Electrochemical Energy Storage for the Grid

Yet-Ming Chiang
Department of Materials Science and Engineering
Massachusetts Institute of Technology

2MW, 0.5 MWh Li-ion battery

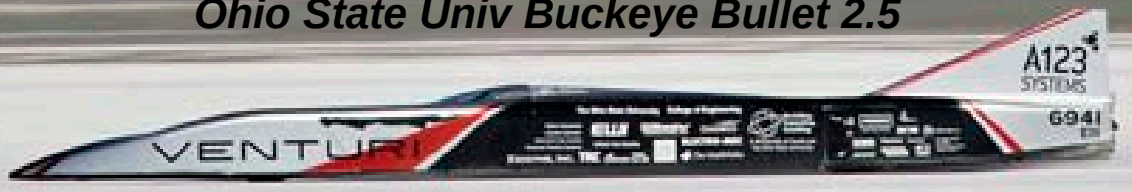
Daimler Orion/BAE Systems


F1


Fisker Karma PHEV

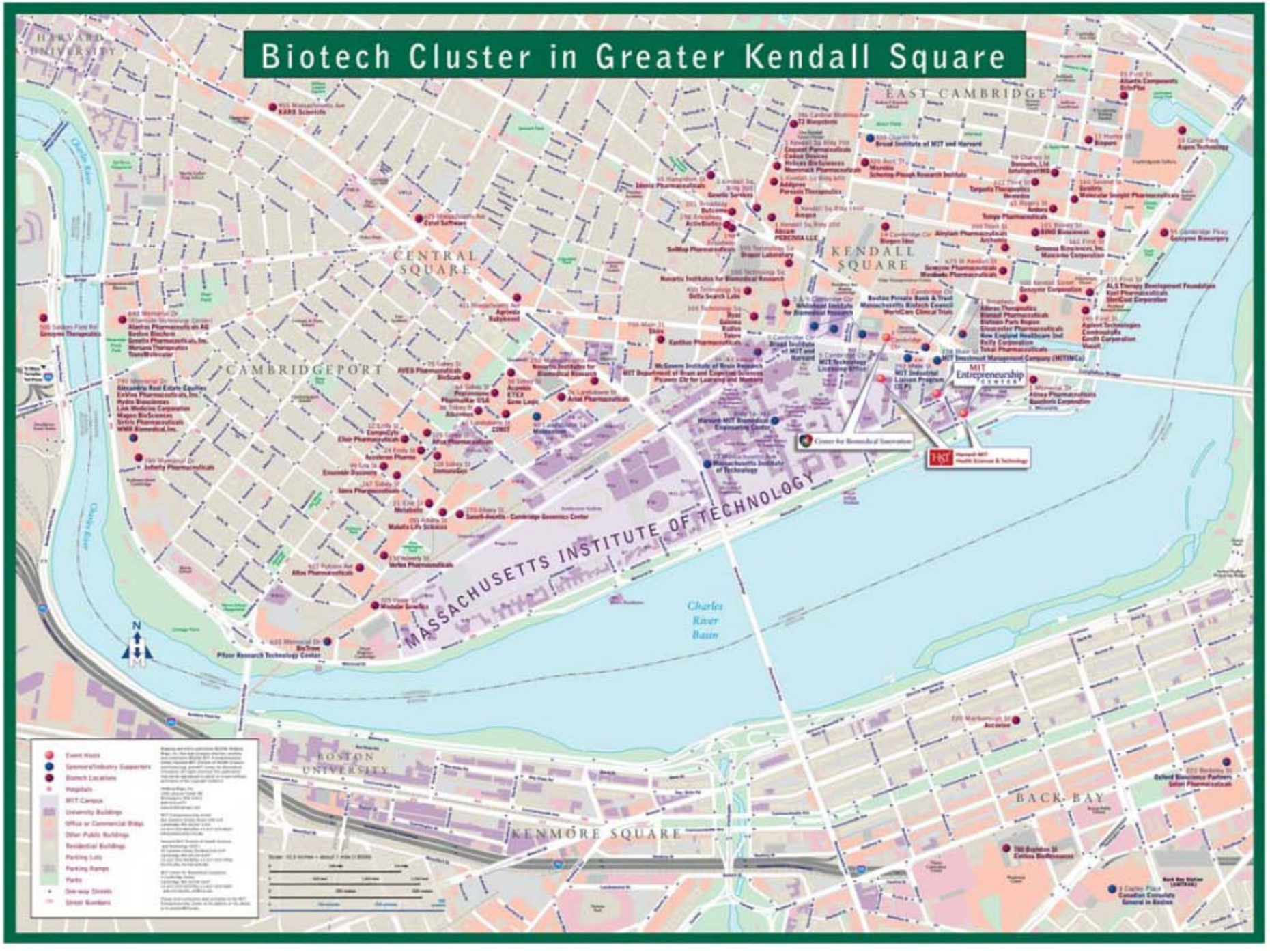

Hymotion PHEV

Ohio State Univ Buckeye Bullet 2.5



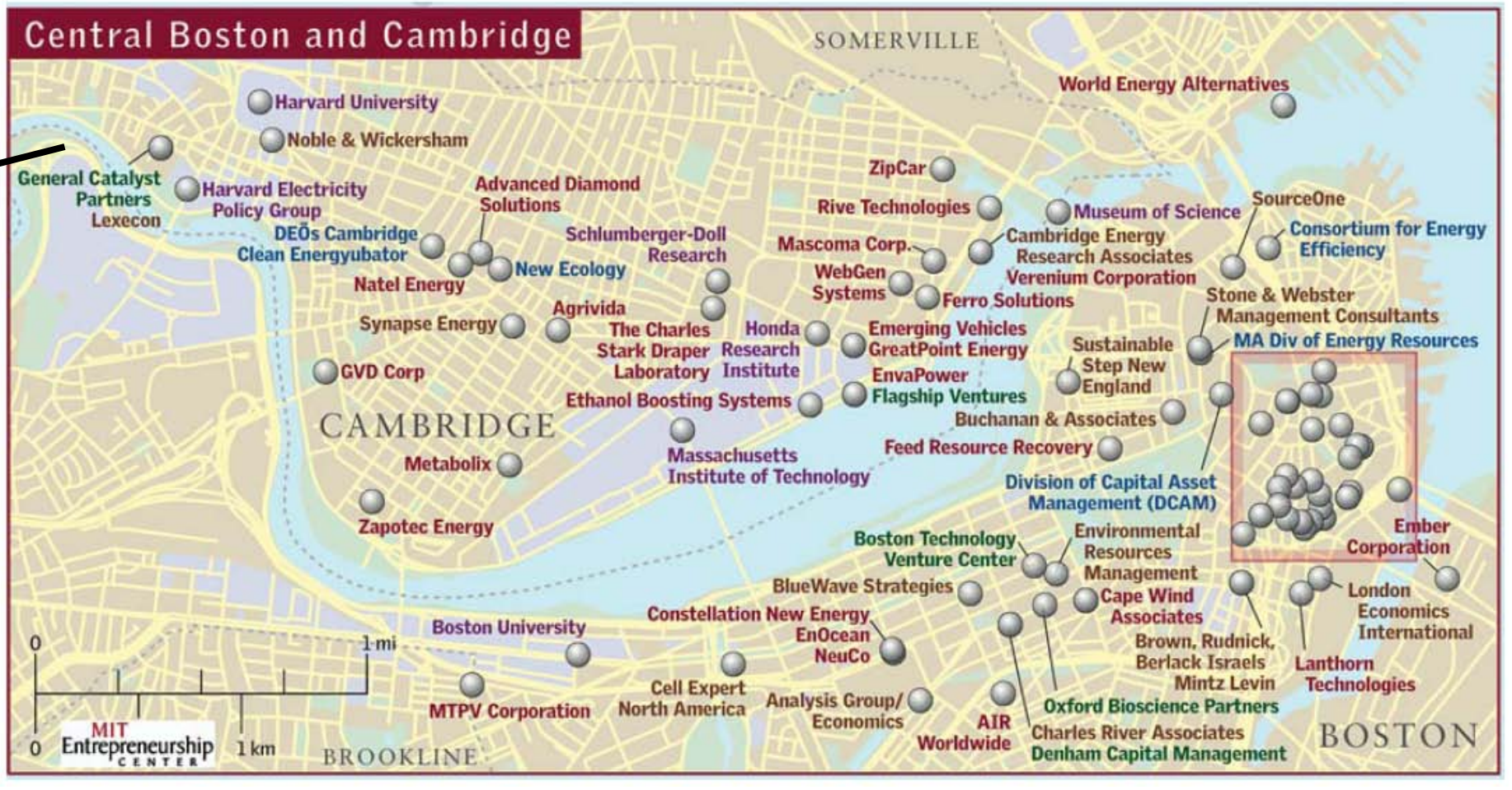
Funded in part by the ARPA-e Program of the U.S. Department Of Energy

Energy Storage Systems Program Review, Nov 4, 2010



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

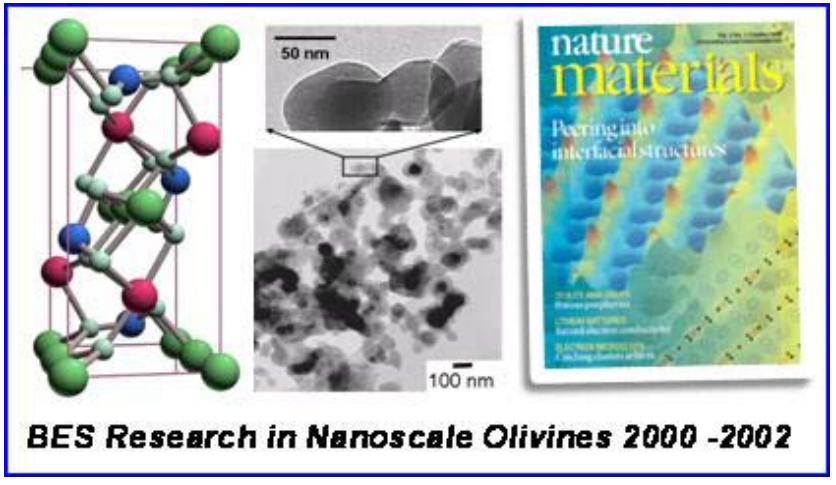
A123 SYSTEMS



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

U.S. DOE Provided Support Along Entire Cycle of Innovation and Commercialization



There is more than one “Valley of Death”

1. Is the researcher/professor *serious* about impact beyond academic glory? (Are you the chicken or the pig? Example: Deshpande Center at MIT)

2. Does the technology actually work? What’s your first product? (And how many strikes do you get before you’re “out?”)

3. Can you scale? How much capital to get to volume manufacturing? Or do you partner? (Licensing is a consolation prize if not an outright failure.)

4. Is your global competition foreign companies, or foreign governments? (Industrial policy)

THE WALL STREET JOURNAL.

WEDNESDAY, NOVEMBER 2, 2005 - VOL. CCXLVI NO. 94 - ★★★★ $1.00

Nov. 2005

New Type of Battery Offers Voltage Aplenty—at a Pre

By William M. Bulkeley

A NEW GENERATION of rechargeable batteries—delivering far more power than their predecessors—is energizing the power-tool industry and generating widespread interest in applications in everything from vacuum cleaners to ride-on lawn mowers to hybrid cars.

The new lithium-ion batteries—powering a host of products already on the market and envisioned for others on the drawing board—are made possible by technical breakthroughs in lightweight lithium-ion cells, introduced in rechargeables in the 1990s but until recently deemed too volatile for safe high-power use.

Black & Decker Corp. says that early next year it plans to introduce a family of 36-volt power tools in its professional DeWalt line, including circular saws, reciprocating saws, a rotary hammer for drilling into concrete and an impact wrench powerful enough to unscrew lug nuts on truck tires. They will have double the power of 18-volt tools, now the most common cordless devices carried by carpenters and contractors.

DeWalt's lithium-ion batteries come from A123 Systems Inc., a Watertown, Mass., start-up that has licensed patents from the Massachusetts Institute of Technology. Germany's Robert Bosch GmbH also plans new high-powered cordless tools next year, and says it is working with two lithium-ion battery suppliers. Earlier this year, Milwaukee Electric Tool Corp., a unit of Hong Kong's TechTronics Ltd., introduced slightly less powerful 28-volt cordless tools powered by lithium-ion batteries made by a Canadian unit of Taiwan's E-One Moli Energy Corp.

Charged Up

World-wide battery sales in 2004, in billions:

Source: Frost & Sullivan

When A123 showed DeWalt its technology two years ago, "it was the first thing we saw that could meet all our needs, particularly on durability and run time," says Christine Potter, DeWalt's cordless-product manager. In DeWalt tests, drills with the new batteries bored 300 to 400 holes through a two-by-four on a single charge versus 100 holes with the 18-volt model.

The technology driving A123 is based on discoveries by MIT professor Yet-Ming Chiang, a materials scientist. Dr. Chiang A123, says "research in batteri tive," because it initially loo power, but many variations tu battery life or make batteries runaway oxidation explosions chemically complex, electrica mechanically complex," he sa

A123 says it coats an alumi side the battery with nano-scal hundred atoms in size, of lith phate. It declines to disclose m Chiang says the phosphate is sa based chemistry used in lithiu day. He says that when compar weight of larger particles, the n release more ions, thereby fre create an electric current.

Dr. Chiang's company has from investors including cellph ola Inc. and Silicon Valley's which helped back Google Inc. Until now, the company "has o mode," says its president, Davi previously vice president of Ame version Corp., the leading make supplies for personal computers

Lithium-ion rechargeable common in cellphones, laptop are much more expensive tha able alternatives or nonrecha batteries. For example, onlin

Please Turn to Page B7,

nature Vol 444|2 November 2006

BUSINESS

Drilling for nanotech gold

One US nanotechnology start-up has hit the jackpot — but for others the prospect of such overnight success seems remote. **Colin Macilwain** reports.

The guys in the aisle at Home Depot don't know it. But that $800 DeWalt cordless power-tool set — the one they really want for Christmas, but are just too scared to ask for — gets its butt-kicking oomph from a *Nature Materials* paper published only four years ago.

It's taken that time for a battery cathode based on phosphate nanocrystals to rip its way from a lab at the Massachusetts Institute of Technology (MIT) in Cambridge, through financing, design, development and manufacture in east Asia, to its current position, driving 36-volt power tools from Black & Decker — owner of the DeWalt professional-grade marque.

"These tools are better than corded ones," says Jamie Mann, director of sourcing for Black & Decker in North America. "And they can take 2,000 recharges. That's big for us — we think it's changed the game."

The company that builds the nanophosphate batteries, A123Systems in Watertown, Massachusetts, was founded in 2002 and has US$100 million worth of orders in hand. It's an instant success story, and one that impressed investors gathered in Cambridge, Massachusetts, last week for the Lux Research Executive Summit, a meeting of the great and the would-be great in the fledgling nanotech sector.

But the MIT spin-off's success won't be matched by most of the estimated 1,500 start-up companies in the sector, the meeting was told. "In every new industry, you have an initial hype, and then a shake-out," says Charles Seeney, president of NanoBioMagnetics, an Oklahoma-based health-products company. "The same thing is going to happen in nanotechnology."

> "It is one of the easiest things in the world to explain why we need better batteries."
> — Yet-Ming Chiang

For those that do survive, partnerships with major corporations — like A123Systems' with Black & Decker — will probably hold the key.

Not that A123's founders — materials scientists Yet-Ming Chiang and Bart Riley, and Ric Fulop, an entrepreneur and business fellow at MIT — had much idea initially where their dramatic success was going to come from. They had solid hopes for the company, and attracted an accomplished business manager — David Vieau, a mechanical engineer with extensive high-technology experience — to come and run it. But the power-tool breakthrough was unexpected: "We were considering things with

motors — we thought a lot about hybrid vehicles," recalls Vieau. "We didn't know where our optimum performance advantage would lie."

The *Nature Materials* paper outlined the basic idea, showing how tiny lithium iron phosphate crystals could be 'doped' to conduct electricity, and proposing that they be used to make battery electrodes (S.-Y. Chung, J. T. Bloking & Y.-M. Chiang *Nature Mater.* 1, 123–128; 2002). Conventional lithium-ion batteries use particles of lithium cobalt oxide about a micrometre across: if they were smaller their electrical conductivity would improve but so would their thermal conductivity — raising possible safety issues. The new material is more chemically stable, and its performance can be optimized by using crystals that are only a few nanometres across. The result prompted fierce controversy over the mechanism that lay behind it (*Nature Mater.* 2, 702–703; 2003).

Chiang says the idea for the venture came when Fulop had walked into his office, and said: "How about starting a battery company?"

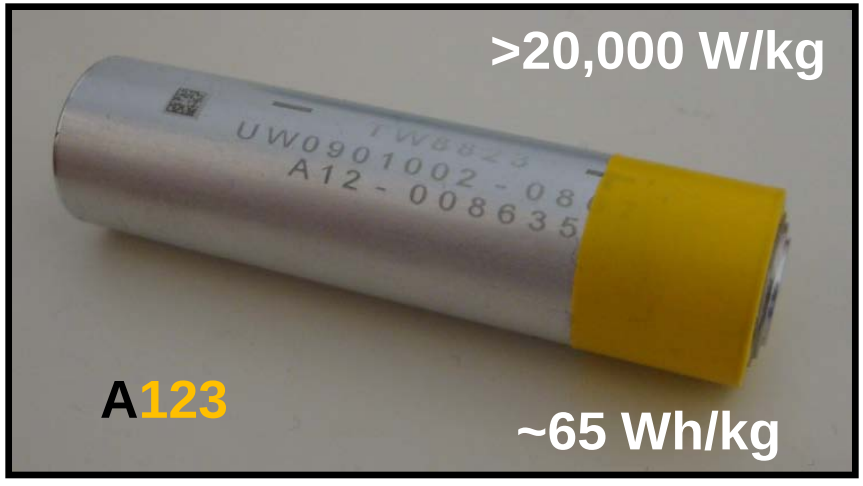
The company didn't take long to get rolling. Chiang felt that it would be a far easier sell than the high-temperature superconducting wire made by his previous start-up, American Superconductor. There, he recalls, he was selling mainly to "utilities that run on 25-year-old technology". Whereas with the new business, "it is one of the easiest things in the world to explain why we need better batteries". The company was taking shape before the paper was published: it hired Vieau in March 2002 and quickly obtained backing from a loyal clutch of investors, including North Bridge Venture Partners of Boston, Sequoia Capital of Menlo Park, California, and investor Desh Deshpande, who became company chairman.

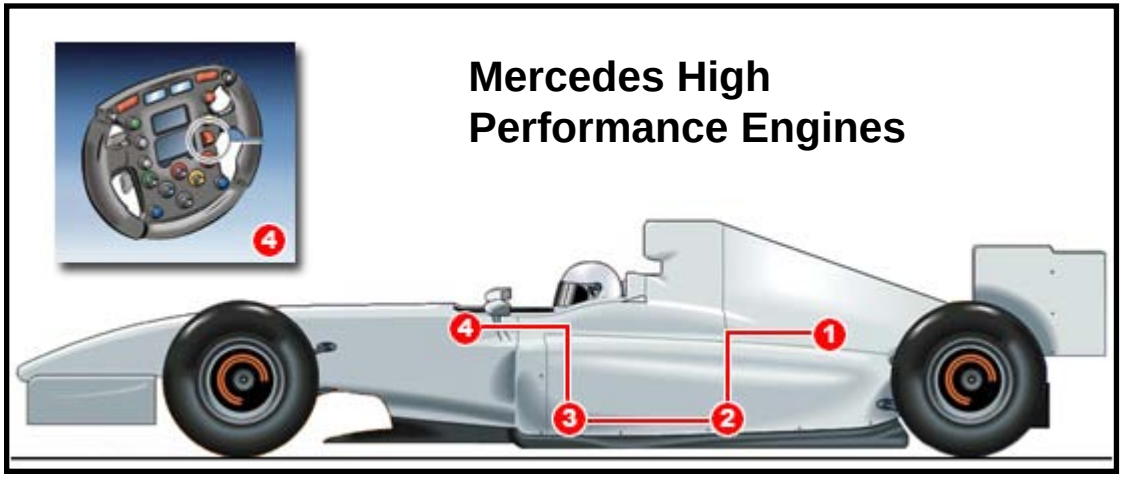
Big boys' toys: but there's nanotechnology inside.

At the time, Black & Decker was searching for a breakthrough that would get it a jump ahead in the fast-expanding cordless power-tool business. "We were scouring the Earth," says Mann. After meeting with the young company, "we were excited, but extremely cautious," he recalls. "We're a $5-billion company, and this was ten guys from Boston! It looked like a good bet, but there was a lot of risk."

The odds were lengthened by the nature of the lithium-ion battery business, which is dominated by huge Japanese corporations, such as Sony, with deep pockets and large, intramural

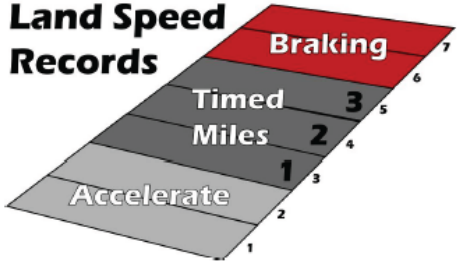
Benchmark in High Power Li-Ion: Formula 1 Racing

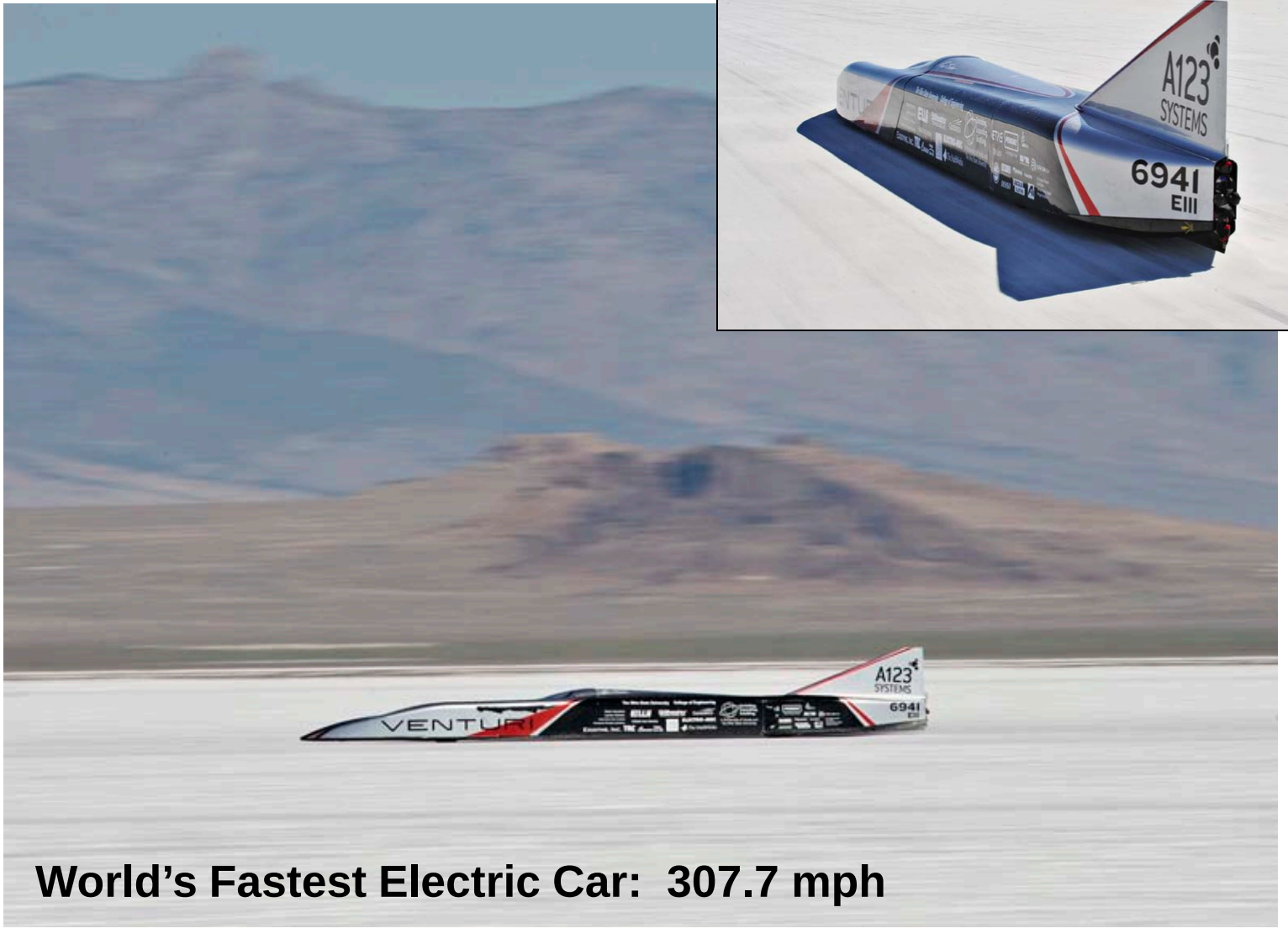




- McLaren-Mercedes - A123 olivine based Kinetic Energy Recovery System (KERS)
- Opening race of 2009 F1 season in Melbourne, AUS
- Lewis Hamilton, 2008 World Champion, starts in 18th position (out of 20) and finishes 4th

OSU Buckeye Bullet VBB2.5: Electric Drive Land Speed Record



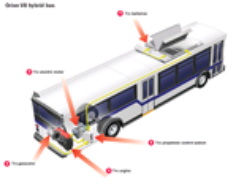


World's Fastest Electric Car: 307.7 mph

Li-Ion Powered Hybrid Buses: >50 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.

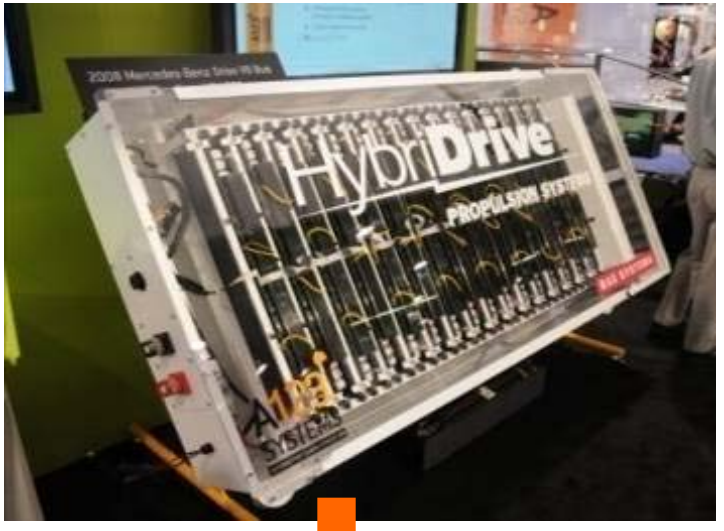
OC Transpo has ordered 202 Orion VII Next Generation diesel-electric hybrid transit buses to be delivered by 2009. This delivery will make OC Transpo the third largest hybrid bus fleet in Canada.

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

Today

Hymotion: Canada

HQ and R&D: Watertown, MA

Pack and Systems: Hopkinton, MA

Materials Research and Automotive Applications: Michigan

300,000+ s.f. of high volume, state of the art manufacturing space in Asia

Prismatic process development center: Icheon, Korea

Powder, cathode coating, cell plants: Changzhou, China

Quality, supply chain: Shanghai, China

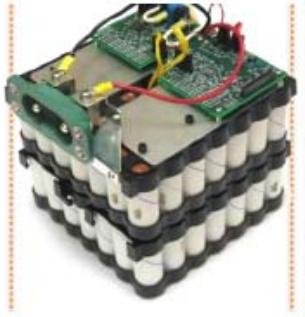
Material science differentiation

Cell engineering innovation

Systems engineering value add

Low cost - high volume & quality manufacturing

Industry leading partners



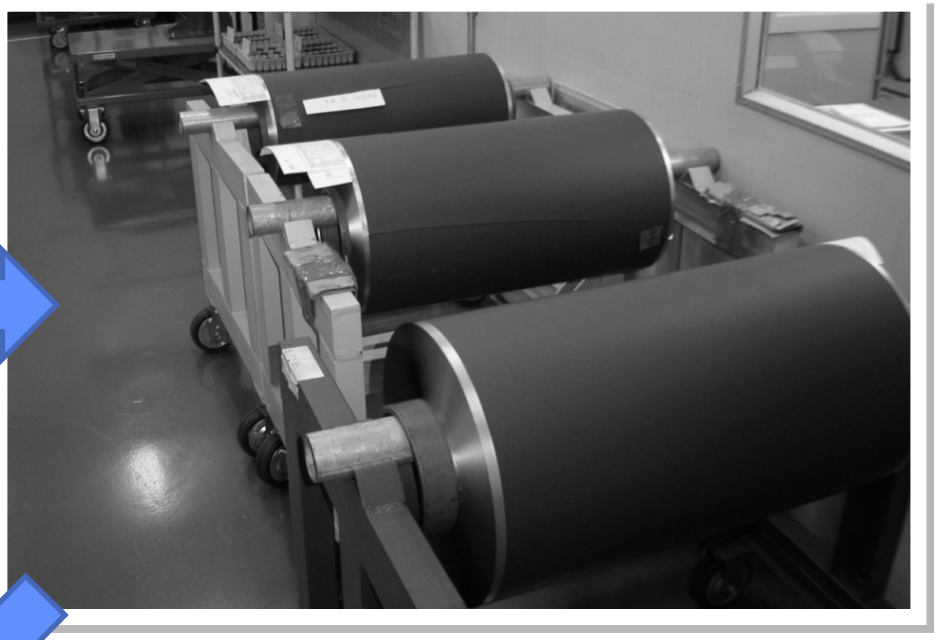
DEWALT, BLACK & DECKER, Cessna, AES, EPRI, GM, DAIMLER, P&G, RENAULT, GE, MAGNA, Continental, COBASYS, DELPHI, THINK, aptera

Coating Plant – Changzhou, China

Built in 2007

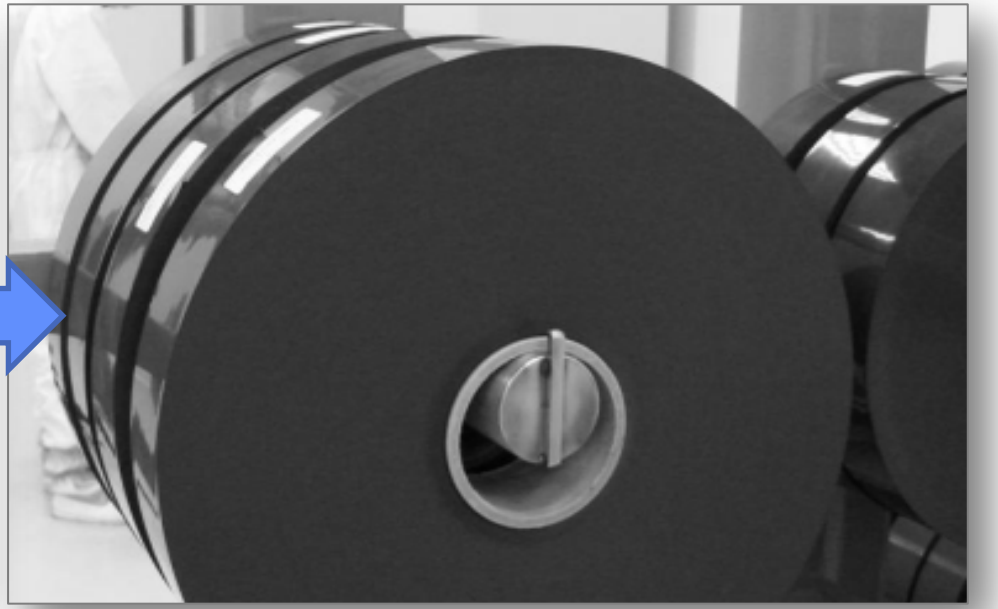
Calendaring

Master Web

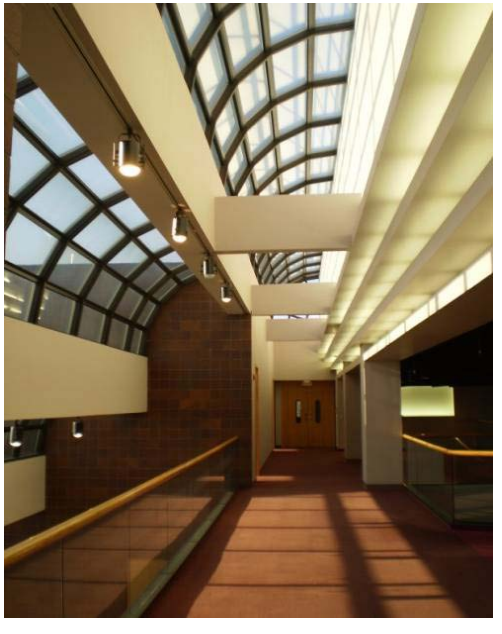


Slitters

Spools



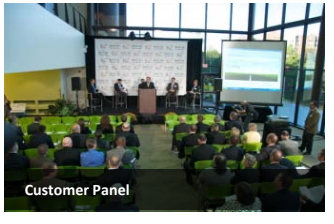
Livonia Michigan Cell Manufacturing Facility



A123 Systems Livonia Factory Grand Opening
September 13, 2010

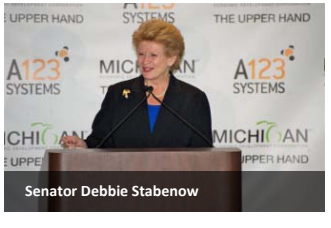

Dave Vieau (CEO), Energy Secretary Chu, Yet-Ming Chiang (A123 co-founder), Bart Riley (CTO, co-founder), and Governor Granholm


Livonia Facility

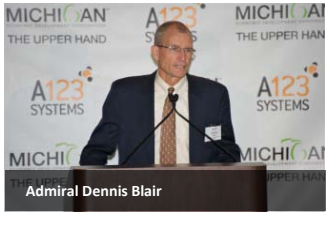

Customer Panel


Phone call from White House


Senator Carl Levin


Senator Debbie Stabenow


Congressman John Dingell


Admiral Dennis Blair


Micky Bly, GM

Romulus, MI Powder & Coating Campus

GOVERNOR GRANHOLM: Good morning. Is that a familiar voice we hear?

THE PRESIDENT: Governor Granholm, this is your friend, Barack Obama. (Applause.)

GOVERNOR GRANHOLM: Mr. President, we're so happy to welcome you to our celebration of A123. I was just explaining how great it is that the Recovery Act provided jobs for Michigan. Maybe you have a few words to those who are assembled here.

THE PRESIDENT: Well, look, I wish I could be there in person to celebrate with you today. But I am calling to

The question of *scale*:

- A123's Livonia plant can produce 30,000 PHEV/EV packs per year
- 33 such factories needed to meet target of 1 million EVs
- 270 million cars in the US today, growing to 500 million by 2030

manufacturing industry to thrive, and with it, that means our communities and our states and our country are going to thrive.

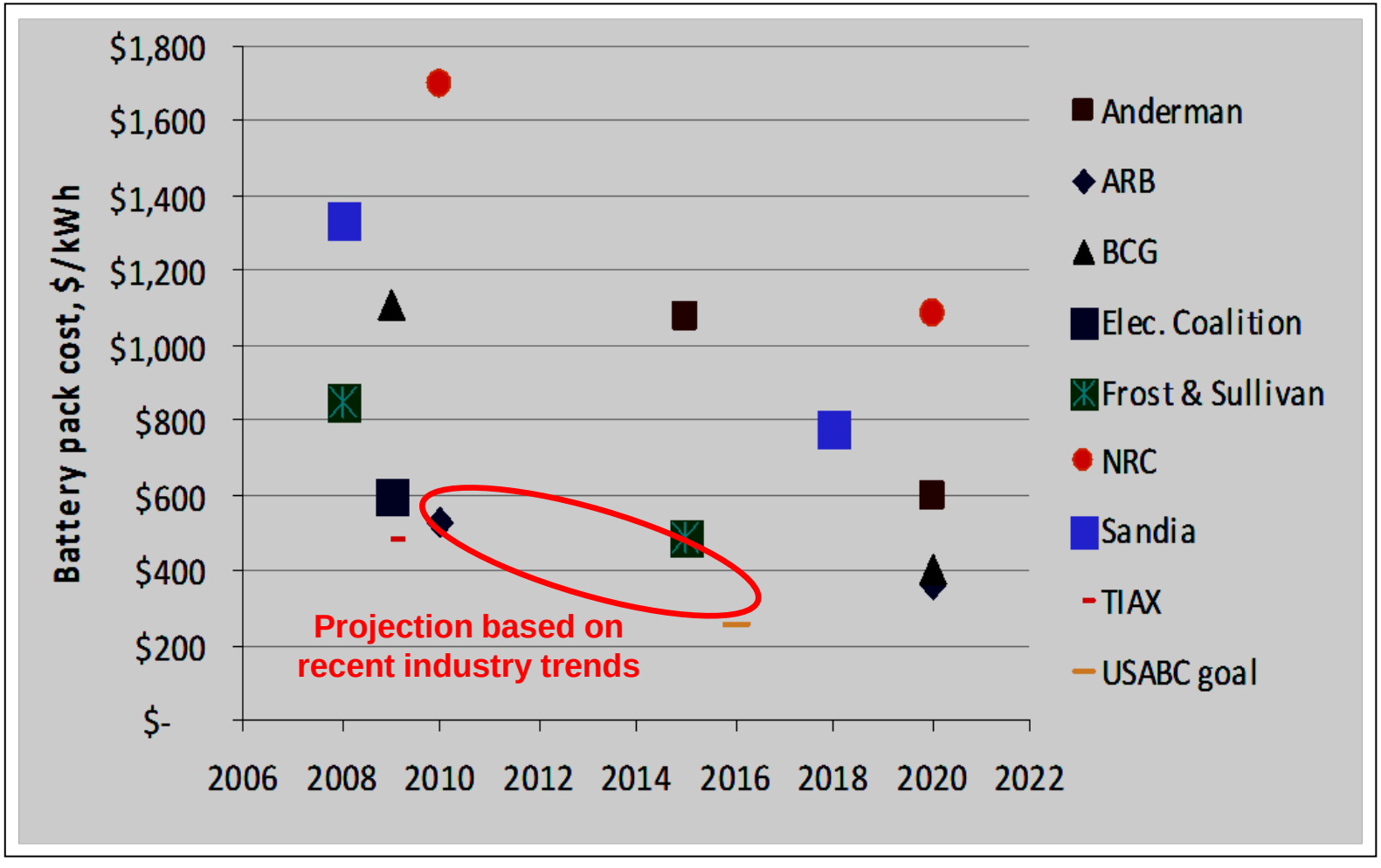
For a long time, our economic policies have shortchanged cutting-edge projects like this one and it put us behind the innovation race. And I don't have to tell folks in Michigan that fewer parts of the economy have been harder hit by this recession than manufacturing. But what I said when you guys were in the White House was I do not see a decline in manufacturing as inevitable for the United States. And I know you don't either.

And so we're starting to reverse that slide. And anybody who doubts that has to go and see what you guys are achieving. And I want everybody to understand just a few years ago American businesses could only make 2 percent of the world's advanced batteries for hybrids and electric vehicles -- just 2 percent. But because of your extraordinary work, thanks to the Recovery Act, we're going to get up to 40 percent of the world's capacity. And that means when folks lift up their hoods on the cars of the future, I want them to see engines and batteries that are stamped: Made in America. And that's what you guys are helping to make happen. (Applause.)

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

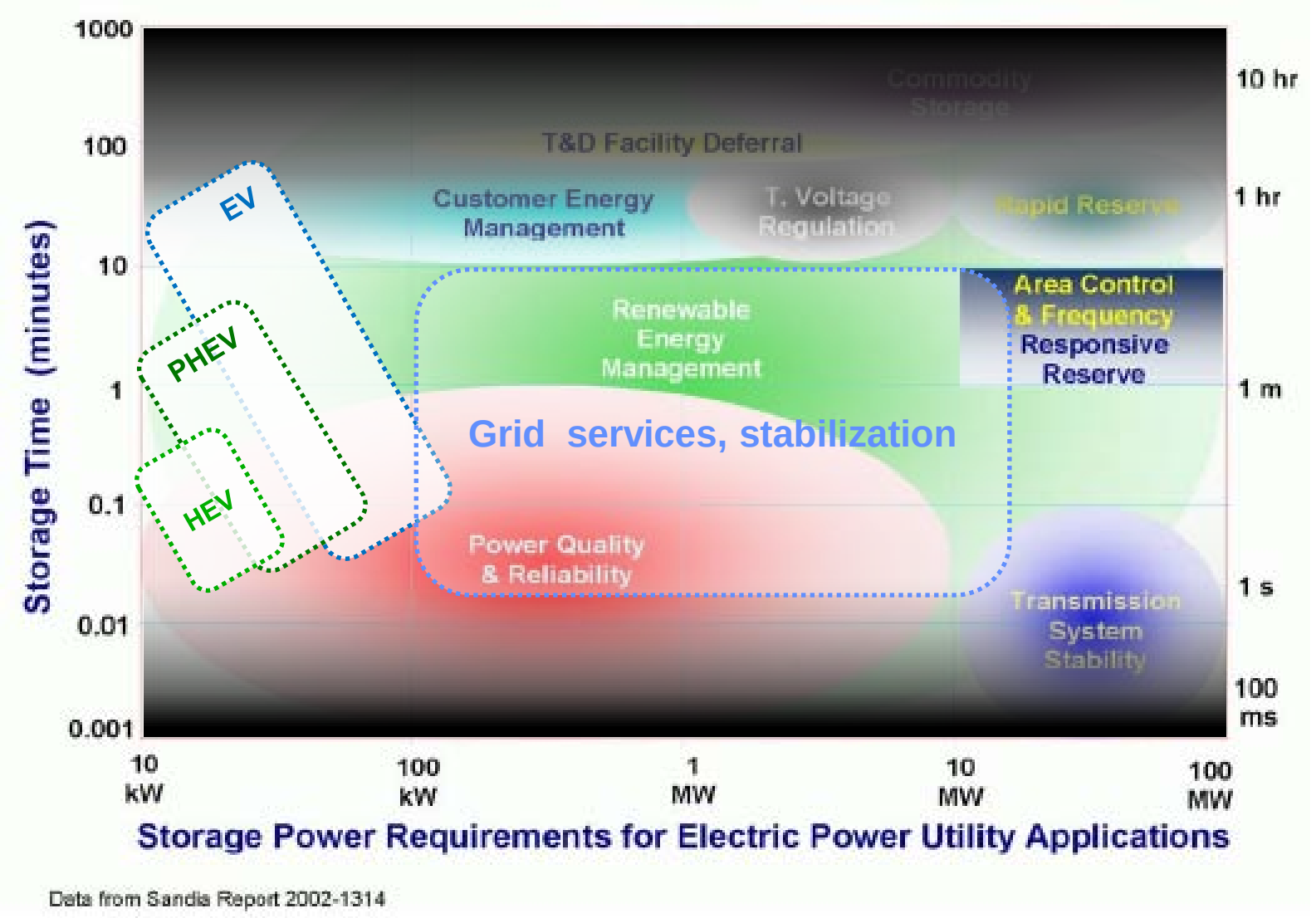
- 1872 MW output (21.5 GW total in U.S.)
- 15,000 MWh stored energy
- 2.5 x 1 mile, 842 acres
- Elevated 400 ft above Lake Michigan

Disagreement on Battery Cost Projections

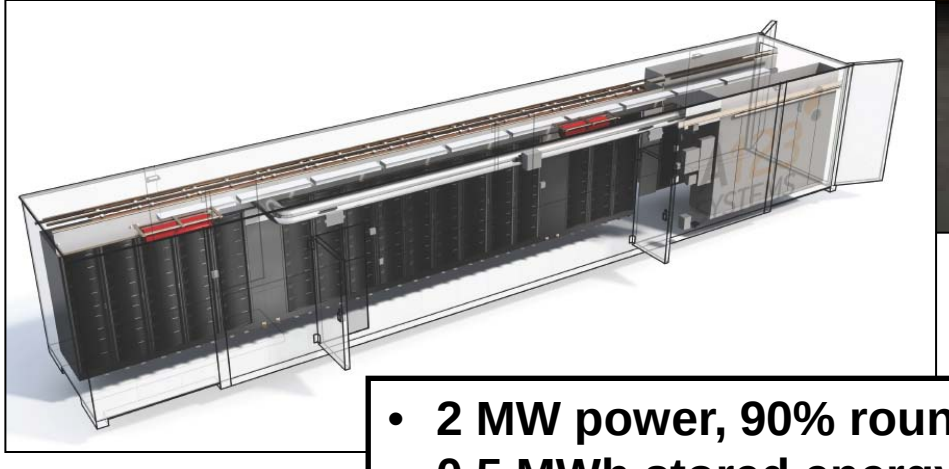


(Chart by Cheah and Heywood, 2010)

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



Megapower using Nanophosphates: Frequency Regulation with the World's largest Li-Ion Battery

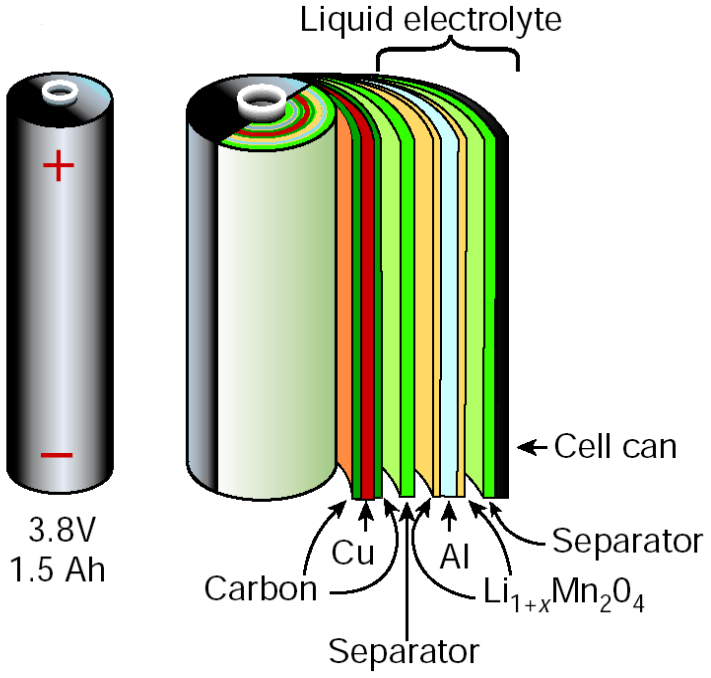


- **2 MW power, 90% round-trip efficiency**
- **0.5 MWh stored energy**
- **82,000 cylindrical 26650 cells**
- **1.2 tonnes cathode material**
- **2.3 x 10^{17} nanoparticles (40 nm dia.)**

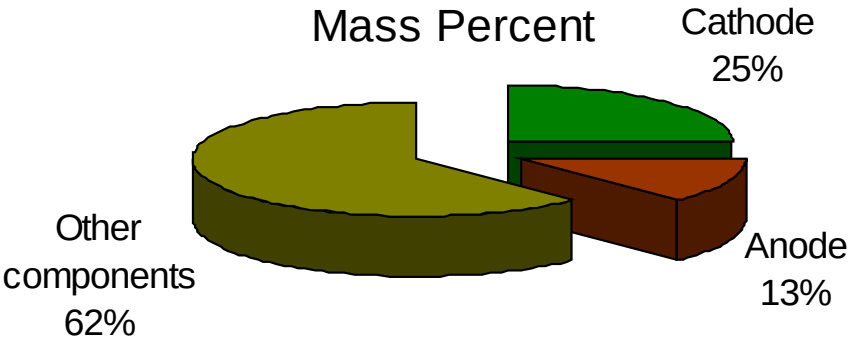
Eight A123 Systems SGSSs™ units providing 16 MW installed on the grid in Chile, performing "spinning reserve" grid stabilization services

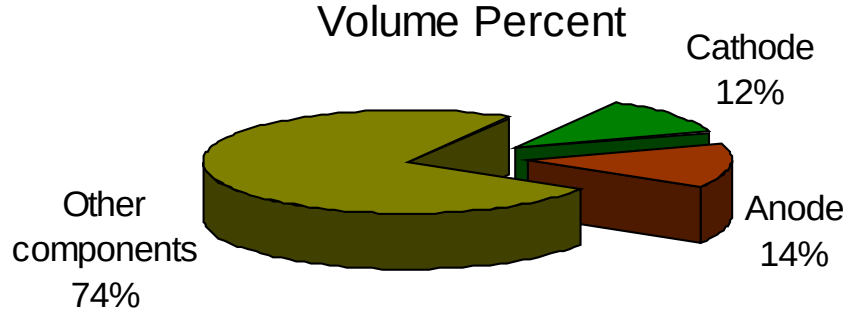
Photo courtesy of AES

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

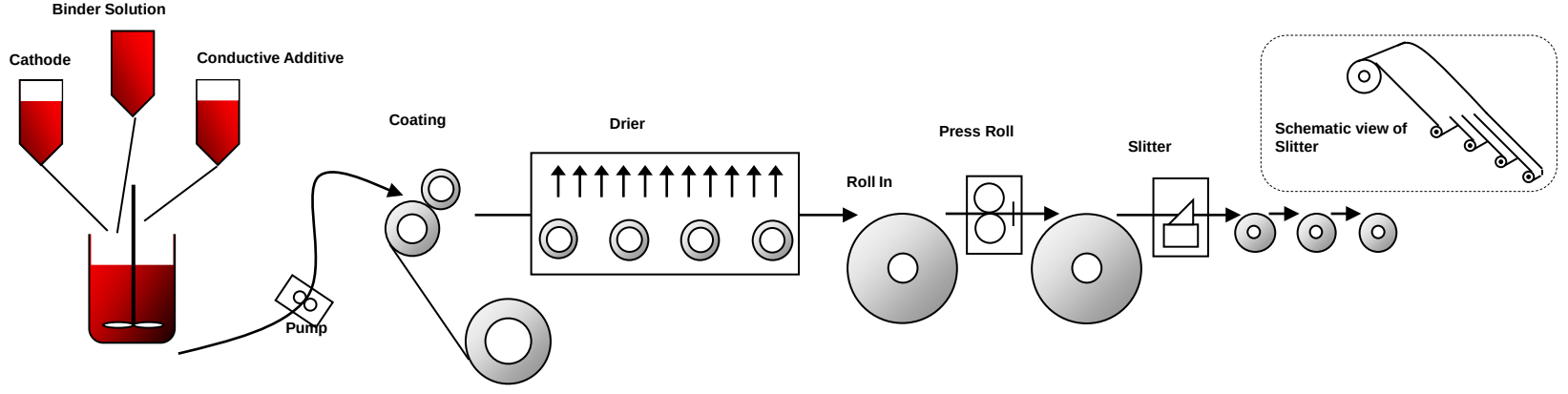


J.-M. Tarascon, *Nature* 414, 359 - 367 (2001)

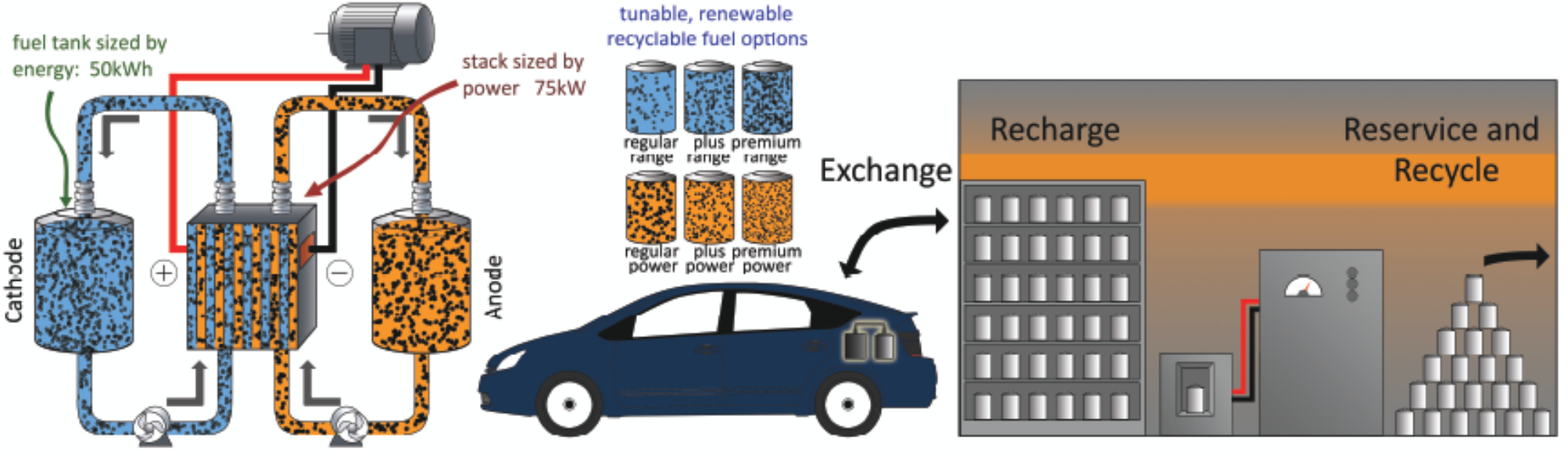


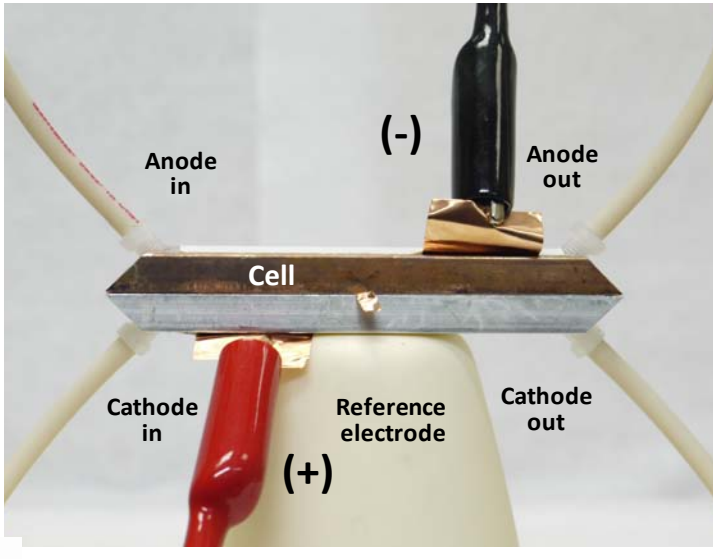


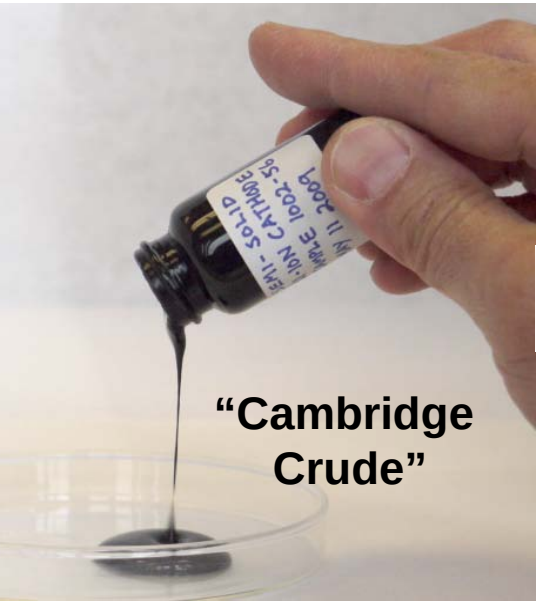
R. Moshtev, *J. Power Sources* 91, 86-91 (2000)



One Example of a New Approach: Semi-solid flow batteries using high energy density electrochemical "fuel"







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Questions?