Electrochemical Energy Storage for the Grid

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2MW, 0.5 MWh Li-ion battery

Daimler Orion/BAE Systems

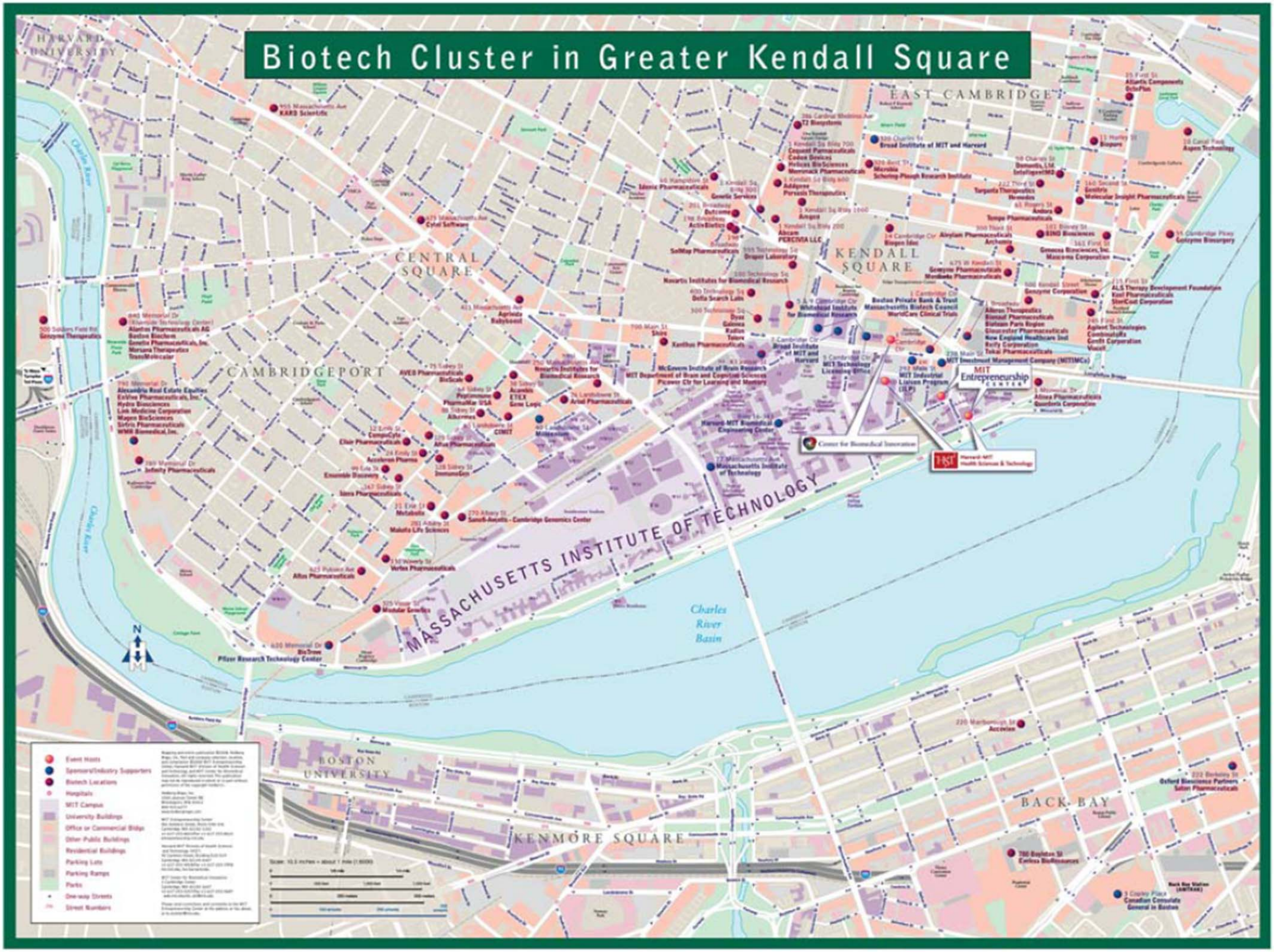
F1

Fisker Karma PHEV

Ohio State Univ Buckeye Bullet 2.5

Hymotion PHEV

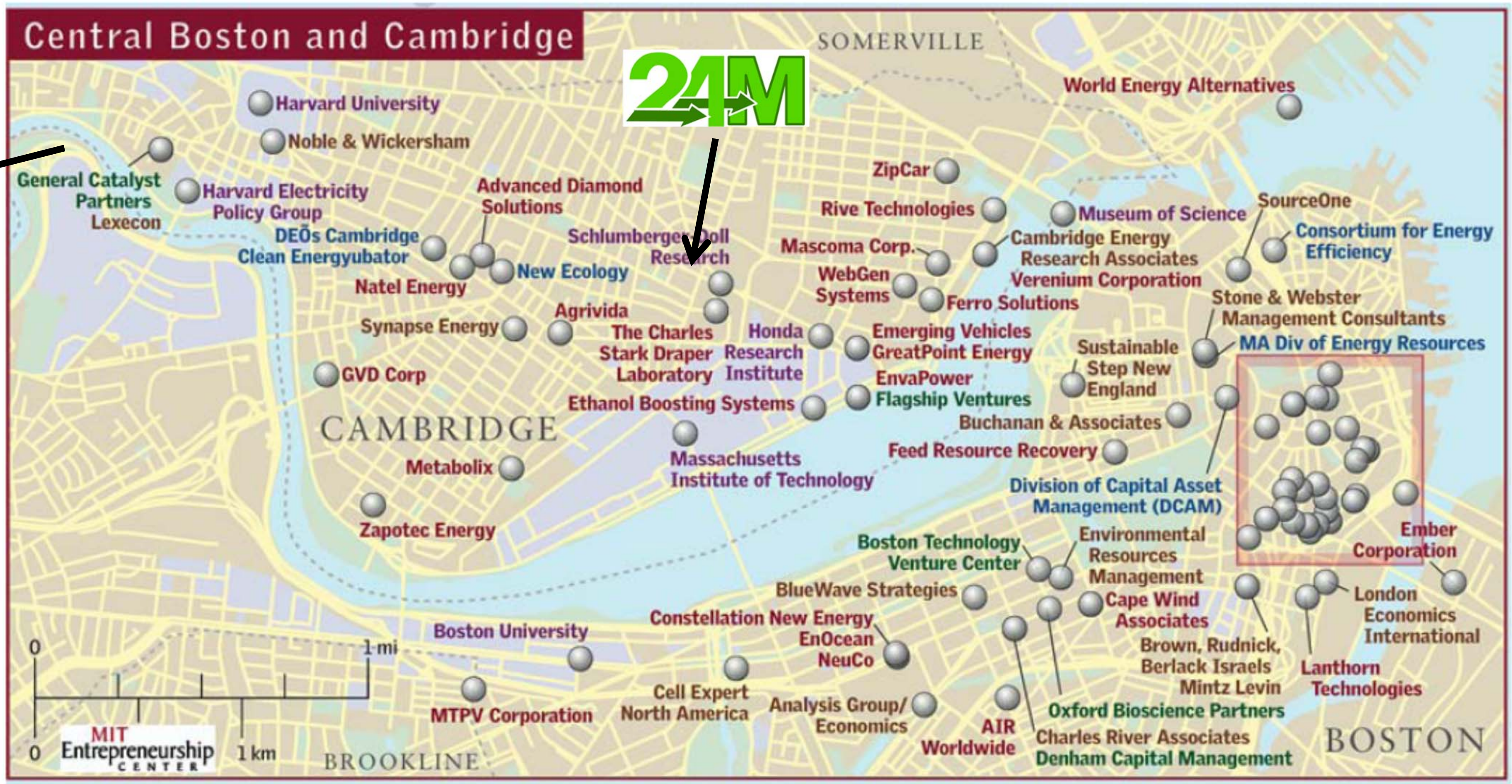
Advanced Energy 2010, New York, NY, Nov 8-9, 2010



Edward B. Roberts and Charles Eesley, Entrepreneurial Impact: The Role of MIT, 2009

The Emerging Energy Cluster in Greater Boston

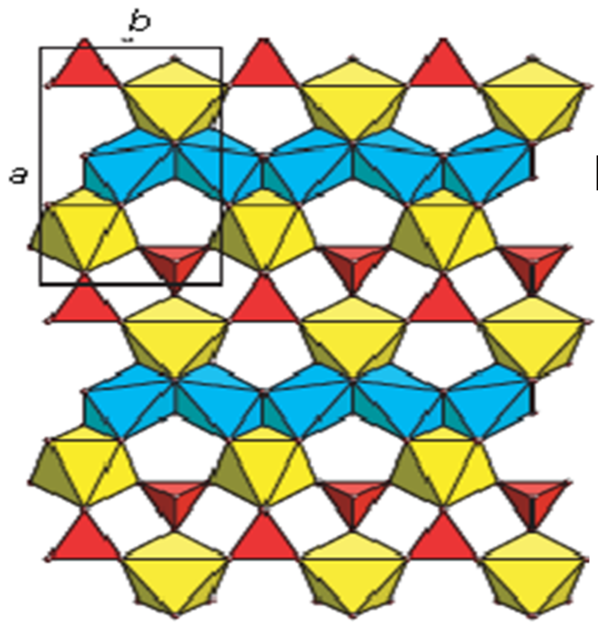
A123 SYSTEMS



Example of impact of research-driven innovation:
Collective revenue of active companies founded by MIT graduates today equals the 17th largest world economy*
(Note: Up from 23rd largest world economy 10 years ago)

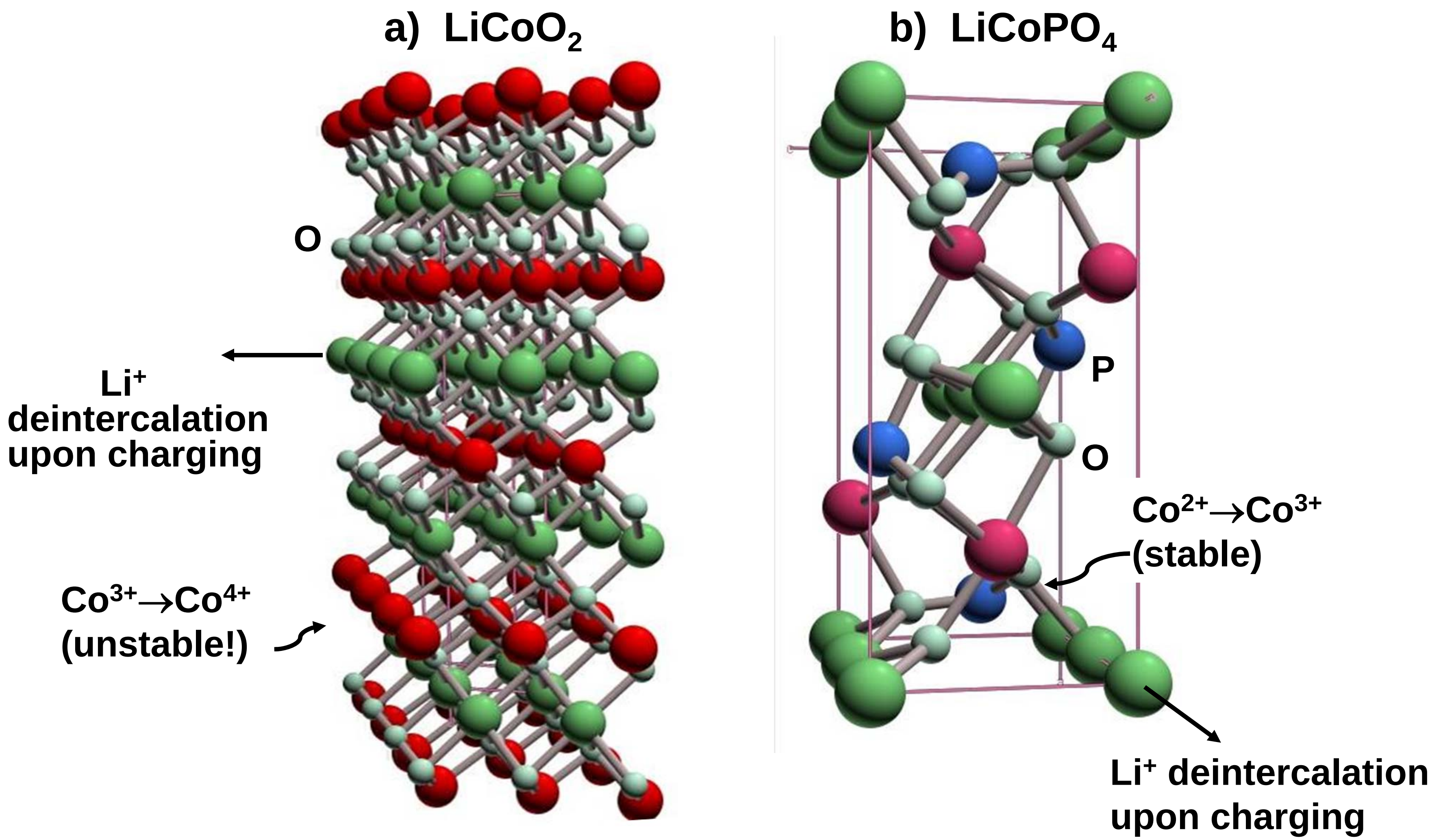
***Edward B. Roberts and Charles Eesley, *Entrepreneurial Impact: The Role of MIT*, 2009**

Purpurite, a natural olivine, $Li_{1-x}MnPO_4$



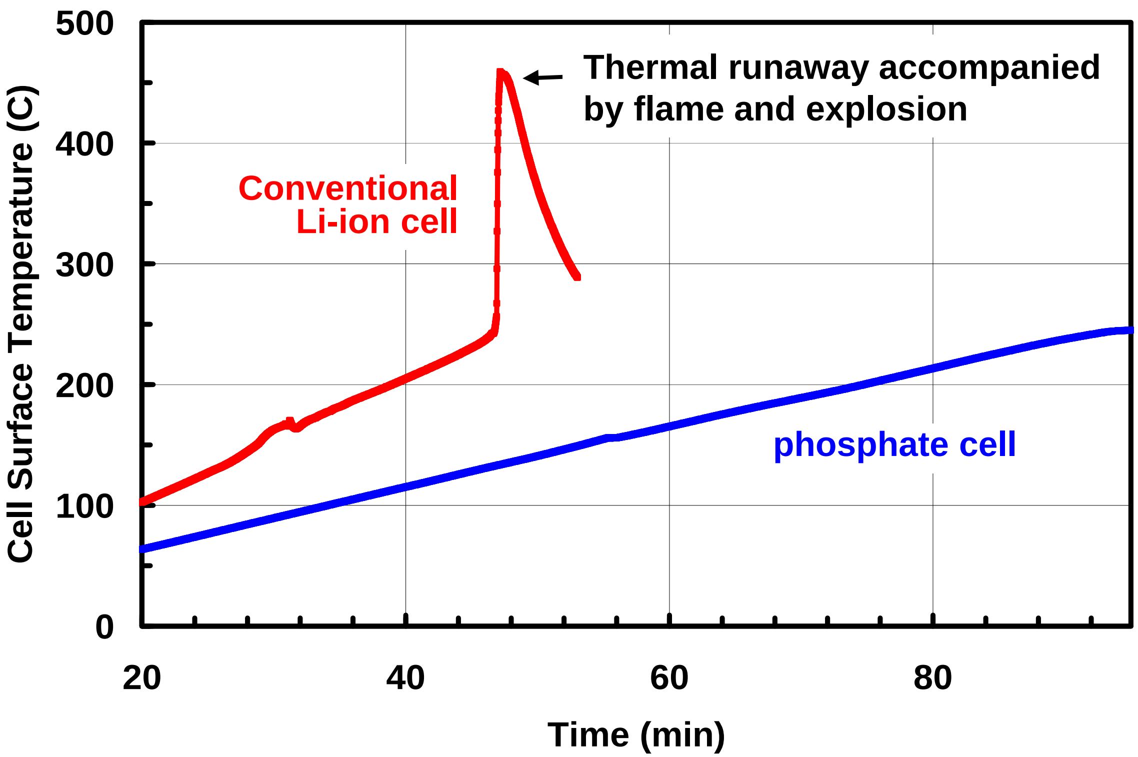
Olivine: Hexagonal close-packed oxygen sublattice
1/8th tetrahedral sites occupied (*P* sites)
1/4th octahedral sites occupied (*M1 and M2* sites)

Battery safety (slightly over)simplified: Cathode transition metal *oxidation state* is a key consideration



$LiCoO_2$ and its nickel-containing derivatives used as the positive electrode in lithium-ion batteries experience an oxidation of Co^{3+} to unstable Co^{4+} (or Ni^{3+} to unstable Ni^{4+}) as Li^+ ions are removed from the lattice upon charging. In contrast, a phosphate-based cathode such as $LiCoPO_4$ undergoes oxidation of Co^{2+} to a stable Co^{3+} state (or Mn^{3+}, or Fe^{3+}), resulting in a safer, fault-tolerant cell chemistry.

Comparison of cells with and without thermal runaway



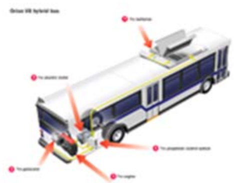
Sandia National Lab test chamber

Comparison of conventional lithium-ion battery exhibiting thermal runaway followed by flaming and explosion, with intrinsically safer phosphate-based lithium ion cells. (Test data performed at Sandia National Laboratory on full-size cylindrical cells. Charged cells are instrumented with thermocouples and heated at constant rate to seek thermal events.)

Li-Ion Powered Hybrid Buses: >60 Million Road Miles (since 2007)

Daimler Receives Orders for 1,052 Orion VII Diesel-Electric Hybrid Buses; Majority to Use Li-Ion Battery Pack

17 December 2007



The Orion VII series hybrid bus. Click to enlarge.

Daimler Buses North America has received orders totaling 1,052 Orion VII Next Generation diesel-electric series hybrid transit buses. MTA New York City Transit has ordered 850 and the City of Ottawa (OC Transpo) has ordered 202. These buses will be powered by BAE Systems' HybriDrive diesel-electric hybrid propulsion system and delivered into 2010.

This order will bring MTA's diesel-electric hybrid bus fleet to almost 1,700 units, making it the largest diesel-electric hybrid fleet in the world. With this order, Orion transit buses will account for almost 50% of MTA New York City Transit's entire fleet.

OC Transpo has ordered 202 Orion VII Next Generation diesel-electric hybrid transit buses to be delivered by 2009. This delivery will make OC Transpo the third largest hybrid bus fleet in Canada.

The hybrid drive in the Orion includes a 6-cylinder, in-line, 5.9-liter Cummins diesel that delivers 194 kW (260 hp) at 2300 rpm; a 120 kW generator; a 32 kWh battery pack (initially lead-acid, but a majority of the new orders will use a lithium-ion battery pack with cells from A123Systems (earlier post), according to Daimler); and a 186 kW (250 hp) traction motor that delivers 2,100 lb-ft (2,847 Nm) of torque (continuous), with 2,700 lb-ft (3,661 Nm) peak.

Compared to standard diesel propulsion, these hybrid buses deliver up to 30% better fuel economy while greatly reducing emissions: 90% less particulate matter, 40% less NO_x and 30% fewer greenhouse gases.

With 1,100 hybrid transit buses already on the road, 460 pending deliveries and the announced new orders, Orion has received more than 2,600 orders for the hybrid since the launch of the Orion hybrid bus in 2003.

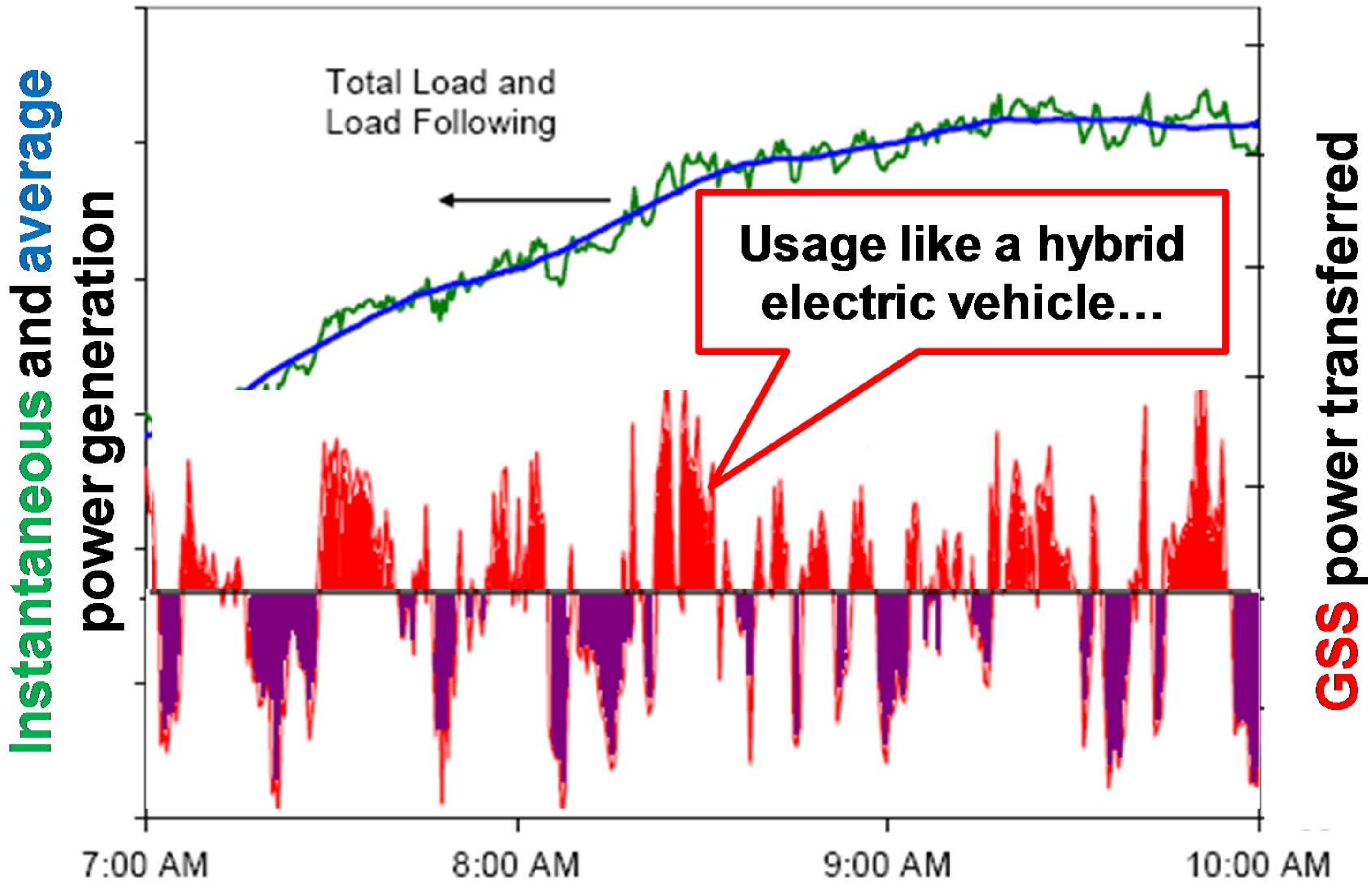
Daimler Buses North America, headquartered in Greensboro, N.C. (United States), is a Daimler AG company. It combines three commercial bus brands under one corporate structure: Orion transit buses, Setra motorcoaches, and the Dodge Sprinter shuttle bus.

200 kW pack saves 3400 lb over Pb-acid

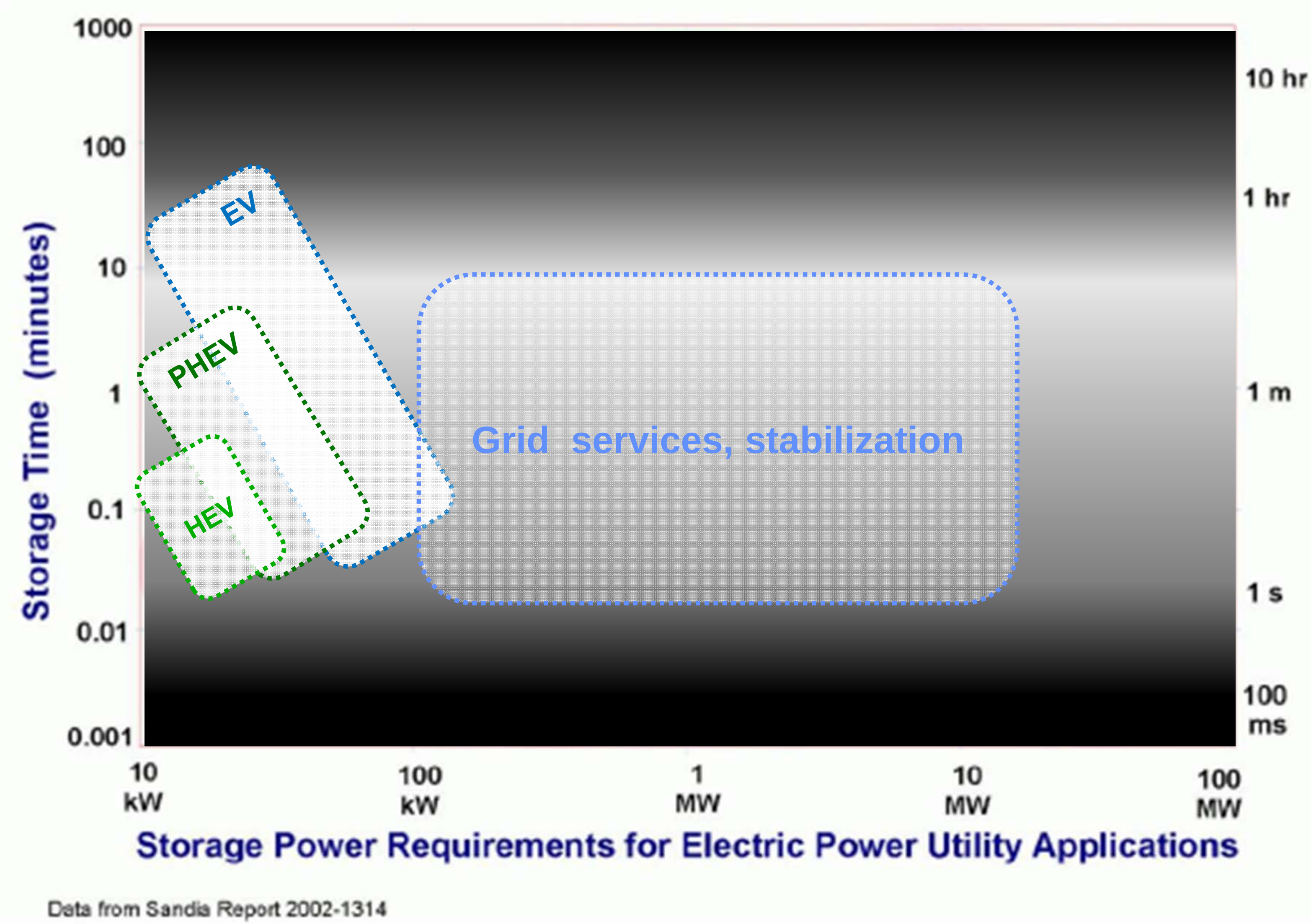
Manufactured in Hopkinton, Massachusetts

Daimler Orion VII Bus/BAE Systems

Frequency Regulation Application: "Hybridizing" Power Plants With Li-Ion Batteries



Automotive Li-Ion Battery Development is Driving Down Battery Cost, Improving Performance, Enabling Grid Applications



Eight A123 Systems SGSSs™ units providing 16 MW installed on the grid in Chile, performing "spinning reserve" grid stabilization services

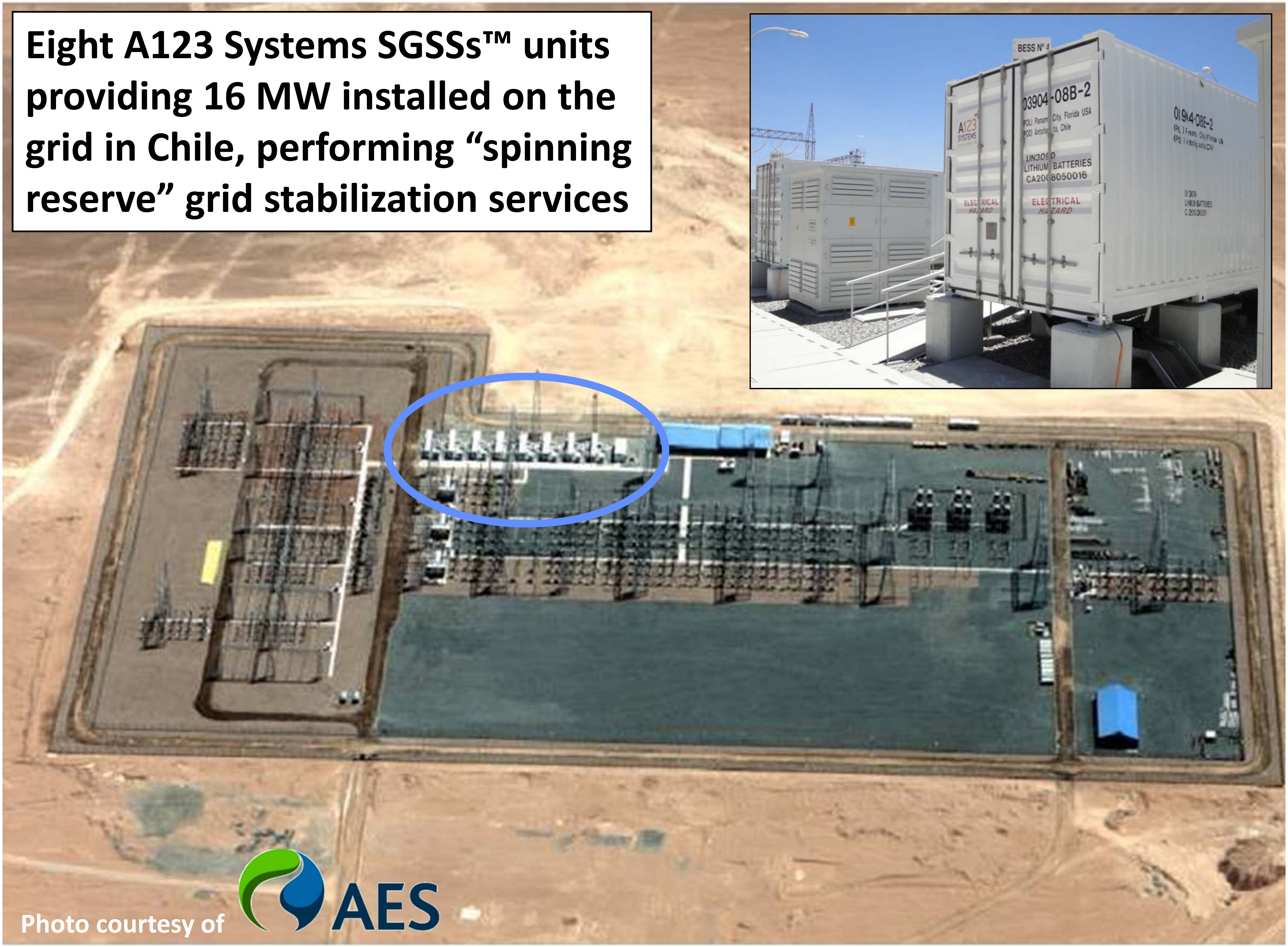
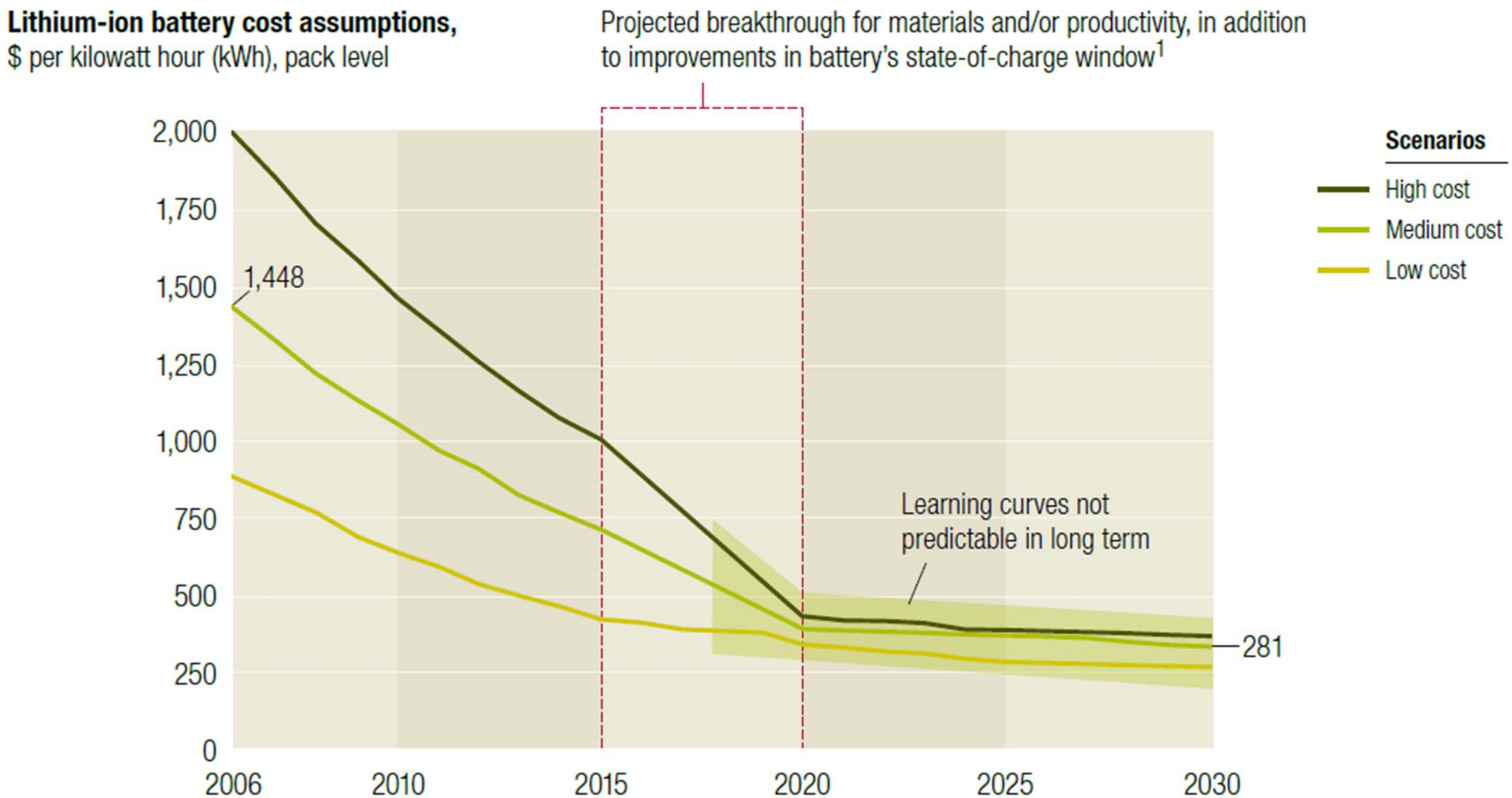


Photo courtesy of AES

Recent Studies Predict Li-ion Battery Pack Costs Will Reach $330-$400/kWh at Scale



[1] State-of-charge window, is the available capacity in a battery relative to its capacity when full. Conservative applications work within a 65% window, whereas more aggressive applications use 80%; over the next 5 to 10 years, most applications will likely migrate to the higher value.

(McKinsey, 2010)

Pumped Hydroelectric Is Lowest Cost Storage (~$100/kWh): Can this be done with electrochemical storage?

- 1872 MW output (21.5 GW total in U.S.)
- 15,000 MWh stored energy
- 2.5 x 1 mile, 842 acres
- 0.04 Wh/L energy density
- Elevated 400 ft above Lake Michigan

Sample calculation:

How much cost in the active materials needed to supply 1 kWh?

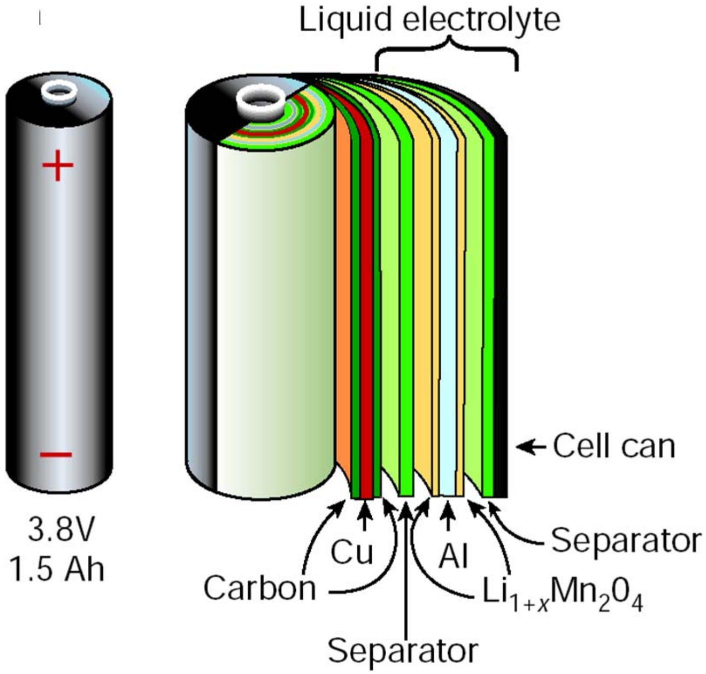
$LiFePO_4$ ($10/kg) – Graphite ($10/kg)
3.3V cell x 303 Ah = 1 kWh

303 Ah/160 Ah/kg = 1.89 kg $LiFePO_4$ ($18.9)
303Ah/340 Ah/kg = 0.89 kg graphite ($8.9)

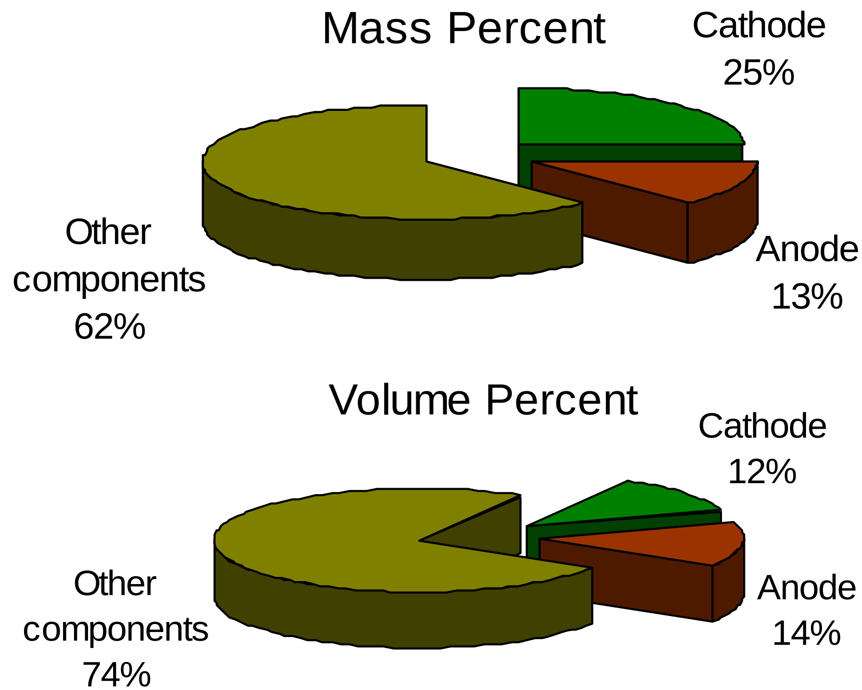
Answer: $27.8/kWh ($100/kWh not out of the question)

Other costs:
All the other components in the cell…..
Manufacturing cost
Module and pack cost
Battery management system

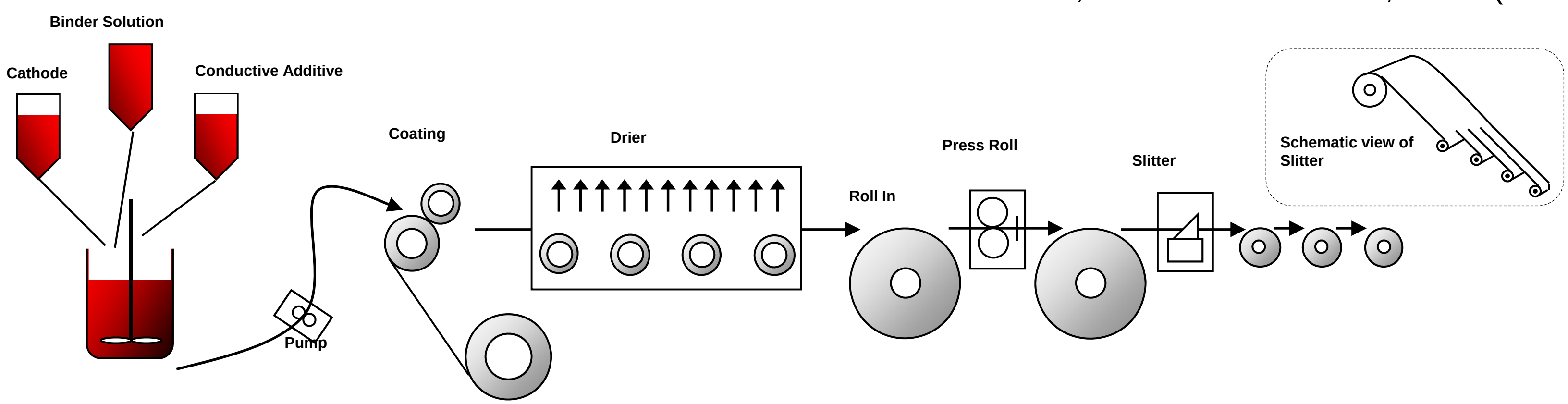
Current Lithium Ion Battery Designs Have Too Much Mass, Volume and Cost Overhead



J.-M. Tarascon, *Nature* 414, 359 - 367 (2001)



R. Moshtev, *J. Power Sources* 91, 86-91 (2000)



One Alternative Approach:

SEMI-SOLID FLOW CELLS

Combining the Best of Rechargeable Batteries and Flow Cells

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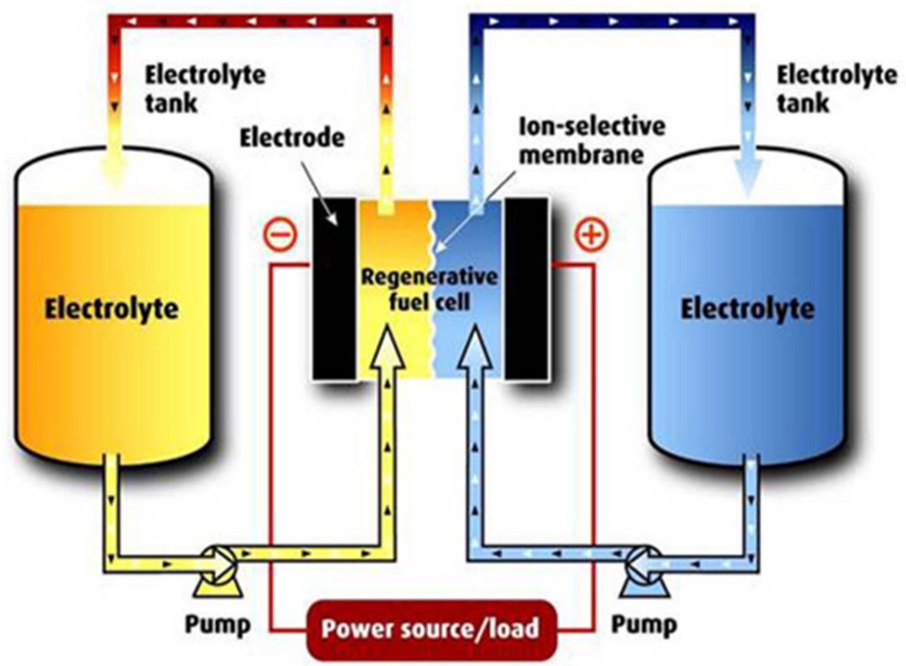
W. Craig Carter (MIT)
Glenn Amatucci (Rutgers)
Angela Belcher (MIT)
Paula Hammond (MIT)
Pimpa Limthongkul (24M P.I.)

Aqueous Flow Batteries



VRB 2 MWh system at Tomamae 4-6 MWh wind farm

Example: Vanadium redox chemistry (1.2V cell)

Positive electrode: $VO^{2+} + O^{2-} \rightarrow VO_2^{+} + e^{-}$ V=0.9 V vs. H_2/H^+ electrode
Negative electrode: $V^{3+} + e^{-} \rightarrow V^{2+}$ V=-0.3 V vs. H_2/H^+ electrode

But: Solid Ion Storage has >10x Higher Concentration of Redox Species than Aqueous Solutions

Redox Active Material	Molar Concentration of Active Species
Typical aqueous flow cell catholyte or anolyte*	1-2M
$LiCoO_2$	51.2M Co^{3+}
$LiFePO_4$	22.8M Fe^{2+}
LiC_6	21.4M Li^+

Assume 50 vol% solids in suspension:

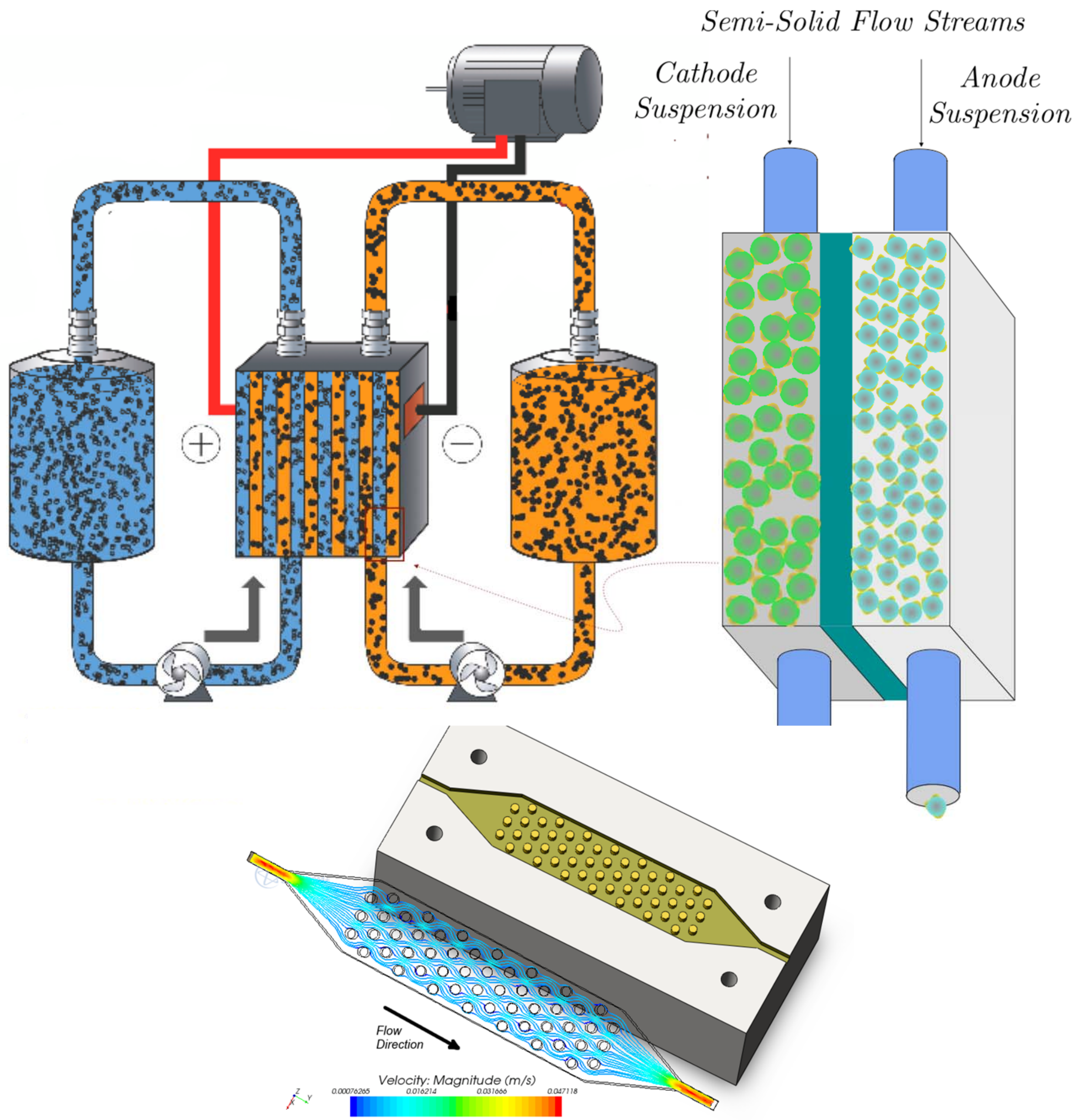
- **~10x higher charge capacity conventional aqueous flow cells (vanadium redox, zinc-bromine)**
- **2-3x higher cell voltage for nonaqueous chemistry**
- **20-30x higher energy density than aqueous solutions**

***e.g., Na-Br, Zn-Br, vanadium redox**

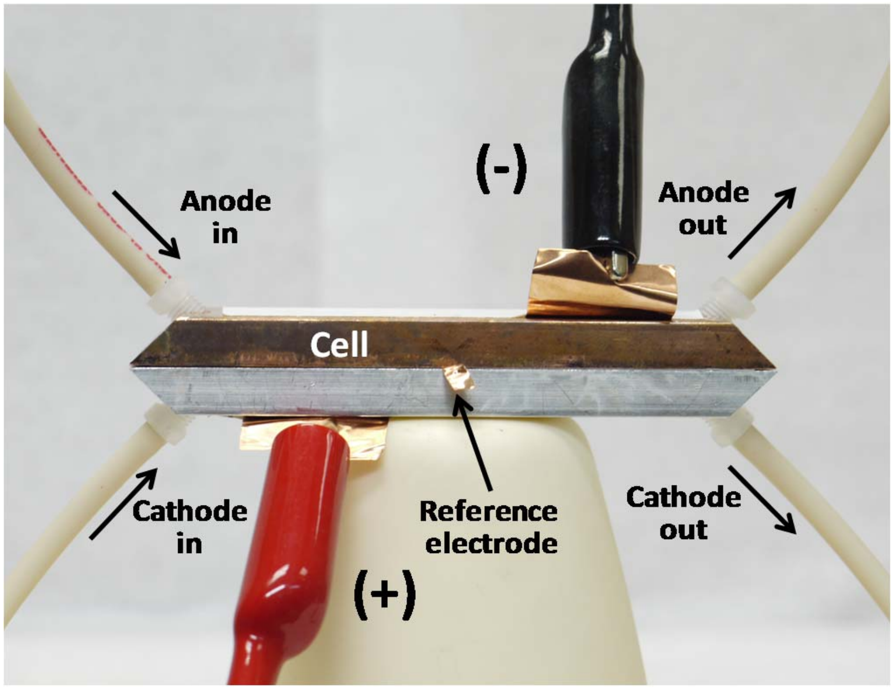
Review article: C. Ponce de León, A. Frías-Ferrer, J. González-García, D.A. Szánto, F.C. Walsh, *J. Power Sources*, 160, 716-732 (2006)

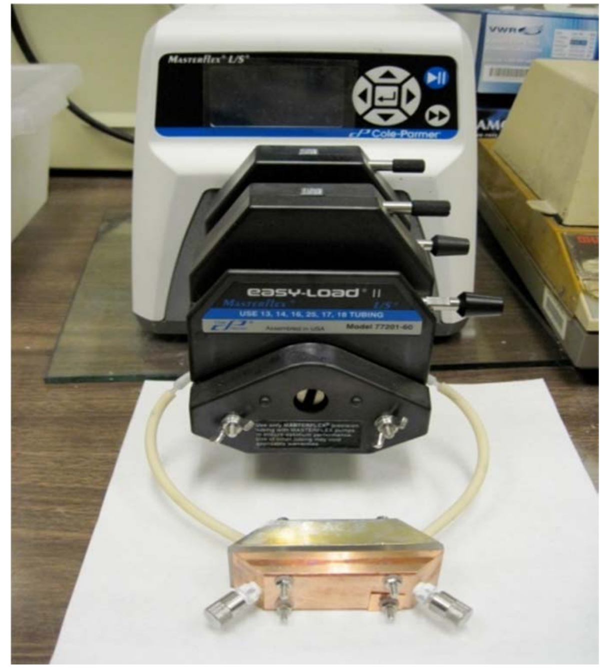
Semi-Solid Flow Cell (SSFC) Approach

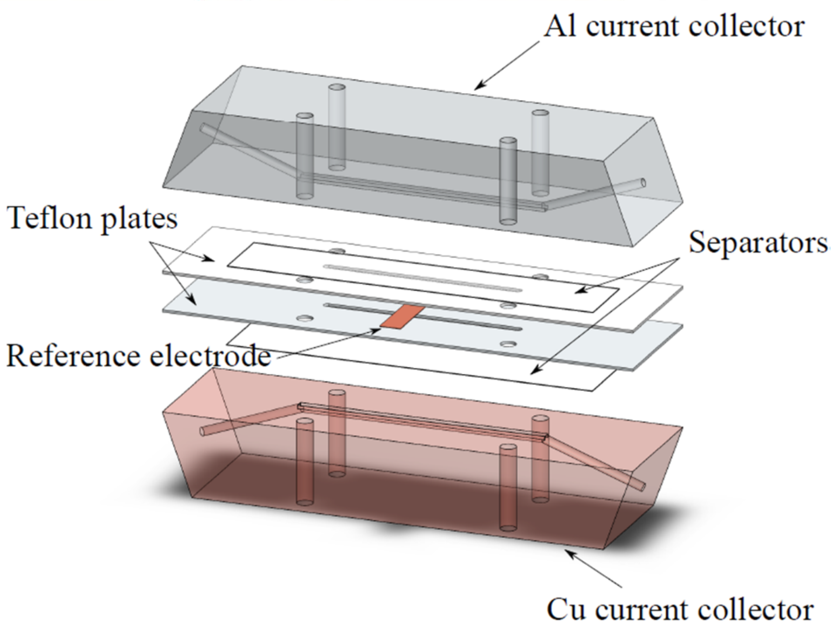
- How to build a reel-to-reel battery that maximizes the utilization of active material?
- Need flowable solid form, hence *semi-solid fuels*
- Concentrated yet flowable colloidal suspension of solid storage compounds that is electronically and ionically conductive



What it looks like in the lab

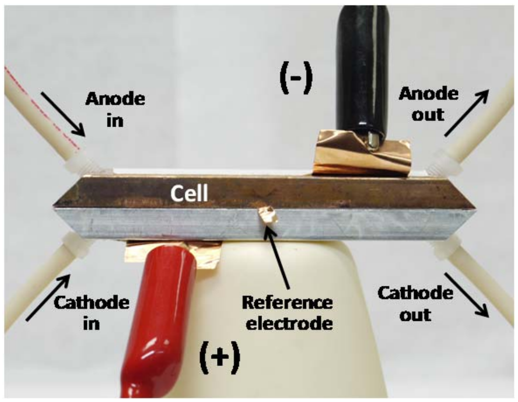


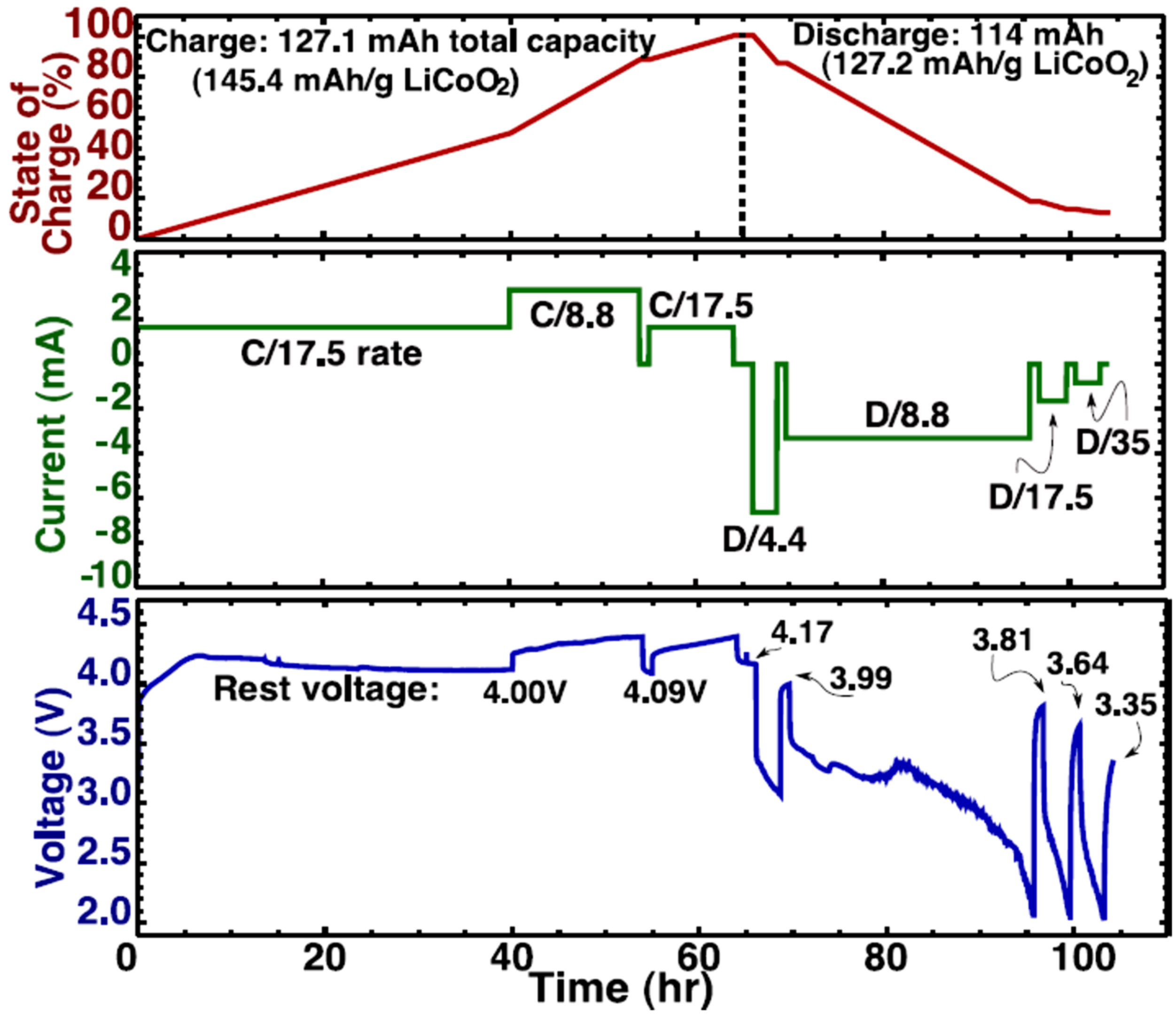




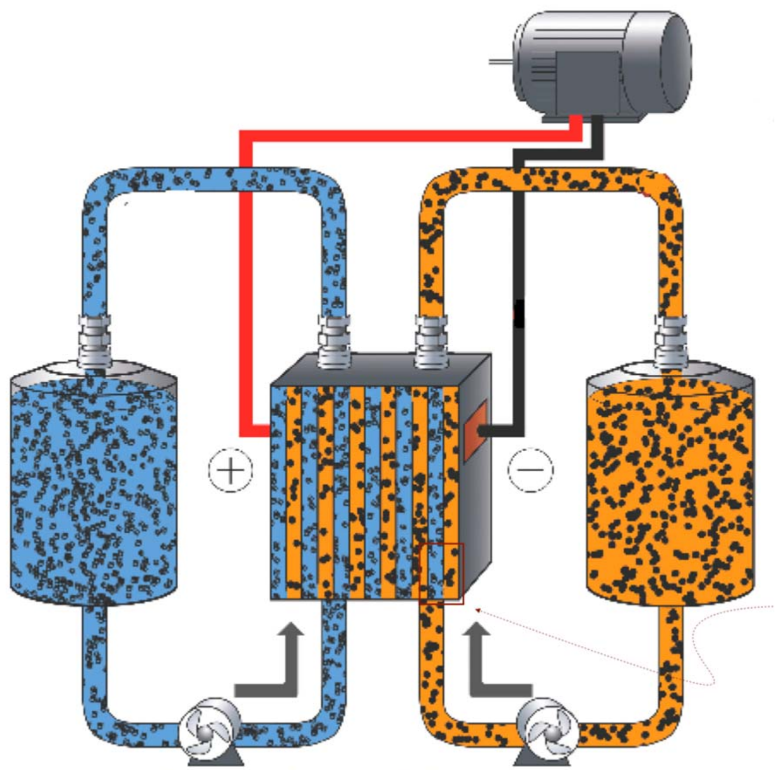
Semi-solid Flow Cell Test

Galvanostatic charging of a $LiCoO_2$–based suspension undergoing continuous flow at 20.3 mL/min rate





Projected Storage Density: Ludington (2 GW, 15 GWh) Equivalent Using 1 MW, 7.5 MWh, SSFC Units

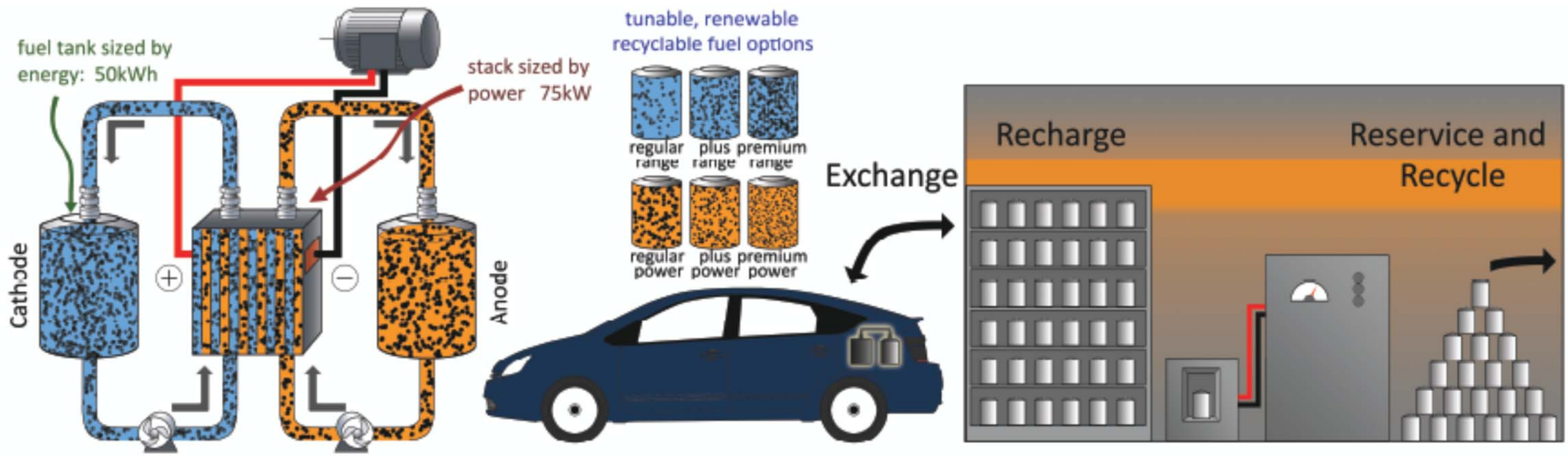


How many 40ft containers?
(2385 ft^3, 61.46 m^3, 61,500L)
(Footprint: 40' x 8')

To replace this (15,000 MWh, 842 acres)

Need:
- **200 Containers (nonaqueous)**
  64,000 sq ft (1.5 acres)

Also Some Interesting Possibilities for Transportation



Questions?