Massachusetts Institute of Technology, USA

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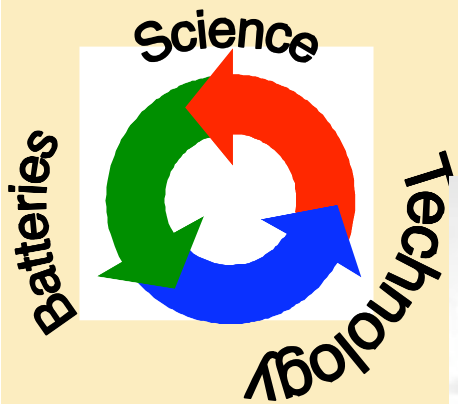
Energy Storage: From Handheld Devices to Automobiles

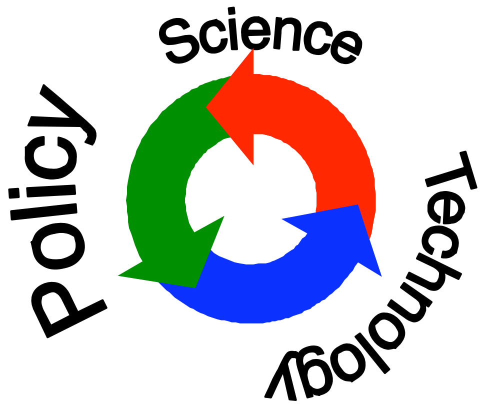
Materials Design for our Energy Future



MIT has engaged to play a significant role in the development of clean energy technology

MIT President, Susan Hockfield, Inaugural address (2005)

"[It is] our institutional responsibility to address the challenges of energy and the environment....Tackling the problems that energy and the environment present will require contributions from all our departments and schools...bringing scientists, engineers and social scientists together to envision the best energy policies for the future."



"to be an honest broker"

- Led to tremendous response from students and faculty.
- Formation of the Energy Council and Energy Initiative

Materials are a key part of Energy Efficiency

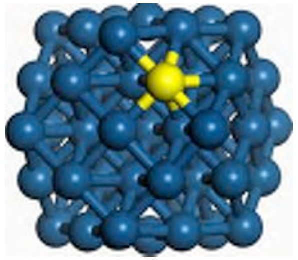
Many promising energy technologies are limited by not having the right materials

Hydrogen Storage

Material needed that can absorb/desorb large quantity of hydrogen

Fuel cell electrocatalysts

Replace expensive Platinum. Find catalysts for more complex hydrocarbons

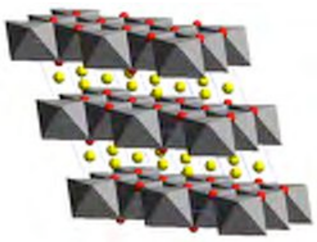


Thermoelectrics

Need higher ZT factor for efficient recovery of waste heat into electricity

Lighter/Stronger materials

Reduce weight in transportation sector: cars, airplanes, … e.g. Titanium



Solar cell materials

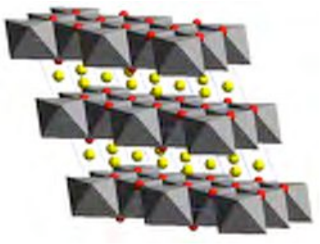
Battery materials

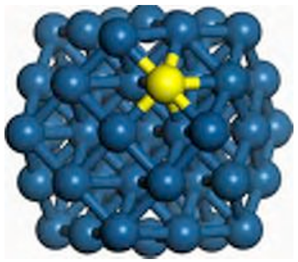
These technologies will not deploy in time if we do not accelerate and modify research and engineering efforts.

Timescales of the problem and solutions

18 years

Average time from concept of new material to its commercialization





50 years

Time left to reach Kyoto CO_2 level (500ppm)

We need radically new approaches to accelerate materials development and to enable its business opportunities in the energy field

The Materials Genome: A new of materials design

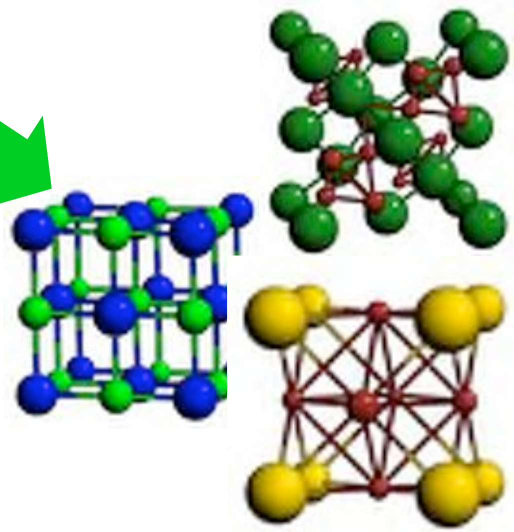
"Determine almost all properties of all materials"

Only way to do this is computational/by simulation

Study hundreds of compounds per month

Data mining and Knowledge Methods

AgCd AgMg AgMo CdMo MoPd
MoRh MoRu MoTc AgNb CdNb
NbPd NbMo NbRh NbRu NbTc
AgPd PdCd AgRh CdRh PdRh
AgRu CdRu RuPd RhRu AlSc
AgTc CdTc TcPd RhTc RuTc
AgTi CdTi MoTi TiPd RhTi
RuTi TcTi TiZr AgY CdY
MoY NbY PdY RhY RuY
TcY YZr AgZr CdZr MoZr
NbZr ZrPd RhZr RuZr TcZr
…



Developing the ability to screen thousands of compounds per month

The storage of electrical energy

Electrical Storage is a critical part of CO_2 reduction

US Carbon Dioxide Emissions (EIA BAU) (Millions of tonnes - Carbon)

	RESIDENTIAL + COMMERCIAL		INDUSTRIAL		TRANSPORTATION		TOTAL	
	2005	2025	2005	2025	2005	2025	2005	2025
Petroleum	43	48	119	142	526	743	688	933
Natural Gas	120	149	122	150	10	14	252	313
Coal	3	3	55	47	0	0	58	49
Electricity	458	675	182	223	4	6	644	904
TOTAL	624	875	478	562	541	763	1643	2199
		1.7%/yr		0.8%/yr		1.7%/yr		1.5%/yr

526 + 458 + 182 = 1166 = 71% of all US CO_2 emissions

How will energy storage make impact ?

US Carbon Dioxide Emissions (EIA BAU) (Millions of tonnes - Carbon)

Storage

Solar, wind, geothermal + Storage

	RESIDENTIAL + COMMERCIAL		**INDUSTRIAL**		**TRANSPORTATION**		**TOTAL**	
	2005	**2025**	**2005**	**2025**	**2005**	**2025**	**2005**	**2025**
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Batteries for Energy Storage in the Transportation Sector

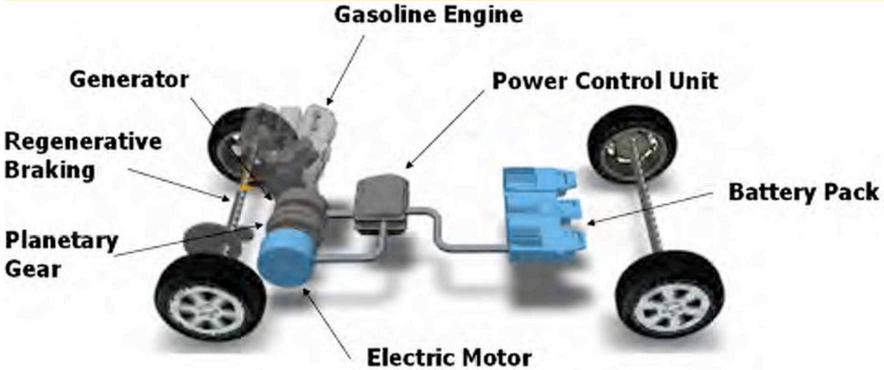
Hybrid Electric Vehicles (HEV) → Efficiency gains

Plug-in Hybrid Electric Vehicles (PHEV) → Displace liquid fuels by electricity

Hybrid Electric Vehicles: Battery as energy buffer

What

- electrical motor assists IC
- draws power from battery



Cost Challenges

☺Engine smaller
☹Battery
☹Electric Motor
☹Power Electronics

Technical Challenges

$1,000 buys about 1-3kWh of energy storage

Brake 3000 lbs car from 40 mph in 10 seconds is 24 kW charge rate

equivalent to battery that can be fully charged in 2.5 minutes

Benefits Energy Buffer

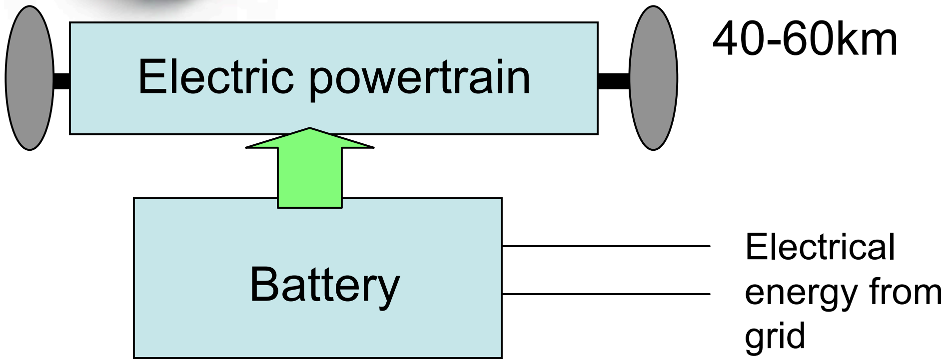
- Assist in Acceleration → Smaller IC needed
- Capture braking energy
- Start and Drive in Electric mode only (Full HEV only)

} Good mileage in city driving

POWER is the issue for HEV, not ENERGY density

Plug-in Hybrid Electric Vehicles: Battery as energy source

Chevy Volt

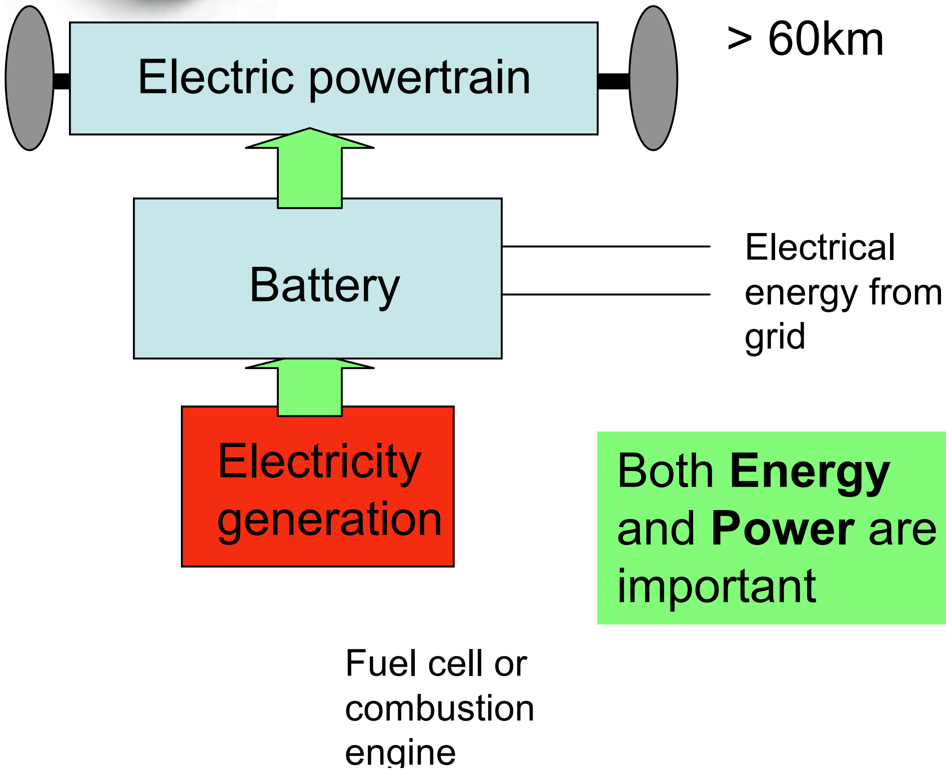


Main characteristics

- ☺Drive is electric
- ☺Battery energy provides for first 30 to 60km of driving
- ☺On-board electricity generation provides for extended range driving
- ☺Regenerative braking
- ☺High Acceleration

Plug-in Hybrid Electric Vehicles: Battery as energy source

Chevy Volt



Both **Energy** and **Power** are important

Main characteristics

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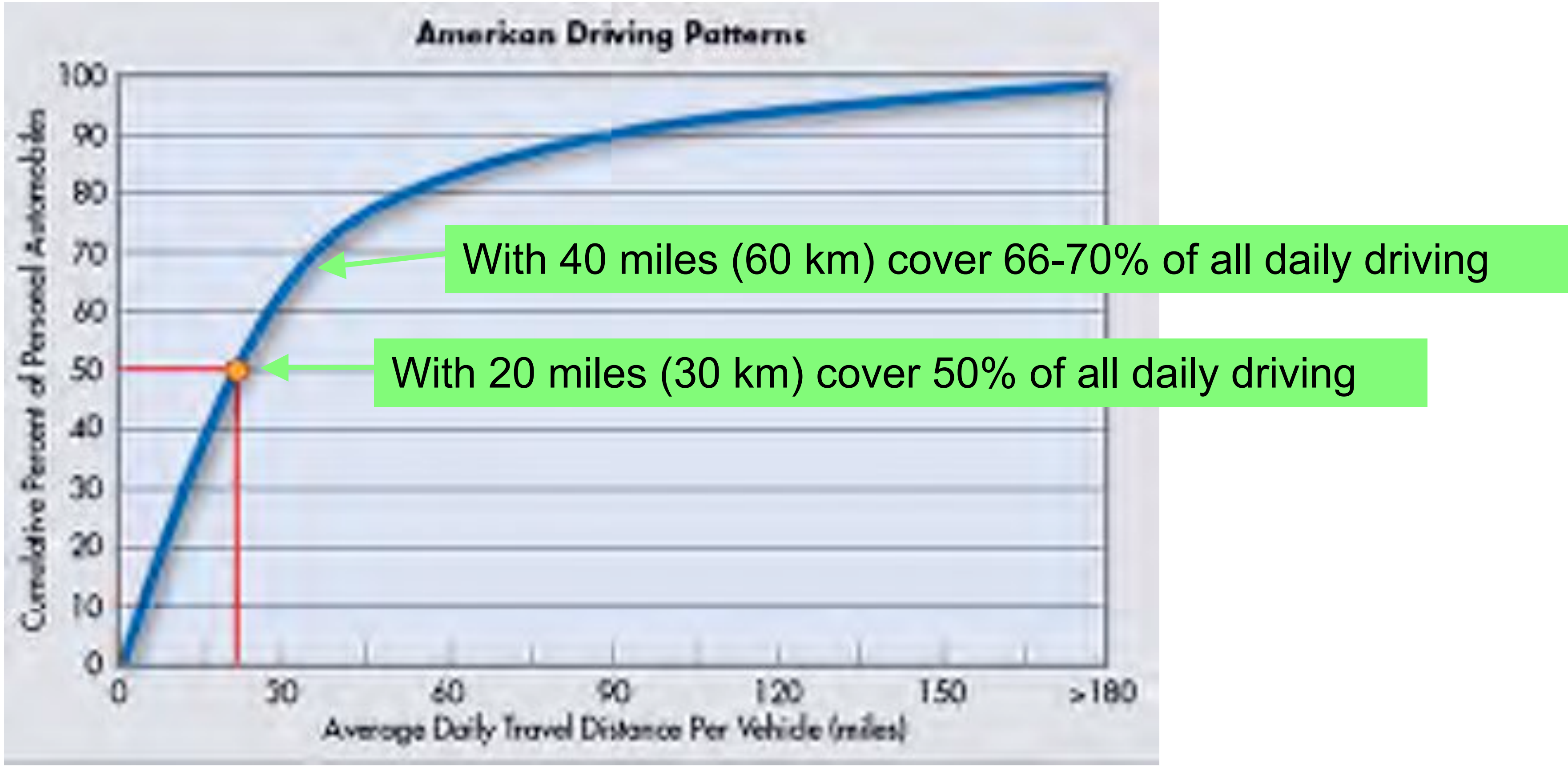
Plug-in Hybrid Electric Vehicles as a game changer

PHEV has the potential to significantly displace liquid fuels !

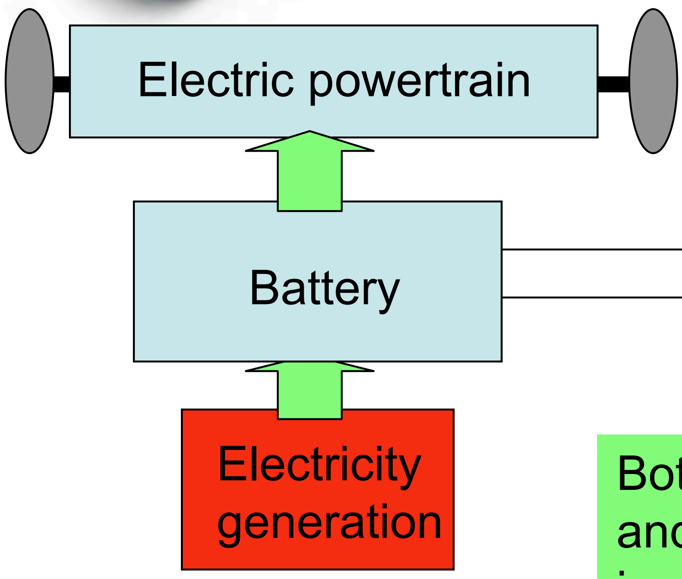


PHEV has the capacity to displace a large amount of oil use in the transportation sector

Source: "Driving the Solution" Lucy Sanna

Plug-in Hybrid Electric Vehicles: Battery challenges

Chevy Volt



> 60km

Electrical energy from grid

Fuel cell or combustion engine

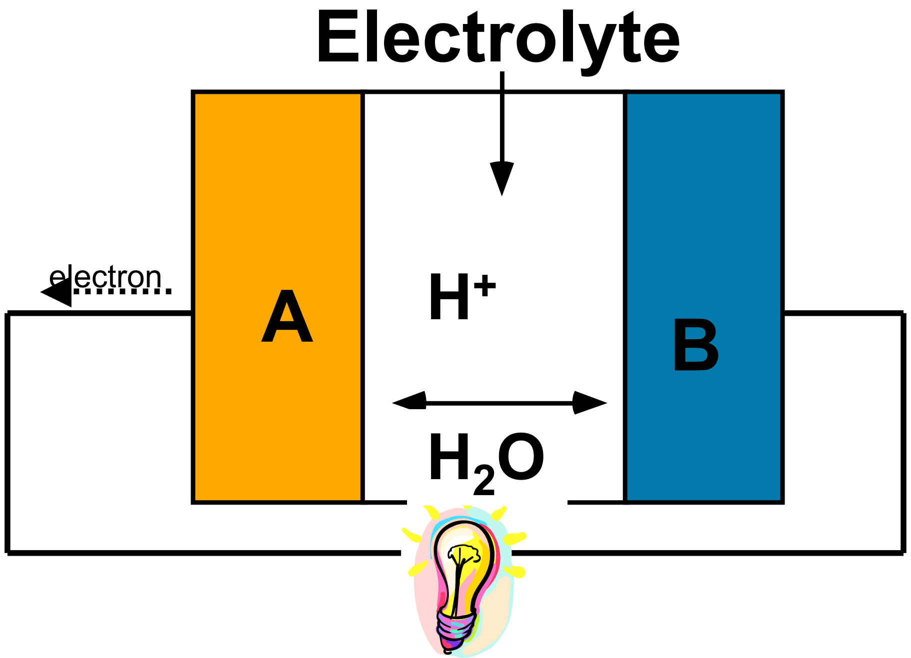
Both **Energy** and **Power** are important

Challenges

- ≈ 3km driving per kWh of capacity
- need 10 to 20 kWh battery
- Target cost of $200/kWh (currently more like $500/kWh)
- 300,000 partial charge/discharge cycles
- warranty

Basic Electrochemical Energy Storage Technologies

Convert chemical energy from a reaction directly into electrical energy



Ni-Cd and Nickel-Metal Hydride

proton based in aqueous electrolytes

cell voltage < 1.2 V

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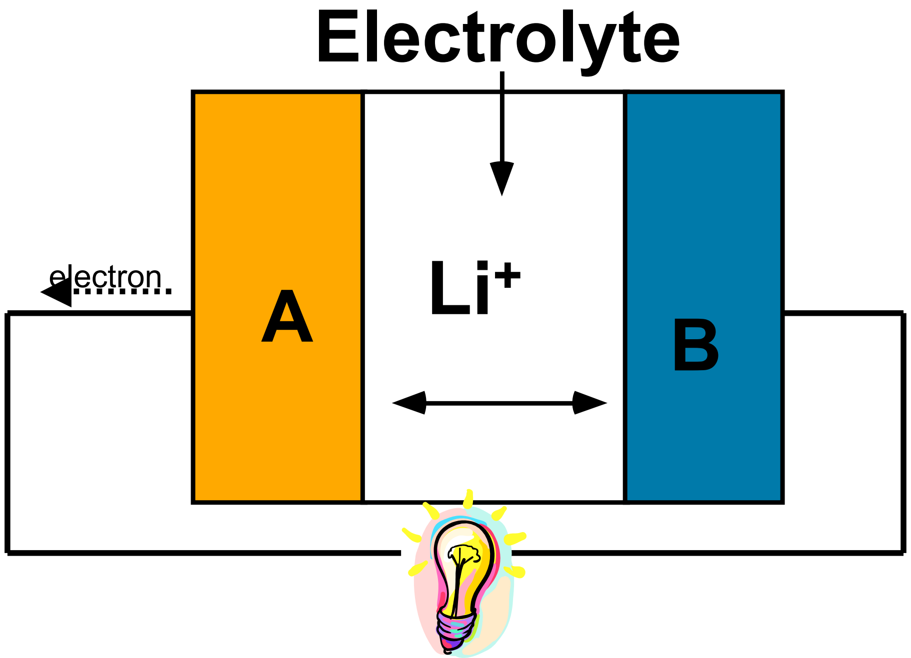


Ni-Cd and Nickel-Metal Hydride

proton based in aqueous electrolytes

cell voltage < 1.2 V

Li-ion

Li^+ (in non-aqueous electrolytes) gives much higher energy density

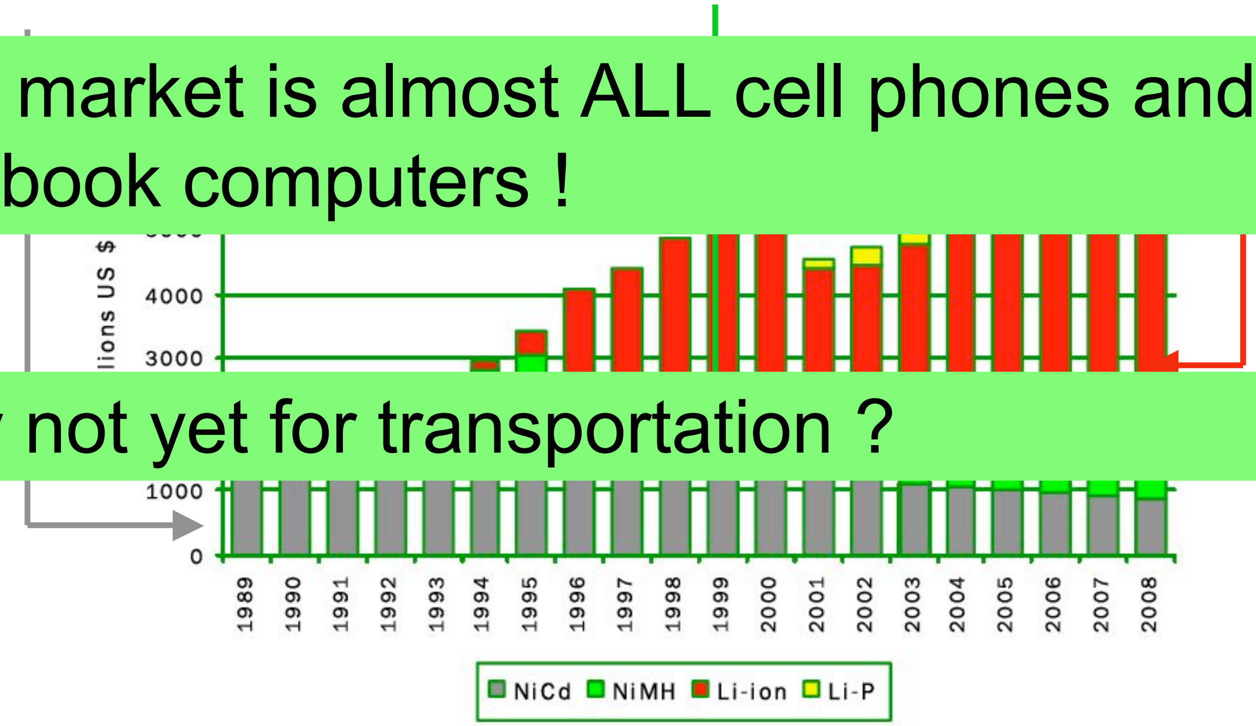
cell voltage > 4 V

Only Li-technology can come even close to meeting the energy storage needs for PHEV !

The High Tech Trio: Markets

	Ni-Cd	Ni-MH	Li-ion
Market	$1 Billion	$0.6 Billion	$4 Billion

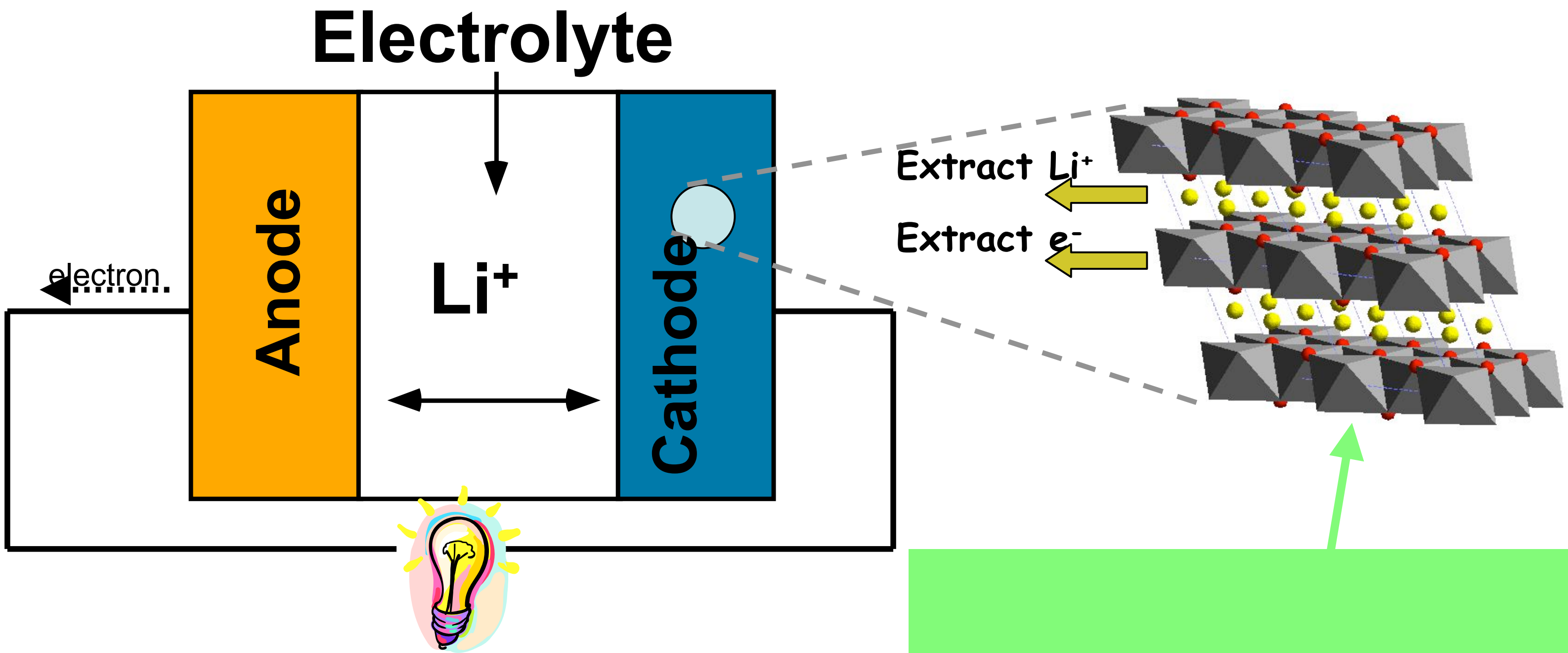
This market is almost ALL cell phones and notebook computers !



Why not yet for transportation ?

Fig. 10 – Worldwide battery market in value (1989-2008)

Li batteries: A family of chemistries



$LiCoO_2$

$LiNiO_2$

$LiMn_2O_4$

$LiFePO_4$

Different cathode materials for different applications

Different Technical Requirements for Batteries in New Applications

Electronics

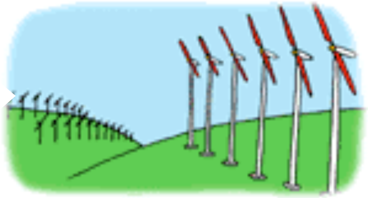
High Energy
Low Power

$ 4 Billion market and growing

$LiCoO_2$ cathode: expensive, safety issues

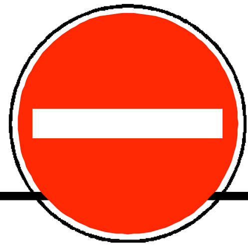
High Power
Low Cost

HEV/Powertools/ Energy Back-up



> $ 20 Billion market

Several candidate materials: $Li(Ni,M)O_2$, $LiMn_2O_4$, $LiFePO_4$, …



Cost for $LiCoO_2$ alone for PHEV battery would be about $500 - $750

Safety of $LiCoO_2$ unacceptable for large format batteries

Safety: (P)HEV battery pack can not be the same chemistry as used in small electronics

How Li-ion became (in)famous

This is not a property of all Li batteries, but specific to the cathode material choice !

How to design better (battery) materials more rapidly?

$$H\Psi = E\Psi$$

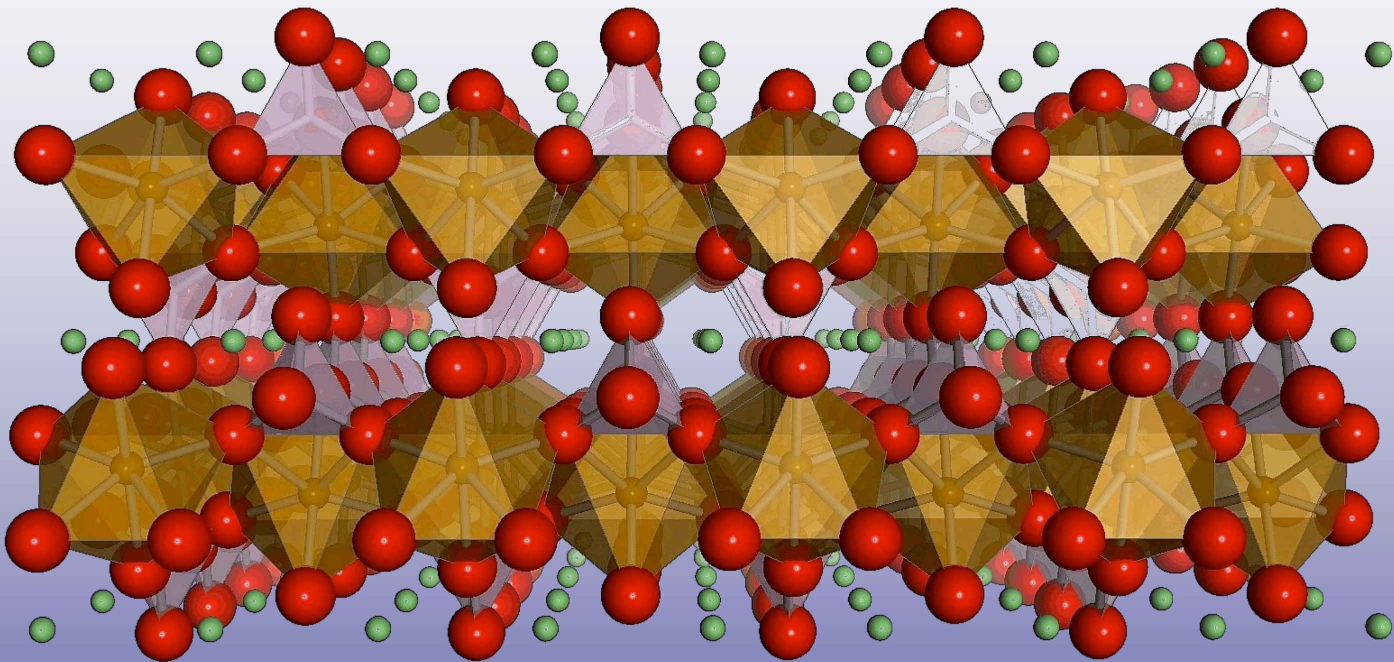
MIT approach

Large-Scale computational Materials Design

Charging and discharging does not have to be slow !

Debunking the myth that Li has low power density

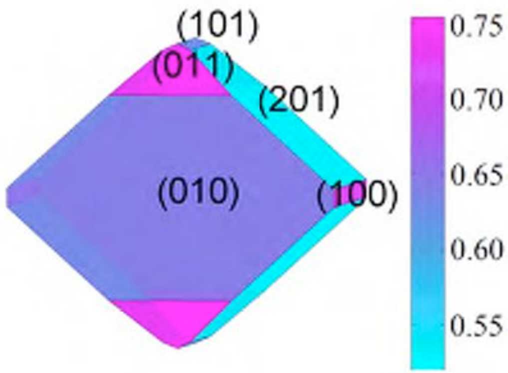
$LiFePO_4$ designed for extreme rate behavior



- Potential to be inexpensive
- Environmentally benign
- Very Stable

- Very low charge/discharge rate capability

$LiFePO_4$ with fully optimized power density

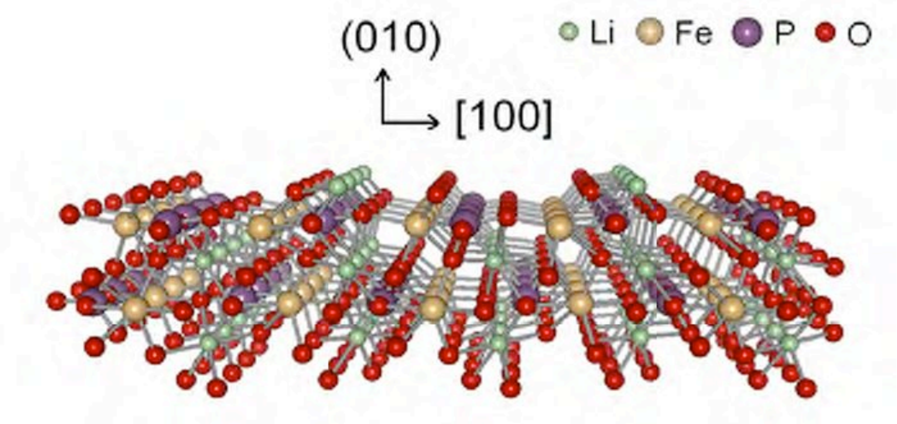


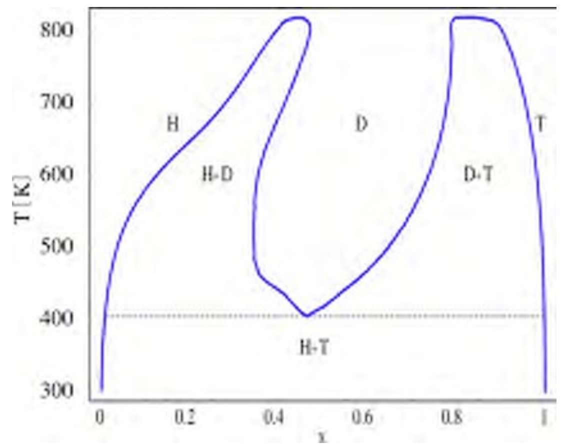
No Edisonian trial and error approach

Full design and optimization in virtual environment

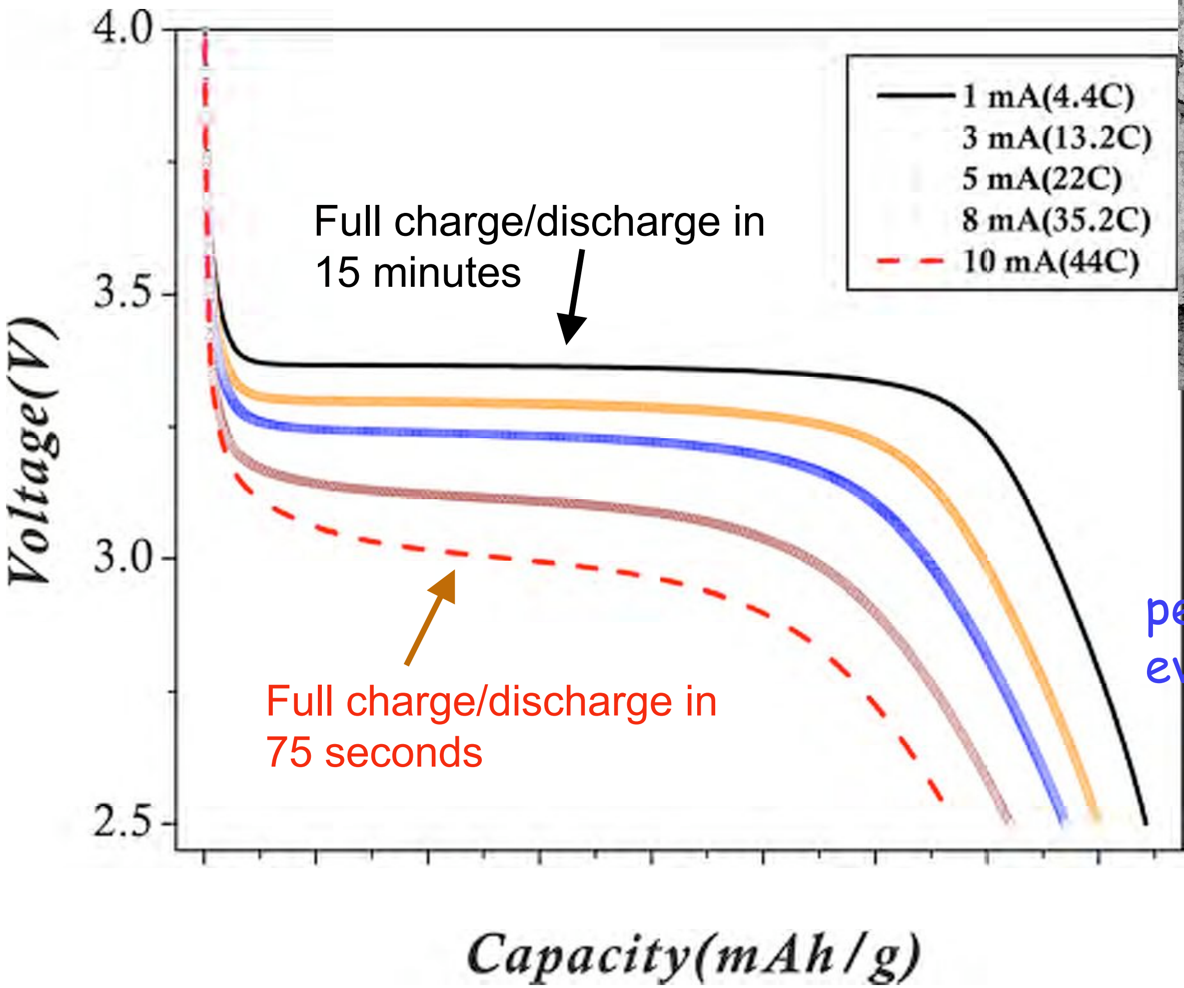
Modeling leads to rapid success in the lab

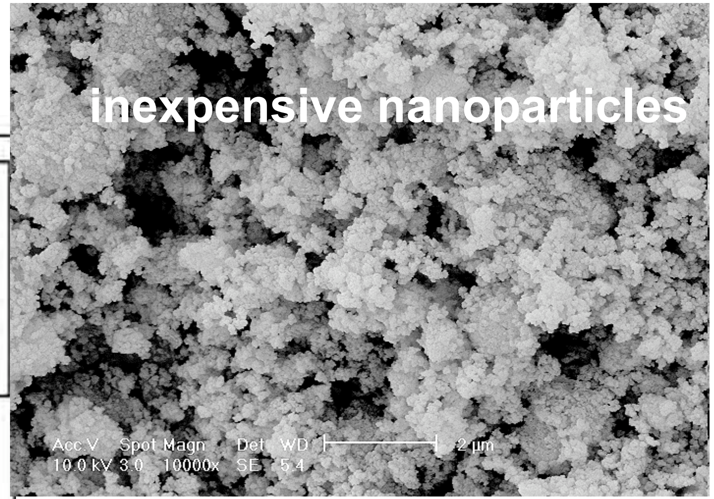
Licensing and scale-up





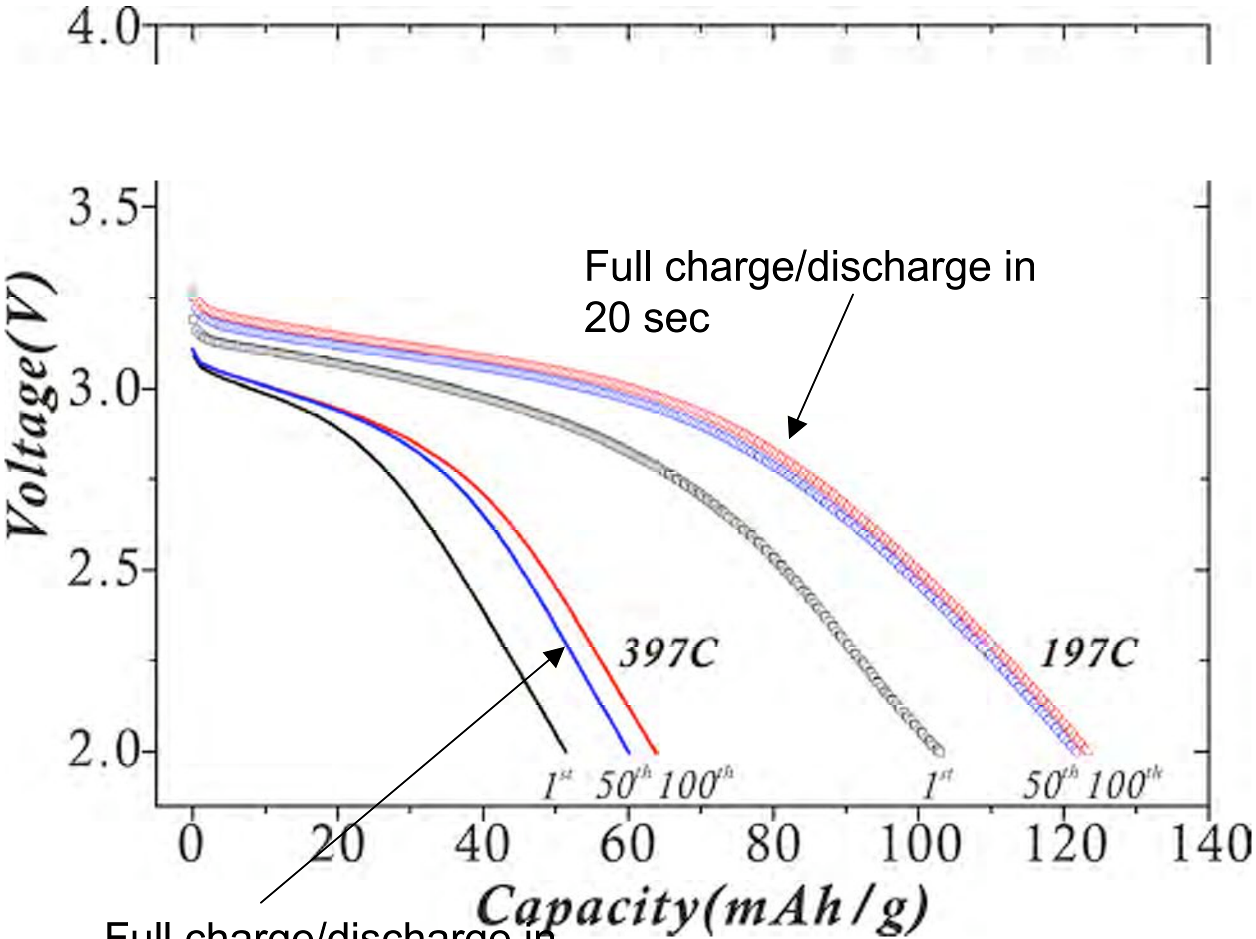
Very high rate material developed





perfect cycle life
even at 20 C !

With some electrode modification can obtain highest rate ever observed in a battery material



Full charge/discharge in 20 sec

Full charge/discharge in 10 sec

400 C is full battery charge/discharge in **9 seconds**

Power density:

175 kW/liter
90kW/kg

at 10-15% pack integration efficiency

> 10 kW/kg

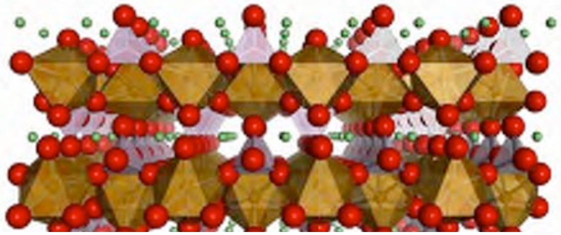
High rate batteries will couple high efficiency to high performance

IC only reaches high power at high RPM

Electric motor has high torque; reaches full power at very low RPM

$LiFePO_4$: Extreme Rate

+



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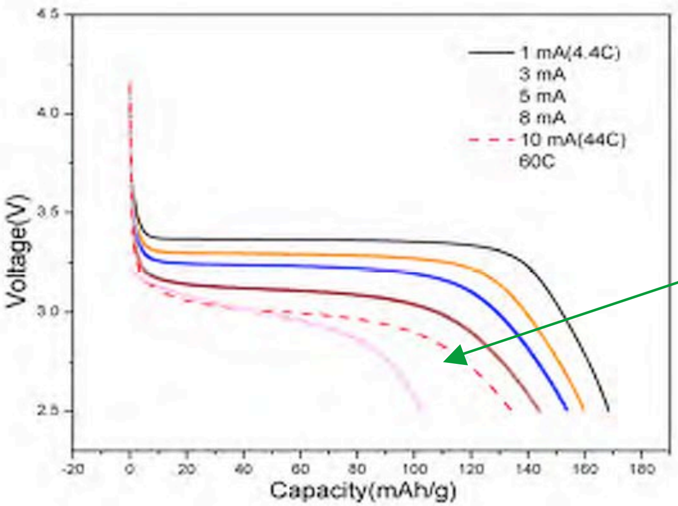


discharge in **1.5** minutes

3kWh battery (6 liter volume)
= 132 kW = 0 to 60 mph in 4 sec

Battery powered tools have more power than tools with wire !

No cord !

More Power

Remaining issues

COST

need to reach ≈ **$200-300/kWh** (this is already reached at the cell level)

Materials

higher energy density (cell cost is largely independent of energy)

less expensive materials

more stable materials reduces weight and cost from protective systems

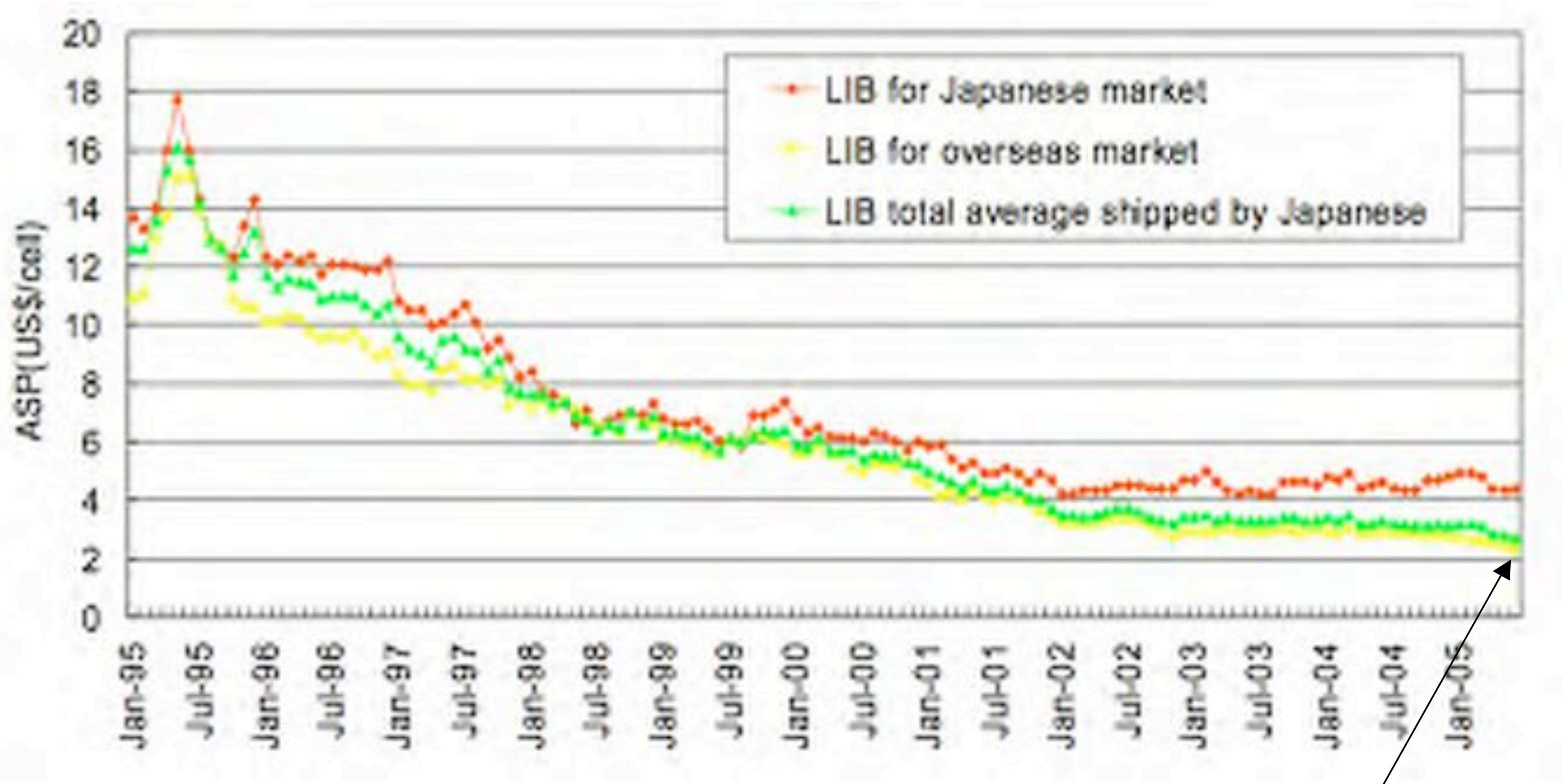
Processing

processing cost needs to be further reduced. Can we get away from the wound cell construction ?

RELIABILITY

Automotive has ultra stringent requirement on reliability

COST evolution of an 18650 Li cell



$2/cell (10Wh) = $200/kWh

From: Takeshita report

Remaining issues

COST

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RELIABILITY

Automotive has ultra stringent requirement on reliability

How “good” can batteries become (in terms of energy density)

There are physical limits on energy density (not on power density)

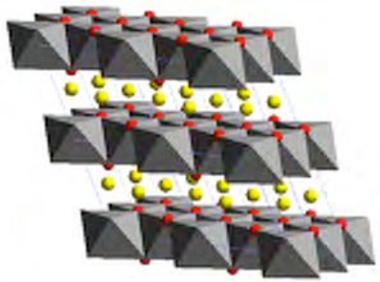
Electrode Capacity

Li^+ ions

intercalation

electrons

shift valence of metal
e.g. Co^{3+}/Co^{4+}



Currently

$LiCoO_2$, $LiNiO_2$, $LiFe(PO_4)$

All use only one electron per metal (e.g. Co^{3+}/Co^{4+})

Theoretical capacity limited **<< 300 mAh/g**

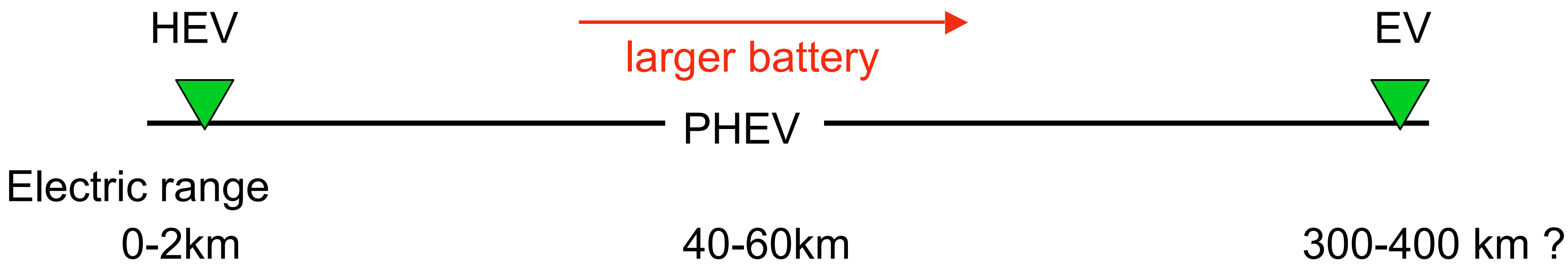
We are approaching 2/3 of this limit in practical cells

The Future

Use multiple redox couples in one metal cation

Factor of 2 increase in energy density

Plug-in HEV is the game changer



Battery cost scales almost linear with driving range

Do you really want to pay for a battery with 300km driving range ?

PHEV is likely to be the future of transportation

Li battery technology is close to being ready for it

The future

The age of combustion will become the age of electrochemistry