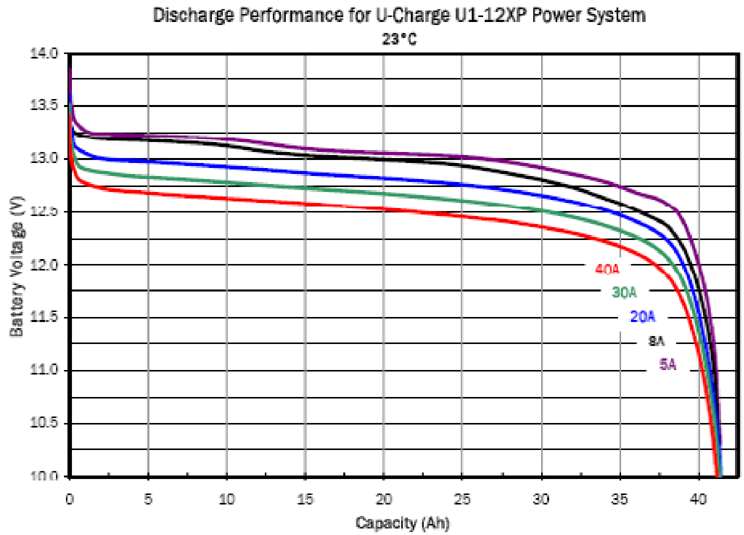
# Many Commercial Oxide Based Li-Ion Batteries are Available

- Johnson Control - Saft
- LG Chem
- Electrovaya
- Kokam
- SK Corp
- NEC Lamilion Energy
- GS Yuasa
- Sony
- Sanyo
- Samsung
- Panasonic
- Nissan
- Lishen
- Pionics
- Altair Nanotechnologies
- Chinese companies






# Lithium Iron Phosphate ($LiFePO_4$) Cathodes




Source: On line brochures from Valence Technolo
http://www.valence.com/ucharge.asp

+ High stability and non-toxic
+ Good specific capacity
+ Flat voltage profile
+ Cost effective (less expensive cathode)
+ Improved safety
– Lower voltage than other cathodes
– Poor Li diffusion ($D_{Li}$~ $10^{-13}$ $cm^2$/Sec)
– Poor electronic conductivity (~ $10^{-8}$ S/cm)

- Approach many use to overcome poor characteristics
  — Use nano $LiFePO_4$ – carbon composite
  — Use larger number of cells
  — Nano structured materials

Source: Various papers from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

# Improvements in Iron Phosphate Li-Ion Batteries

## Valence Technology 18650 Cells
**100 Wh/kg in cell 84 Wh/kg in U Charge module**



The battery with standard lead acid battery form factor includes a battery management system.

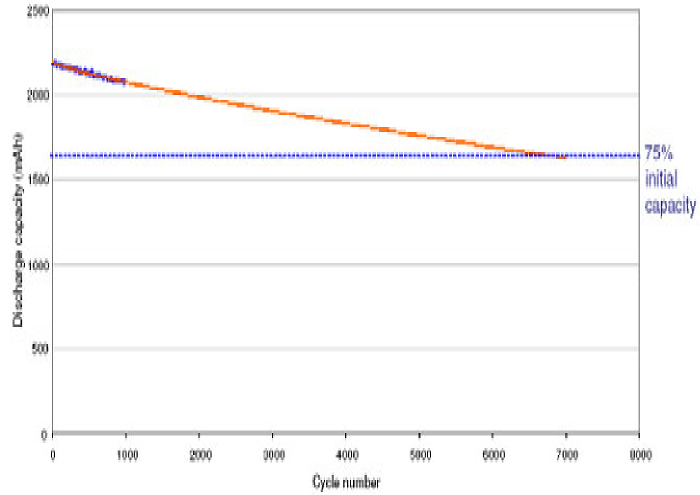
| Specifications | | U1-12XP | U24-12XP |
|---|---|---|---|
| Voltage | | 12.8 V | 12.8 V |
| Capacity (C/5) | | 40 Ah | 100 Ah |
| Specific energy | | 84 Wh/kg | 82 Wh/kg |
| Energy density | | 110 Wh/l | 126 Wh/l |
| Standard Discharge | Max. cont. current | 80 A | 150 A |
| | Max. 30 sec. pulse | 120 A | 300 A |
| | Cut-off voltage | 10 V | 10 V |

Source: 2006 On line brochures from Valence Technology, http://www.valence.com/ucharge.asp

| Power Density (<3Ah cy cells) | Weight to discharge @1500W | Safety | Life at 100% DoD 1C rate | Environmental |
|---|---|---|---|---|
| 3600 W/Kg | 0.9 lbs | ✓ | ~7000 | ✓ |

Based on: Novel nano scale doped phosphate active materials (pat. pending)
Low impedance cell design and electrolyte (pat. pending)


## A123 Systems with 26650 Cells 100 Wh/kg



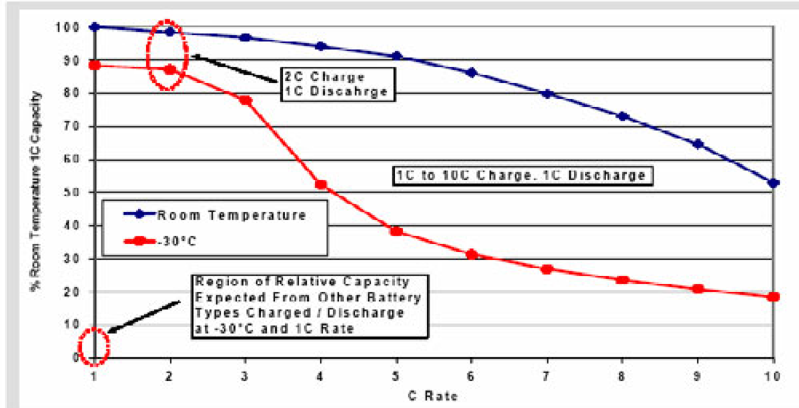

100%DOD 1C charge, 1C discharge cycling data.
Using first 1000 cycles, extrapolated cycle life: ~7000 cycles.

NREL National Renewable Energy Laboratory

Source: Andrew Chu (A123 Systems) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

# Improving Li-Ion Batteries with Titanate Anode

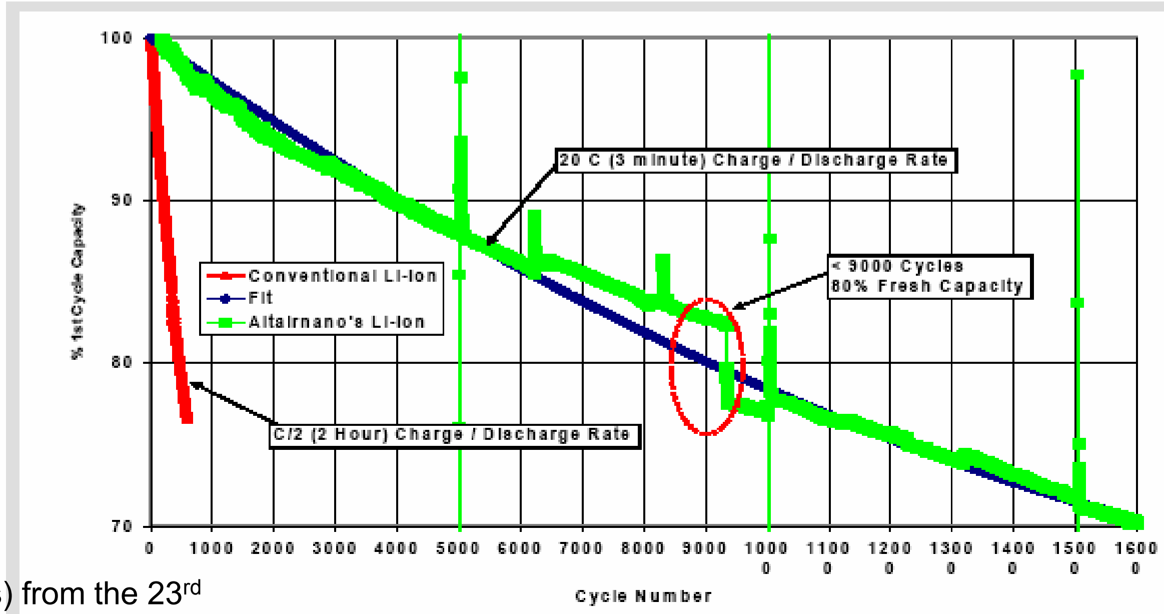
| Characteristic | Traditional Li Ion Batteries | Li Ion Batteries Using Altairnano materials |
|---|---|---|
| Electrode Materials | | |
| Anode | Graphite | Lithium titanate spinel |
| Cathode | Cobaltate | Nano-Structured oxides |
| Performance | | |
| Charge rate | ½ C | 20 C and greater |
| Discharge rate | 4 C | 40 C and greater |
| Cycle life | 300-500 cycles | 9,000 cycles (full DOD) |
| Calendar life | 2-3 years | 10-15 years |




~90% SOC of RT Cell at -30°C and 1-2C Charge Rate!

Altaire Nanotechnologies Inc.

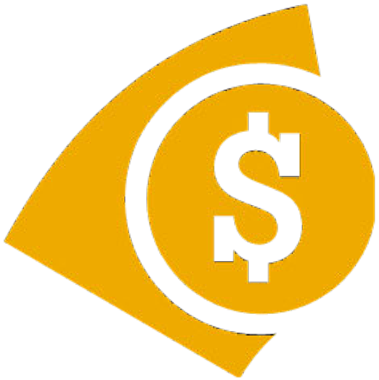
- Improved low temperature performance
- Faster charge acceptance
- Longer cycle life
- 80-100 Wh/kg
- 2000-4000 W/kg




Source: E. House (Altair Nanotechnologies) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

# Exciting Times for Li-Ion Batteries

- New Cathodes
  - Lower cost
  - Higher power
  - Better safety
  - Improved life
- New Anodes
  - Faster charge rate
  - Improved life
- New Electrolyte
  - Improved safety
  - Improved low temperature performance
- New Separator
  - Lower cost
  - Improved safety



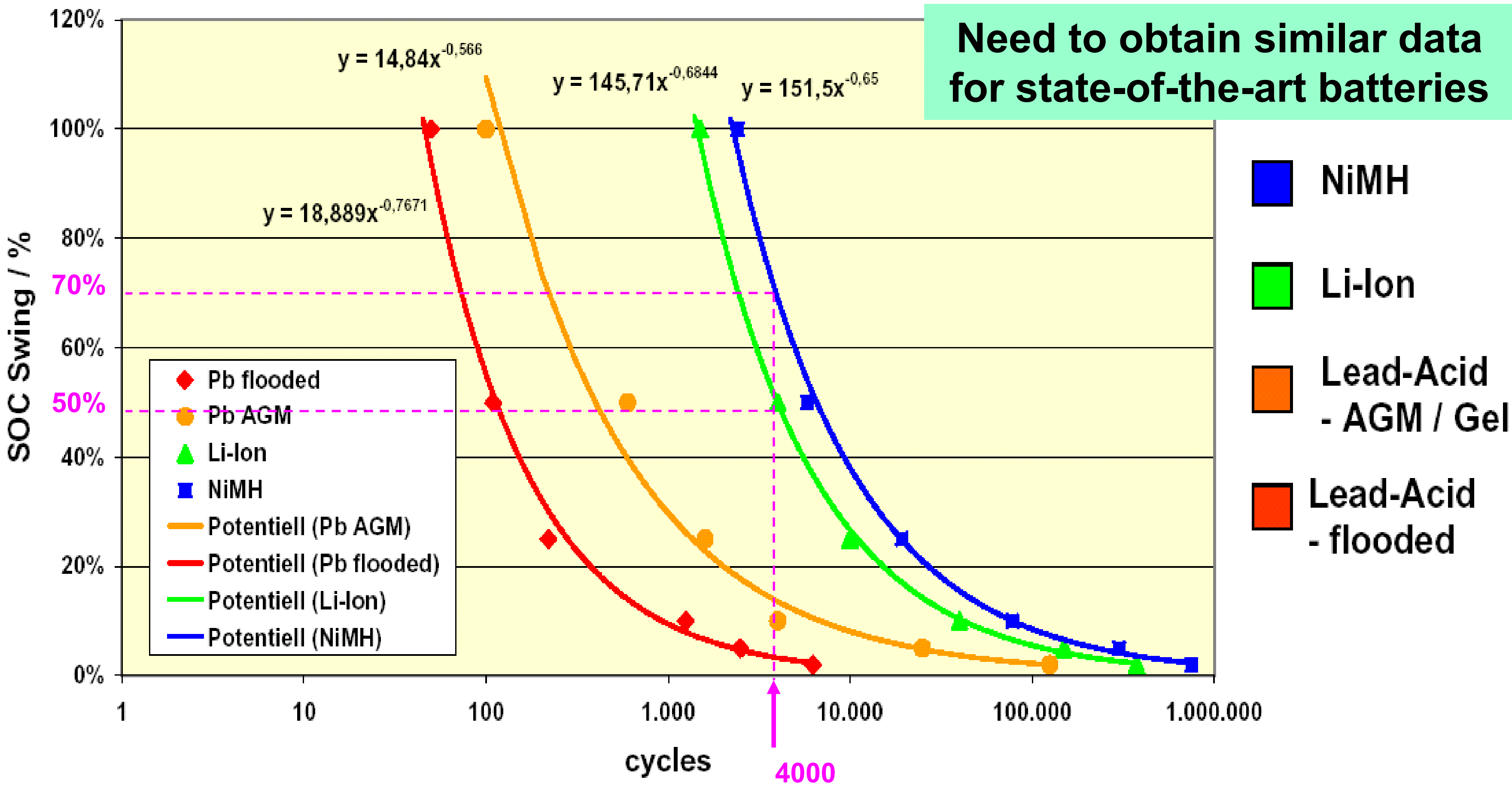
*Main barrier is cost!*

# Other Energy Storage Potential Choices for Plug-In Hybrid Electric Trucks (PHET)

- Sodium Nickel Chloride battery (NaNiCl) – Zebra
  - High energy density
  - Low power density
  - Inexpensive
- Zinc Air battery/fuel cell (ZnAir)
  - Types
    - The “Refuellable” ZnAir Fuel Cell
    - The “Mechanically Rechargeable” ZnAir Fuel Cell
    - The Electrically Rechargeable ZnAir Battery
  - High energy density
  - Low power density
  - Inexpensive
- Ultracapacitors
  - High power density
  - Low energy density
  - Expensive now, could become lower in cost
- Combination of ultracapacitors with NaNiCl or ZnAir
  - The need for DC/DC converter may increase cost, volume/mass

# Battery Cycle Life Depends on State of Charge Swing

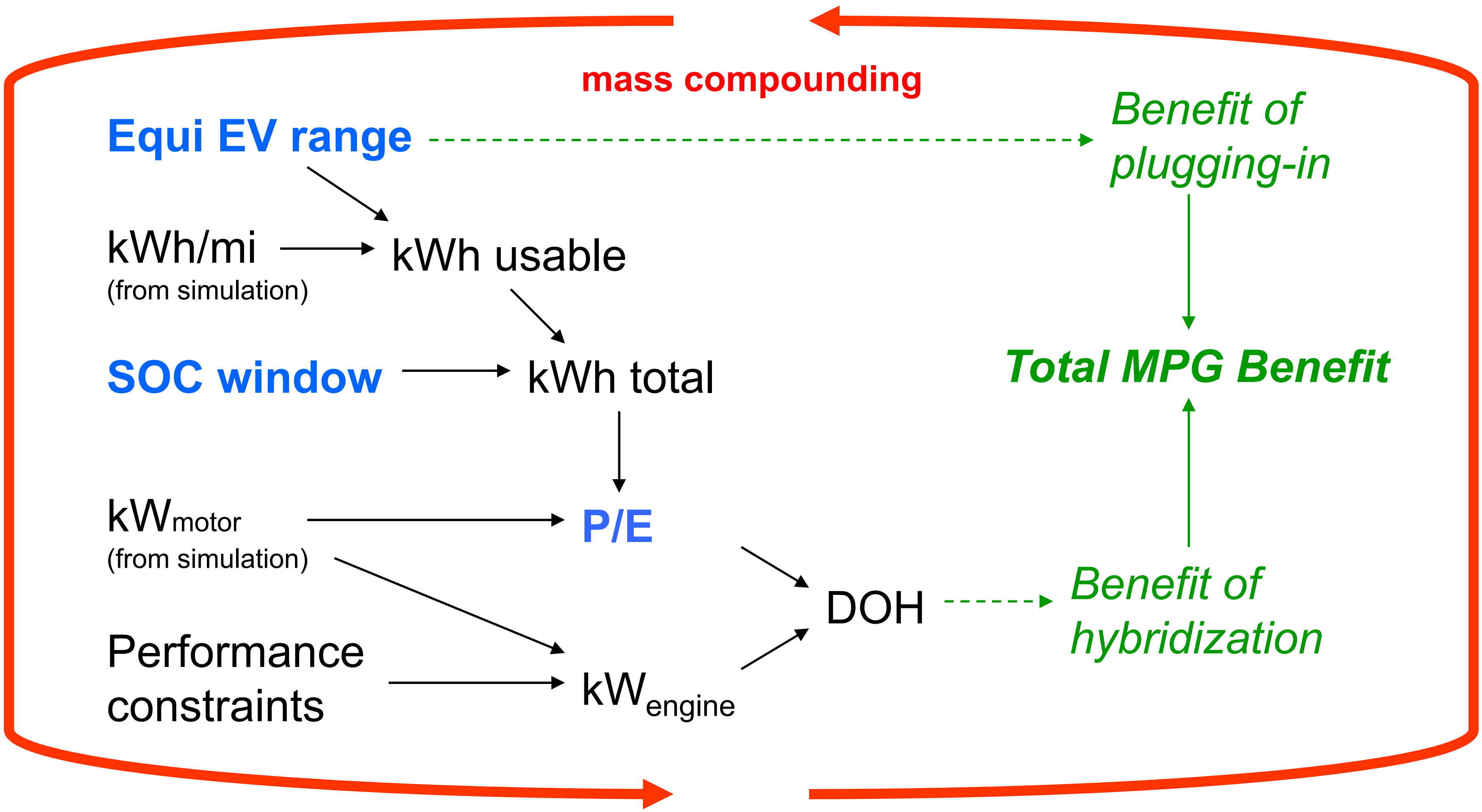
- PHEV battery likely to deep-cycle each day driven: 15 yrs equates to 4000-5000 deep cycles
- Also need to consider combination of high and low frequency cycling




Source: Christian Rosenkranz (Johnson Controls) at EVS 20, Long Beach, CA, November 15-19, 2003

# Battery Sizing Depends on:

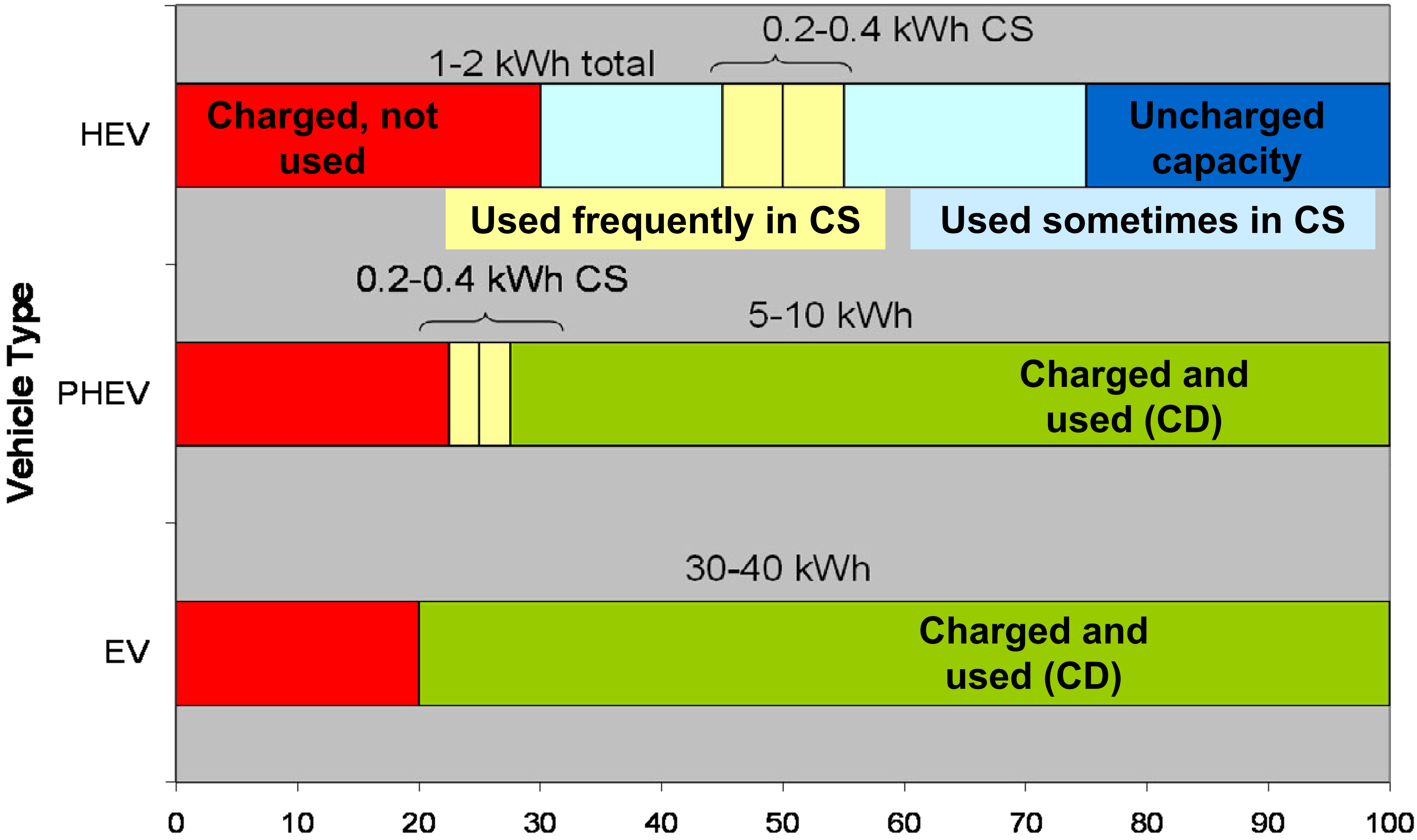
## EV range, vehicle (mass, aerodynamic, etc.), drive cycle, strategy




DOH = degree of hybridization

Source: Tony Markel and Andrew Simpson, Milestone Report, National Renewable Energy Laboratory, Golden, CO, September 2005.

# Battery Usage in EVs, HEVs, and PHEVs




SOC Range (%)

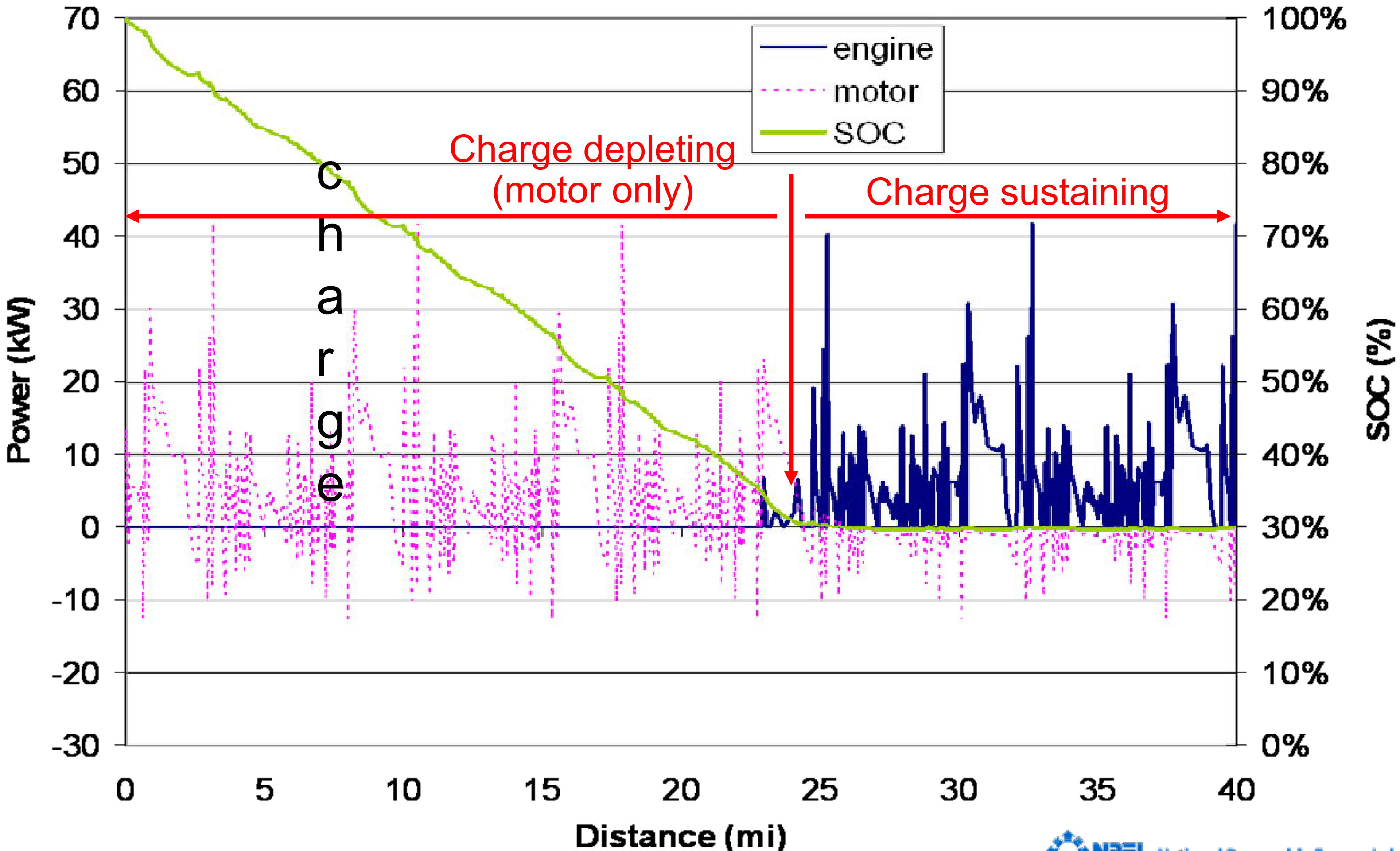
kWh: Battery energy for midsize car

**CS: Charge Sustaining** **CD: Charge Depleting**

# Alternative PHEV Design Strategies: Charge Depleting EV vs. Charge Depleting HEV

- Engine turns on when battery reaches low state of charge
- Requires high power battery and motor

## *Charge-Depleting EV (All-Electric)*



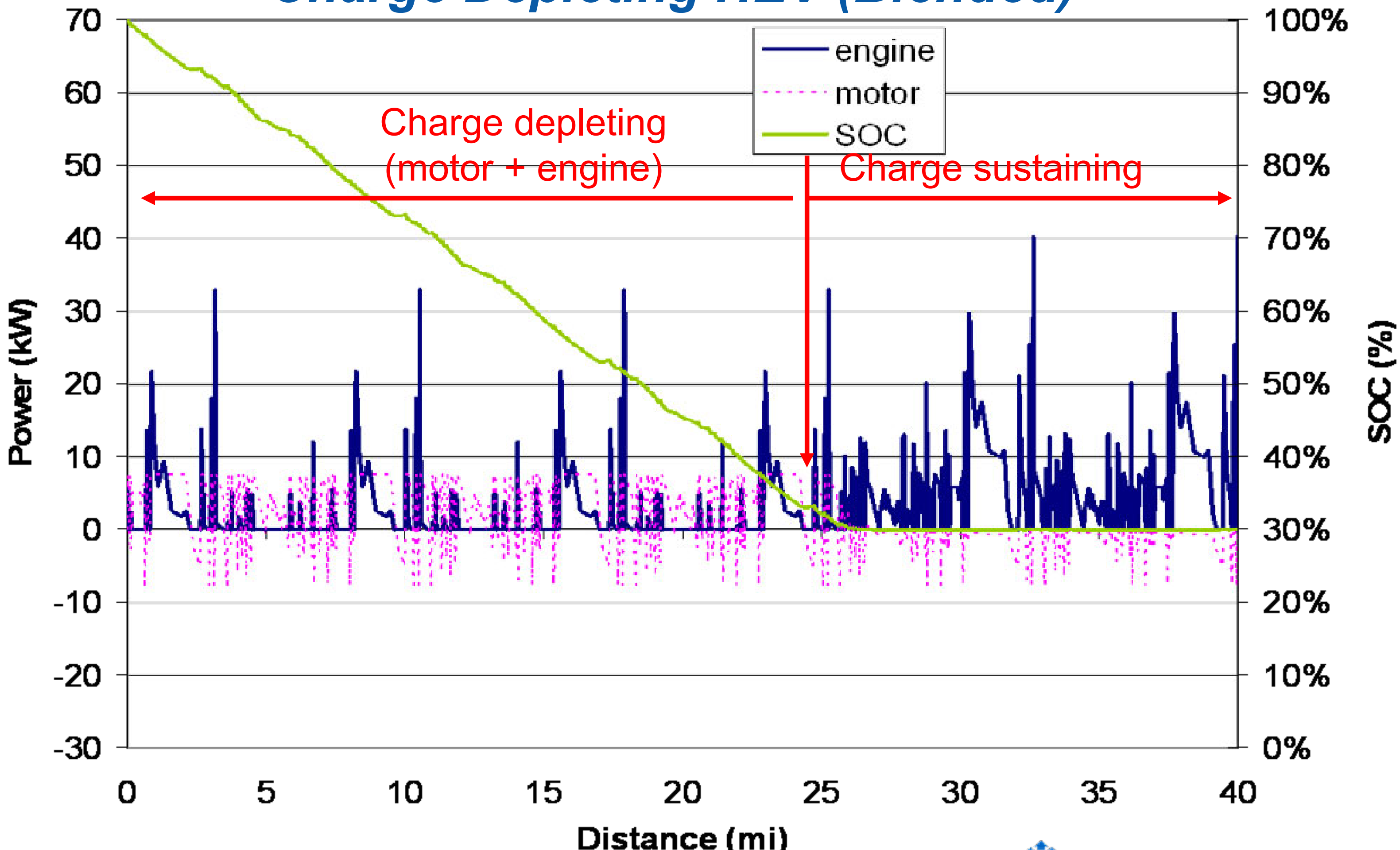



Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006

# Alternative PHEV Design Strategies: Charge Depleting EV vs. Charge Depleting HEV

- Engine turns on when power exceeds battery power capability
- Engine only provides load that exceeds battery power capability

## *Charge Depleting HEV (Blended)*






Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006

# Example of Battery Requirements for Plug-in Hybrid Vehicles

| | Characteristics at EOL (End of Life) | |
|---|---|---|
| Sysetm Targets | Maximum System Production Price @ 100k units/yr | $ |
| | Calendar Life, 40°C | year |
| | Maximum System Weight | kg |
| | Maximum System Volume | Liter |
| | SOC Range | % |
| Charge Depleting HEV Mode | Reference Equivalent Electric Range | miles |
| | Available Energy for CD Mode, 10 kW Rate | kWh |
| | CD Life / Discharge Throughput | Cycles/MWh |
| | Suggested Total Energy (at 10 kW rate) | kWh |
| | Maximum System Recharge Rate at 30°C | kW |
| Charge Sustaing HEV Mode | Peak Pulse Discharge Power (10 sec) | kW |
| | Peak Regen Pulse Power (10 sec) | kW |
| | Available Energy for CS (Charge Sustaining) Mode | kWh |
| | Minimum Round-trip Energy Efficiency (USABC HEV Cycle) | % |
| | Cold cranking power at -30°C, 2 sec - 3 Pulses | kW |
| | CS HEV Cycle Life, 50 Wh Profile | Cycles |
| Battery Limits | Max. Current (10 sec pulse) | A |
| | Maximum Operating Voltage | Vdc |
| | Minimum Operating Voltage | Vdc |
| | Maximum Self-discharge | Wh/day |
| | Survival Temperature Range | °C |
| | Unassisted Operating & Charging Temperature Range | °C |

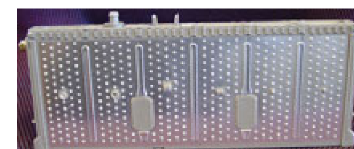
# Battery Energy Requirements for Heavy-Duty PHET

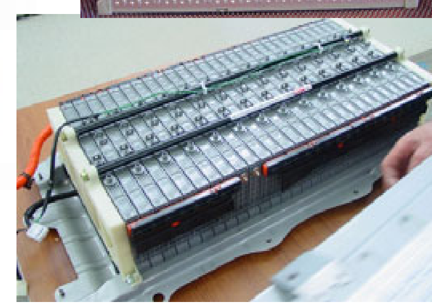
- The energy efficiency of light-duty vehicles are about 200 to 400 Whr/mile
  - 5 to 12 kWhr battery for 30 mile
  - 2 Second power: 30 to 60 kW
  - Power to energy ratio (P/E) from 2 to 15
- Sprinter van delivery PHEV is estimated to consume about 600 Whr/mile in charge depleting (CD) mode
- Heavy-duty trucks could consume from 1000 to 2000 Whr/mile
  - 30 to 60 kWh battery for 30 mile range
  - Some may require additional kWh energy during idling or vocational operation
  - Power need: 50 to 150 kW or even more
  - Volume, weight, and cost are big issues
  - Thermal management is a concern

# Battery Pack 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)
  - — Life?


- Fewer large cells
  - — Higher cost
  - — Increased reliability
  - — Lower assembly cost
  - — Higher weight and volume efficiency
  - — Thermal management (tougher)
  - — Safety ??
  - — Better Reliability (lower number of components)
  - — Life?





# Concluding Remarks

- Batteries with low power to energy ratios are needed for PHEVs and PHETs
- Widening of the energy storage system usable state of charge window while maintaining life will be critical for reducing system cost and volume, but could decrease the life
- A blended operating strategy as opposed to an all electric range focused strategy may provide some benefit in reducing cost and volume while maintaining petroleum consumption benefits
- The key barrier to commercialization of PHEVs and PHETs are battery life, packaging, and cost.

# Acknowledgments


- DOE Program Support
  - Dave Howell
  - Tien Duong
- Technical Support
  - Tony Markel (NREL)