Princeton E-ffiliates Third Annual Meeting

Panel Discussion: Large Format Energy Storage

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Advanced Research Projects Agency – Energy (ARPA-E)

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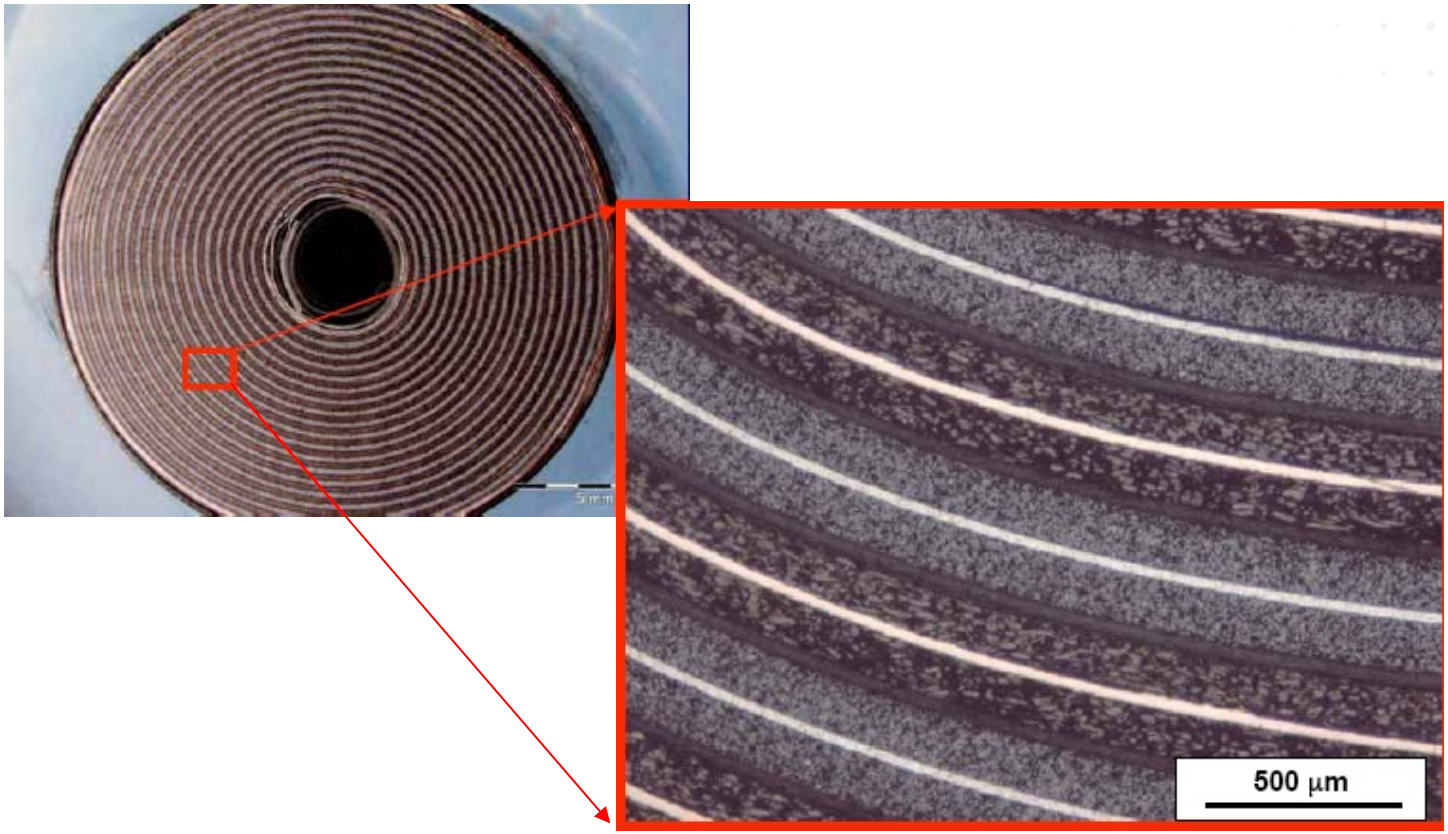
Background and interest in batteries

Berkeley UNIVERSITY OF CALIFORNIA

A lithium-ion battery is composed of many thin layers.

18650 cell

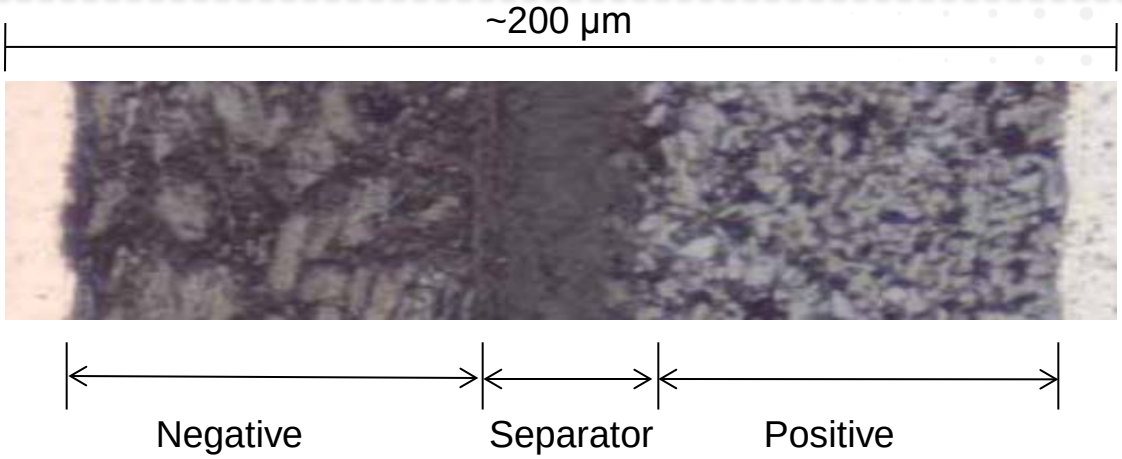


Background and interest in batteries

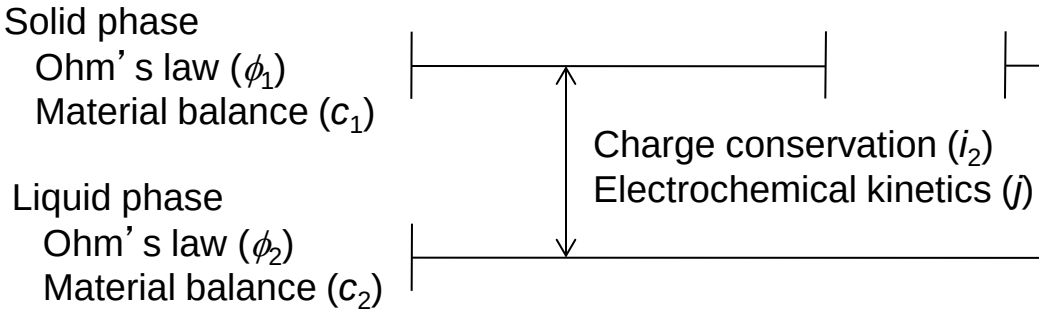
Berkeley UNIVERSITY OF CALIFORNIA

I focused on mathematical modeling of the physical processes taking place in a lithium-ion battery.

Physical picture of Li-ion battery



Physics-based model

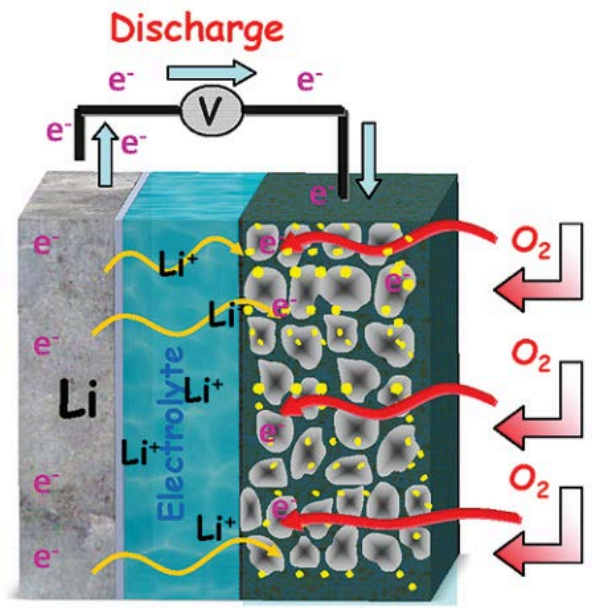


Background and interest in batteries

BOSCH At Bosch Research I explored several new chemistries.

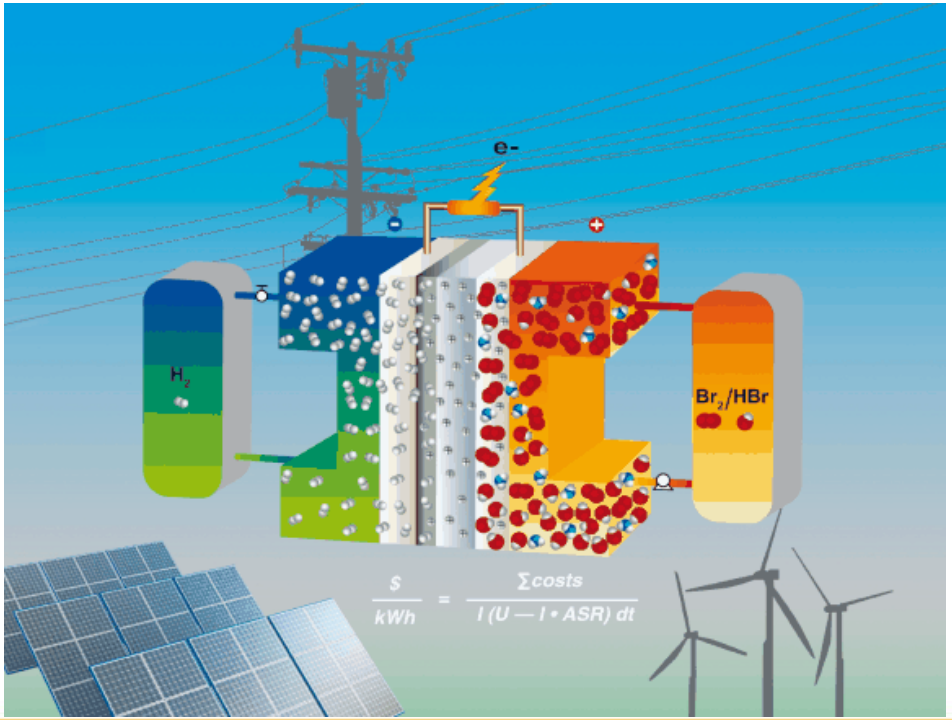
Li/O_2 battery: High-energy reactants, automotive application.

$2Li + O_2 \rightarrow Li_2O_2$



H_2/Br_2 flow battery: Low-cost reactants, grid storage application.

$H_2 + Br_2 \rightarrow 2HBr$



Girishkumar et al., *J. Phys. Chem. Lett.* 2010, 1, 2193–2203
Cho et al., *Energy Technology,* 2013, 1(10), 596-608.

Solid ion conductors are my current focus

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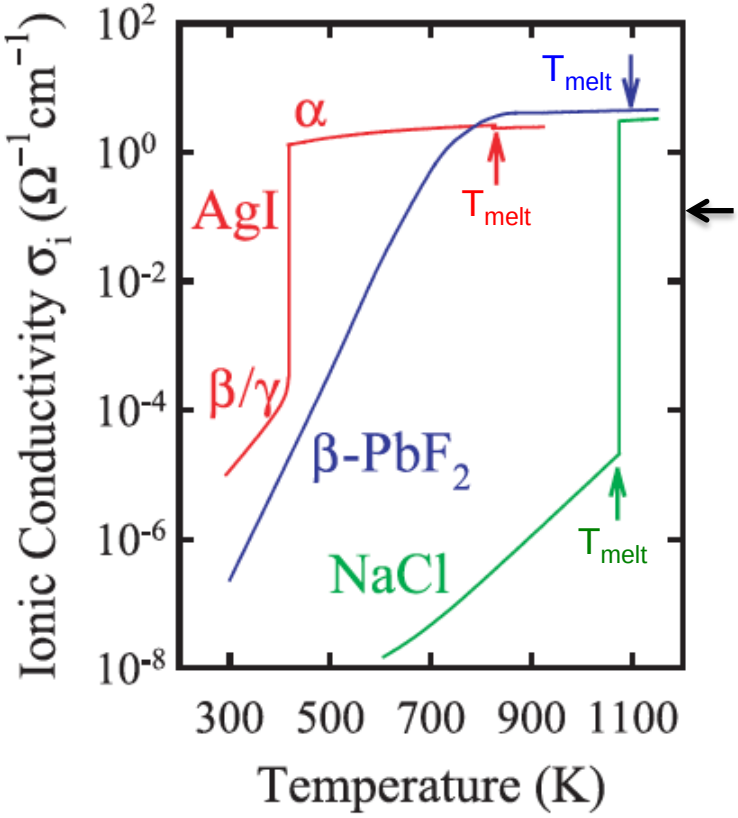
There are solid materials that transport ions as fast as liquids! These are superionic conductors.



1M NaCl (aq) at 25° C.

Select benefits of solid ion conductor cells:
- Block liquid and gas transport
- Separate chemical compartments
- Safety
- …

Hull, Rep. Prog. Phys., 67 (2004), 1233.

Solid ion conductors are my current focus

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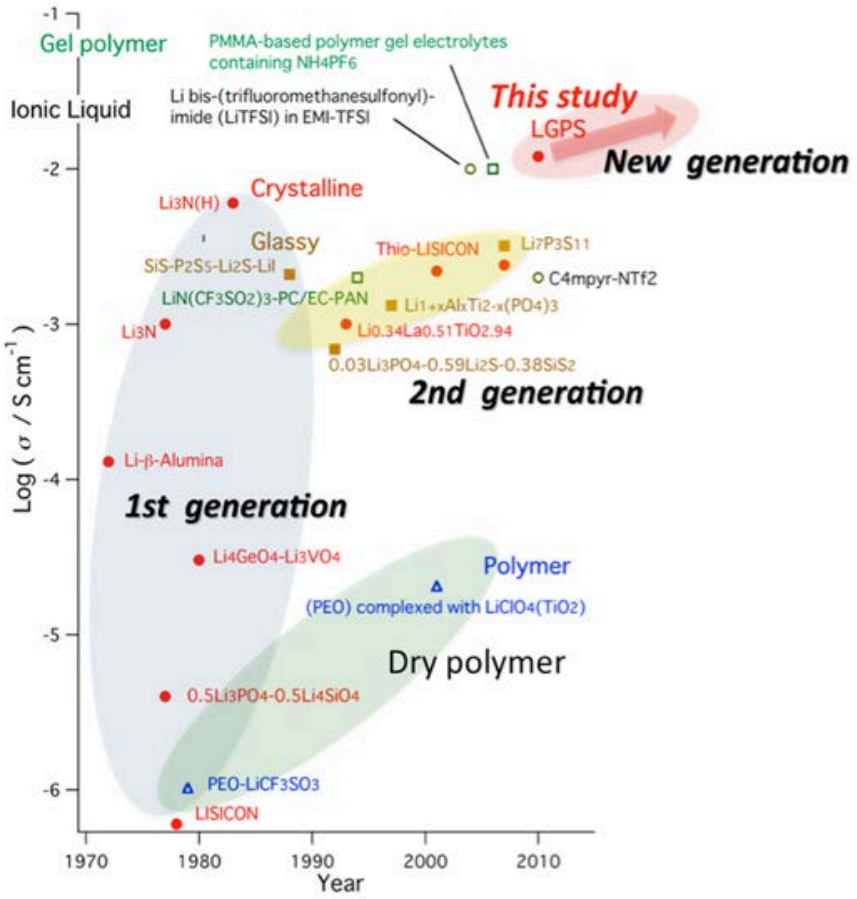
In the past few years Li^+ superionic conductors have been discovered.



$Li_{10}GeP_2S_{12}$ and $Li_{11}Si_2PS_{12}$ are more conductive than Li^+ liquid electrolytes!

Kamaya et al., Nature Materials, 10, 2011, 682.

Solid ion conductors are my current focus

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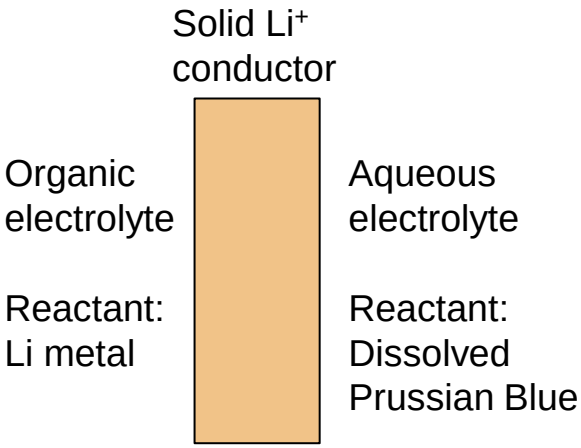
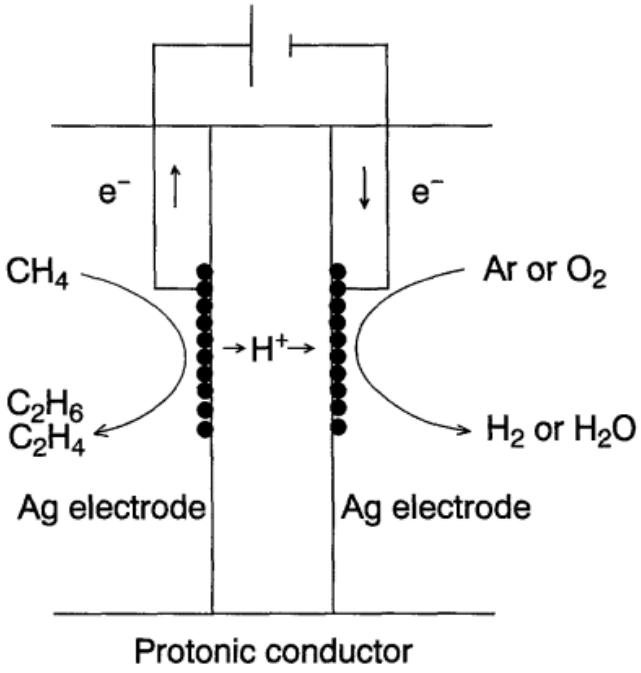
Solid ion conductors are relevant for numerous energy technologies.

Dual-electrolyte batteries with expanded potential range operation[1]

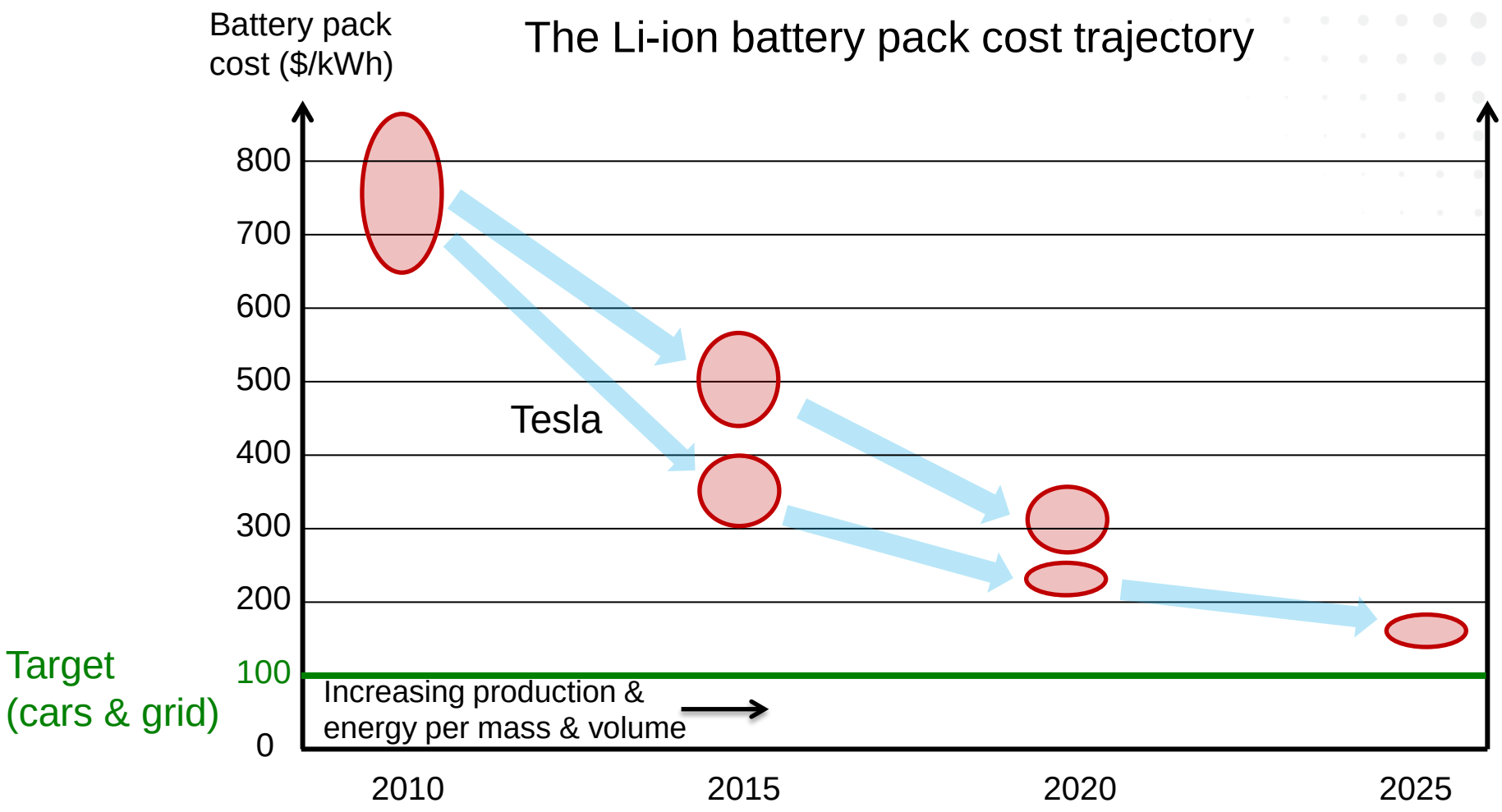


Electrochemical methane coupling[2]



[1] Lu and Goodenough, J. Mater. Chem., 2011, 21, 10113
[2] Hamakawa et al., J. Electrochem. Soc., 140(2), 1993, 459.

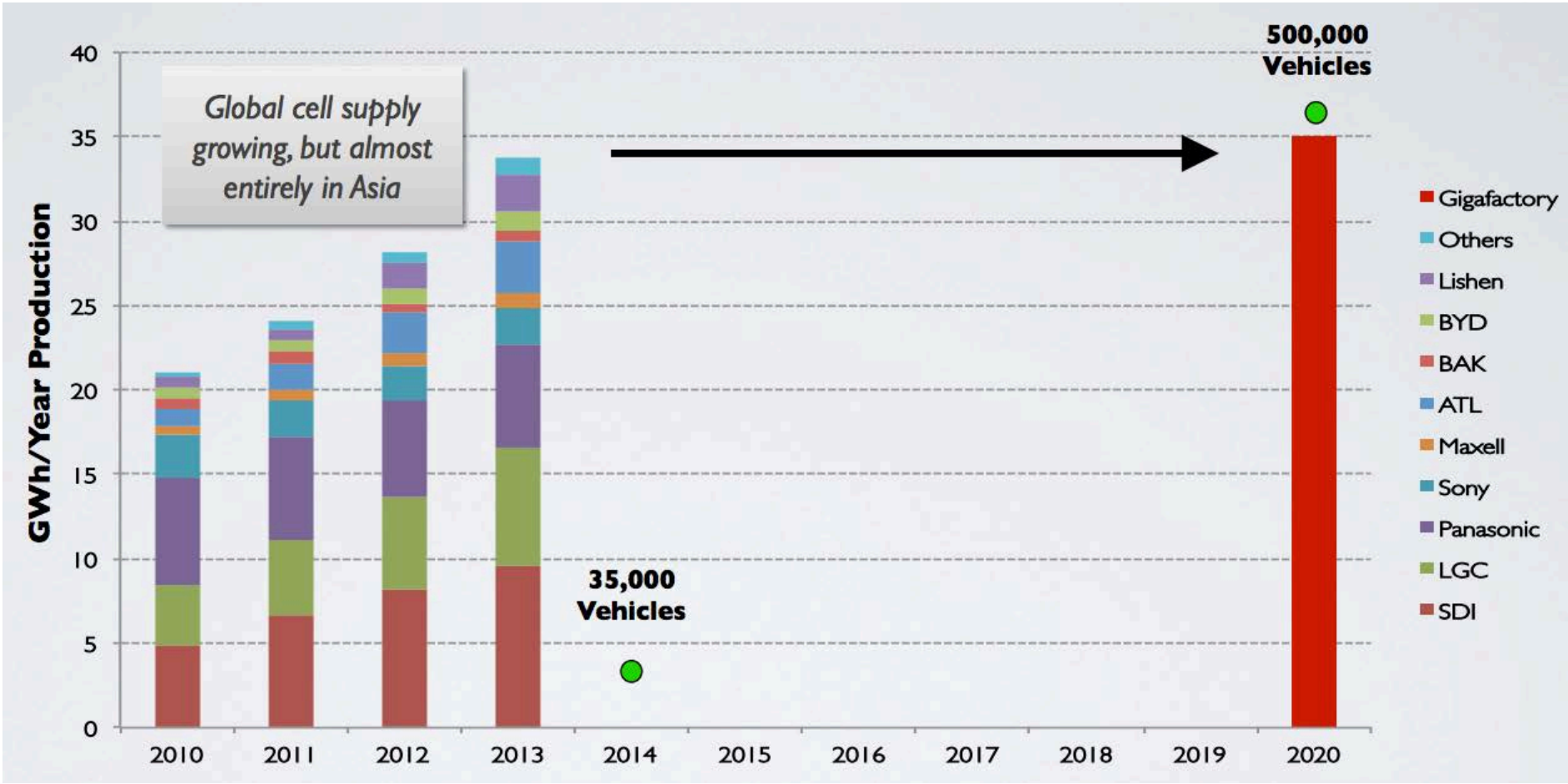
Big news for batteries in the coming years



Sources: Tiax, Institute of Information Technology, AAB

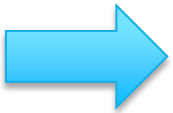
Big news for batteries in the coming years

Tesla Gigafactory: total investment of $4-5 Billion by 2020.



The race for 21st century transportation fuels

Oil, with increased efficiency
(35 mpg by 2025 for a sedan)



Biofuels (e.g., cellulosic ethanol,
eventually a drop in fuel)

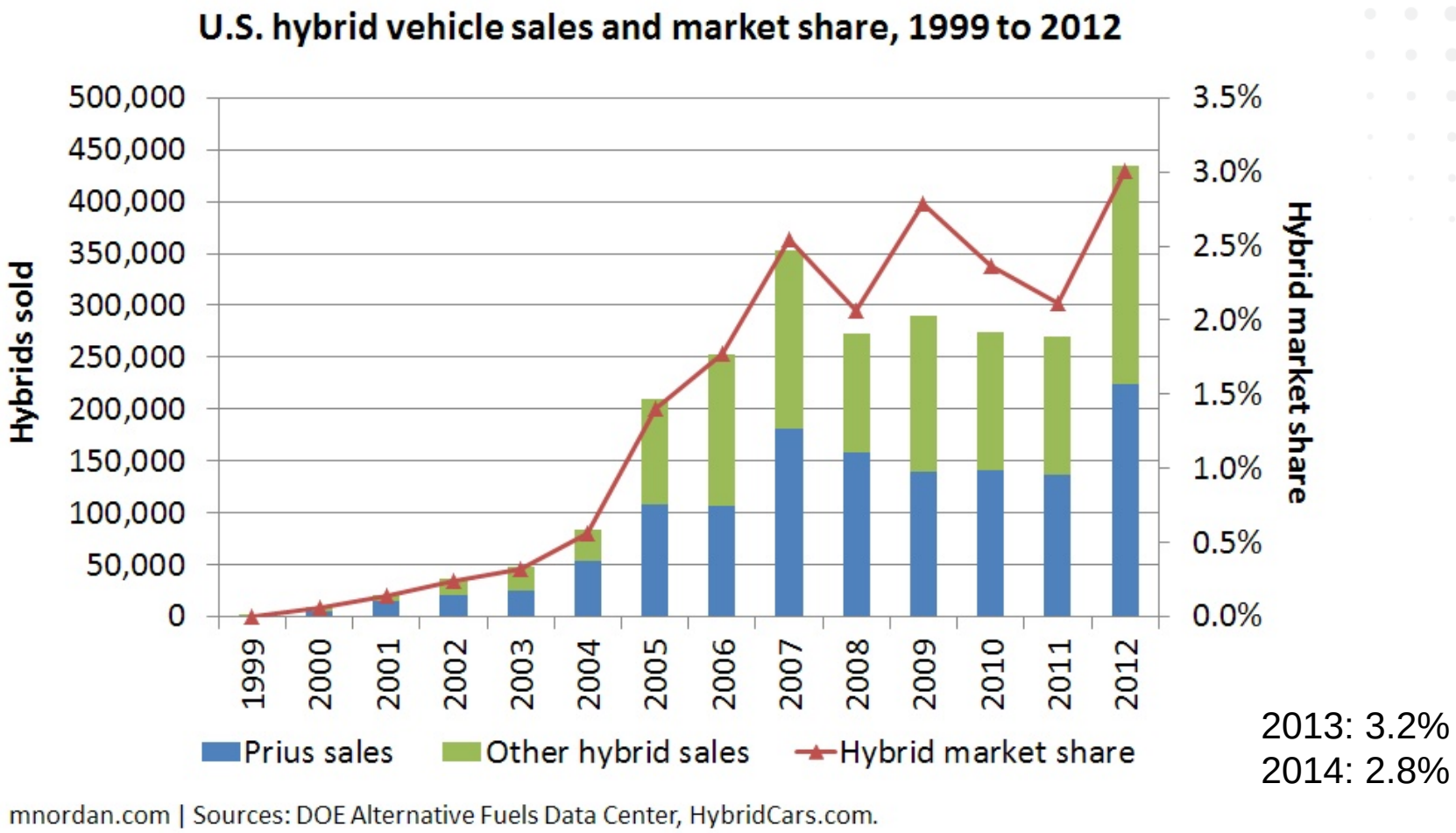
Natural gas (esp. for trucking)

Electricity (plug-in vehicles)

Hydrogen (e.g., fuel cell vehicles)

Economics is a key driving force; infrastructure change is another.

Hybrids stuck at 2-3% of total sales for 7 years



2013: 3.2%
2014: 2.8%

After four years on the market, plug-ins have <1% market penetration.

There are many options for adding renewables

If the problem we are solving with grid energy storage is variable renewables, here too there are numerous options.

Ramping natural gas plants

Demand response (including thermal load shifting)

Grid expansion to reduce fluctuations

Electrical energy storage (95% pumped hydro today)

Simple example:
~3% of all US electricity is consumed by residential hot water heaters, which can store ~10kWh for an installed cost of <100 $/kWh. This could help manage fluctuating renewables!

Opportunity: passionate people, good ideas

Start ups:

AQUION ENERGY

eos energy

PRIMUS POWER

Alveo Energy

POLYPLUS

QuantumScape

24m

URBAN ELECTRIC POWER

amprius

EnerVault

ENOVIX

AMBRI

Others!

Incumbents:

Panasonic

SAMSUNG

LG Chem

SONY

GE

3M

NGK INSULATORS, LTD.

BYD

LISHEN

Others!

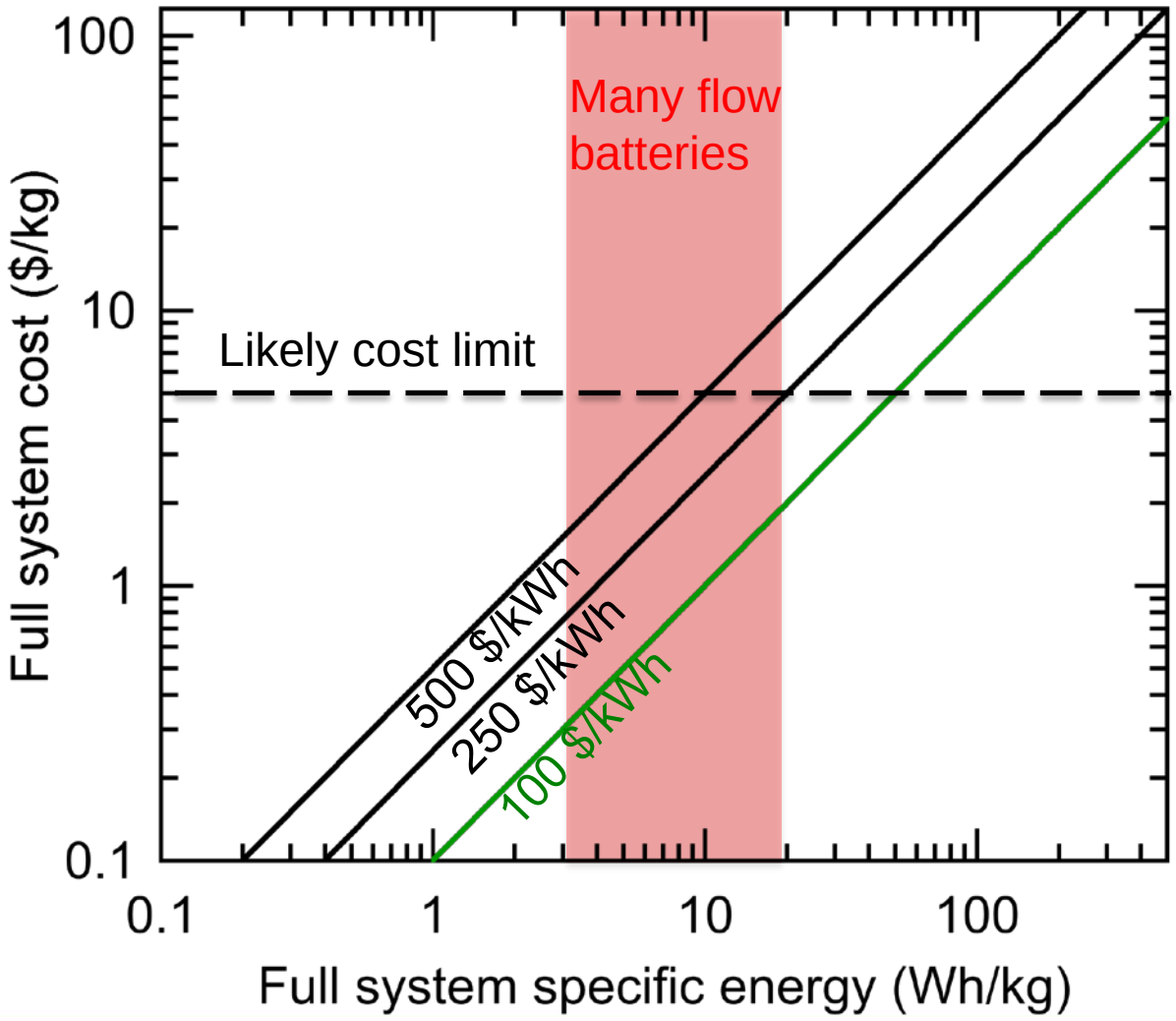
<u>Market needs:</u>

Cost
Safety
Energy per mass
Power per mass
Density
Cycle life
Calendar life

Major rechargeable chemistries:

Li-ion, Lead acid
Ni/MH, Na-Beta

One potential red herring: low-energy batteries



Li-ion battery: 50 $/kg

Honda Civic: 12 $/kg
Washing machine: 7 $/kg
Lead-acid battery: 5 $/kg

It is really hard to make an inexpensive battery with a low energy content!

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