State of Battery Performance and Projected Automotive Needs

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GE Global Research

Battery Technology Symposium 2008

Thursday October 23, 3:30-4:00 pm

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Overview

- Electric vehicle market is projected to explode
- Types of electric vehicles and their battery requirements
- Survey of lithium-ion batteries

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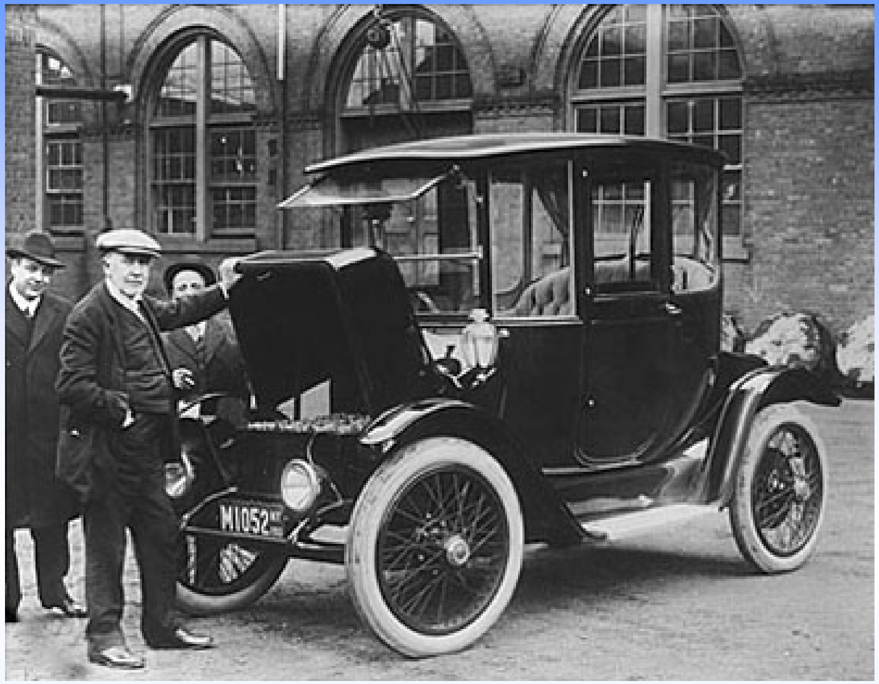
Electric Vehicle History

- The years 1899 and 1900 were the high point of electric vehicles in America, as they outsold all other types of cars. Electric vehicles had many advantages over their competitors in the early 1900s. They did not have the vibration, smell, and noise associated with gasoline cars.



Thomas Edison inspects electric car in 1914. He and Henry Ford had planned to use Edison's nickel iron battery to power clean, efficient, affordable cars that would be recharged by home wind turbines, according Edwin Black in 'Internal Combustion'.

http://www.evworld.com/article.cfm?storyid=1212

The decline of the electric vehicle was brought about by several major developments:

- Roads connecting cities brought need for longer-range vehicles.
- ~~Discovery of Texas crude oil made gasoline affordable to the average consumer.~~
- ~~The electric starter of Charles Kettering in 1912 eliminated the need for the hand crank.~~
- Henry Ford's use of mass production made internal combustion engine vehicles widely available and affordable. In 1912, an electric roadster sold for $1,750, while a gasoline car sold for $650.

Acceleration provided by gas engine is fun!

Acceleration provided by electric motor is more fun!

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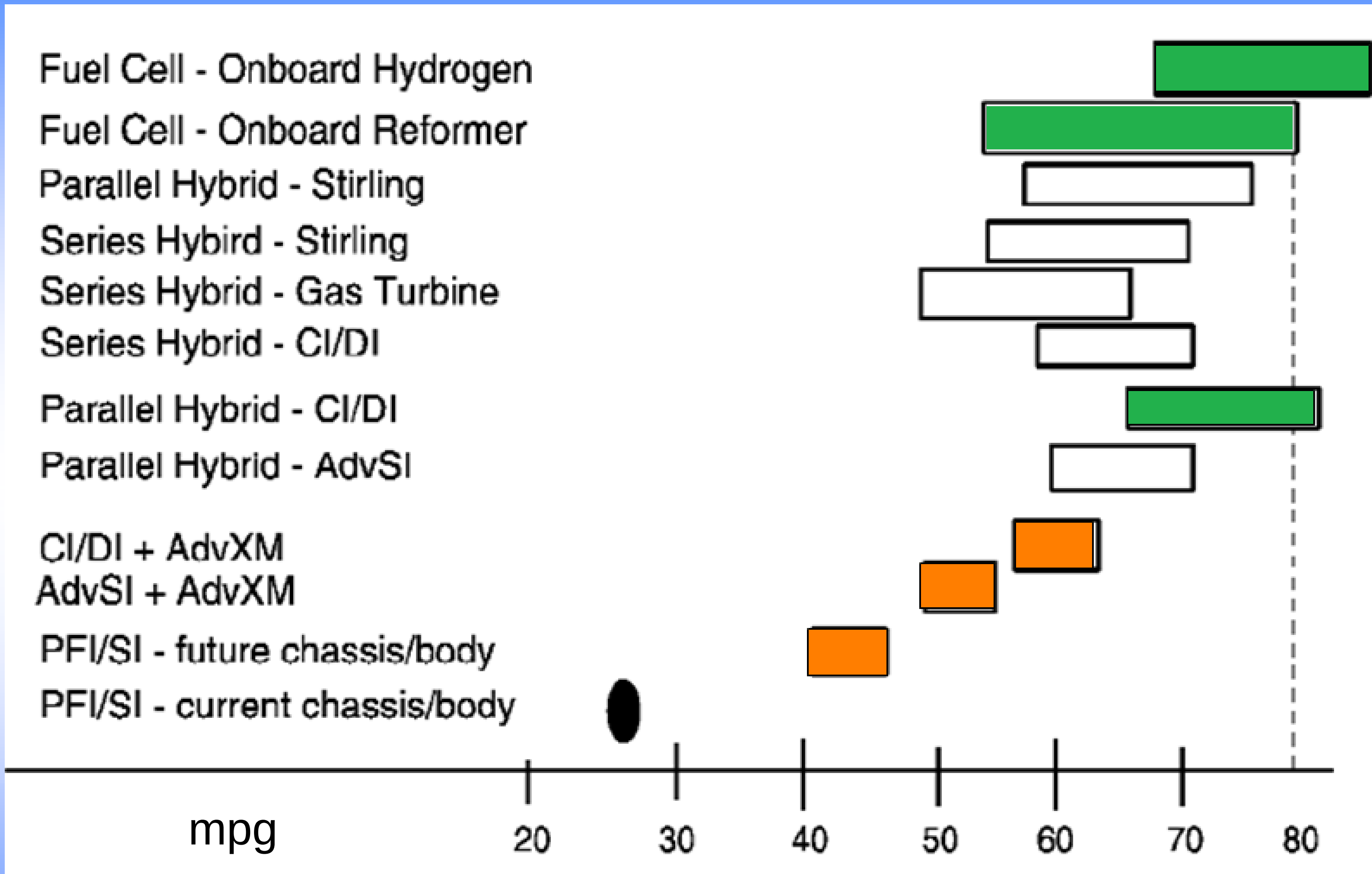
Fuel Efficiency of Concept Vehicles



Gas/Electric Hybrids provide outstanding fuel economy.

Vehicle Types

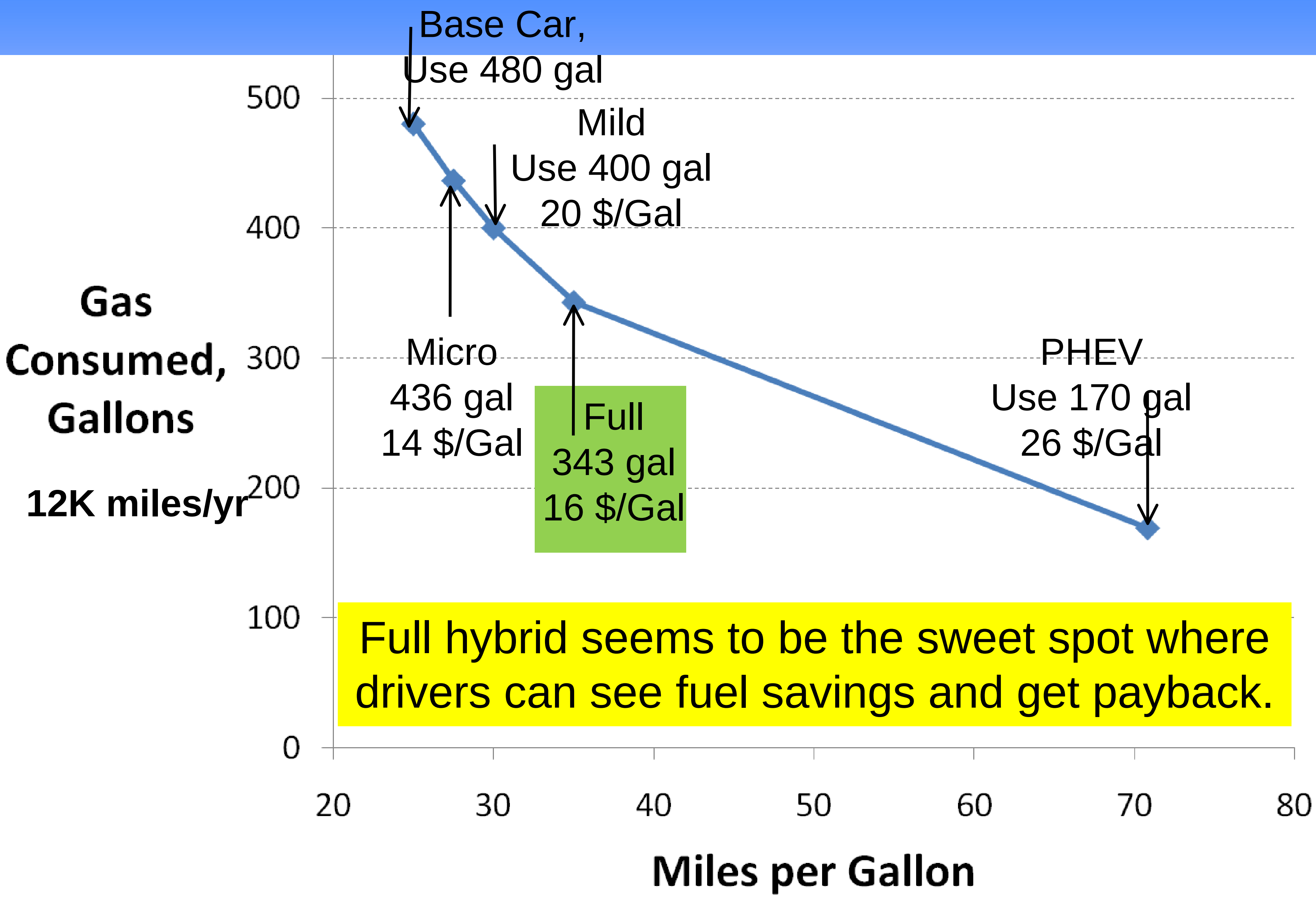
1) Micro hybrid: Stop/start and regenerative braking
2) Mild hybrid: micro plus power for acceleration
3) Full hybrid: mild plus electric launch
4) Plug-In hybrid: EV range, then functions as full hybrid.
5) Full Power Battery Electric Vehicle (FPBEV): fully powered by batteries.

Costs and Fuel Benefits of Vehicle Types

	Battery Cost, $	Non Battery Incremental Cost, $	Total Cost, $	Fuel Efficiency Gain, %
Micro Hybrid	100	500	600	5-10
Mild Hybrid	600	1,000	1,600	10-20
Full Hybrid	1,200	1,000	2,200	25-40
PHEV	6,000	2,000	8,000	40-65
EV	11,000	0	11,000	100

Deutsche Bank 2008

Diminishing Return from Improving Fuel Economy



Vehicle Energy Storage System Performance Requirements (1) Power/Energy

EDV Type	Weight (max. kg)	Peak Power (min. kW)	Power Density (min. W/kg)	ES Capacity (min. kWh)	Energy Density (min. Wh/kg)
Full HEV	50[1]	40[1]-60	800-1200	1.5-3 [0.7][2]	30-60
Plug-in HEV[3]	120	65[4]; 50[5]	540[4]; 400[5]	6[4]; 12[5]	50[4]; 75[5]
FPBEV	250	50[6]; 100[7]	200[6]; 400[7]	25[6]; 40[7]	100[6]; 160[7]

[1] Data taken from Deiml (2005)

[2] Minimum energy required to perform the electric launch function

[3] PHEV data derived from Duvall (2001) are considered preliminary

[4, 5] Requirements for midsize passenger PHEVs with nominal electric ranges of 20 and 40 miles, respectively

[6, 7] Requirements for small and midsize FPBEVs, respectively, with weight, performance and accommodations comparable to similar size ICEVs

Source: Status and Prospects for Zero Emissions Vehicle Technology Report of the ARB Independent Expert Panel 2007

Vehicle Energy Storage System Performance Requirements (2)
Cycle Life

Vehicle Type	Deep Cycles		Shallow Cycles
	Energy[2] (MWh)	Number[3] @80%DoD	Number[4] @ 50Wh[5]
Full HEV	n.a.	n.a.	200k [300k]
PHEV-20	~12 [~17]	2400 [3500]	fewer than full HEV
PHEV-40	~17 [~25]	2300 [3400)	fewer than full HEV
Battery EV	~32[6]	1000 [1500]	fewer than full HEV

[1] for battery operation over a 10-year life [15-year life and total energy delivery requirements in brackets]
[2] energy delivered by battery over its life time in form of deep discharges
[3] number of equivalent 80% DoD cycles to be delivered by battery over its life time
[4] number of shallow cycles to be delivered by battery over its life time
[5] maximum energy to be delivered by battery in single pulse
[6] for mid-size FPBEV with 40kWh battery discharged to 20%SoC

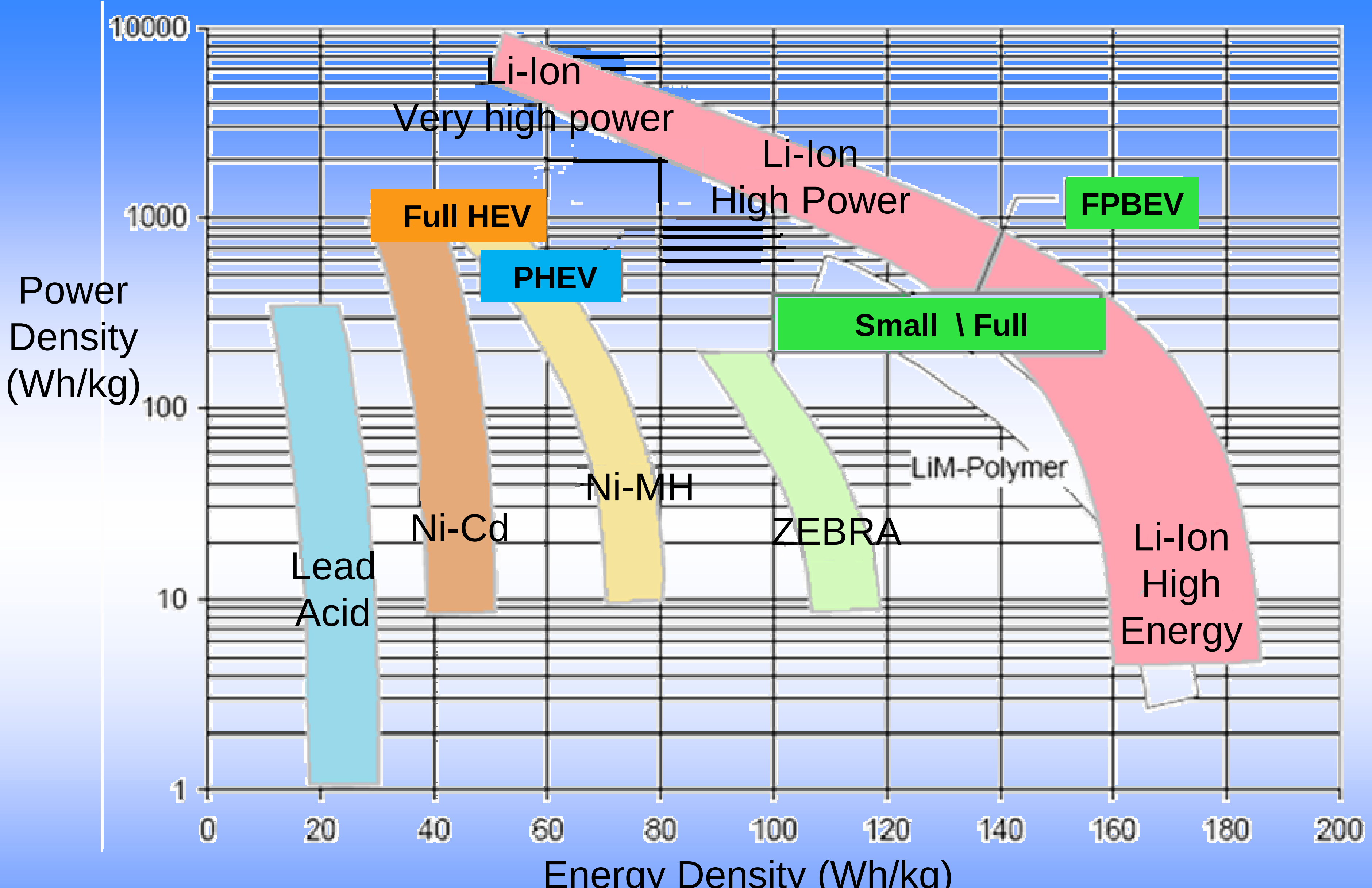
Source: Status and Prospects for Zero Emissions Vehicle Technology Report of the ARB Independent Expert Panel 2007

Vehicle Energy Storage System Performance Requirements (3) Cost Goals

Vehicle Type	Battery Rating	Production Rate (Batteries/year)	Specific Capacity Cost[2] ($/kWh)	Specific Power Cost[3] ($/kW)
FPBEV	40 kWh	25k	<150 [< $6,000]	n.a.
HEV	25--40 kW	100k	n.a.	<20 [< $500 – $800]
PHEV	(10 kWh)	(100k)	(<300) [< $3000]	n.a.

[1] selling Price to OEMs
[2] in brackets: cost goals for complete batteries of rated energy storage capacity
[3] in brackets: cost goals for complete batteries of rated peak power capability

Source: Status and Prospects for Zero Emissions Vehicle Technology Report of the ARB Independent Expert Panel 2007



Only Li-Ion batteries can meet the whole range of vehicle applications from HEV to PHEV to FPBEV.

Li-Ion Companies

Significant Players

- Toyota (PEVE)
- JCS
- Japan Lithium Energy
- AESC
- LG/CP
- SK
- Sanyo
- Samsung/Bosch
- BYD

Start-ups

- A123
- American Lithium Energy
- Altair Nano
- Enerdel
- ElectroEnergy
- Electrovaya
- Gaiaa/LTC
- Kokam
- LionCell
- Valence

Billions of dollars spend and thousands of people working on lithium-ion.

Ni/MH

- Works for HEV!
  - \> 1 million vehicles
  - Life proven
  - Cost
  - Reliability
- Major producers
  - PEVE
  - Sanyo
- Cell design and chemistry continually improved

Nickel metal hydride will be hard to displace from HEV.

ZEBRA: $2Na + NiCl_2 \leftrightarrow Ni + 2NaCl$
2.58 Volts, 270-350ºC

- Liquid sodium negative, sodium-aluminum chloride electrolyte, separators are beta-alumina ceramic tubes.
- Start-up heating and thermal insulation to prevent significant thermal energy loss.
- Tolerance of the ceramic tubes and their seals to occasional freeze-thaw cycles of the cells.
- Facilitates battery cooling and makes operation independent of either high or low environmental temperatures

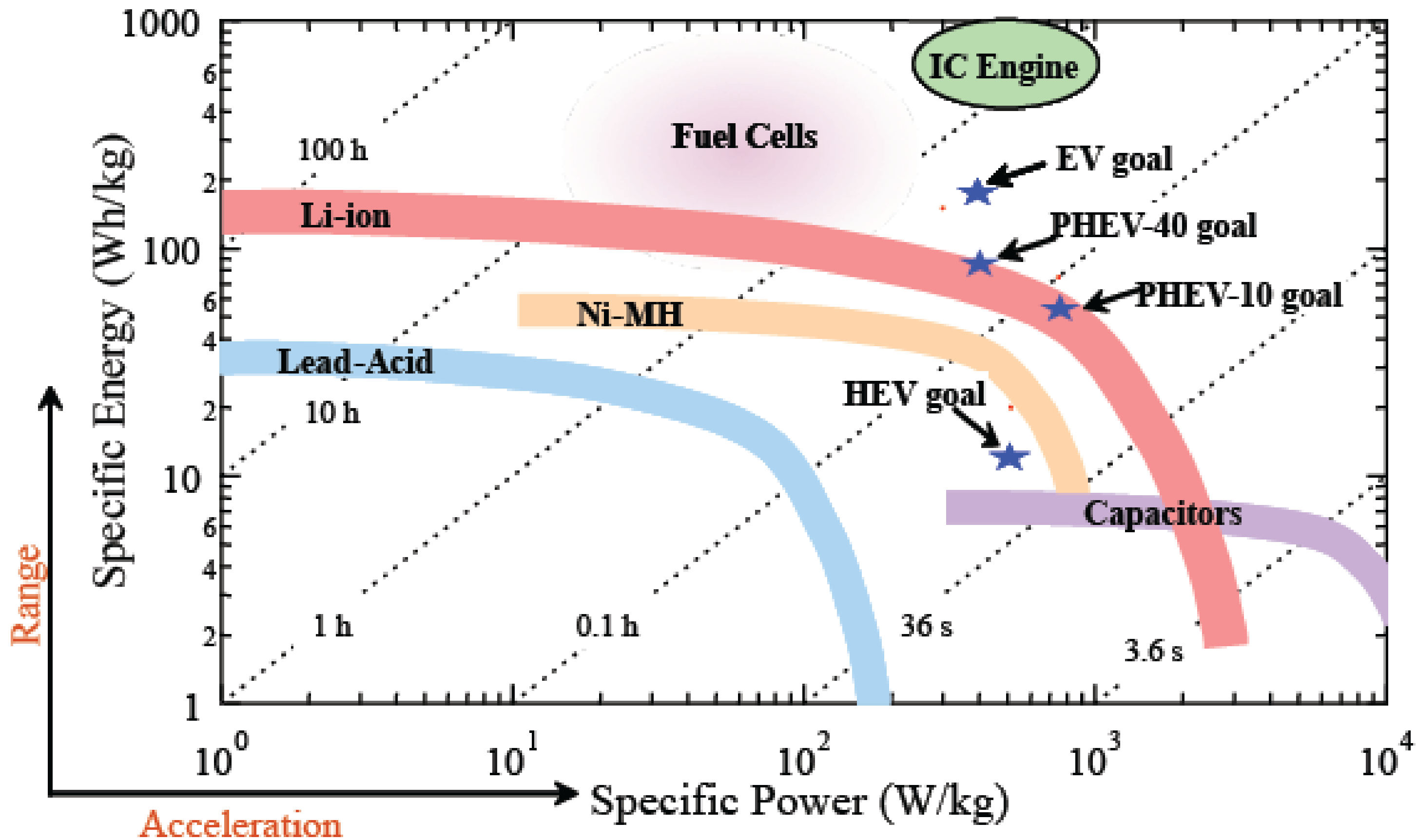
The most serious drawback is peak power density of ~180W/kg (battery level). This limits the power even of BEV-design and disqualifies for HEV and PHEV applications.

ZEBRA faces real challenge for acceptance.

Ragone Plot

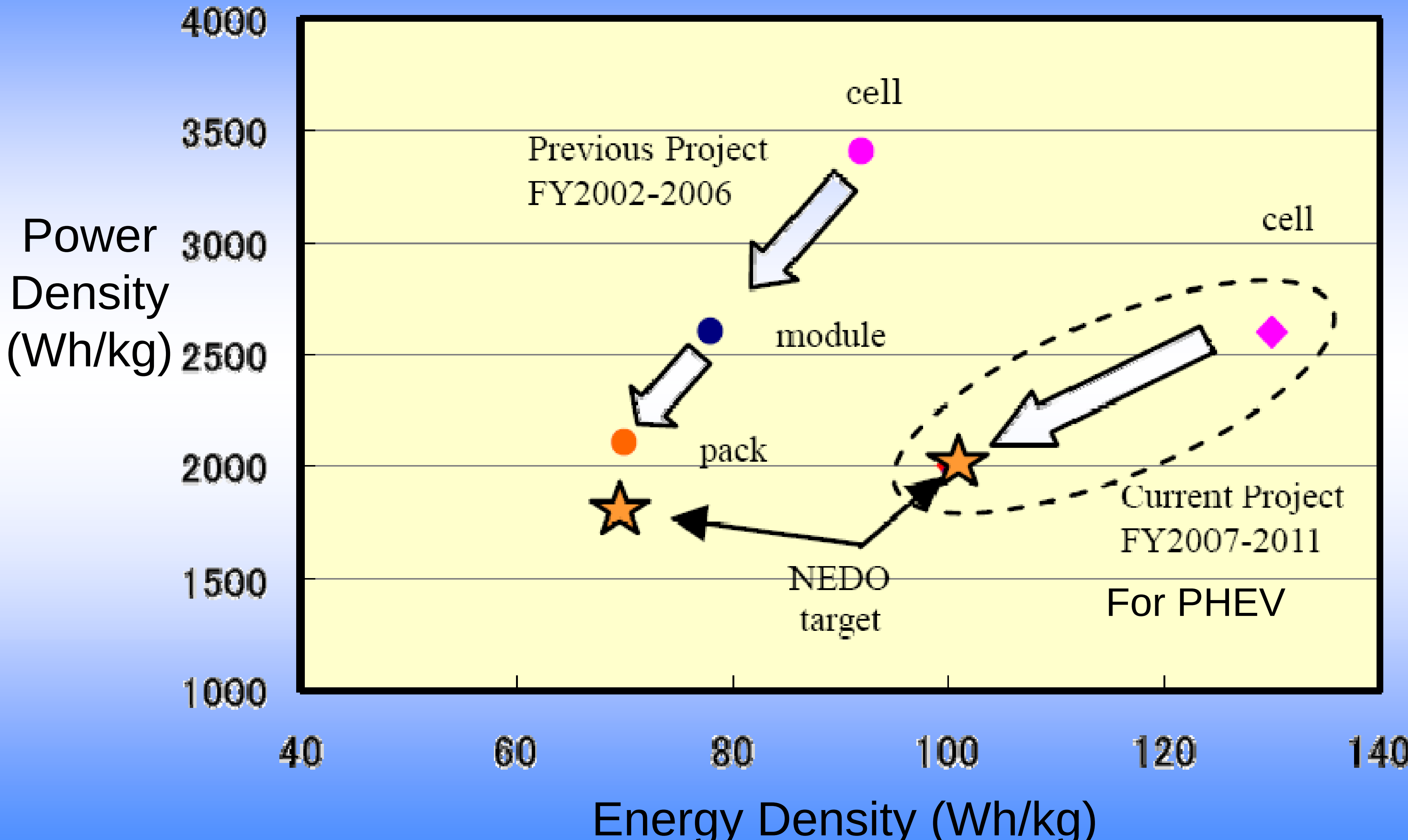
Energy Efficiency & Renewable Energy

Relative Performance of Various Electrochemical Energy Storage Devices

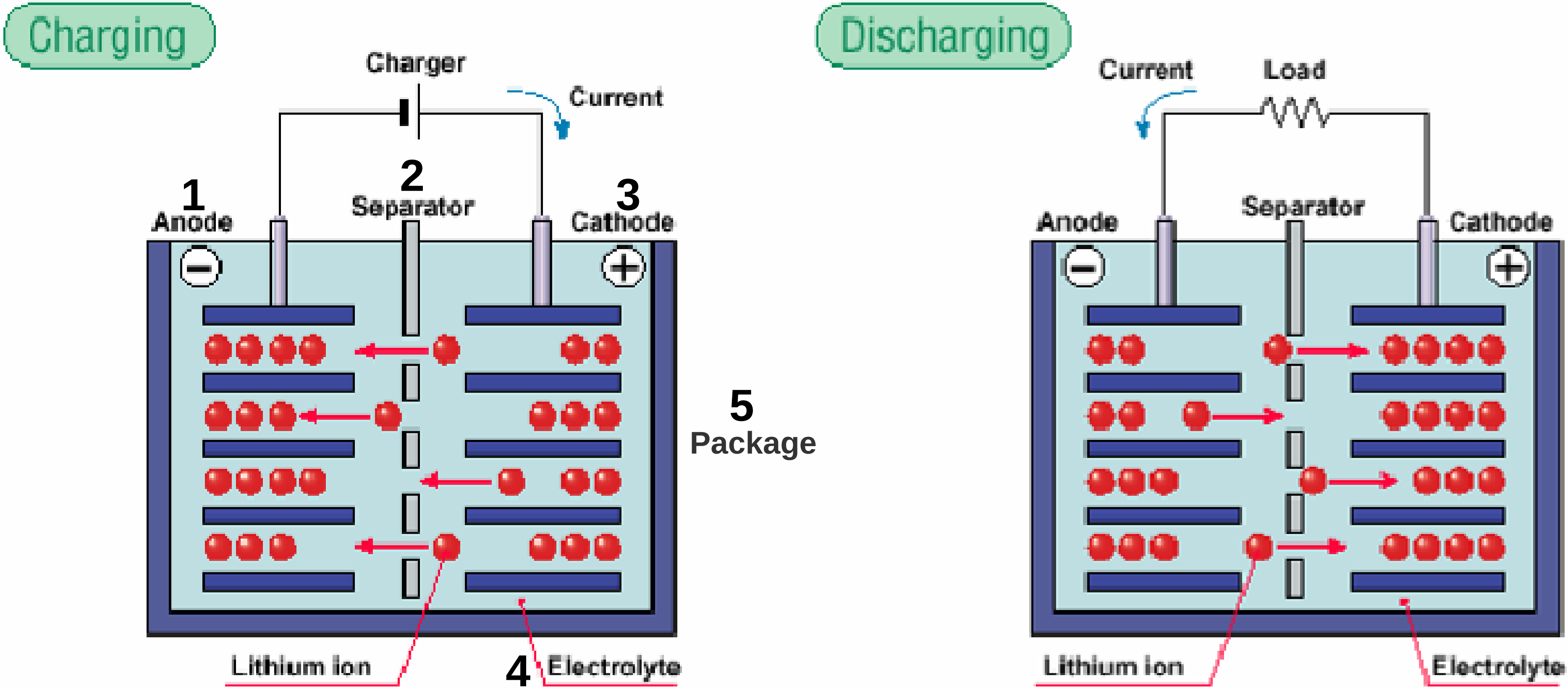


US Dept. of Energy –
FPBEV still out of range for battery technology.

Panasonic (T. Inoue, 2008)



Lithium-Ion Battery Operating Principle



Key Parameters:

- **Safety**
- **Wh/kg, Wh/l**
- **Temperature range**
- **Cycle life, calendar life**
- **Cost**
- **Voltage (higher voltage reduces number of cells to achieve car operating voltage)**

Lithium-Ion Cathode Chemistries (High Energy Designs)

Cathode Material	Average V	Wh/kg	Wh/l	Thermal Stability
Cobalt Oxide	3.7	195	560	Poor
Nickel Cobalt Aluminum Oxide (NCA)	3.6	220	600	Poor
Nickel Cobalt Manganese Oxide (NCM)	3.6	205	580	Poor
Lithium manganese oxide (Spinel)	3.9	150	420	Fair
Iron Phosphate (LFP) (carbon coated)	3.2	90-130	333	Excellent

- Iron phosphate has excellent thermal stability but low energy
- Oxides have poor thermal stability and excellent energy

“Mastering battery technology is regarded in the auto industry as the linchpin to the production of electric cars”

What Are the Pain points in Battery technology?

- Safety

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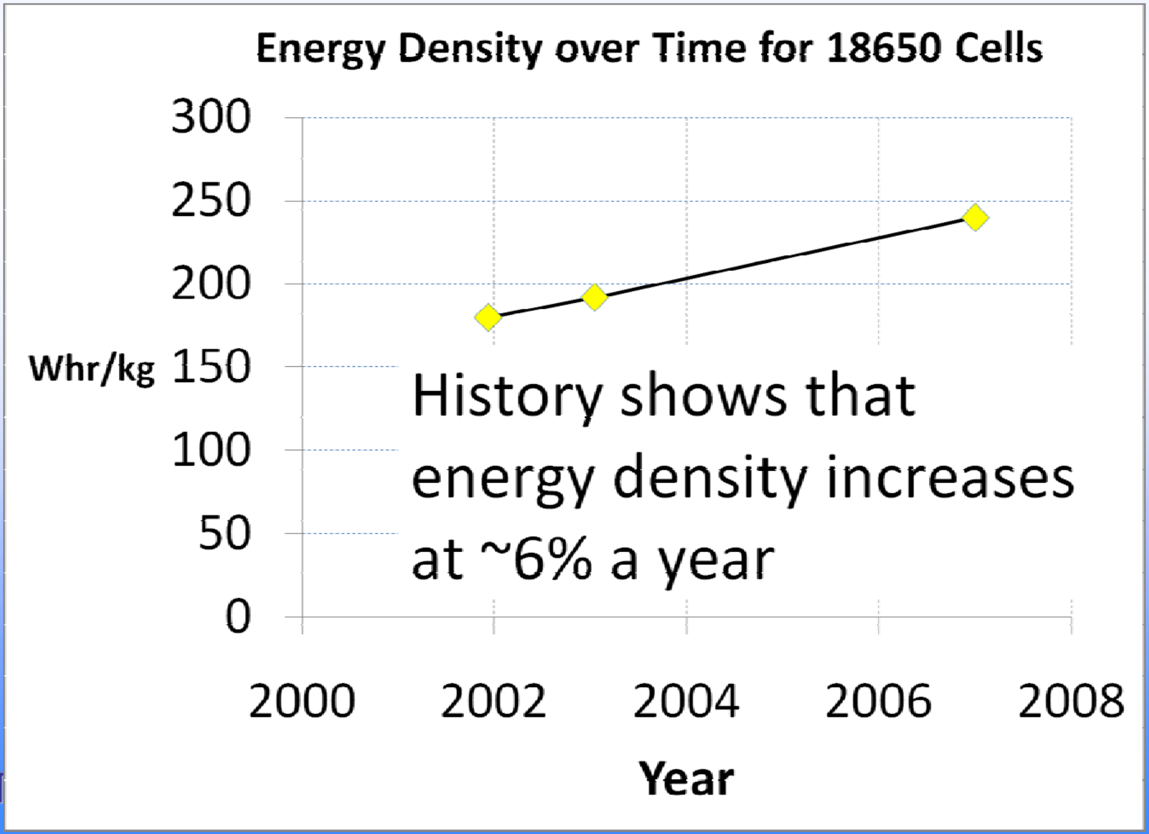
- Slow progress in capacity increase



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"Mastering battery technology is regarded in the auto industry as the linchpin to the production of electric cars"

What Are the Pain points in Battery technology?

- Safety
- Slow progress in capacity increase
- Cost
  - Current price ≥ $1K/kWh (16kWh in GM's Volt)
  - Best cost projection is $200/kWh for the cells
    - $3x10^6$ kWh volume
    - Excluding pack costs
- Extreme temperature performance
  - Above 60^{o}C, battery degrades rapidly
  - Low temperature operation is very challenging
- Calendar life difficult to demonstrate

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Life Prediction

- Mechanisms of capacity fade still a research problem
- Currently need to rely on real-time testing. Encouraging data
  - Saft: INL has ~4.5 years, Lockheed Martin (Aerospace) ~7.5 years
  - Hitachi ~2.5 years
  - A123 ~2 years
  - AESC, LG, ~ 1 year

There is risk that lithium-ion may fail under real-world use conditions.

Lithium Energy Japan (GS Yuasa/Mitsubishi)

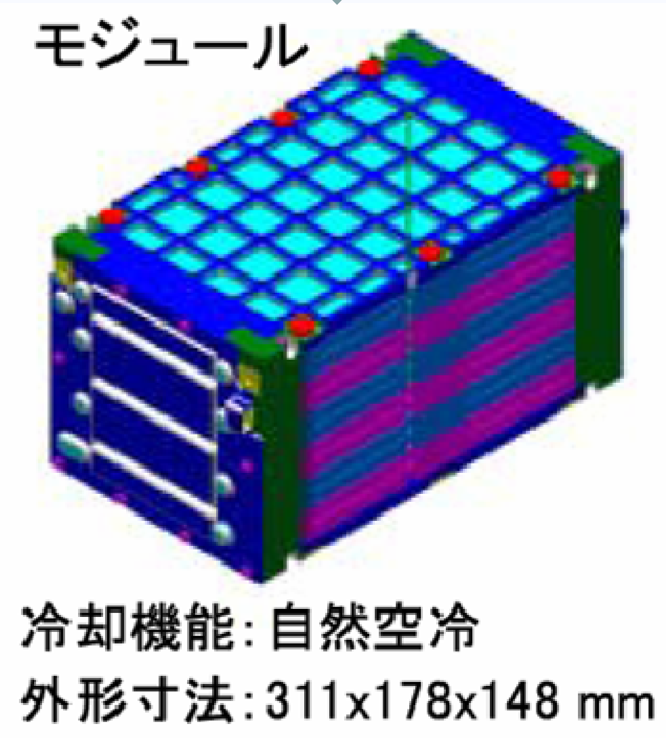
■ Specifications

Type		LEV50	LEV50-4
Norminal voltage(V)		3.7	14.8
Capacity(Ah)		50	50
	Length	171	175
Dimensions(mm)	Width	43.8	194
	Height	113.5	116
Mass(kg)		1.7	7.5

Nominal ~109 Wh/kg

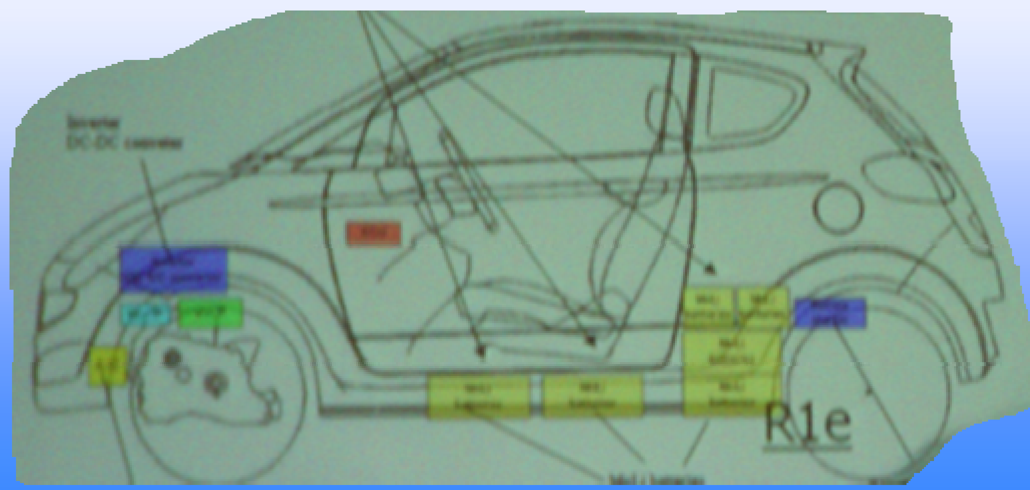
Automotive Energy Supply Corporation (NEC/Nissan)

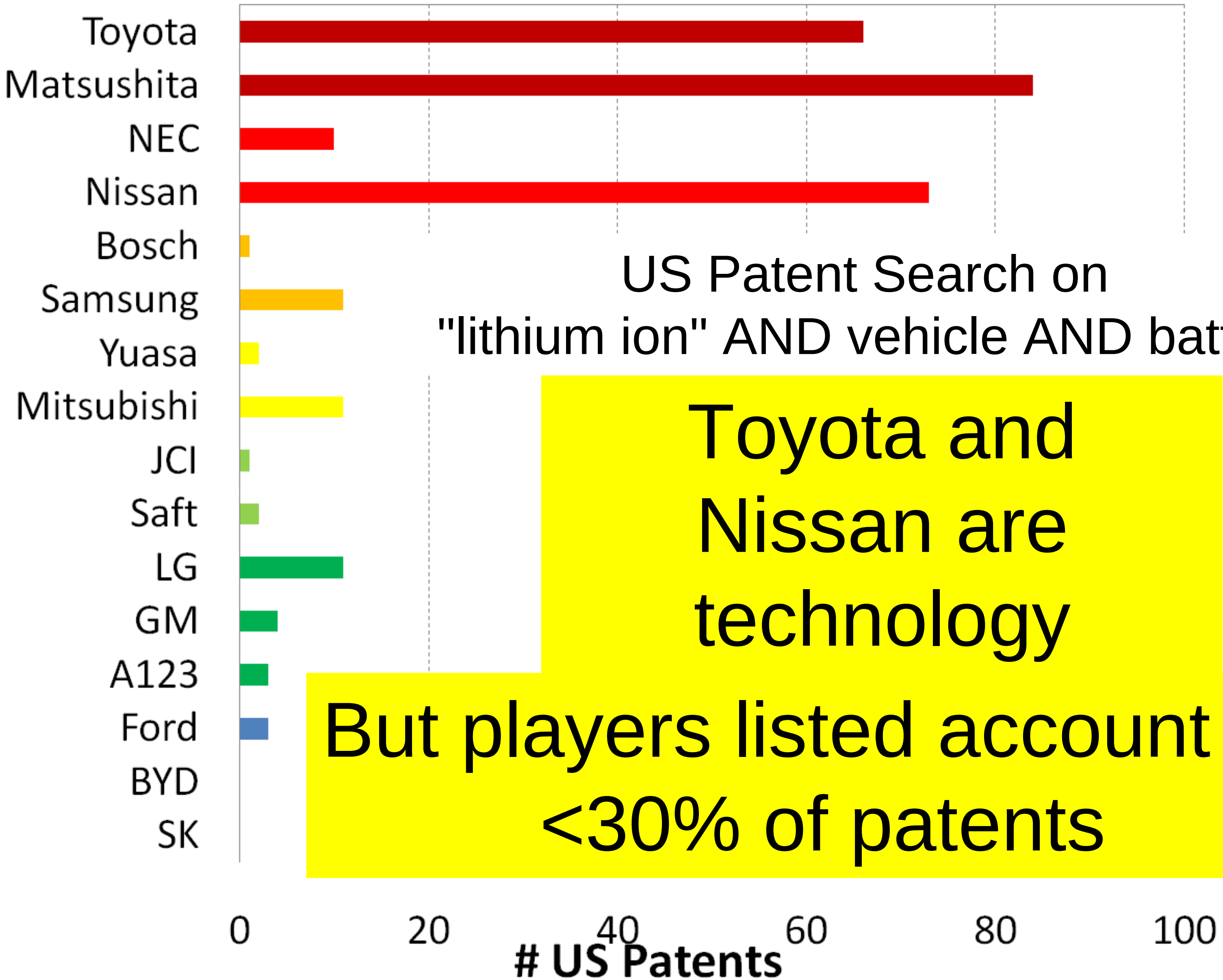
12 cells in a module
(2 parallel and 6 series)



16 modules in a car

Voltage : 346 V
Capacity : 25 Ah





US Patent Search on
"lithium ion" AND vehicle AND battery

Toyota and Nissan are technology

But players listed account for <30% of patents

Summary

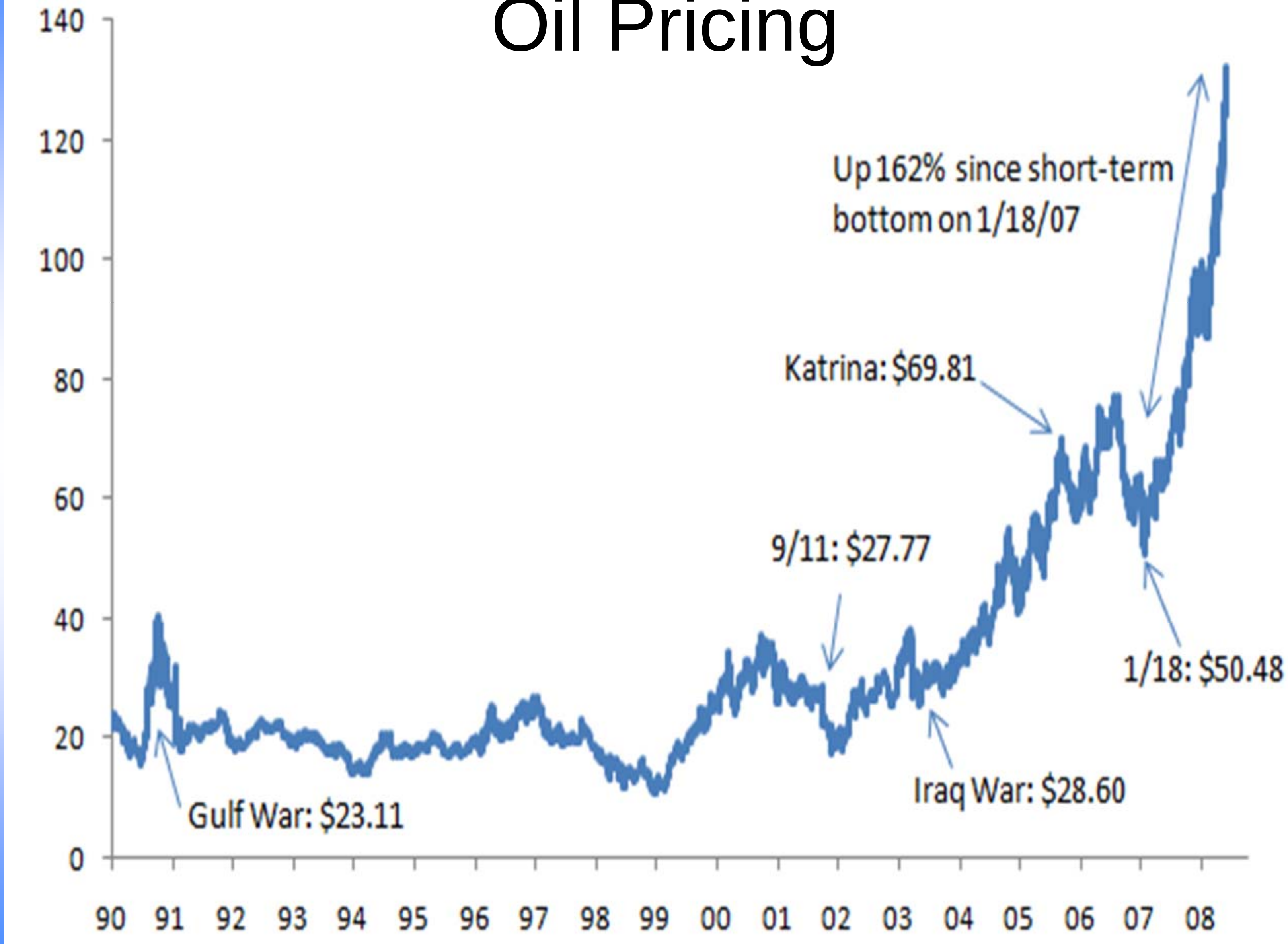
- Tremendous worldwide interest in electric vehicles
- “The good is the enemy of the best” – HEV versus PHEV
- Lithium-ion is technically close – calendar life and cost are key concerns
- Amount of innovation is cause for optimism

Acknowledgements

- My colleagues at American Lithium:
  - Dr. Sass Somekh for providing some of slides and helpful comments.
  - Dr. Jiang Fan for his comments.
- Dr. Menahem Anderman for critical comments

Backups

Oil Pricing



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Public Offerings, Mergers and Acquisitions Are On the Rise

The New York Times
nytimes.com

September 30, 2008

Buffett Buys Stake in Chinese Battery Manufacturer

By KEITH BRADSHER

HONG KONG — The investor Warren E. Buffett announced on Monday that he had agreed to buy a 9.89 percent stake in a Chinese battery manufacturer that plans to sell electric cars in the United States by 2010.

The MidAmerican Energy Holdings Company, will pay 1.8 billion Hong Kong dollars — about $230 million — for the stake in the battery maker, the BYD Company. Mr. Buffett's Berkshire Hathaway owns 87.4 percent of

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accounts for nearly a third of its revenue and makes fuel-efficient compact and subcompact cars for the Chinese market.

BYD is one of the world's largest makers of batteries and also has a fast-growing auto-making unit

The president of BYD, Wang Chuanfu, said that the alliance with Mr. Buffett was not just about raising capital for the manufacturer, which relies heavily on short-term debt.

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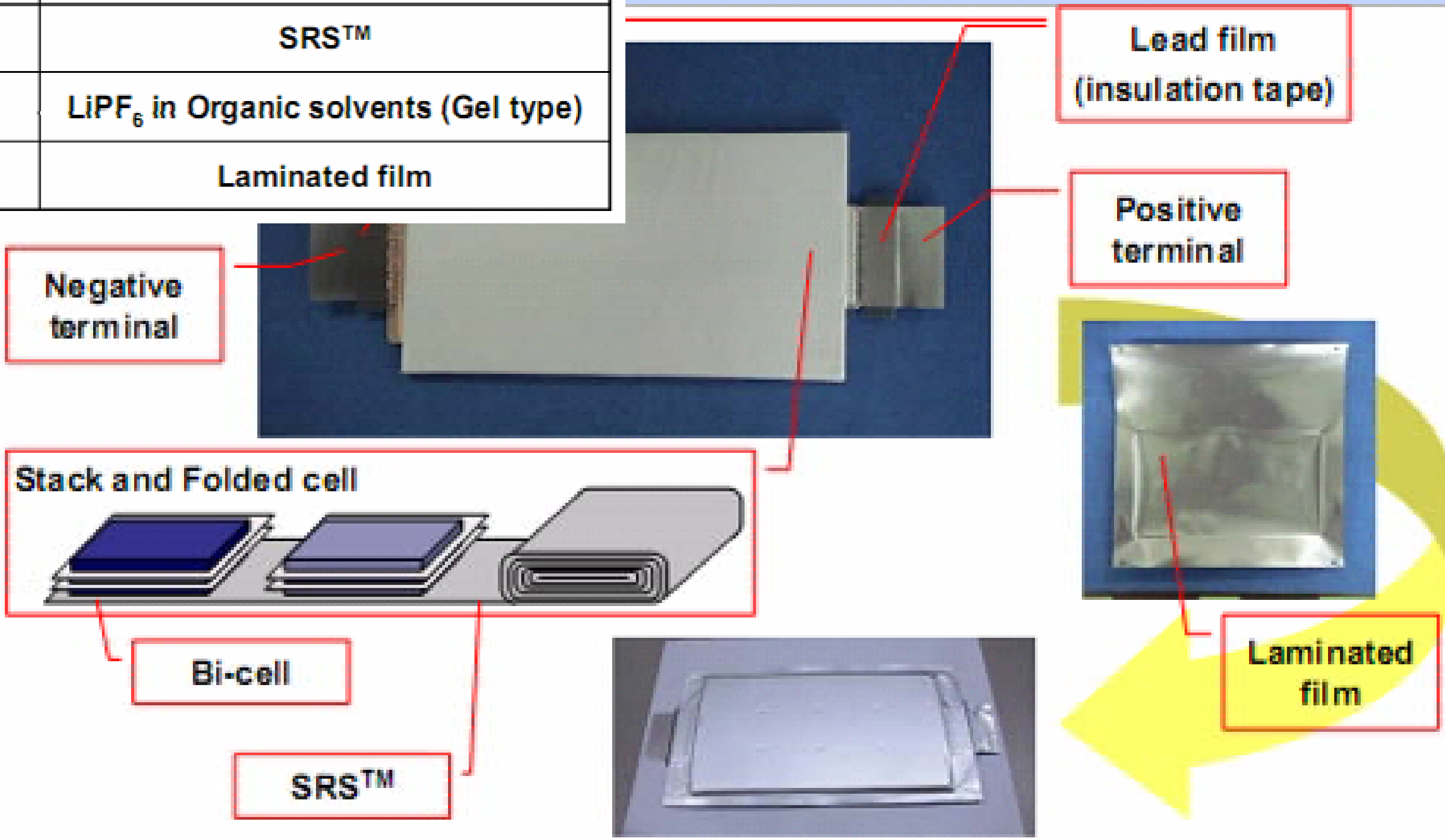
with manmade global warming, Mr. Sokol

Expertise in automotive design and manufacturing is easy to acquire…battery expertise is much harder to find. Mastering battery technology is regarded in the auto industry as the linchpin to the production of electric cars

LG Chem's Product Offering

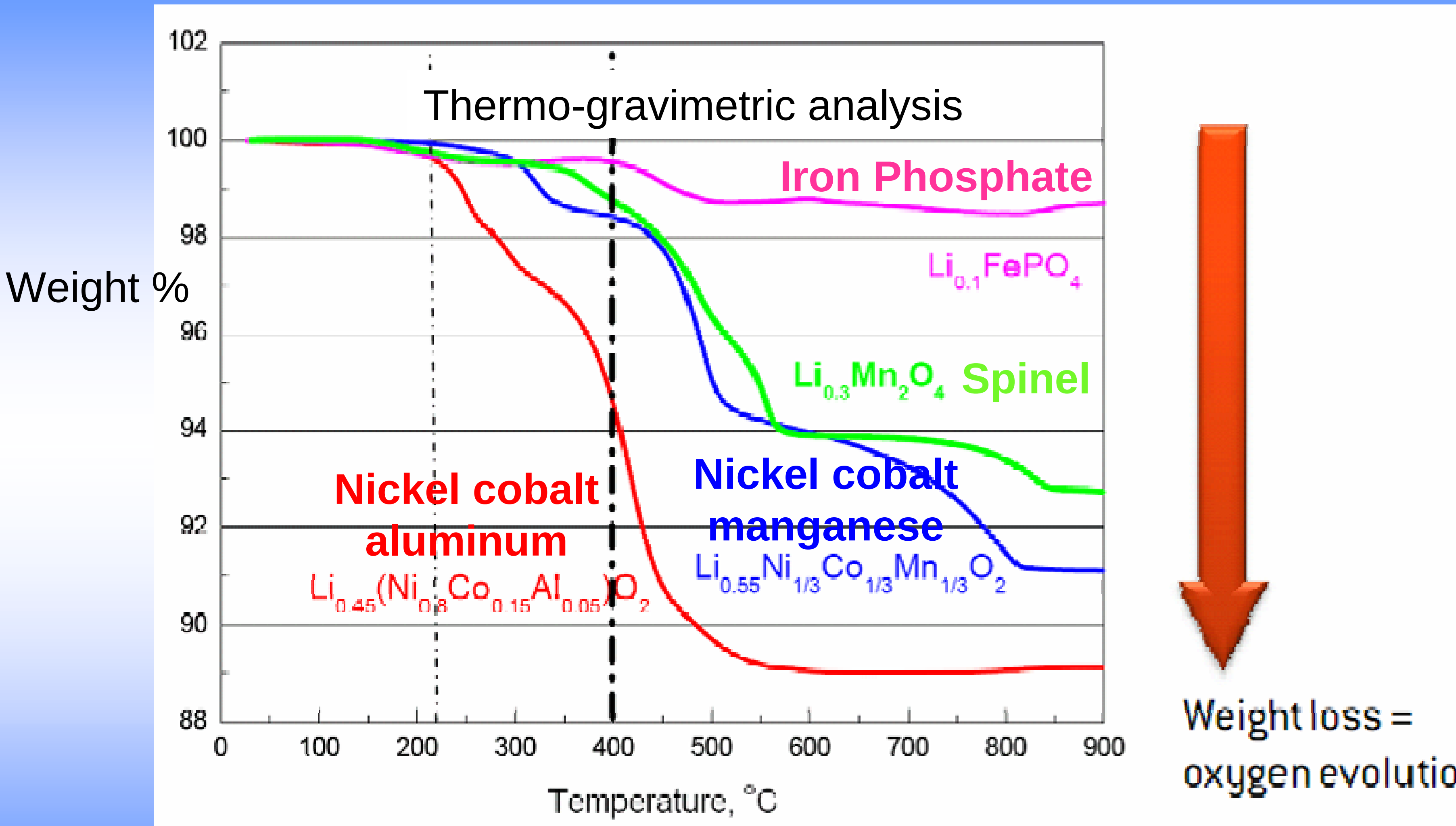
Components	Materials
Cathode	Mn-Spinel based
Anode	Amorphous-carbon
Separator	SRS™
Electrolyte	$LiPF_6$ in Organic solvents (Gel type)
Packaging	Laminated film



Saft's Product Offering for EV (VL45E)

Electrical characteristics	
Nominal voltage (V)	3.6
Average capacity C/3 after charge to 4.0 V/cell (Ah)	45
Minimum capacity C/3 after charge to 4.0 V/cell (Ah)	42
Specific energy after charge to 4.0 V/cell (Wh/kg)	149
Energy density after charge to 4.0 V/cell (Wh/dm³)	313
Specific power (30s peak/50% DOD) (W/kg)	664
Power density (30s peak/50% DOD) (W/dm³)	1392
Mechanical characteristics	
Diameter (mm)	54.3
Height (mm)	222
Typical weight (kg)	1.07
Volume (dm³)	0.51
Voltage limits	
Charge (V)	4.0 (4.1 for peak)
Discharge (V)	2.7 (2.3 for peak)
Current limits	
Max continuous current (A)	100

Oxygen Release Causes Safety Issue



Iron Phosphate is thermally safe. Oxides have problems.

“Cost/benefit proposition is straightforward and compelling” Deutsche Bank

Incremental cost of upgrading a vehicle to a basic 1 kWh HEV will decline to approximately $1600 ($600 for the battery, and $1000 for the associated system controls, motors, power split devices and wiring). We estimate annual fuel savings at $4 per gallon and 12,000 of driving miles per year at $533, implying a 3 year payback.

The payback for a 40 mile plug-in hybrid electric vehicle would be roughly 7.4 years in the US, assuming $1100 of annual fuel savings and $8000 of incremental cost.

Automotive Energy Supply Corporation (NEC/Nissan)

13.2 Ah, 25 cm long, 14 cm wide, and 9 mm thick.
Manganese-based positive.