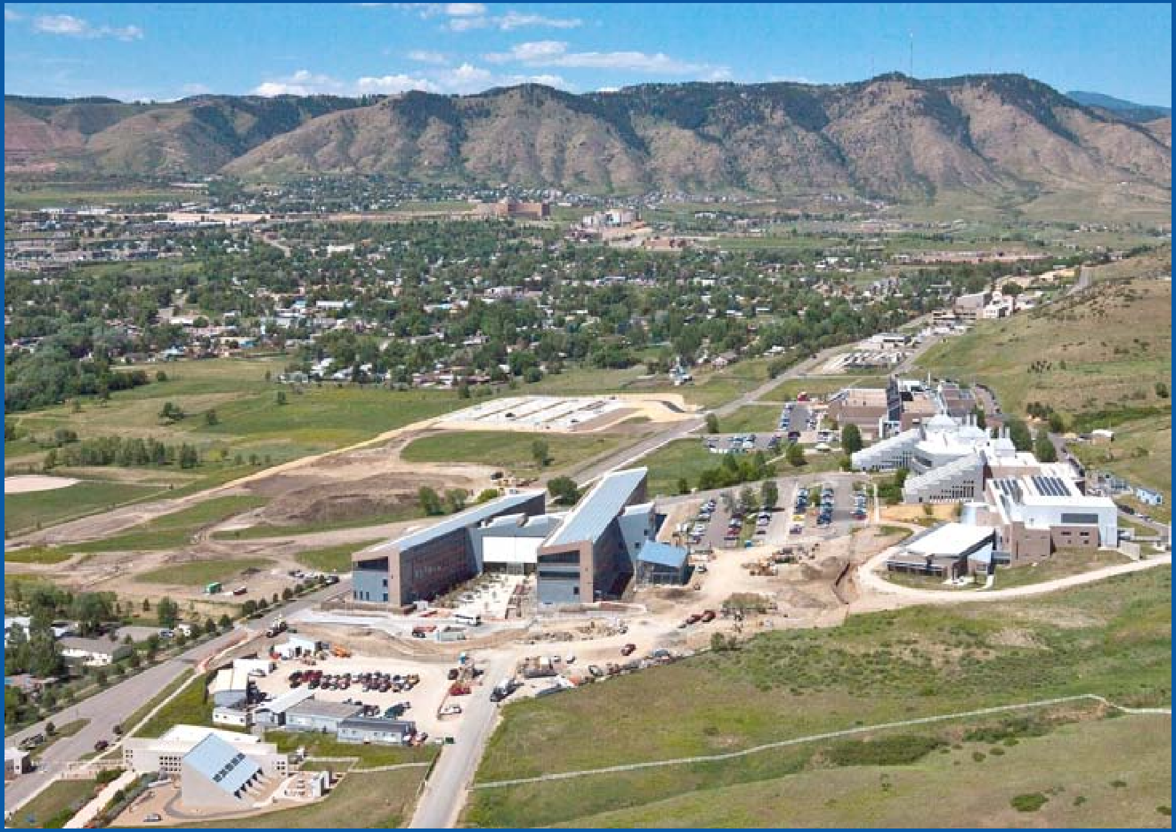
Choices and Requirements of Batteries for EVs, HEVs, PHEVs



A CALSTART Webinar

Ahmad A. Pesaran

National Renewable Energy Laboratory

April 21, 2011

NREL/PR-5400-51474

Outline of the Presentation

Introduction to NREL

Introduction to Electric Drive Vehicles (EDVs)

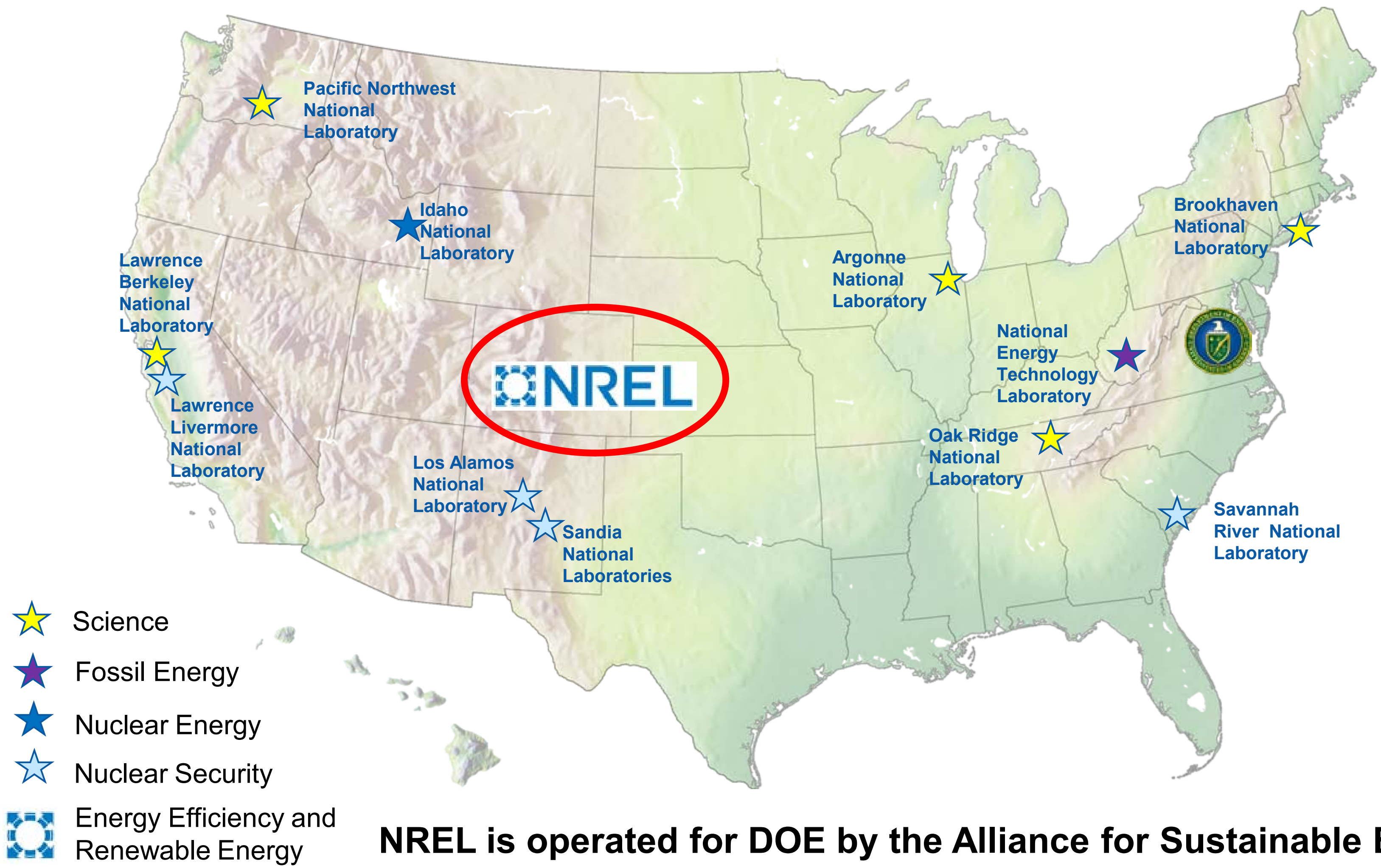
Battery Technologies for Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs) & Electric Vehicles (EVs)

Battery Requirements for EDVs

Concluding Remarks

U.S. Department of Energy National Labs

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)

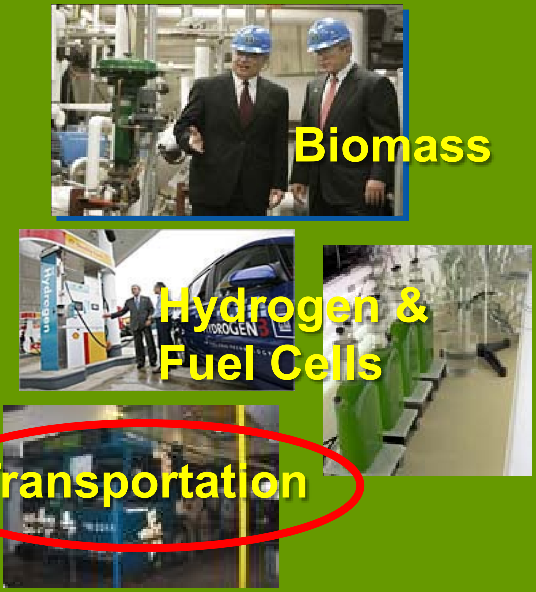
NREL's Portfolio on Energy Efficiency and Renewable Energy

Electricity

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

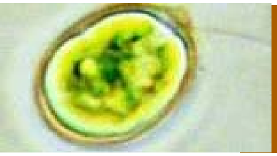
From Concept to Consumer

Fuels



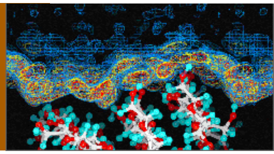
- Renewable Fuels
- Efficient and Flexible Vehicles

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



Underpinned with Science

Photoconversion Computational Science Systems Biology



Center for Transportation Technologies and Systems

Supporting DOE's Vehicle Technologies Office and its FreedomCAR and Fuel Partnership and 21st Century Truck Partnership

Advanced Vehicles
- Advanced Power Electronics
- Energy Storage
- Vehicle Ancillary Loads Reduction

Performance Fuels
- Health Impacts
- Advanced Petroleum-Based Fuels
- Non-Petroleum Based Fuels

Testing & Analysis
- Systems Analysis
- Fleet Test & Evaluation
- ReFUEL Lab
- Electric Vehicle Grid Integration
- Tires
- CoolCAB

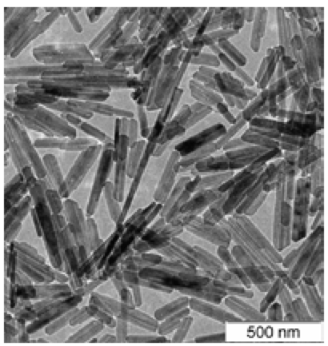
Emphasis on light-, medium-, and heavy-duty vehicles

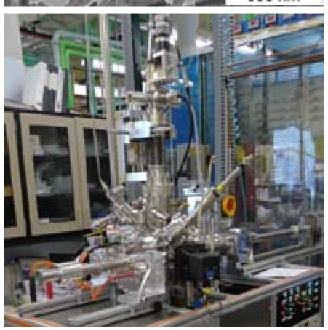
NREL Energy Storage Projects

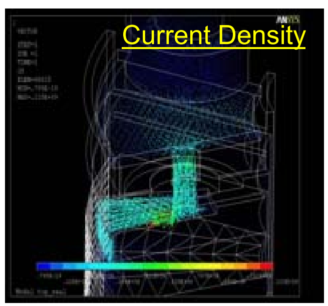
Supporting DOE and helping industry to achieve energy storage targets for electrified vehicles

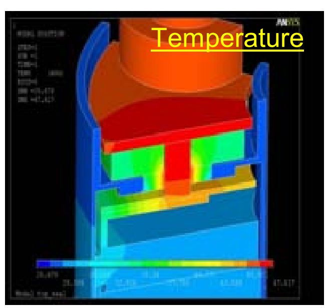
Energy Storage Task

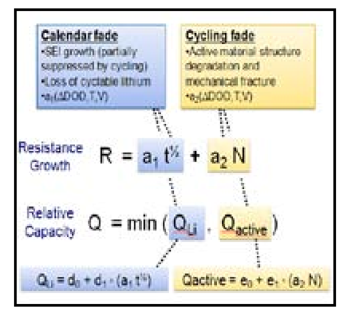
- **Materials Development**
- **Components Modeling**
- **Components Testing**
- **Life Studies**
- **System Evaluation**

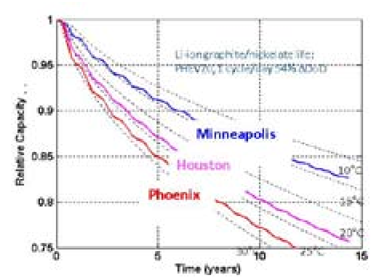


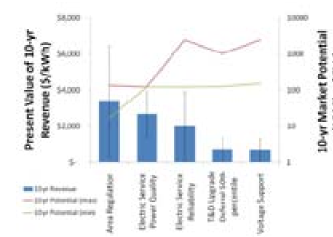












Images courtesy of NREL Energy Storage team

Outline of the Presentation

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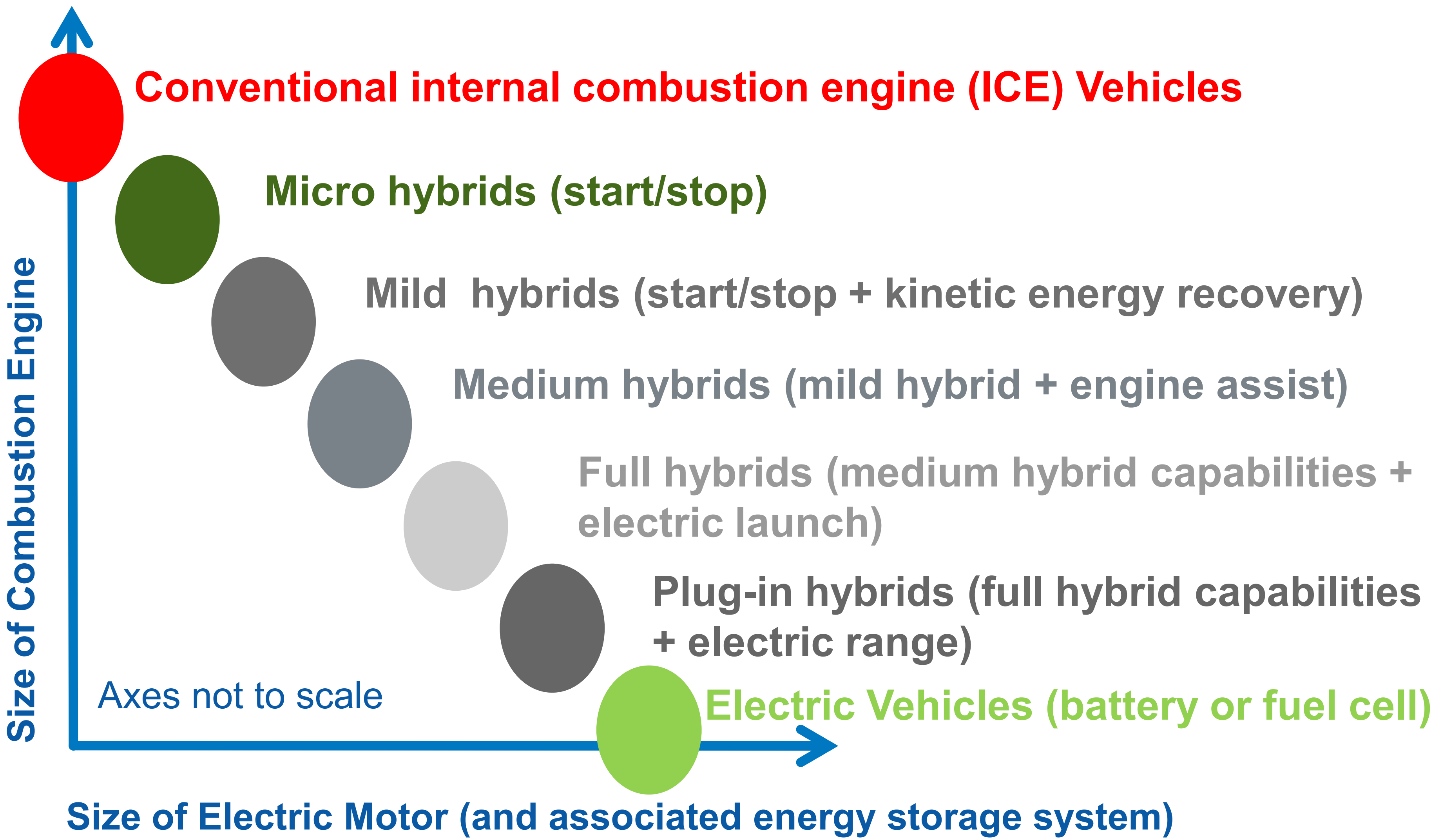
Battery Technologies for HEVs, PHEVs & EVs

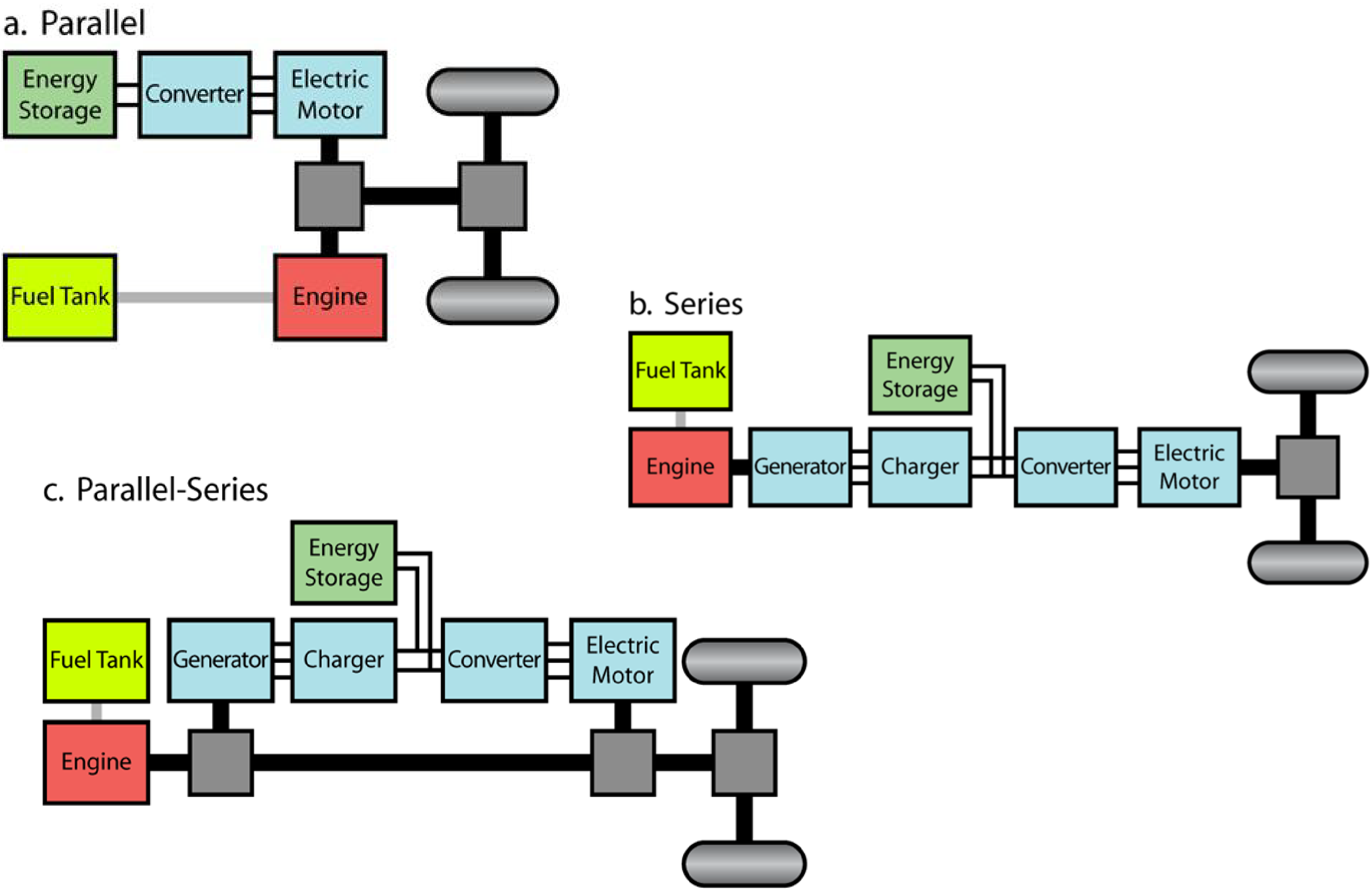
Battery Requirements for EDVs

Concluding Remarks

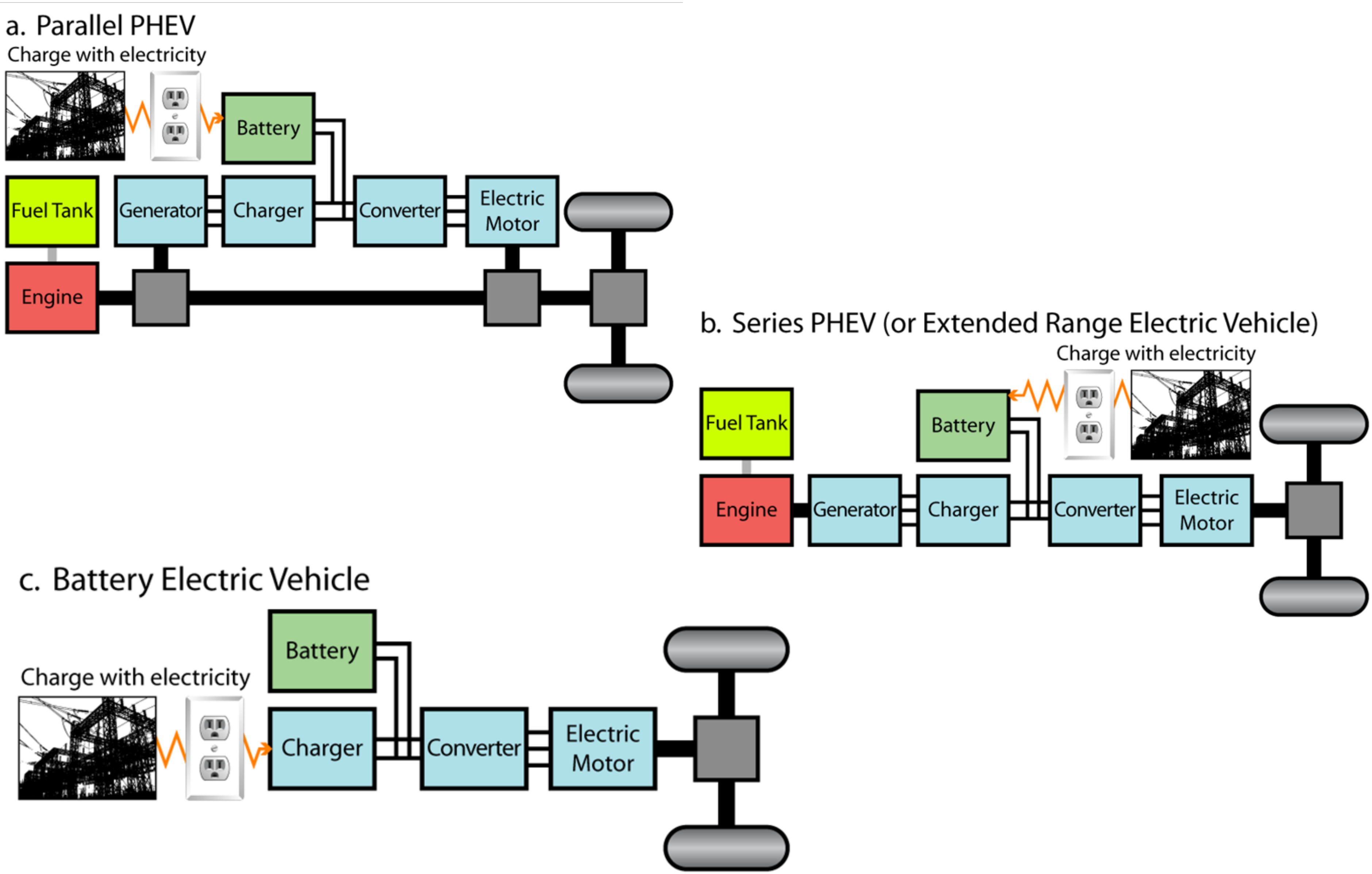
Spectrum of EDV Technologies



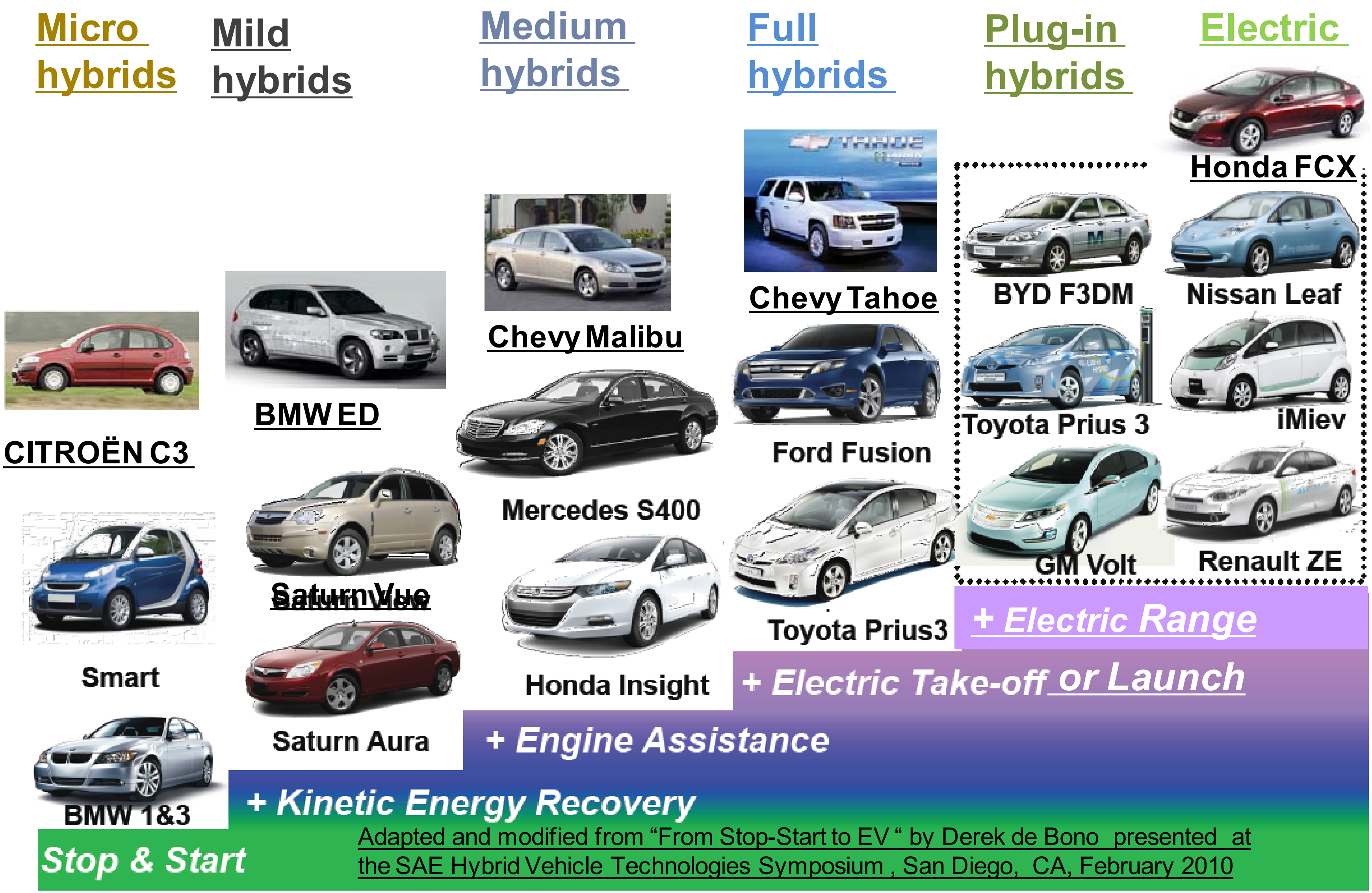
Hybrid Electric Vehicle Configurations



Plug-In Vehicle Configurations



Examples of Light-Duty EDVs in the Market



Battery is the Critical Technology for EDVs

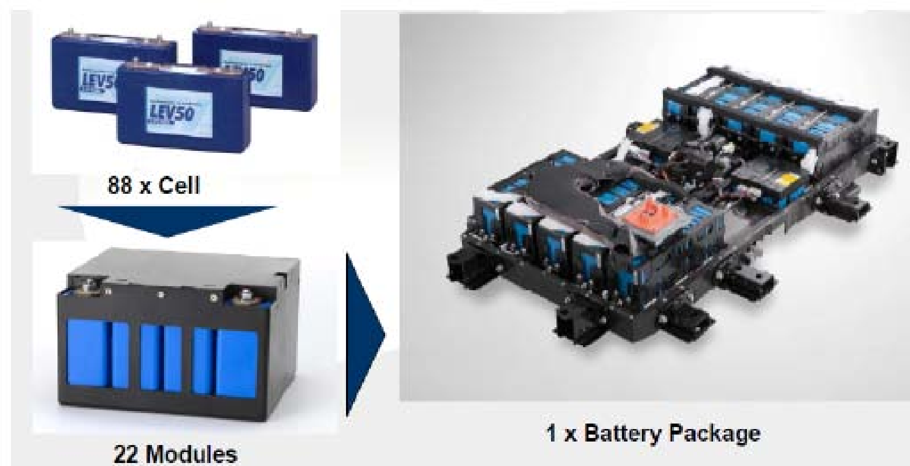
- ✓ Enables hybridization and electrification
- ✓ Provides power to motor for acceleration
- ✓ Provides energy for electric range and other auxiliaries
- ✓ Helps downsizing or eliminating the engine
- ✓ Stores kinetic and braking energy

Saves fuel and reduces emissions

Adds cost, weight, and volume

Decreases reliability and durability

- × Decreases performance with aging
- × Raises safety concerns



Lithium-ion battery cells, module, and battery pack for the Mitsubishi iMiEV
(All images courtesy of Mitsubishi)

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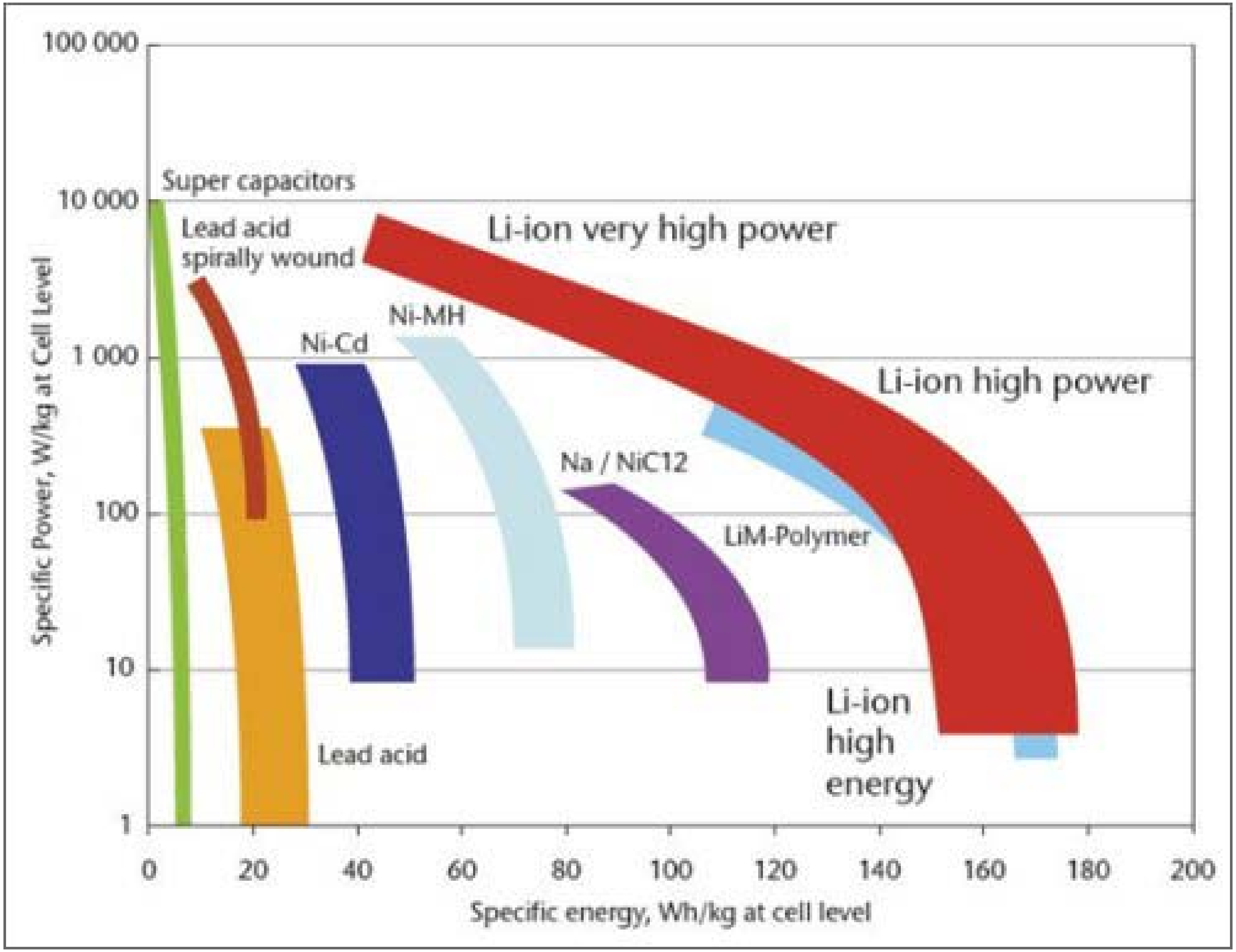
Battery Choices: Energy and Power



NiMH proven sufficient for many HEVs. Still recovering early factory investments.

Lithium ion technologies can meet most of the required EDV targets in the next 10 years.

Source: www1.eere.energy.gov/vehiclesandfuels/facts/2010_fotw609.html

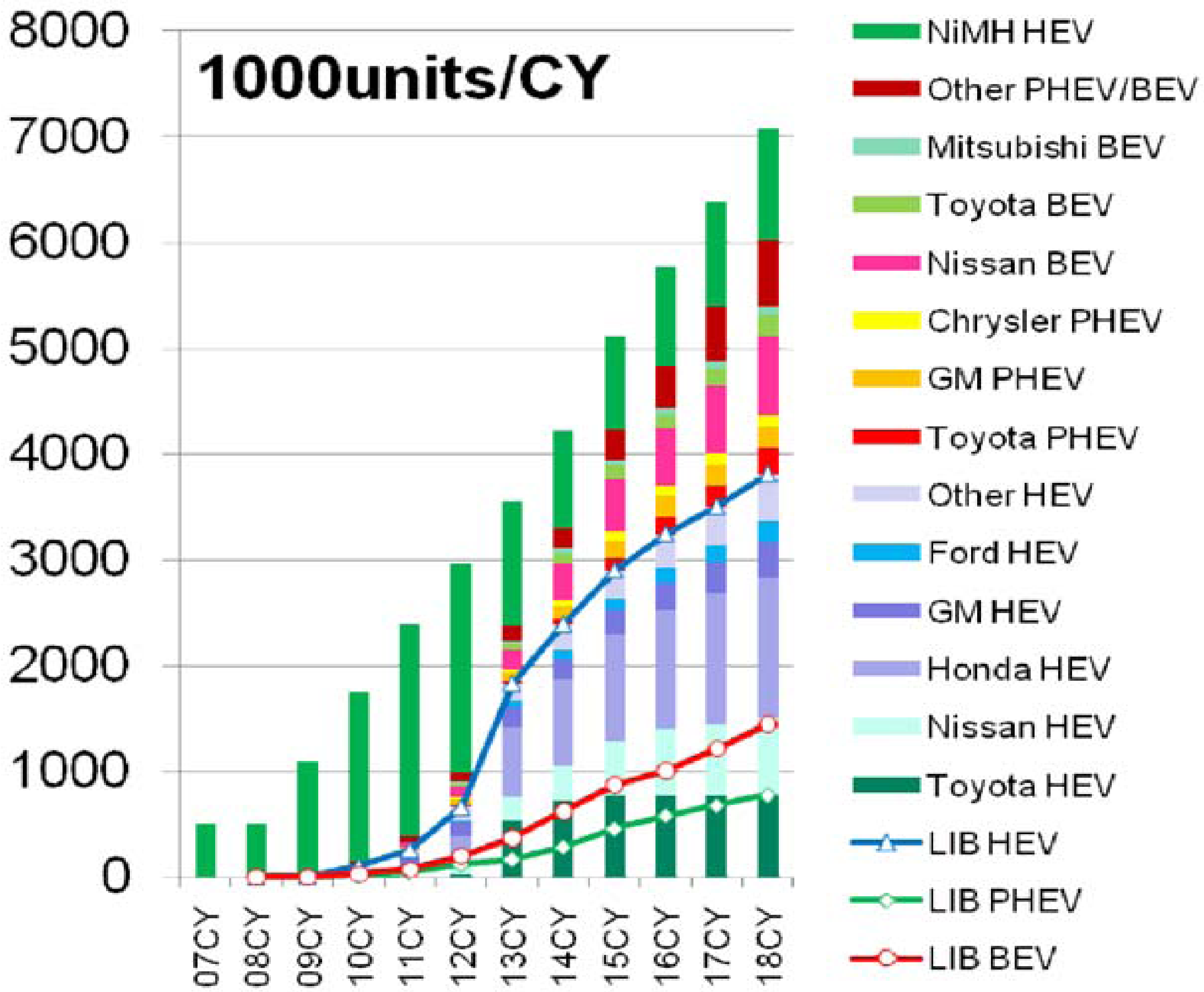
Qualitative Comparison of Major Automotive Battery Technologies

Key

Key
Poor
Fair
Good

Attribute	Lead Acid	NiMH	Li-Ion
Weight (kg)	Poor	Fair	Good
Volume (L)	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	Fair	Good
Calendar Life (years)	Poor	Good	Fair
Cost ($/kW or $/kWh)	Good	Poor	Poor
Safety- Abuse Tolerance	Good	Good	Fair
Maturity – Technology	Good	Good	Fair
Maturity – Manufacturing	Good	Good	Fair

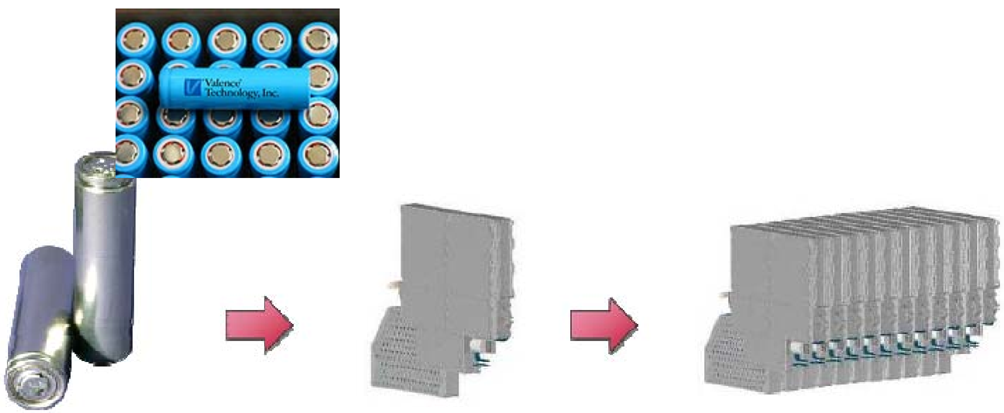
Projections for Automotive Batteries

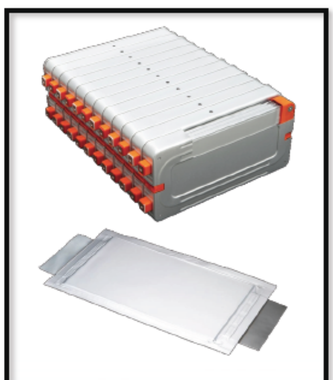


Source: Hiroshi Mukainakano, AABC Europe 2010

Challenges & Opportunities with Li-Ion Technologies for EDVs

- High cost, many chemistries, cell sizes, shapes, module configurations, and battery pack systems.
- Integration with proper electrical, mechanical, safety, and thermal management is the key.
- New developments and potential advances make it difficult to pick winners.

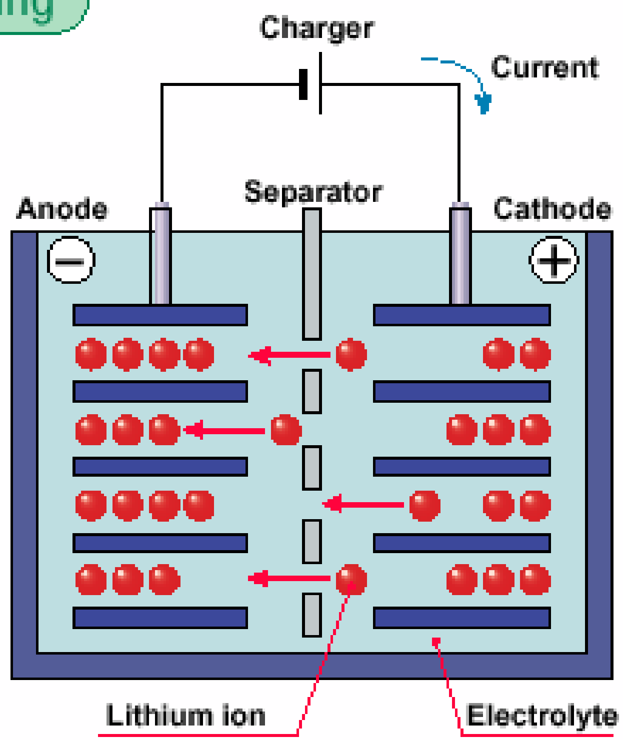



Laminated cell type
Li-ion battery

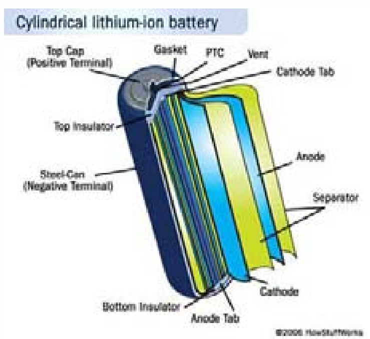
Various sources:
2009 DOE Merit Review
2010 ETDA Conference
2010 SAE HEV Symposium

Lithium Ion Battery Technology—Many Chemistries

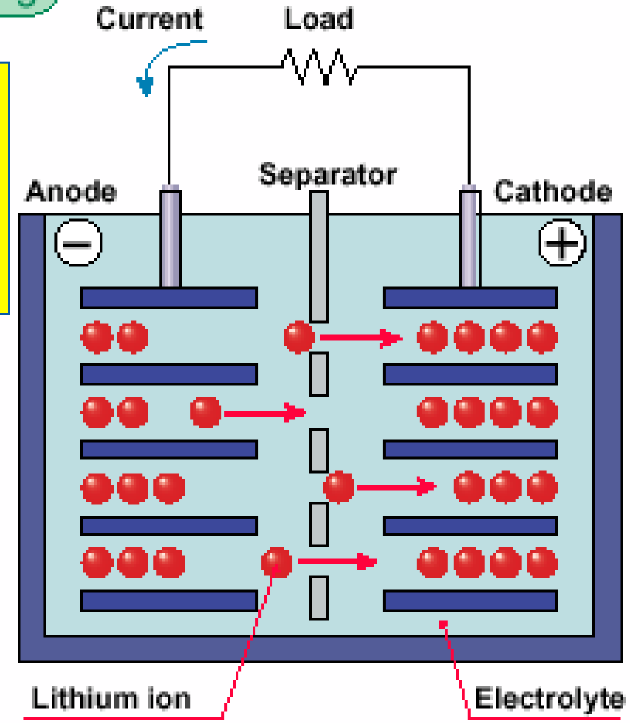
Charging



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



Discharging



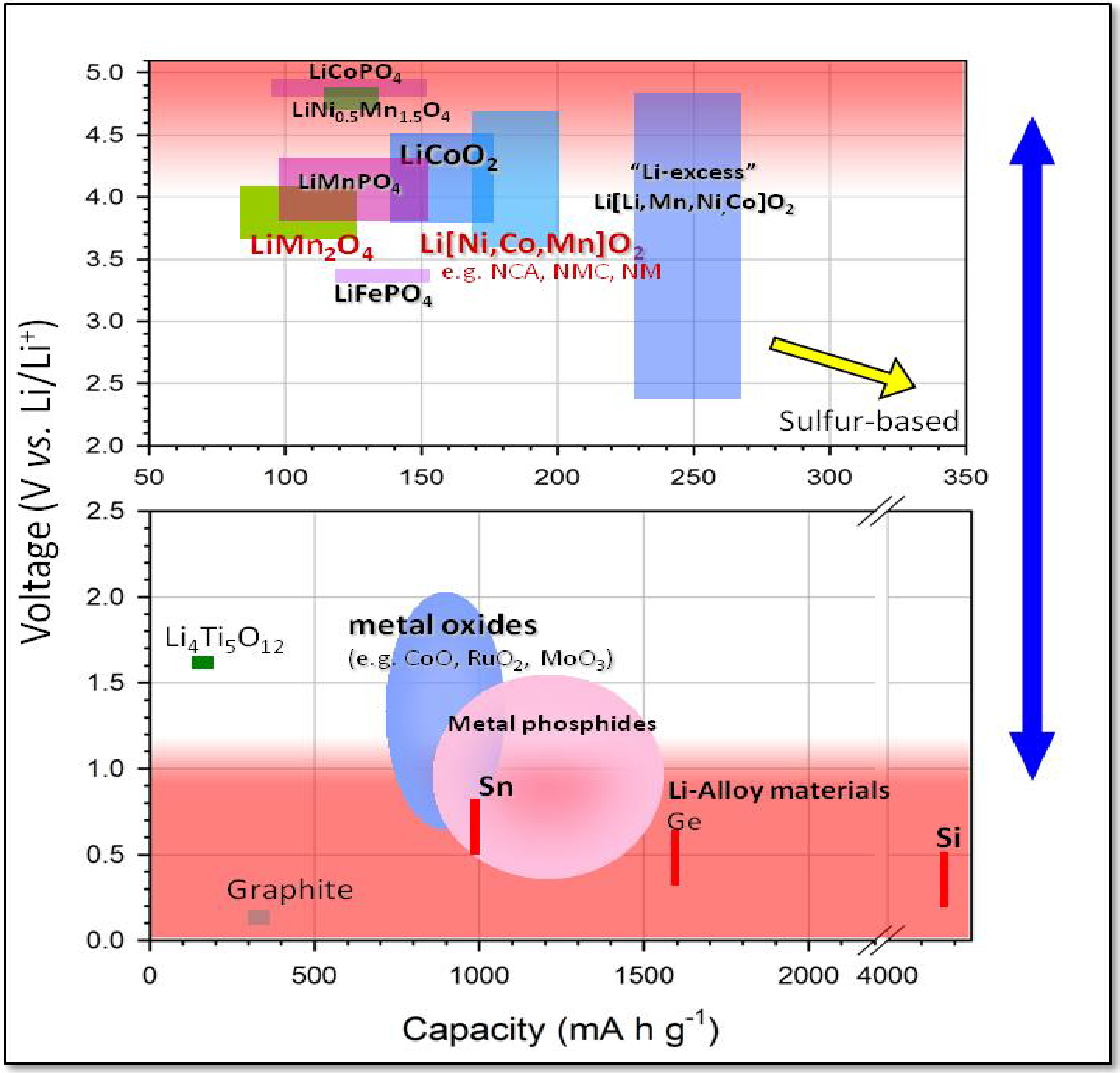
Many anodes are possible
Carbon/Graphite
Titanate ($Li_4Ti_5O_{12}$)
Titanium-oxide based
Silicon based
Metal oxides

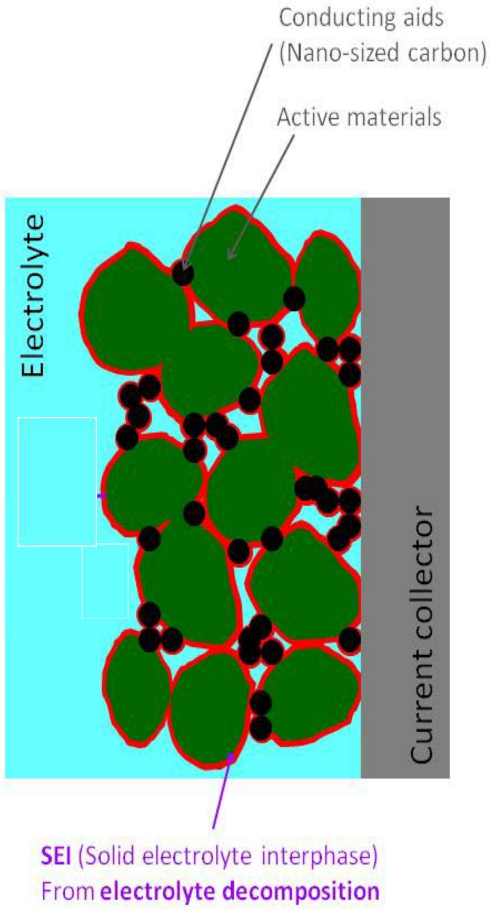
Many electrolytes are possible
$LiPF_6$ based
$LiBF_4$ based
Various solid electrolytes
Polymer electrolytes
Ionic liquids

Many cathodes are possible
Cobalt oxide
Manganese oxide
Mixed oxides with nickel
Iron phosphate
Vanadium-oxide based

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

Electrochemical Window in Lithium Ion Batteries





Source: Yoon Seok Jung, et. al. Presented at 2011 MRS Spring Meeting, San Francisco, CA

Characteristics of Cathode Materials

Theoretical values for cathode materials relative to graphite anode and $LiPF_6$ electrolyte

Material	Δx	mAh/g	Avg. V	Wh/kg	Wh/L
$LiCoO_2$ (Cobalt)*	0.55	151	4.00	602	3,073
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA)*	0.7	195	3.80	742	3,784
$LiMn_2O_4$ (Spinel)*	0.8	119	4.05	480	2,065
$LiMn_{1/3}Co_{1/3}Ni_{1/3}O_2$ (NMC 333)*	0.55	153	3.85	588	2,912
$LiMn_xCo_yNi_zO_2$ (NMC non-stoichiometric)	0.7	220	4.0	720	3,600
$LiFePO_4$ (Iron Phosphate)*	0.95	161	3.40	549	1,976

Mixed metal oxide cathodes are replacing cobalt oxide as the dominant chemistry.
Mn_2O_4 has been around for many years – good for high power; improvements in high temperature stability reported recently.
$LiFePO_4$ is now actively pursued by many as the cathode of choice for vehicle applications

- safe on overcharge
- need electronics to accurately determine state of charge (SOC)
- may require larger number of cells due to lower cell voltage

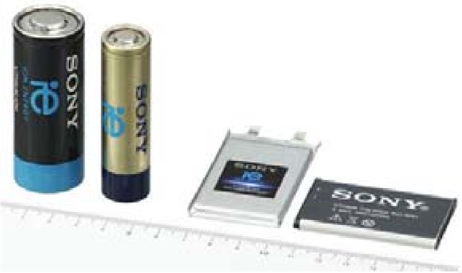
Other high voltage phosphates are currently being considered.

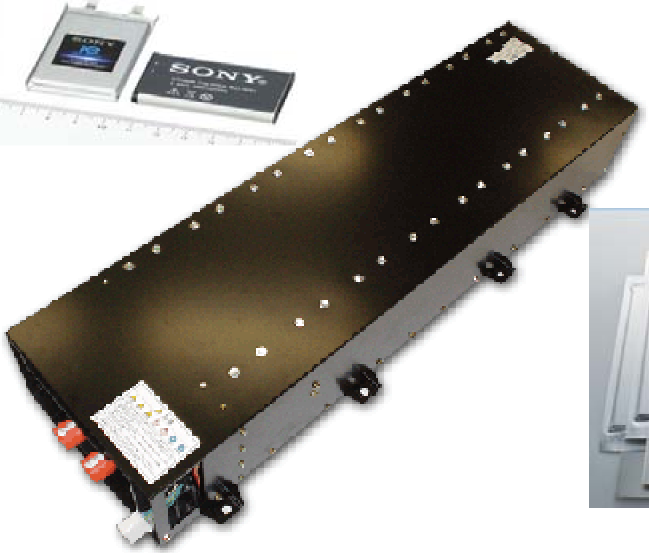
*Source: Robert M. Spotnitz, Battery Design LLC

Many Commercial Cathode Oxide-Based Li-Ion Batteries are Available

Johnson Control-Saft
Altair Nanotechnologies
LG Chem
Electrovaya
Dow Kokam
SK Innovation
NEC/Nissan
GS Yuasa
Sony
Sanyo
Samsung
Panasonic
Lishen
Pionics
Other Chinese companies

Mixed metal oxide cathodes (> 200 mAh/g)





CALSTART Energy Storage Compendium
Conhttp://www.calstart.org/Libraries/Publications/Energy_Storage_Compendium_2010.sflb.ashx

Lithium Iron Phosphate ($LiFePO_4$) Cathodes

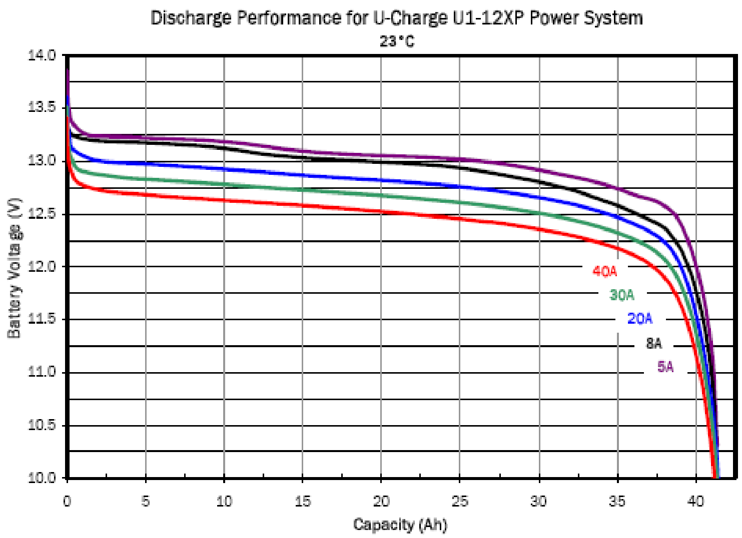
+ High stability and non-toxic
+ Good specific capacity
+ Flat voltage profile
+ Cost effective (less expensive cathode)
+ Improved safety

Issues addressed recently:

– Lower voltage than other cathodes
(Alternate phosphates – manganese, vanadium, etc. – are currently being investigated)

– Poor Li diffusion (D_{Li}~ 10^{-13} cm^2/sec)
(Overcome by doping the cathode)

– Poor electronic conductivity (~ 10^{-8} S/cm)
(Overcome by blending/coating with conductive carbon)



Source: Online brochures from Valence Technology, http://www.valence.com/ucharge.asp

Other approaches used 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 Phosphate-based Cathodes

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

K2 Energy

3.2-Ah Real Capacity
15-mOhm

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

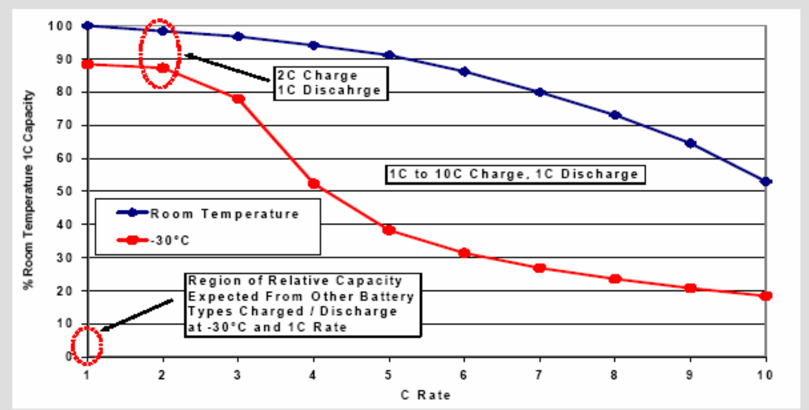
Source: Andrew Chu (A123 Systems) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

Under R&D

Newer Phosphates	Voltage vs. Li
Iron	3.6 V
Manganese	4.1 V
Cobalt	4.8 V
Nickel	5.1 V

Improvements on the Anode—Titanate

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



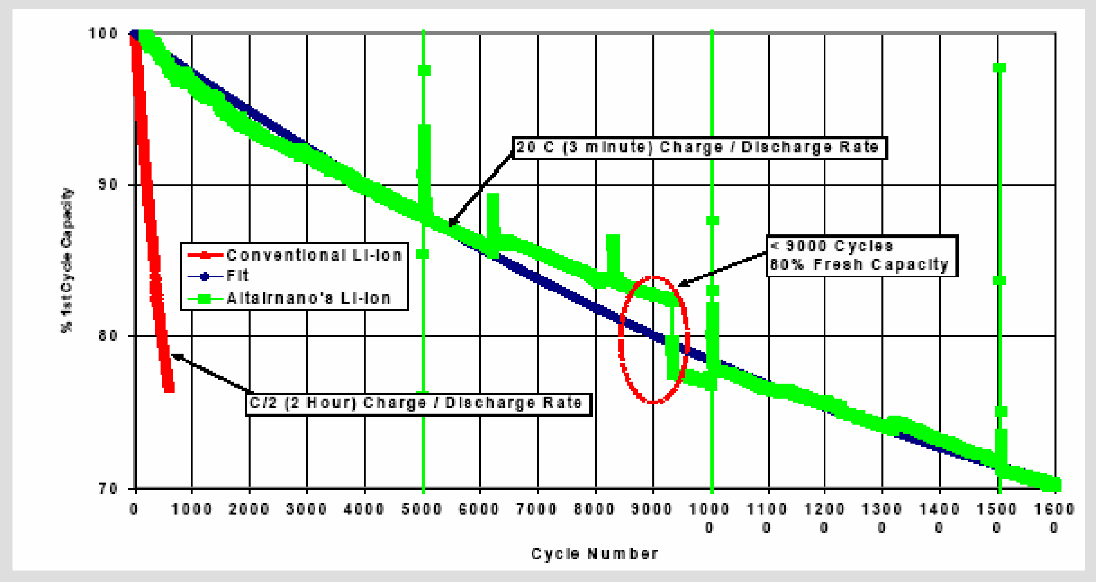
~90% SOC of RT Cell at -30°C and 1-2C Charge Rate!

Altair Nanotechnologies Inc.

Improved low temperature performance

80–100 Wh/kg

2,000–4,000 W/kg



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

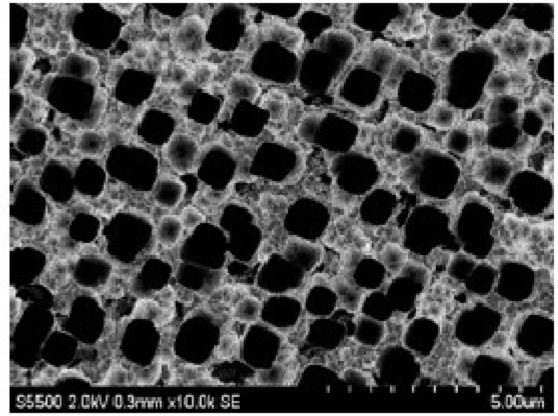
Improvements on the Anode—Silicon

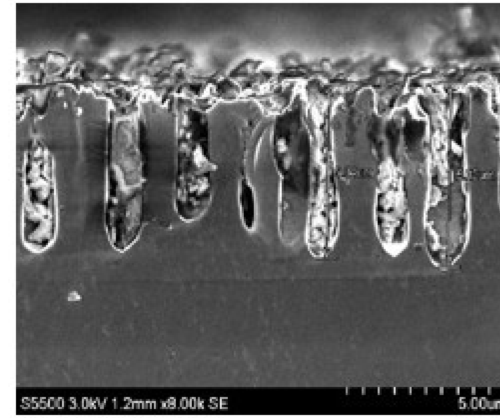
Advantages:

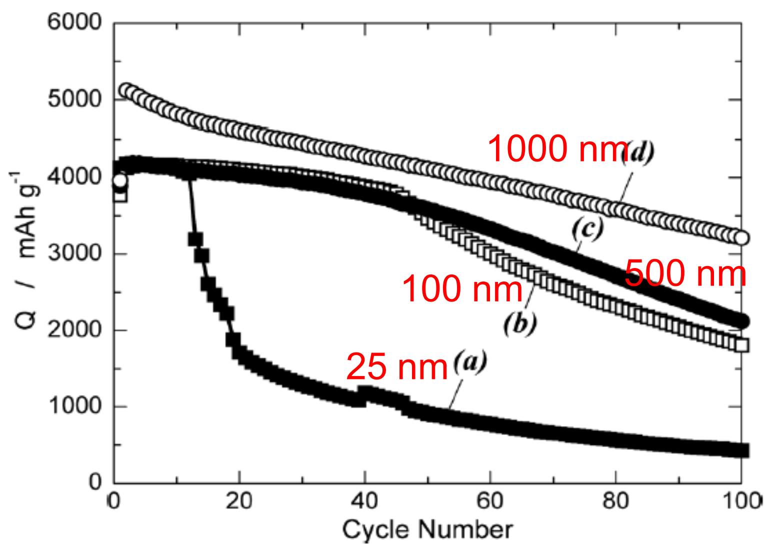
- Very high theoretical capacity
- No lithium deposition
- High rate capability
- No need for an SEI

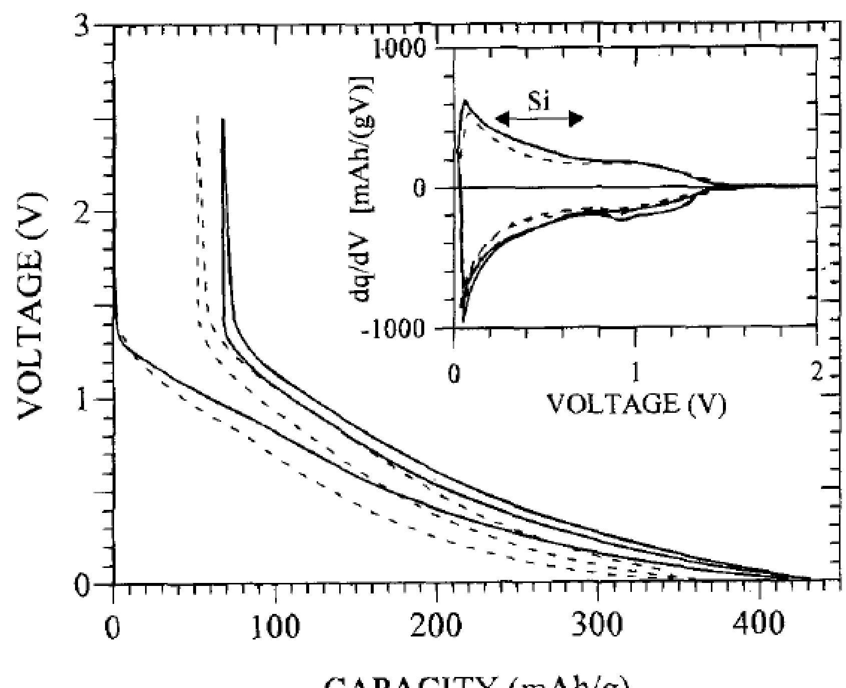
Issues at hand:

- High volume expansion
- Low cell voltage
- Poor cyclability



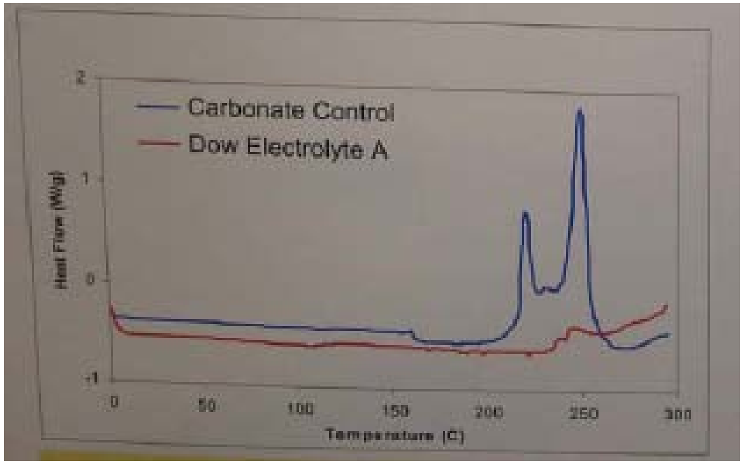






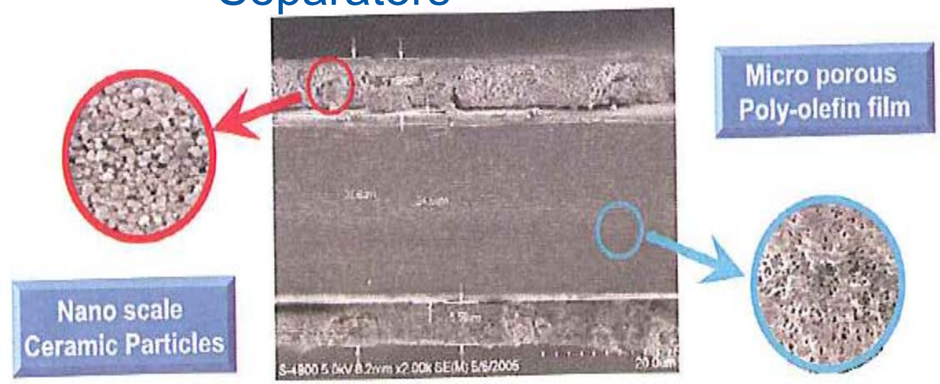
Source: Recent (2011) Reports on SiO Carbon Composite Anodes (Shriram Santhanagopalan-NREL)

Improvements to Other Components



Dow's High Temperature Electrolytes claimed to be stable up to 5 V

Separators

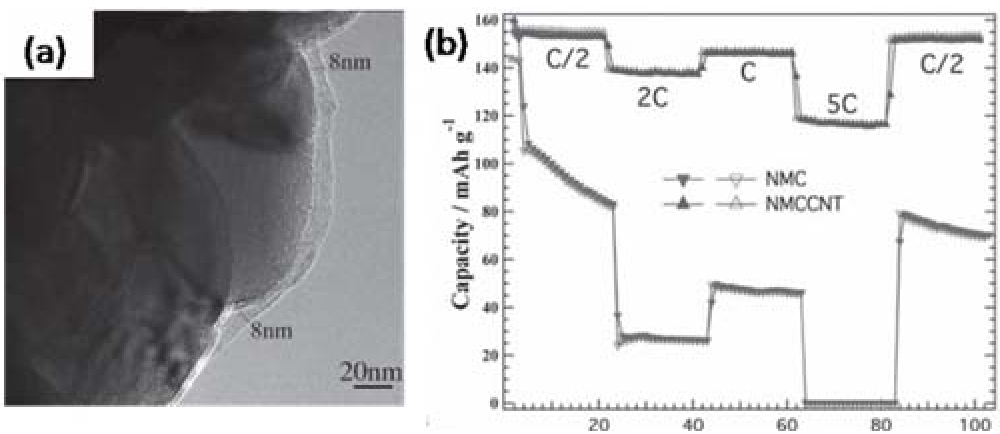


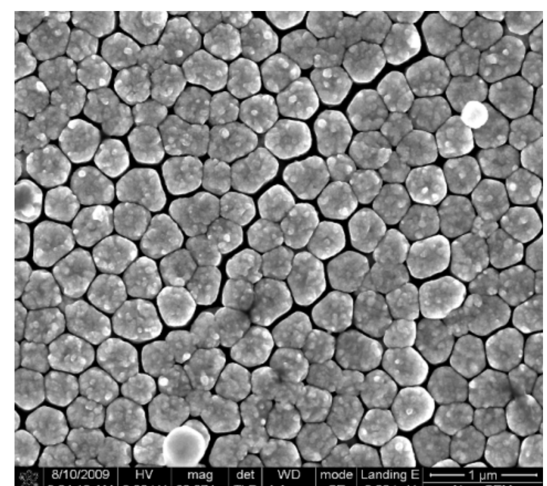
LG Chem's Safety Reinforcing Separator (SRS)

Binders:

- Shift from fluoride-based binders
- SBR and CMC increasingly popular

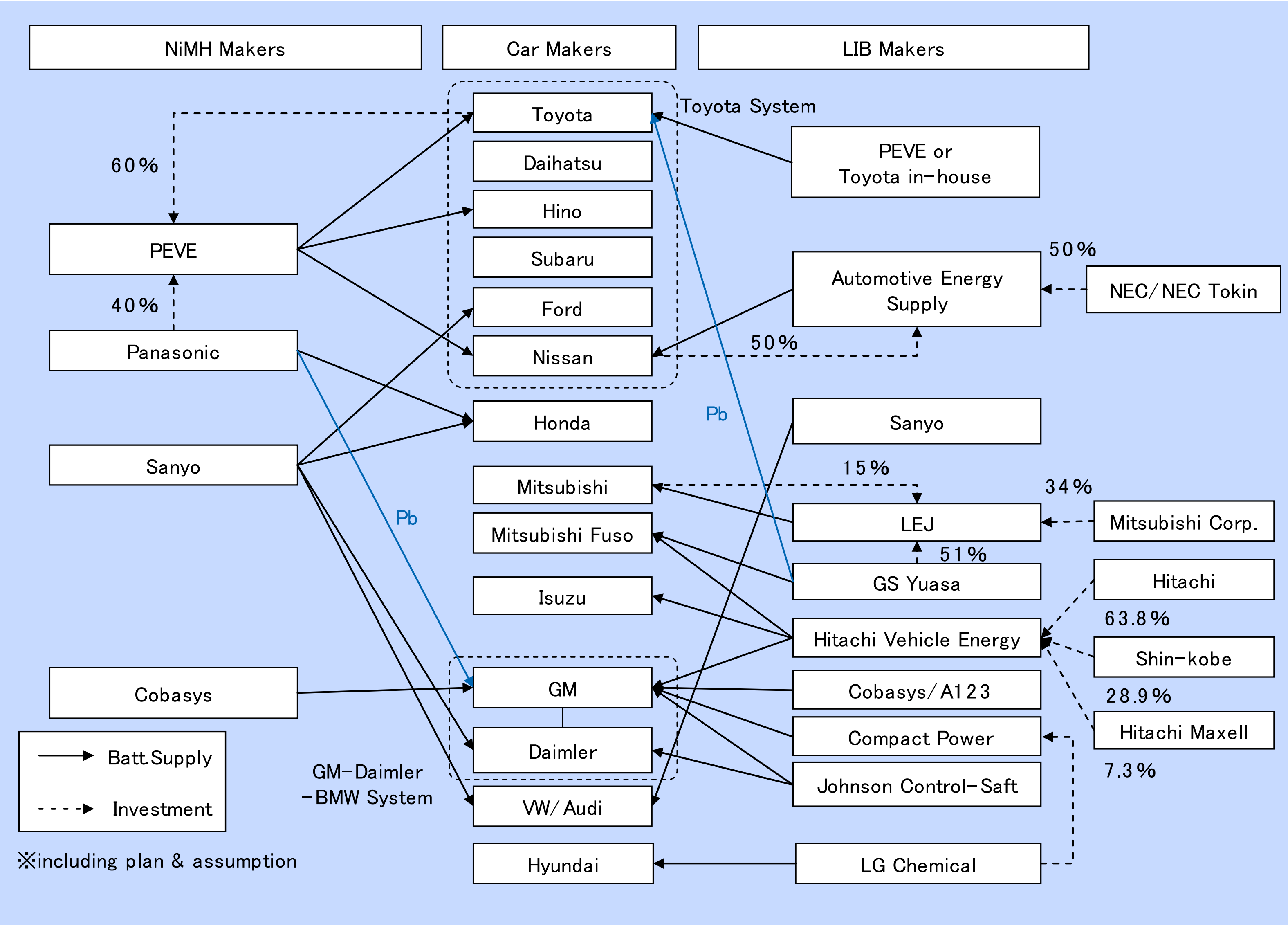
Conductive Coatings





Sources: Shriram Santhanagopalan and Anne Dillon (NREL)

Relationship Between Car Makers and Battery Makers



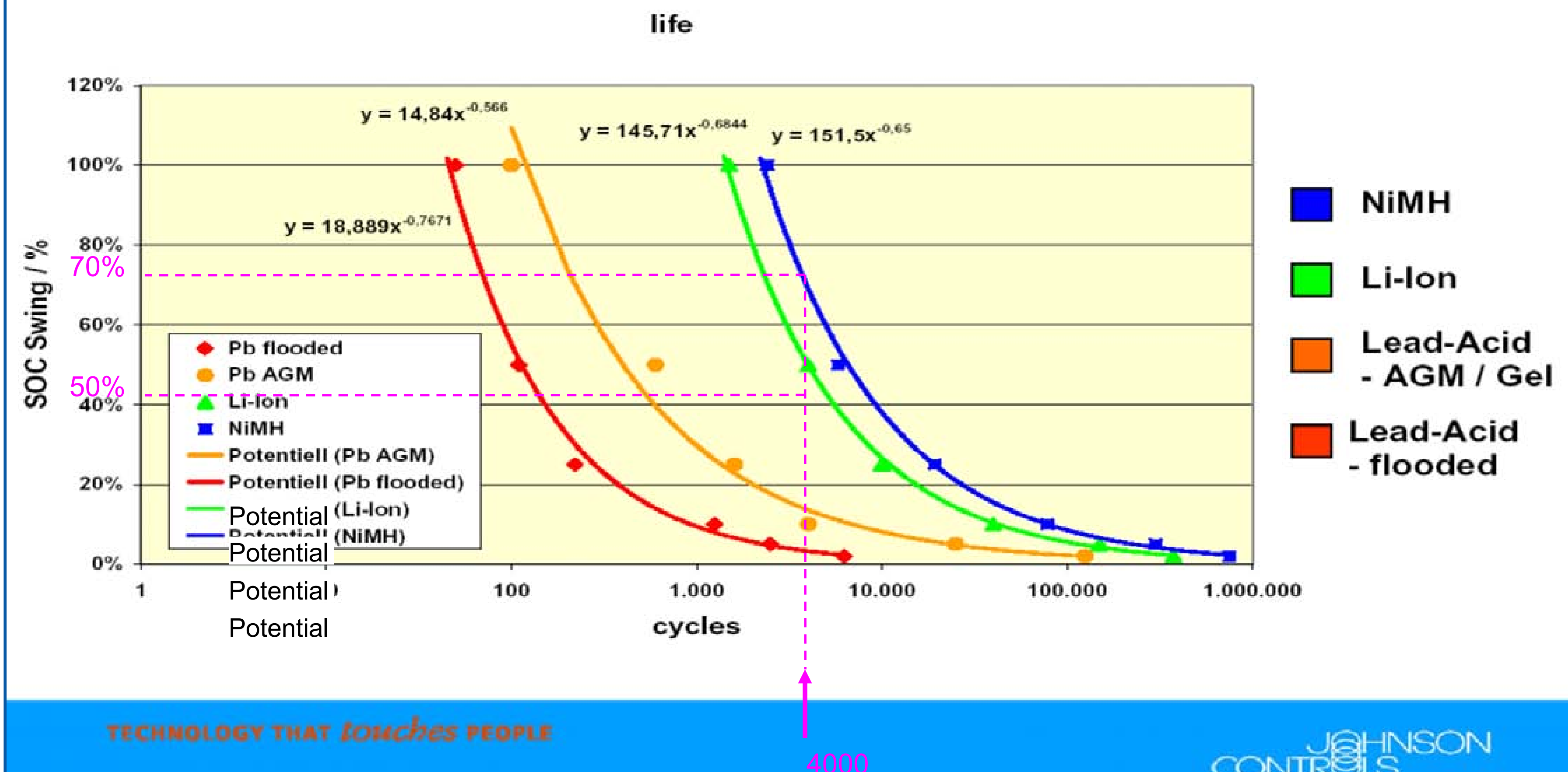
Source: Nomura Research Institute, Ltd.

Anode Aging

- **Solid/Electrolyte Interphase (SEI) Layer**
  - Passive protective layer, product of organic electrolyte decomposition
  - Mostly formed during first cycle of battery, but continues to grow at slow rate
  - May penetrate into electrode & separator pores
  - High-temperature effects
  - Low-temperature effects (during charging)
- **Changes of Active Material**
  - Volume changes during insertion/de-insertion (~10%)
  - Solvent intercalation, electrolyte reduction, gas evolution inside Li_xC_6 → Stress → Cracks
- **Changes of Composite Electrode**
  - SEI & volume changes cause:
    - Contact loss between Li_xC_6, conductive binder, and current collector
    - Reduced electrode porosity

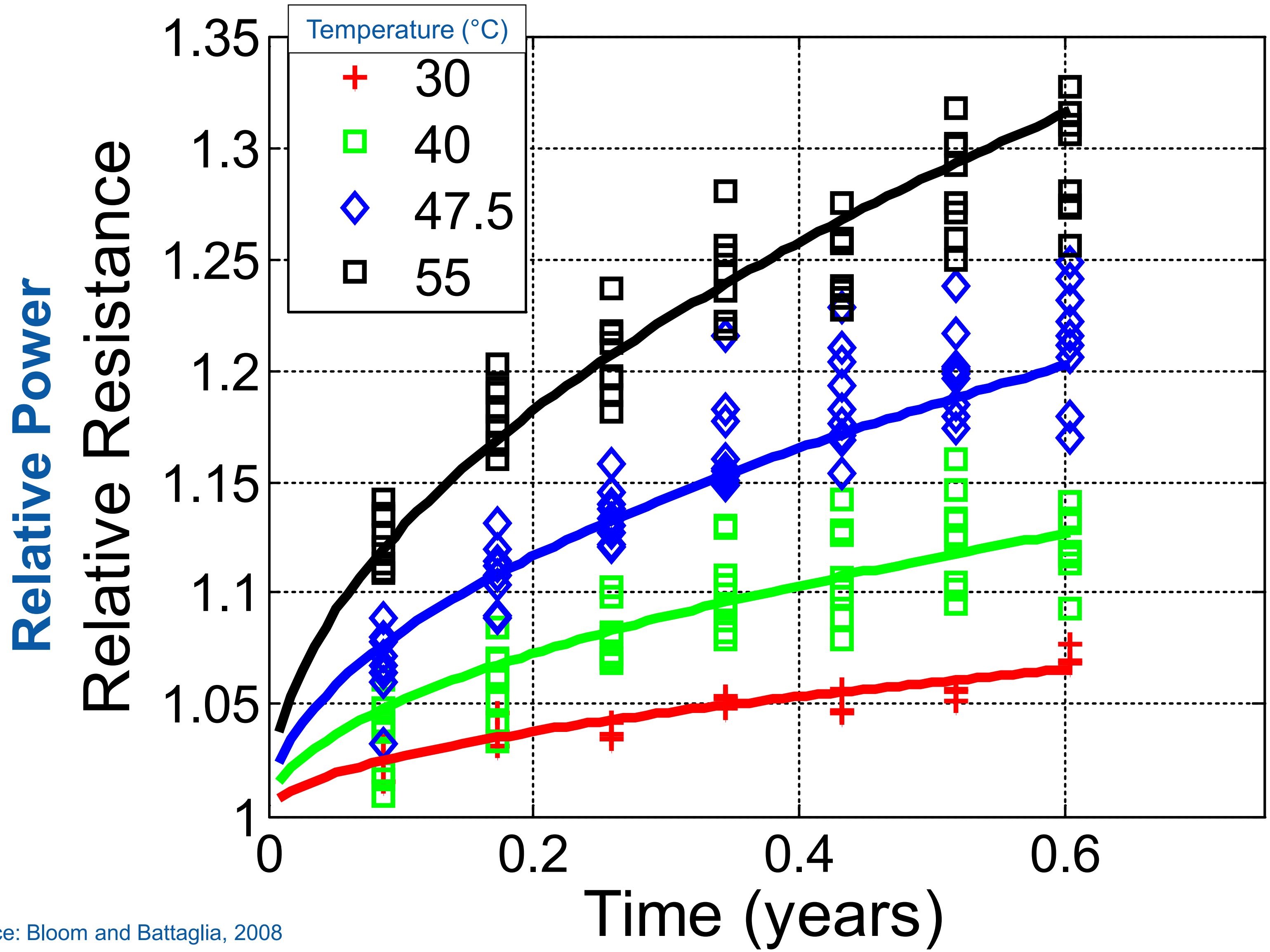
Battery Cycle Life Depends on State-of-Charge Swing

- PHEV battery likely to deep-cycle each day driven: 15 yrs equates to 4,000–5,000 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 Degrades Faster at Higher Temperatures
Calendar (Storage) Fade



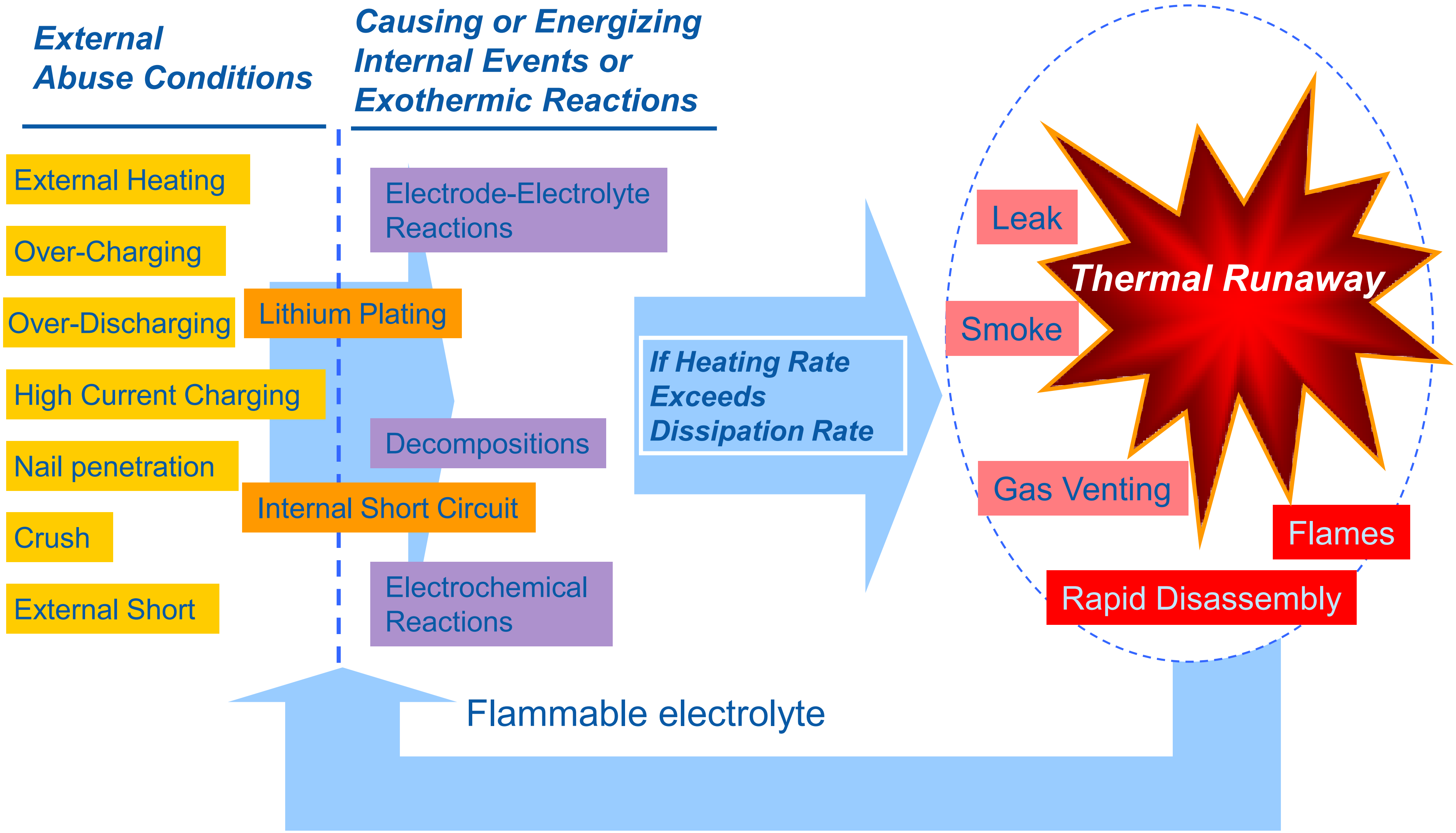
Source: Bloom and Battaglia, 2008

Summary of Aging and Degradation

Capacity decreases and resistance increases by:

- Both high and low SOC charge-discharge
- High temperatures
- Low temperatures during charging
- Surface chemistry (anode and cathode)
- Phase transitions/structural changes (cathode)

Safety—Li-Ion Thermal Runaway



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Energy Storage Requirements

(Power, Energy, Cycle Life, Calendar Life and Cost)

Vehicle size (weight and shape)

Electrification/hybridization purpose

- Start/stop
- Assist or launch
- Electric drive

Degree of hybridization

Driving profiles and usage

Auxiliary or accessory electrification

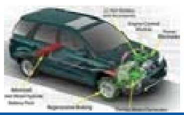
Expected fuel economy

Electric range

Energy storage characteristics (acceptable SOC range)

Vehicle simulation tools are usually used to estimate power and energy needs.
Economics and market needs are used to identify life and cost.

Energy Needs in Light-Duty Electric-Drive Vehicles

	Energy Storage Technology	Min **in use** energy needed
Micro Hybrids (12V-42V: Start-Stop, Launch Assist) 	NiMH and Li-ion: Yes Ucap: Likely Ucap + VRLA: Possible	15-25 Wh
Mild/Med Hybrids (42V-150V: Micro HEV Function + Regen)  	NiMH and Li-ion: Yes Ucaps: Likely if engine is not downsized much Ucaps + VRLA: Possible	25-80 Wh
Full/Med Hybrids (150V-350V: Power Assist HEV)  	NiMH and Li-ion: Yes Ucaps: Possible Ucaps + (NiMH or Li-Ion): Possible	70-200 Wh
Fuel Cell Hybrids  	NiMH and Li-ion: Yes Ucaps: Likely if fuel cell is not downsized Ucaps + (NiMH or Li-Ion): Possible	70-200 Wh
Plug-in HEV (and EV)  	NiMH: No Li-ion: Yes Ucaps + high energy Li-ion: Possible	PHEV: 5-15 kWh (50-90 Wh*) EV: 20-40 kWh

http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/45596.pdf

* Energy for a ultracapacitor in combination with Li-Ion

Power Needs in Light-Duty Electric-Drive Vehicles

	Energy Storage Technology	Range of **Power** needed
Micro Hybrids (12V-42V: Start-Stop, Launch Assist) 	NiMH and Li-ion: Yes Ucap: Likely Ucap + VRLA: Possible Power/Energy use = 200-300	3-5 kW
Mild/Med Hybrids (42V-150V: Micro HEV Function + Regen)  	P/E use = 50-200 NiMH and Li-ion: Yes Ucaps: Likely if engine is not downsized much Ucaps + VRLA: Possible	5-15 kW
Full/Med Hybrids (150V-350V: Power Assist HEV)  	NiMH and Li-ion: Yes Ucaps: Possible Ucaps + (NiMH or Li-Ion): Possible P/E use = 20-150	15-50 kW
Fuel Cell Hybrids  	P/E use = 20-150 NiMH and Li-ion: Yes Ucaps: Likely if Fuel Cell is not downsized Ucaps + (NiMH or Li-Ion): Possible	15-50 kW
Plug-in HEV (and EV)  	NiMH: No Li-ion: Yes P/E use = 3-8 Ucaps + high energy Li-ion: Possible P/E use = 1.5-4	PHEV: 20-50 kW EV: 80-120 kW

http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/45596.pdf

* Energy for a ultracapacitor in combination with Li-Ion

USABC/FreedomCAR Battery Requirements

Developed jointly by U.S. DOE (with support from national labs), automotive OEMs (through USABC), with input from battery industry

Requirements and targets are specified to make EDVs eventually competitive with conventional ICE vehicles on a mass-produced scale

Energy Storage Requirements for Micro Hybrids
(at End of Life)

System Attributes	12V Start-Stop (TSS)		42V Start-Stop (FSS)		42V Transient Power Assist (TPA)	
Discharge Pulse	4.2 kW	2s	6 kW	2s	13 kW	2s
Regenerative Pulse	N/A		N/A		8 kW	2s
Cold Cranking Pulse @ -30°C	4.2 kW	7 V Min.	8 kW	21 V Min.	8 kW	21 V Min.
Available Energy (CP @1kW)	15 Wh		30 Wh		60 Wh	
Recharge Rate (kW)	0.4 kW		2.4 kW		2.6 kW	
Cycle Life / Equiv. Road Miles	750k / 150,000 miles		750k / 150,000 miles		750k / 150,000 miles	
Cycle Life and Efficiency Load Profile	UC10		UC10		UC10	
Calendar Life (Yrs)	15		15		15	
Energy Efficiency on UC10 Load Profile (%)	95		95%		95%	
Self Discharge (72hr from Max. V)	<4%		<4%		<4%	
Maximum Operating Voltage (Vdc)	17		48		48	
Minimum Operating Voltage (Vdc)	9		27		27	
Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52	
Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66	
Maximum System Weight (kg)	5		10		20	
Maximum System Volume (Liters)	4		8		16	
Selling Price ($/system @ 100k/yr)	40		80		130	

http://www.uscar.org/guest/article_view.php?articles_id=85

Energy Storage Requirements for Micro Hybrids

(at End of Life)

System Attributes	12V Start-Stop (TSS)		42V Sta[illegible] (FSS[illegible]		[illegible]	
Discharge Pulse	4.2 kW	2s	6 kW	2s	13 kW	2s
Regenerative Pulse	N/A		N/A		8 kW	2s
Cold Cranking Pulse @ -30°C	4.2 kW	7 V Min.	8 kW	21 V Min.	8 kW	21 V Min.
Available Energy (CP @1kW)	[illegible]		30 Wh		60 Wh	
Recharge Rate (kW)	[illegible]		2.4 [illegible]		2.6 kW	
Cycle Life / Equiv. Road Miles	[illegible]		750k / 150,000 [illegible]		750k / 150,000 miles	
Cycle Life and Efficiency Load Profile	UC10		UC10		[illegible]	
Calendar Life (Yrs)	15		15		[illegible]	
Energy Efficiency on UC10 Load Profile (%)	[illegible]		95%		[illegible]	
Self Discharge (72hr from Max. V)	[illegible]		<4%		[illegible]	
Maximum Operating Voltage (Vdc)	[illegible]		48		48	
Minimum Operating Voltage (Vdc)	[illegible]		27		[illegible]	
Operating Temperature Range (°C)	-30 to +52		-30 [illegible]		[illegible]	
Survival Temperature Range (°C)	[illegible] 66		-46 to [illegible]		[illegible]	
Maximum System Weight (kg)	[illegible]		10		20	
Maximum System Volume (Liters)	4		8		16	
Selling Price ($/system @ 100k/yr)	40		80		130	

Discharge Power:
6 kW for 2s

Cycle Life:
750,000 (150,00
miles)

Available
Energy: 30 Wh
at 1 kW rate

Calendar life:
15 years

Weight and
Volume
Restrictions

Mass Produced
System Price: $80
($13.3/kW)

http://www.uscar.org/guest/article_view.php?articles_id=85

Energy Storage Requirements for Low-Voltage Mild Hybrids

FreedomCAR 42 V Energy Storage System End-of-Life Performance Goals (August 2002)

42 Volt Targets Rev. August 2002	Start-Stop		M-HEV		P-HEV	
Discharge Pulse Power (kW)	6	2 sec	13	2 sec	18	10 sec
Regenerative Pulse Power (kW)	N/A		8	2 sec	18	2 sec
Engine-Off Accessory Load (kW)	3	5 min	3	5 min	3	5 min
Available Energy (Wh @ 3 kW)	250		300		700	
Recharge Rate (kW)	2.4 kW		2.6 kW		4.5 kW	
Energy Efficiency on Load Profile (%)	90		90		90	
Cycle Life, Miles/Profiles (Engine Starts)	150k (450k)		150k (450k)		150k (450k)	
Cycle Life and Efficiency Load Profile	Zero Power Assist (ZPA)		Partial Power Assist (PPA)		Full Power Assist (FPA)	
Cold Cranking Power @ -30°C (kW)	8	21 V Min.	8	21 V Min.	8	21 V Min.
Calendar Life (Years)	15		15		15	
Maximum System Weight (kg)	10		25		35	
Maximum System Volume (Liters)	9		20		28	
Selling Price ($/system @ 100k/yr)	150		260		360	
Maximum Open Circuit Voltage (Vdc) after 1 sec	48		48		48	
Minimum Operating Voltage (Vdc)	27		27		27	
Self Discharge (Wh/day)	<20		<20		<20	
Heat Rejection Coefficient (W/°C)	N/A		N/A		>30	
Maximum Cell-to-Cell Temperature Difference (°C)	N/A		N/A		<4	
Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52	
Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66	

http://www.uscar.org/guest/article_view.php?articles_id=85

Energy Storage Requirements for Low-Voltage Mild Hybrids

FreedomCAR 42 V Energy Storage System End-of-Life Performance Goal

42 Volt Targets Rev. August 2002	Start-Stop		M-HEV			
Discharge Pulse Power (kW)	6	2 sec	13	2 sec	18	10 sec
Regenerative Pulse Power (kW)	N/A		8	2 sec	18	2 sec
Engine-Off Accessory Load (kW)	3	5 min	3	5 min	3	5 min
Available Energy (Wh @ 3 kW)	250		300		700	
Recharge Rate (kW)	[illegible]		2.6 kW		[illegible]	
Energy Efficiency on Load Profile (%)	[illegible]		90		[illegible]	
Cycle Life, Miles/Profiles (Engine Starts)	[illegible]		150k (450k)		[illegible]	
Cycle Life and Efficiency Load Profile	Zero Power Assist (ZPA)		Partial Power Assist (PPA)		Full Power Assist (FPA)	
Cold Cranking Power @ -30°C (kW)	8	21 V Min.	8	21 V Min.	8	21 V Min.
Calendar Life (Years)	[illegible]		15		15	
Maximum System Weight (kg)	[illegible]		25		35	
Maximum System Volume (Liters)	[illegible]		20		28	
Selling Price ($/system @ 100k/yr)	150		260		[illegible]	
Maximum Open Circuit Voltage (Vdc) after 1 sec	48		48		[illegible]	
Minimum Operating Vo[illegible]	27		27		[illegible]	
Self Discharge (W[illegible]	<20		<20		[illegible]	
Heat Rejection Co[illegible]	N/A		N/A		>30	
Maximum Cell-to-Cell Tempe[illegible] (°C)	N/A		N/A		<4	
Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52	
Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66	

Discharge Power: 13 kW for 2s

Available Energy: 300 Wh at 3 kW rate

Cycle Life: 450,000 (150,00 miles)

Calendar Life at 30°C: 15 years

Mass Produced System Price: $260 ($20/kW)

Weight and Volume Restrictions

http://www.uscar.org/guest/article_view.php?articles_id=85

For Medium or Full Hybrids, and Fuel Cell Vehicles
(at End of Life)

FreedomCAR Energy Storage System Performance Goals for Power-Assist Hybrid Electric Vehicles (November 2002)

Characteristics	*Units*	*Power-Assist (Minimum)*	*Power-Assist (Maximum)*
Pulse Discharge Power (10s)	kW	25	40
Peak Regenerative Pulse Power (10s)	kW	20 (55-Wh pulse)	35 (97-Wh pulse)
Total Available Energy (over DOD range where power goals are met)	KWh	0.3 (at C_1/1 rate)	0.5 (at C_1/1 rate)
Minimum Round-trip Energy Efficiency	%	90 (25-Wh cycle)	90 (50-Wh cycle)
Cold Cranking Power at -30°C (three 2-s pulses, 10-s rests between)	kW	5	7
Cycle Life for Specified SOC Increments	cycles	300,000 25-Wh cycles (7.5 MWh)	300,000 50-Wh cycles (15 MWh)
Calendar Life	years	15	15
Maximum Weight	kg	40	60
Maximum Volume	l	32	45
Operating Voltage Limits	Vdc	max ≤ 400, min ≥ (0.55 x V_{max})	max < 400, min > (0.55 x V_{max})
Maximum Allowable Self-discharge Rate	Wh/day	50	50
Temperature Range: Equipment Operation Equipment Survival	°C	-30 to +52 -46 to +66	-30 to +52 -46 to +66
Production Price @ 1,000,000 units/year	$	500	800

http://www.uscar.org/guest/article_view.php?articles_id=85

For Medium or Full Hybrids, and Fuel Cell Vehicles
(at End of Life)

FreedomCAR Energy Storage System Performance Goals for Power-Assist Hybrid Electric Vehicles (November 2002)

Characteristics	*Units*	*Power-Assist (Minimum)*	*Power-Assist (Maximum)*
Pulse Discharge Power (10s)	kW	25	[illegible]
Peak Regenerative Pulse Power (10s)	kW	20 (55-Wh pulse)	[illegible]
Total Available Energy (over DOD range where power goals are met)	KWh	0.3 (at C_1/1 rate)	0.5 (at C_1/1 rate)
Minimum Round-trip Energy Efficiency	%	90 (25-Wh cycle)	[illegible]
Cold Cranking Power at -30°C (three 2-s pulses, 10-s rests between)	kW	5	[illegible]
[illegible]	[illegible]	300,000 25-Wh cycles (7.5 MWh)	300,000 50-Wh cycles (15 MWh)
[illegible]	[illegible]ears	15	15
Maximum Weight	kg	40	60
M[illegible]	l	32	45
Operating Voltage Limits	Vdc	max ≤ 400, min ≥ (0.55 x V_{max})	max < 400, min > (0.55 x V_{max})
Maximum Allowable Self-discharge Rate	Wh/day	50	50
Temperature Range: [illegible]	°C	-30 to +52 -46 to +66	-30 to +52 -46 to +66
Production Price @ 1,000,000 units/year	$	500	800

Peak Power Discharge (10s) = 25 kW

Available Energy = 300 Wh at C_1/1 rate

Cycle Life (charge sustaining) = 300,000 cycles (150,000 miles)

Calendar Life at 30°C = 15 years

Cost for Mass Produced System = $500 ($20/kW)

http://www.uscar.org/guest/article_view.php?articles_id=85

USABC 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 (10 sec)	kW	45	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
Max. Current (10 sec pulse)	Amps	300	300
Maximum System Production Price @ 100k units/yr	$	$1,700	$3,400

http://www.uscar.org/guest/article_view.php?articles_id=85

USABC Requirements of End of Life Energy Storage Systems for PHE...

40 Mile EV Range

Characteristics at EOL (End of Life)		High Power/Energy Ratio ...y	High E... Batt...y
Reference Equivalent E...			40
Peak Pulse Discharge P...			38
Peak Regen Pulse Power (10 sec)	kW	30	25
Avai...			11.6
Avai...			0.3
Minimum Round-trip Energy Efficiency (USABC HEV Cycle)	%	90	90
Cold cranking power at -30°C, 2 sec - 3 Pulses			7
CD Life / Discharge Throughput		...7	5,000 / 58
CS HEV Cycle Life, 50 Wh Profile	Cycles	300,000	300,000
Calend...			15
Maxim...			120
Maximum System Volume	Liter		80
Maximum Operating Voltage	Vdc	400	400
Minimum Operating Voltage		...max	>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...		...66	-46 to +66
Max. Current (10 sec ...			300
Maximum System Production Price @ 100k units/yr	$	$1,700	$3,400

Peak Power Discharge (10S) = 38 kW
C-rate ~ 10–15 kW

Available Energy = 11.6 kWh (ΔSOC = 70%)
Capacity (EOL) = 16.6 kWh

Cycle Life (charge depleting) = 5,000 cycles

Cycle Life (charge sustaining) =200K–300K cycles

Calendar Life at 35°C = 15 years

Cost for Mass Produced System = $3,400 ($300/kWh available energy)

http://www.uscar.org/guest/article_view.php?articles_id=85

USABC Goals for Advanced Batteries for EVs

Parameter (Units) of Fully Burdened System	*Minimum Goals for Long Term Commercialization*	*Long Term Goal*
Power Density (W/L)	460	600
Specific Power – Discharge, 80% DOD/30 sec (W/kg)	300	400
Specific Power – Regen, 20% DOD/10 sec (W/kg)	150	200
Energy Density – C/3 Discharge Rate (Wh/L)	230	300
Specific Energy – C/3 Discharge Rate (Wh/kg)	150	200
Specific Power/Specific Energy Ratio	2:1	2:1
Total Pack Size (kWh)	40	40
Life (Years)	10	10
Cycle Life – 80% DOD (Cycles)	1,000	1,000
Power & Capacity Degradation (% of rated spec)	20	20
Selling Price – 25,000 units @ 40 kWh ($/kWh)	<150	100
Operating Environment (°C)	-40 to +50 20% Performance Loss (10% Desired)	-40 to +85
Normal Recharge Time	6 hours (4 hours desired)	3 to 6 hours
High Rate Charge	20-70% SOC in <30 min @ 150 W/kg (<20 min @ 270 W/kg Desired)	40-80% SOC in 15 min
Continuous Discharge in 1 Hour – No Failure (% of rated energy capacity)	75	75

http://www.uscar.org/guest/article_view.php?articles_id=85

USABC Goals for Advanced Batteries for EVs

Parameter (Units) of Fully Burdened System	*Minimum Goals for Long Term Commercialization*	*Long Term Goal*
Power Density (W/L)	460	
Specific Power – Discharge, 80% DOD/30 sec (W/kg)	300	
Specific Power – Regen, 20% DOD/10 sec (W/kg)	150	200
Energy Density – C/3 Discharge Rate (Wh/L)	230	300
Specific Energy – C/3	150	200
Specific Power/Specifi	2:1	
Total Pack Size (kWh)	40	
L	10	10
C	1,000	1,000
Power & Capacity Degradation (% of rated spec)	20	20
Selling Price – 25,000 units @ 40 kWh ($/kWh)	<150	100
Operating Environment (°C)	-40 to +50 Performance Loss (10% Desired)	-40 to +85
Normal Recharge Time	6 hours (4 hours desired)	3 to 6 hours
H	20-70% SOC in <30 min @ 150 W/kg (<20 min @ 270 W/kg Desired)	40-80% SOC in 15 min
C (% of rated energy capacity)	75	75

Peak Power Discharge (10S) = 80 kW

Available Energy = 40 kWh at C/3 rate

Calendar Life at 30°C = 10 years

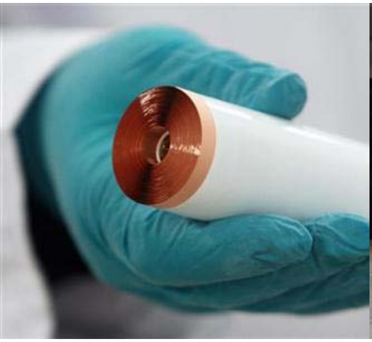
Cycle Life (full charge depleting) = 1,000 cycles (150,000 miles)

Cost for Mass Produced System = $6,000 ($150/kWh)

http://www.uscar.org/guest/article_view.php?articles_id=85

Summary:
DOE and USABC Battery Performance Targets

DOE Energy Storage Goals	HEV (2010)	PHEV (2015)	EV (2020)
Equivalent Electric Range (miles)	**N/A**	**10–40**	**200–300**
Discharge Pulse Power (kW)	**25**	**38–50**	**80**
Regen Pulse Power (10 seconds) (kW)	**20**	**25–30**	**40**
Recharge Rate (kW)	**N/A**	**1.4–2.8**	**5–10**
Cold Cranking Power @ -30°C (2 seconds) (kW)	**5**	**7**	**N/A**
Available Energy (kWh)	**0.3**	**3.5–11.6**	**30–40**
Calendar Life (year)	**15**	**10+**	**10**
Cycle Life (cycles)	**3,000**	**3,000–5,000, deep discharge**	**750+, deep discharge**
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**





Source: David Howell, DOE Vehicle Technologies Annual Merit Review

Outline of the Presentation

Introduction to NREL

Introduction to HEVs, PHEVs and EVs

Battery Technologies for HEVs, PHEVs & EVs

Battery Requirements for EDVs

Concluding Remarks

Integrating Cells into Packs

- 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)

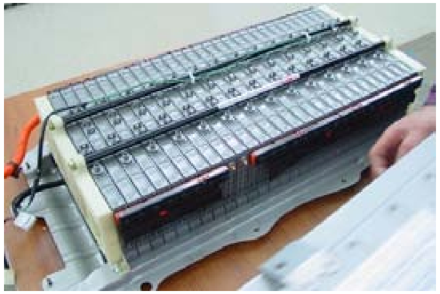
Source: Valance Technologies

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 EDVs

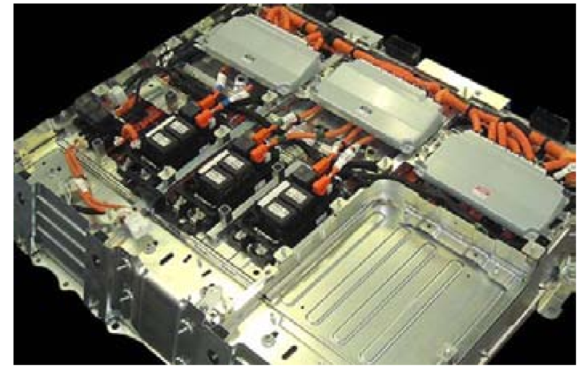
Chevy Volt

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

Nissan Leaf

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

Prius PHEV



http://www.toyota.com/esq/articles/2010/Lithium_Ion_Battery.html

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

Fiat 500 EV

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

Investments in Factories to Reduce Battery Cost (based on Recovery and Reinvestment Act of 2009)

$1.5 Billion for Advanced Battery Manufacturing for Electric Drive Vehicles "Commercial Ready Technologies"

Material Supply	Cell Components	Cell Fabrication	Pack Assembly	Recycling
Lithium Supply Chemetall Foote	Cathode Prod. A123 BASF Toda	Iron Phosphate A123	Iron Phosphate A123	Lithium Ion TOXCO
	Anode Prod. EnerG2 Pyrotek FutureFuel	Nickel Cobalt Metal JCI SAFT EnerDel	Nickel Cobalt Metal JCI SAFT EnerDel	
	Electrolyte Prod. Novolyte Honeywell	Manganese Spinel CPI-LG DOW-Kokam	Manganese Spinel GM DOW-Kokam	
	Separator Prod. Celgard ENTEK/JCI		Advanced Lead Acid Batteries Exide East Penn	
	Other Component H&T Waterbury			
$28.43 M	$259 M	$735 M	$462 M	$9.55 M

Source: David Howell, Energy Storage Program Overview, 2010 DOE Annual Merit Review

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 battery for 30 miles
- 2-Second power: 30 to 60 kW
- P/E from 2 to 15

Sprinter PHEV consumes about 600 Wh/mile in charge-depleting (CD) mode

Heavy-duty vehicles could consume from 1,000 to 2,000 Wh/mile

- 30 to 60 kWh battery for 30-mile range
- Volume, weight, and cost are big issues
- Thermal management is a concern

Examples of Medium- and Heavy-Duty EDVs

http://green.autoblog.com/photos/fedex-hybrid-truck/

http://www.greenoptions.com/forum/thread/2029/coke-uses-hybrid-electric-trucks

http://articles.sfgate.com/2009-12-06/business/17182903_1_hybrid-garbage-trucks-volvo-group

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Examples of Medium- and Heavy-Duty EDVs and Their Batteries

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An Example of an Investigation to Evaluate Medium-Duty Electric Drive Vehicles

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CALSTART

Model-Based Analysis of Electric Drive Options for Medium-Duty Parcel Delivery Vehicles

Robb A. Barnitt

Paper K5U7P24S

EVS25: Shenzhen, China

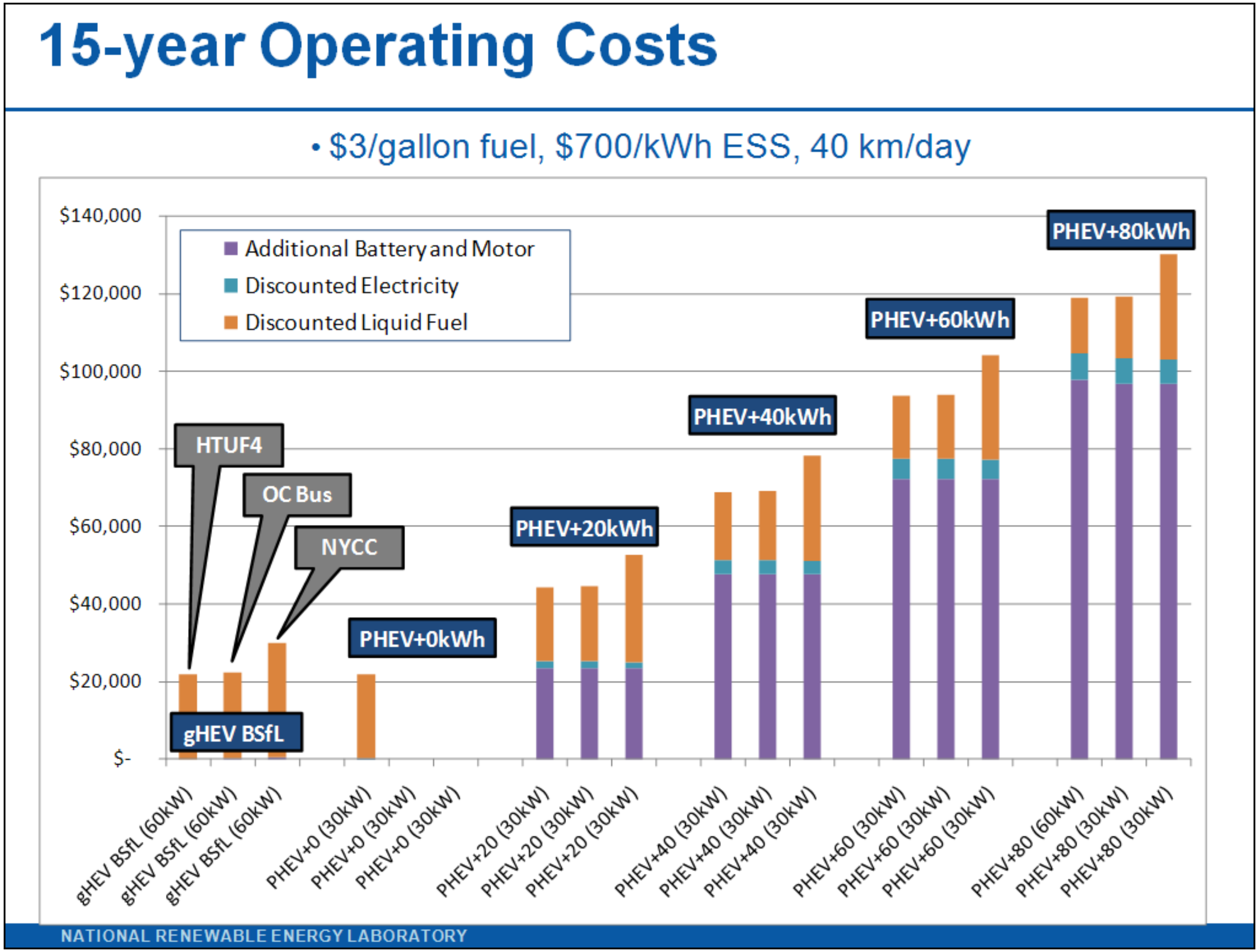
November 8, 2010

For more information, see the complete conference paper, **NREL/CP-5400-49253**

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Example Results Comparing Different Electrification Options for a Medium-Duty Vehicle

Battery and fuel costs dominate economics; lowering battery costs is critical to EDV penetration. Optimizing route (intensity and distance) selection can minimize petroleum use and costs.



Source: Rob Barnitt, EVS-25 Presentation, Shenzhen, China, Nov, 2010

Concluding Remarks

- There are many types of electric drive technologies and thus battery solutions
- Batteries with high power-to-energy ratios are needed for HEVs
- Batteries with low power-to-energy ratios are needed for EVs and PHEVs
- NiMH batteries would be the technology of choice for HEVs for the next 5 years, and then they will be gradually replaced by Li-ion
- Li-ion batteries have the power and energy densities for PHEV and EV applications, but cost is an issue for mass-produced adoption
- There are a number of Li-ion chemistries with prismatic or cylindrical formats that could be mass produced in the market
    - Difficult to predict technology winner
    - Many companies are performing R&D and high-volume manufacturing in the United States, Japan, Korea, and China
- The key barriers to commercialization of PHEVs and EVs are battery life, packaging and cost (Recovery Act funding is expected to reduce battery cost)
- Battery technologies being developed for light duty vehicles can be used for medium- and heavy-duty applications

Acknowledgments

DOE Program Support

- Dave Howell
- Tien Duong
- Brian Cunningham

NREL Technical Support

- Shriram Santhanagopalan
- Anne Dillon
- Matt Keyser
- Kandler Smith
- Gi-Heon Kim
- Jeremy Neubauer

nrel.gov/vehiclesandfuels/energystorage/

Thank You!

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