Electrical Energy Storage and Its Importance to Sustainable Renewable Energy

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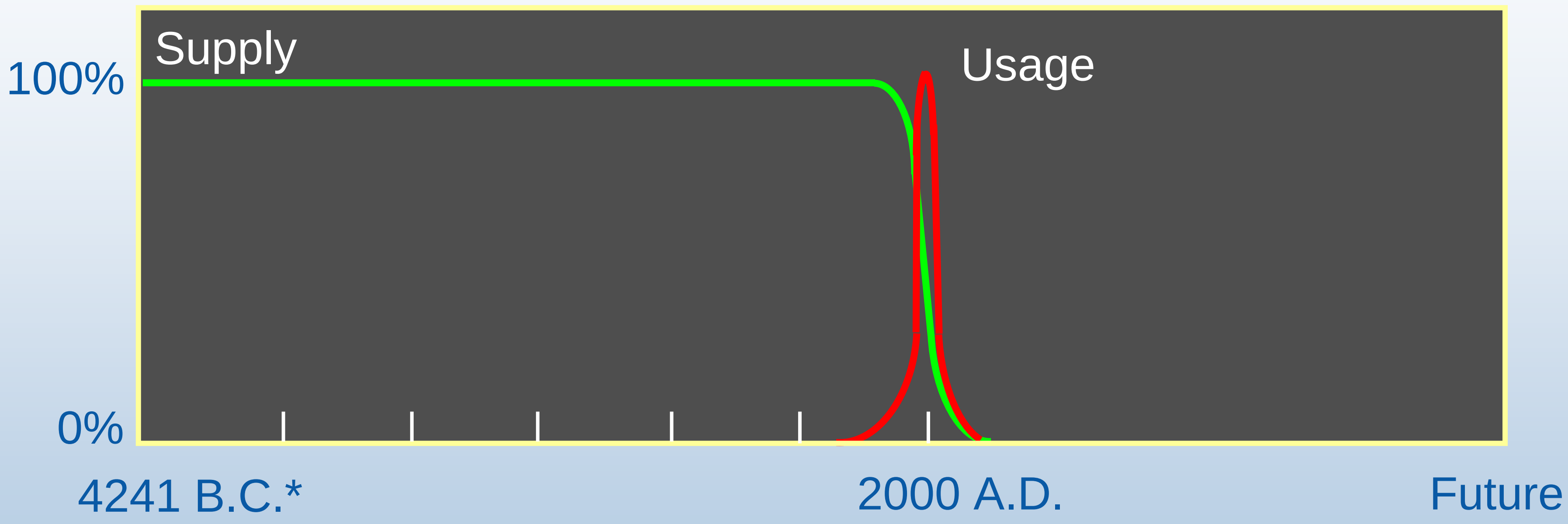
Long-Range Perspective of the Fossil Fuel Energy Dilemma



- <u>“The supply of fossil fuel is rapidly diminishing and **environmental pollution** is rapidly peaking.”</u>
- *Earliest recorded date in Egyptian history

Oscar goes to…

“Inconvenient Truth”

Is there a Sustainable Solution for 6.7 billion Humans on the Planet? Renewable energy

Intermittent Renewable energy (solar, wind, etc) needs energy storage to be sustainable.

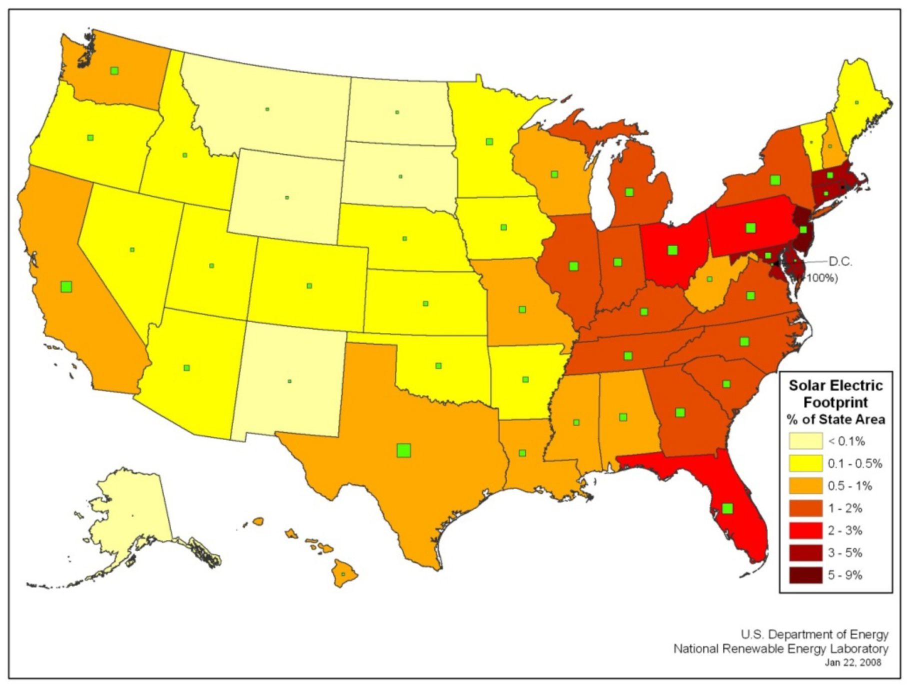
Energy generation, storage, conversion, and conservation

e.g. Electrochromic windows can save *several quads per year*

- energy saving

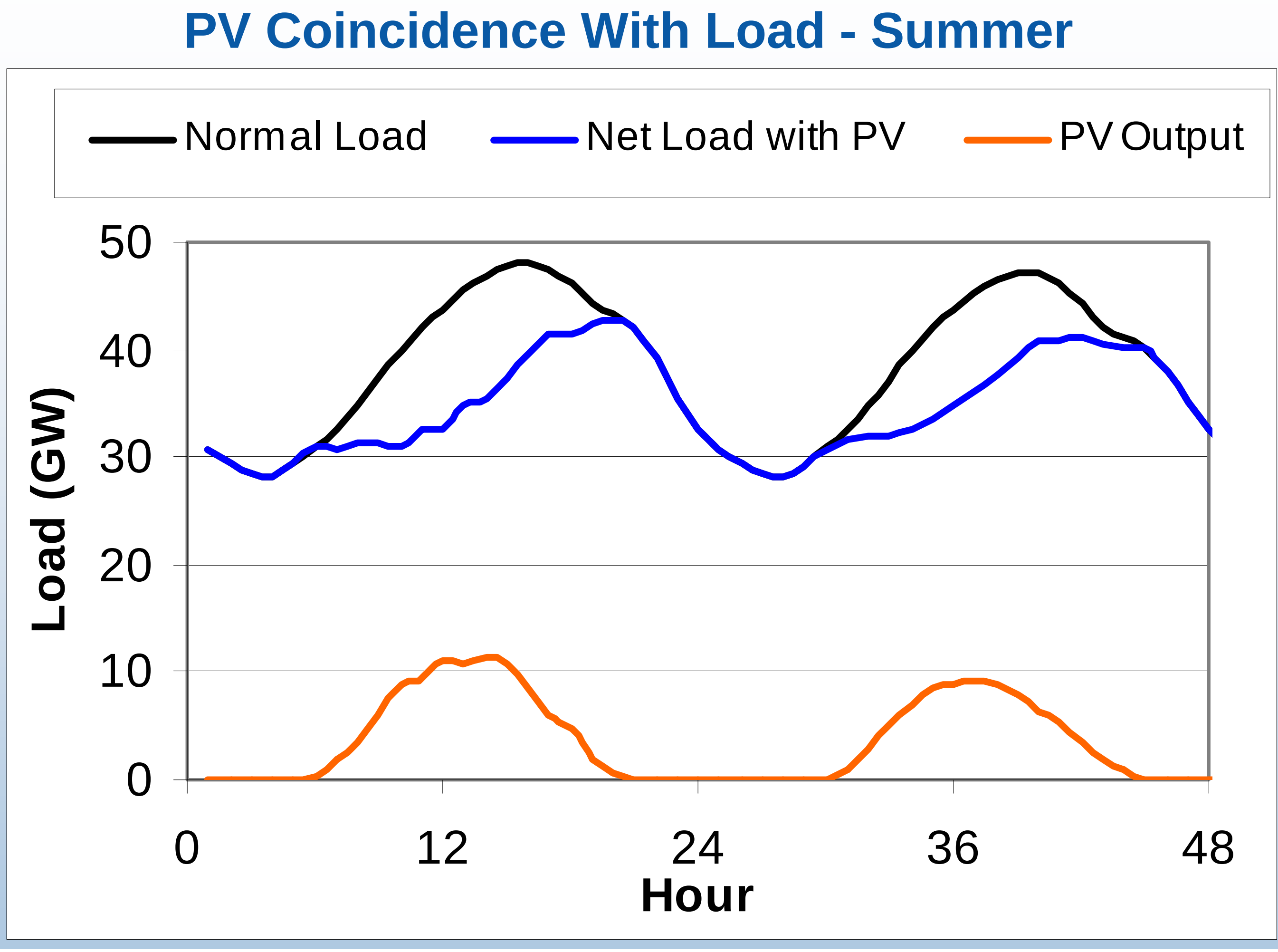
Courtesy of SAGE Electrochromics

An Opportunity



Land area required to meet 100% of nation's electricity demand from solar photo-voltaic (PV) power.

A Problem

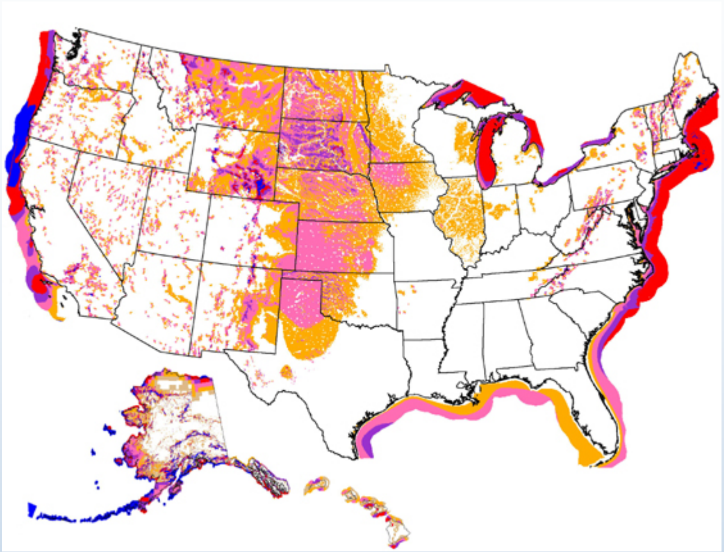


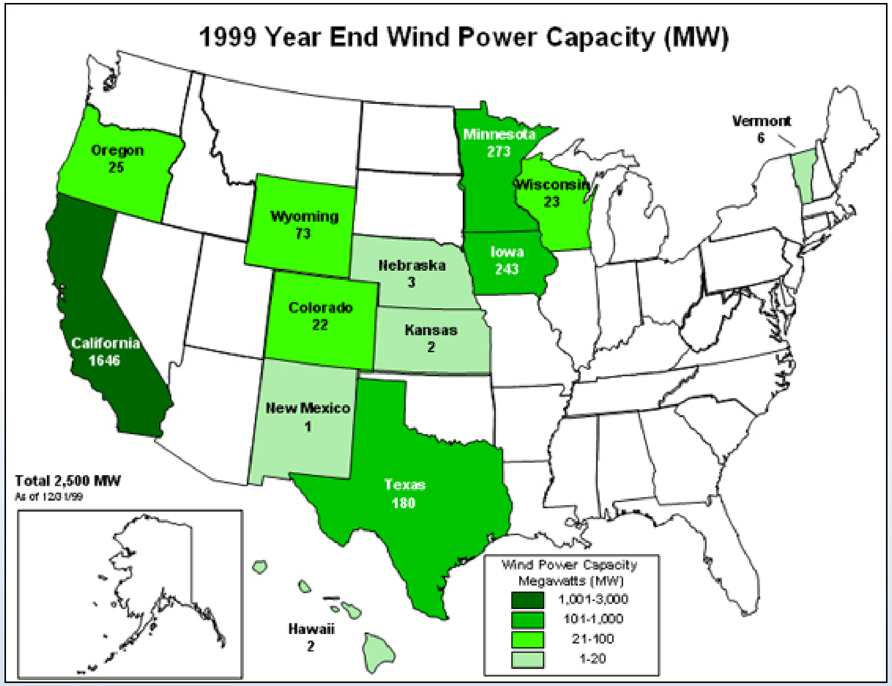
16 GW simulated PV system providing 11% of system's energy

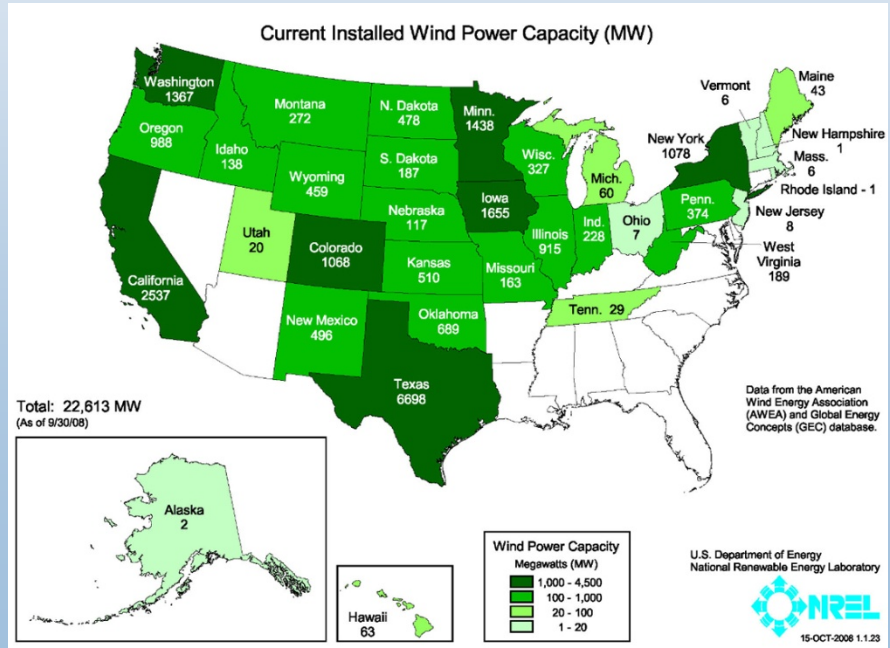
Even in the summer PV generation remains of phase with the load making storage necessary.

Courtesy Paul Denholm, NREL

US Wind Resource Maps
Installed U.S. Wind Capacity







Reaching 1,000 MW of wind energy in 1985, it took more than a decade for wind to reach the 2,000-MW mark in 1999. Since then, installed capacity has grown ninefold. As of 9/30/2008, 22,613 MW have been installed.

Courtesy of NWTC at NREL

Example Wind Applications in Japan

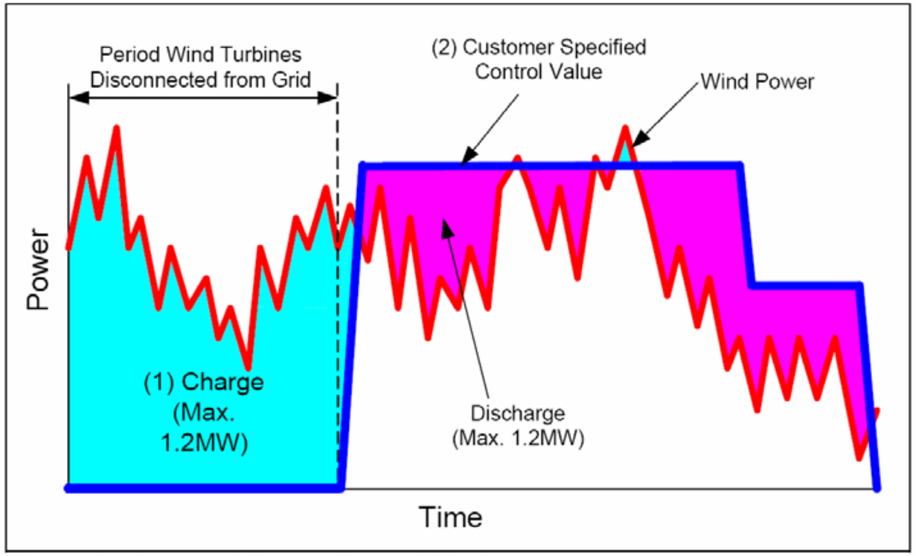


Figure 1. Constant Power Control Mode

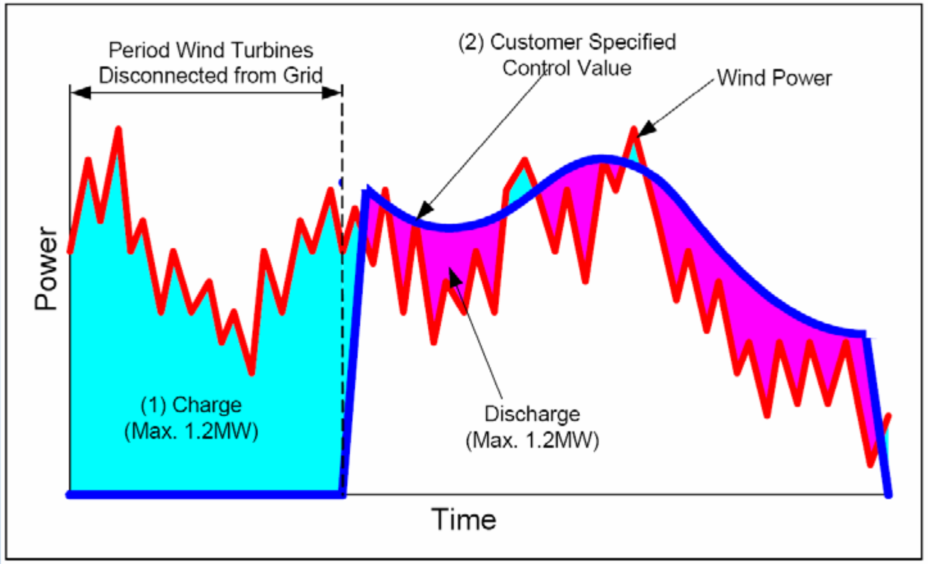
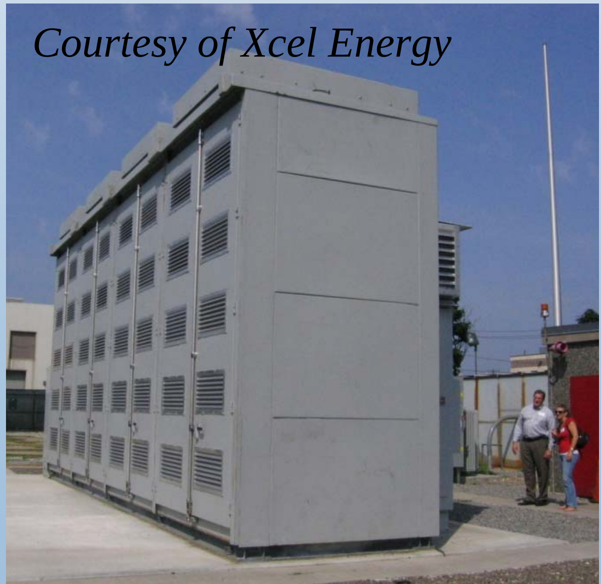
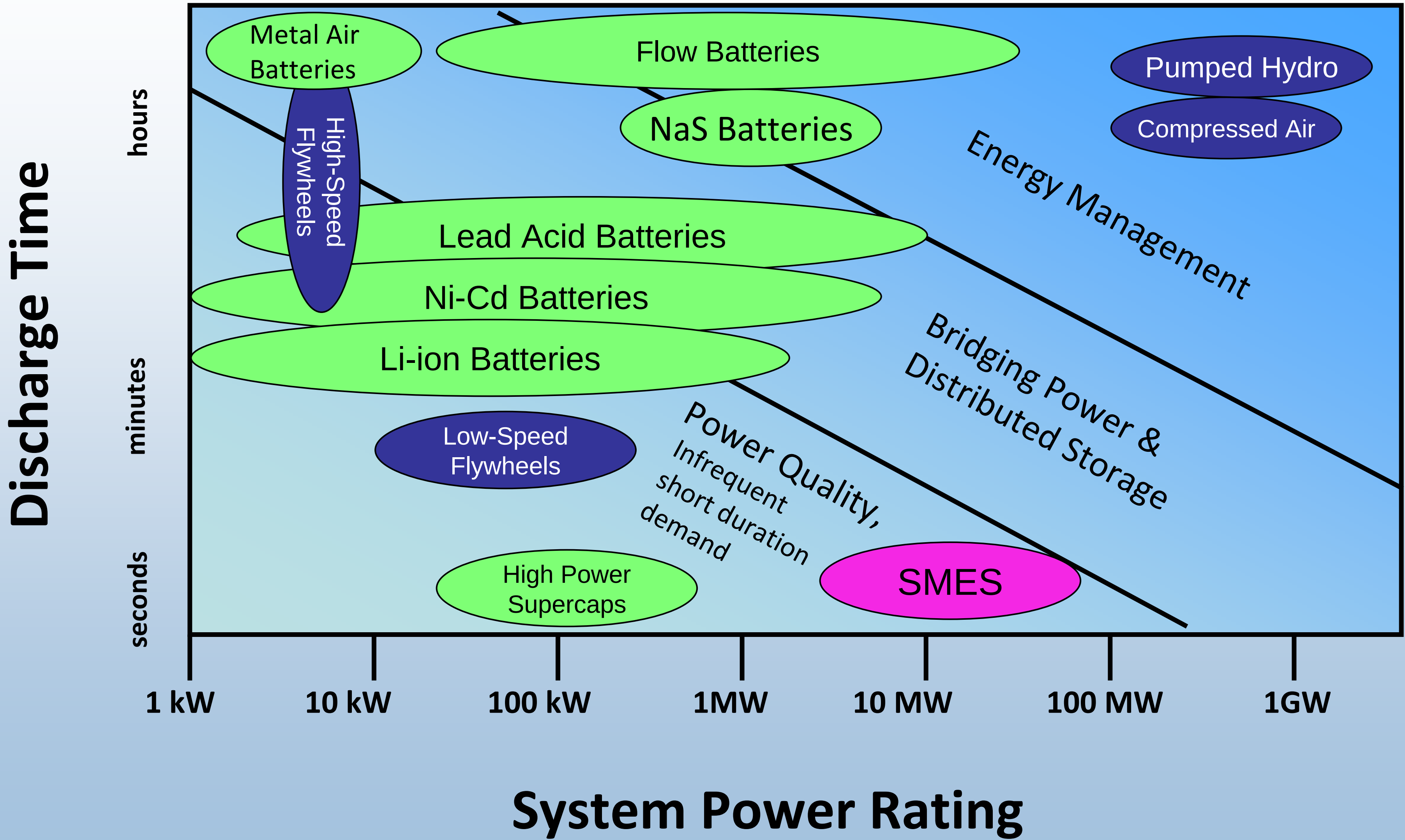


Figure 2. Smoothing Power Control Mode



In Japan, wind developers are required to stabilize wind generator output before connecting to the grid, and NGK has demonstrated NAS batteries in two operating modes to meet T&D utility requirements for interconnection.

Energy Storage Technologies



Adapted from ORNL

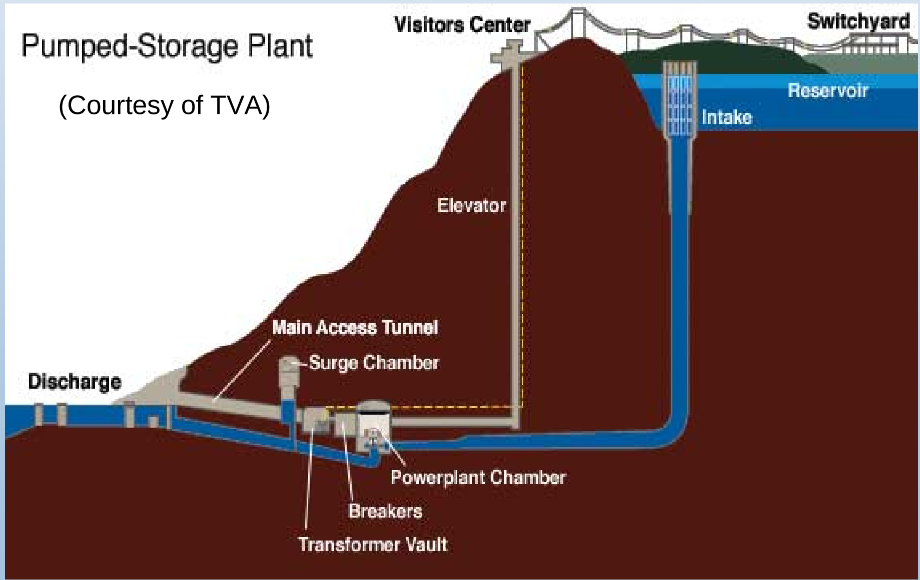
Energy Management

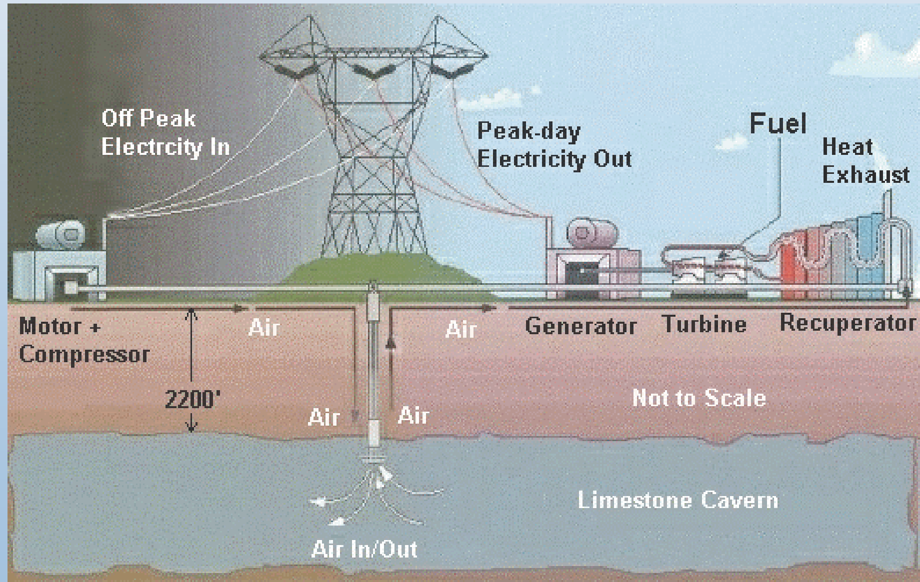
Pumped Hydroelectric Storage

- Considered mature technology
  - AC-AC eff.: 65-80%
- US: 150 sites with 22 GW total
- Growth limited by topography & environmental issues
- Opportunities:
  - Underground PHS
  - Smaller PHS applications

Compressed Air Energy Storage

- Developing technology
  - AC-AC eff.: ~50-80% est.
- US: 1 site with 110 MW (2.7 GW proposed)
- Growth limited by economic issues, conservative economics
- Opportunities:
  - Adiabatic CAES





(Courtesy of Norton Energy Storage LLC)

Power Quality

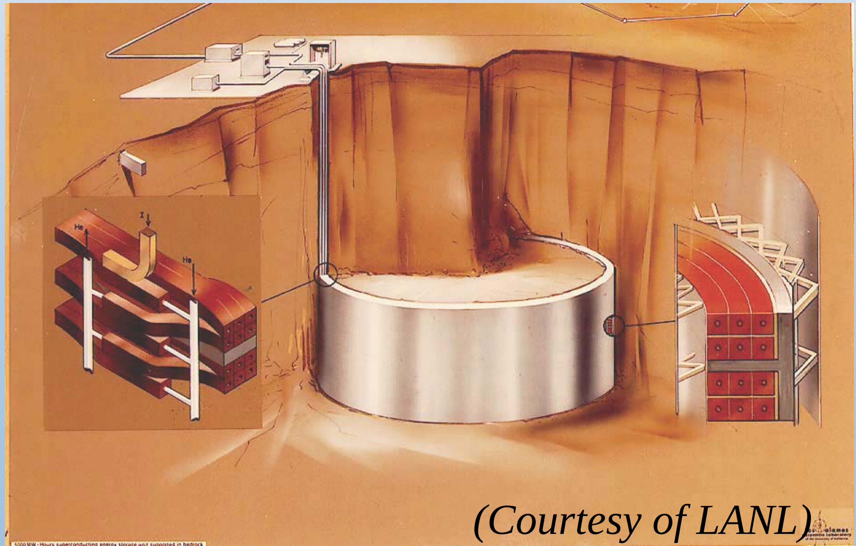
Superconducting Magnetic Energy Storage (SMES)

– Commercial micro-SMES
– Good efficiency & cycling
    • AC-AC eff.: ~80-95% est.
– Economically not viable
    (Niche specific)
– Research Opportunities:
    • Basic research HTS
    • Push for lower cost

Ultracapacitors

(aka electrochemical cap., supercap., psuedocaps.)

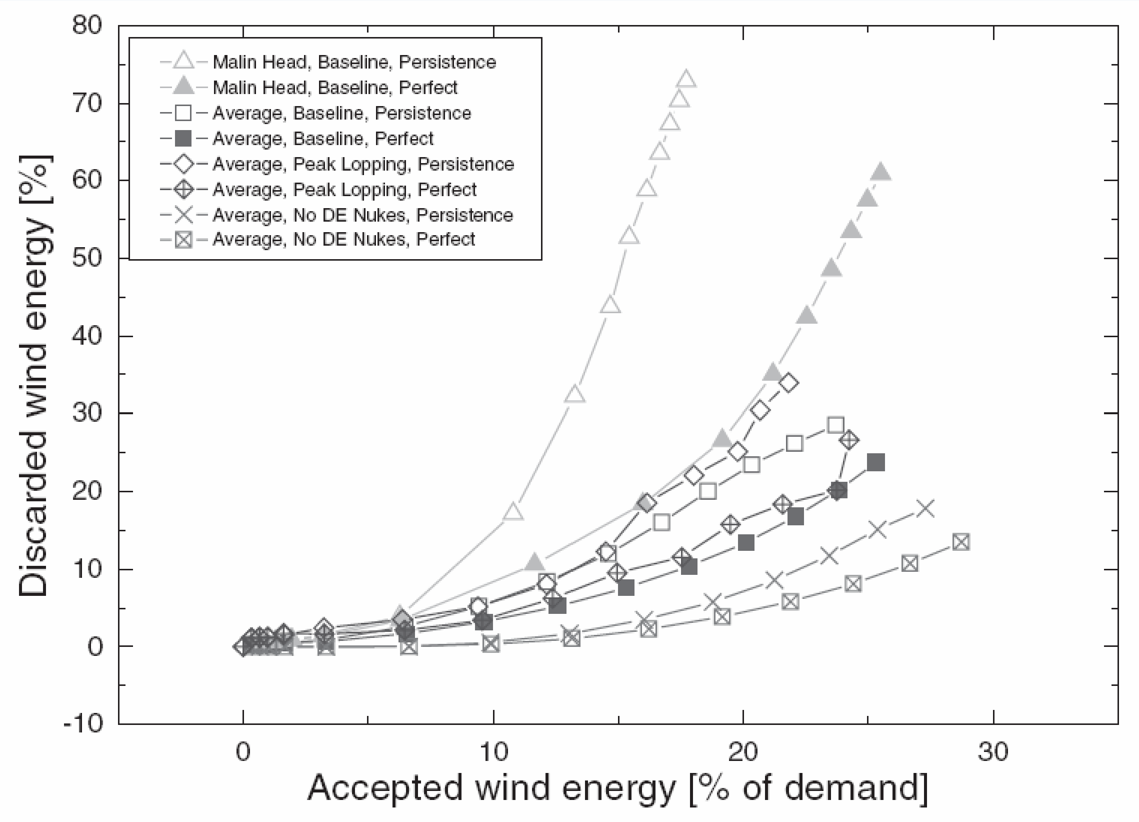
– Commercially available
– Short-duration applications
– Good efficiency & cycling
– Research Opportunities:
    • Improved electrode materials/electrolytes


(Courtesy of LANL)

Additional Technologies for Electrical Storage

- Hydrogen
  - With sufficient round-trip efficiency, may be feasible (fuel cells, turbines)
  - May couple with Hydrogen Economy to enable load leveling (‘cheap’ electricity $\rightarrow H_2$)
  - Research opportunities: storage, conversion
- Thermal Storage
  - Critical components for concentrated solar power, ACAES
  - Distributed thermal storage provides load leveling (residential & commercial buildings)
  - Research opportunities: New heat storage media
- **Distributed Electrical Energy Systems**
  - Examples: PHEV, Residential
  - “Smart” grid needed, new economics
  - Research opportunities: Power electronics (grid coupling)

Wind Energy in Europe

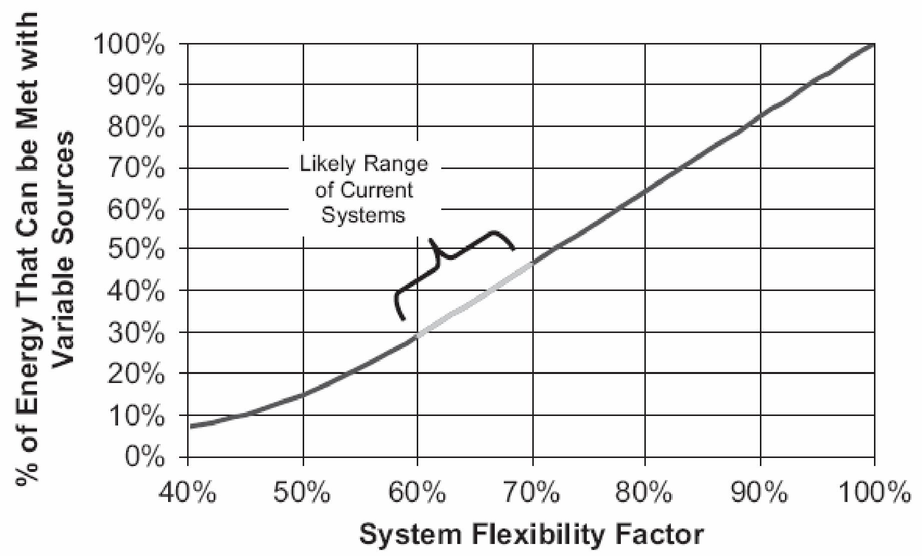


- Small penetrations, nearly no wind energy has to be discarded, while at higher penetrations the percentage of discarded wind energy rises strongly.
- Wind energy can contribute more than 20% of the European demand without significant changes in the system.

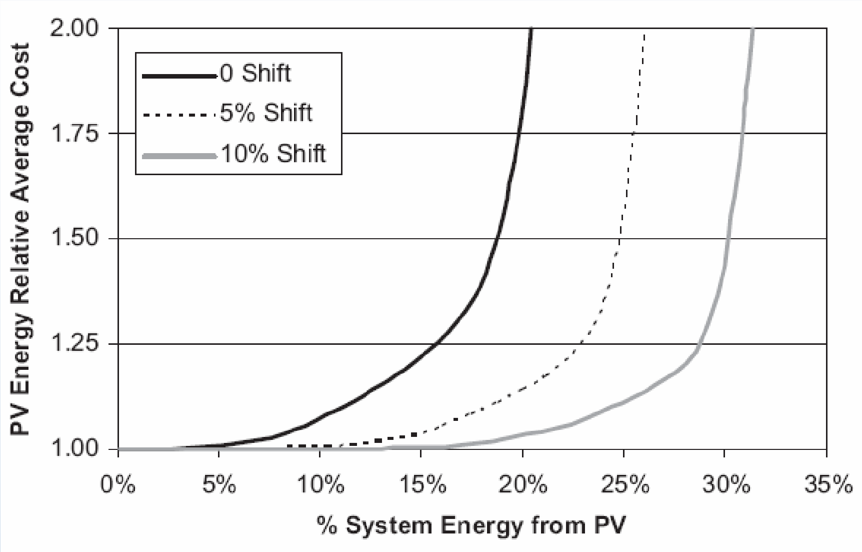
G. Giebel, Wind Energy, 10, 69 (2007)

Three ways to increase renewables penetration

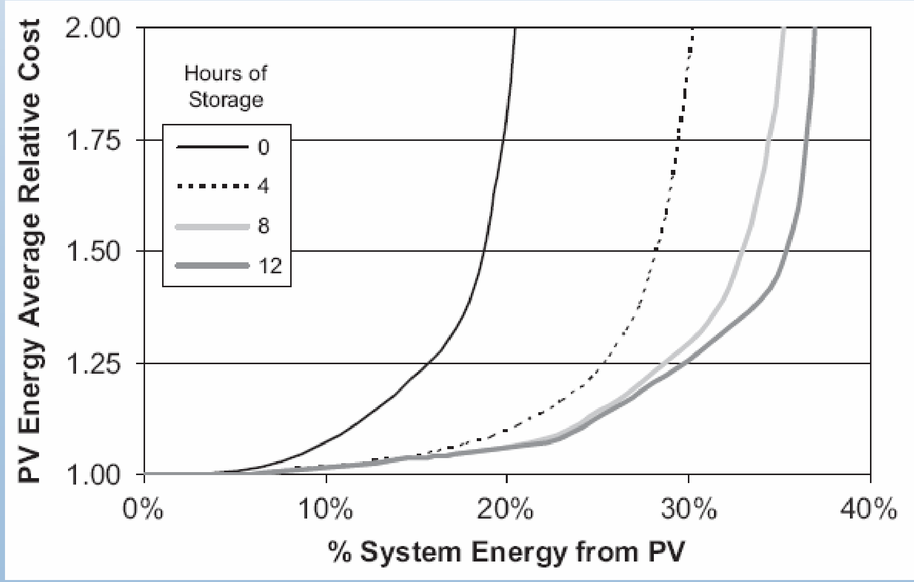
1. Improved system flexibility



2. Load shifting



P. Denholm and R. M. Margolis, Energy Policy 35, 4424 (2007)



3. Energy storage

Why Storage?

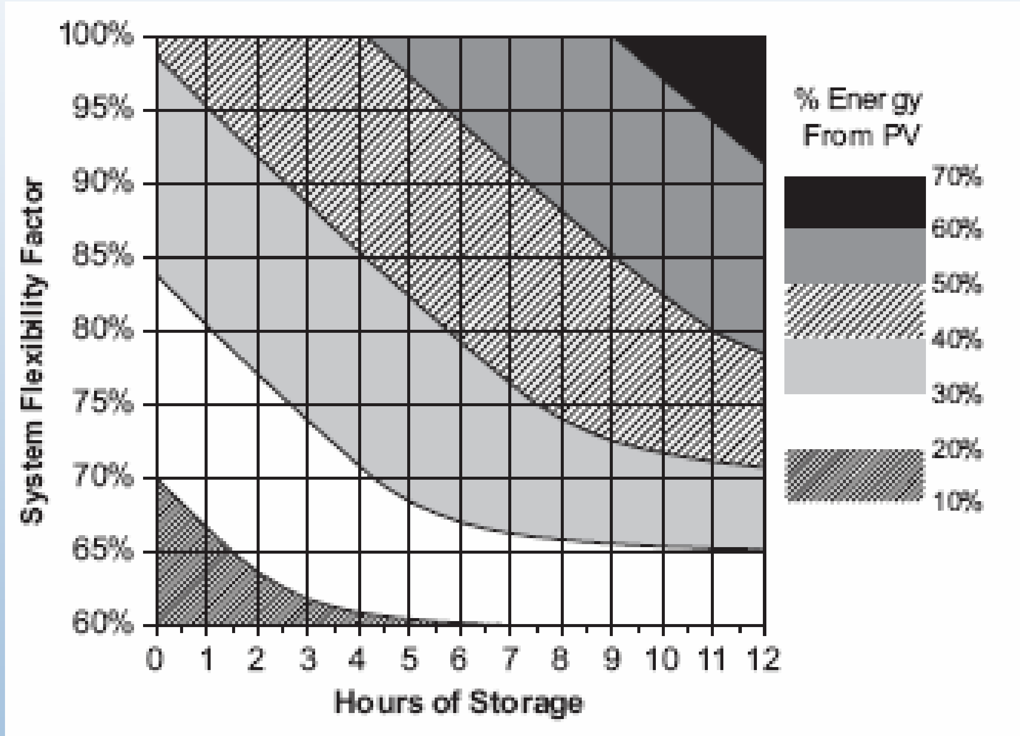
- Energy storage represents the “ultimate” solution to the problem of intermittent generation.
- Energy storage increases the usefulness of intermittent renewables in two ways.

1. It absorbs excess PV or Wind energy and allow PV or Wind energy to be used when it is not produced.
2. Large-scale energy-storage deployment allows increased flexibility in utility system operation.

- The combination of renewables and storage could effectively replace baseload generation, and thus increase the penetration of variable source generation in the system

Storage and increased flexibility

- A combination of storage and increased flexibility could enable intermittent renewables (PV or Wind) to achieve very high levels of penetration.



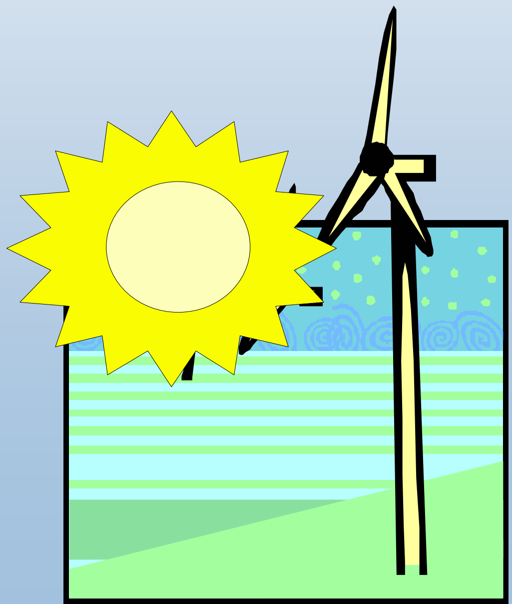
P. Denholm and R. M. Margolis, Energy Policy 35, 4424 (2007)

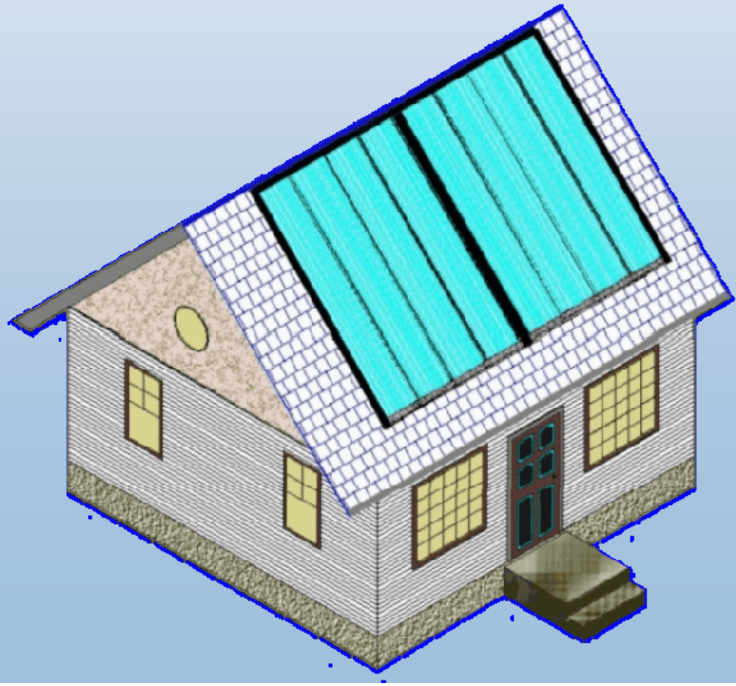
- This level of renewable energy penetration would truly require a raidical transformation of the current electricity system – from a centrally controlled to **a highly distributed and interactive system.**

Your Future Green Home with Distributed Energy System

Energy generation, storage, conversion, and conservation.

- Electricity or H_2 Production via Electrolysis
- H_2 Storage, Rechargeable Battery, Plug-in Hybrid Electric Vehicle
- H_2 Fuel Cell
- Electrochromic Windows





Plug-In Hybrid Electric Vehicles

Detroit, 9/16/08

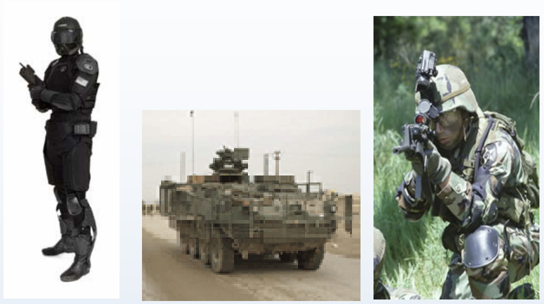
- ❑ Chevy Volt - GM 40 mile PHEV
  - Designed to move more than 75 percent of America's daily commuters without a single drop of gas†

    - **Zero gasoline usage and zero emission production for < 40 mile/day driving**
  - Li-Ion batteries
  - 2010 launch

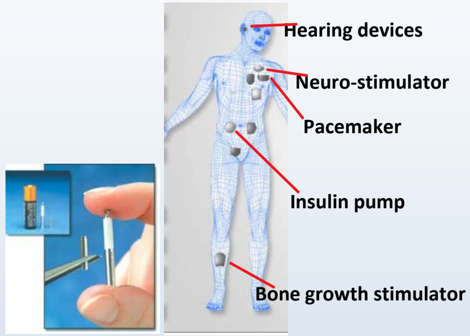
† *www.Chevrolet.com/ElectricCar*

Diverse Applications of Li-ion Batteries

Consumer Electronics



Military Applications



Medical Devices

Li-ion Batteries as power sources

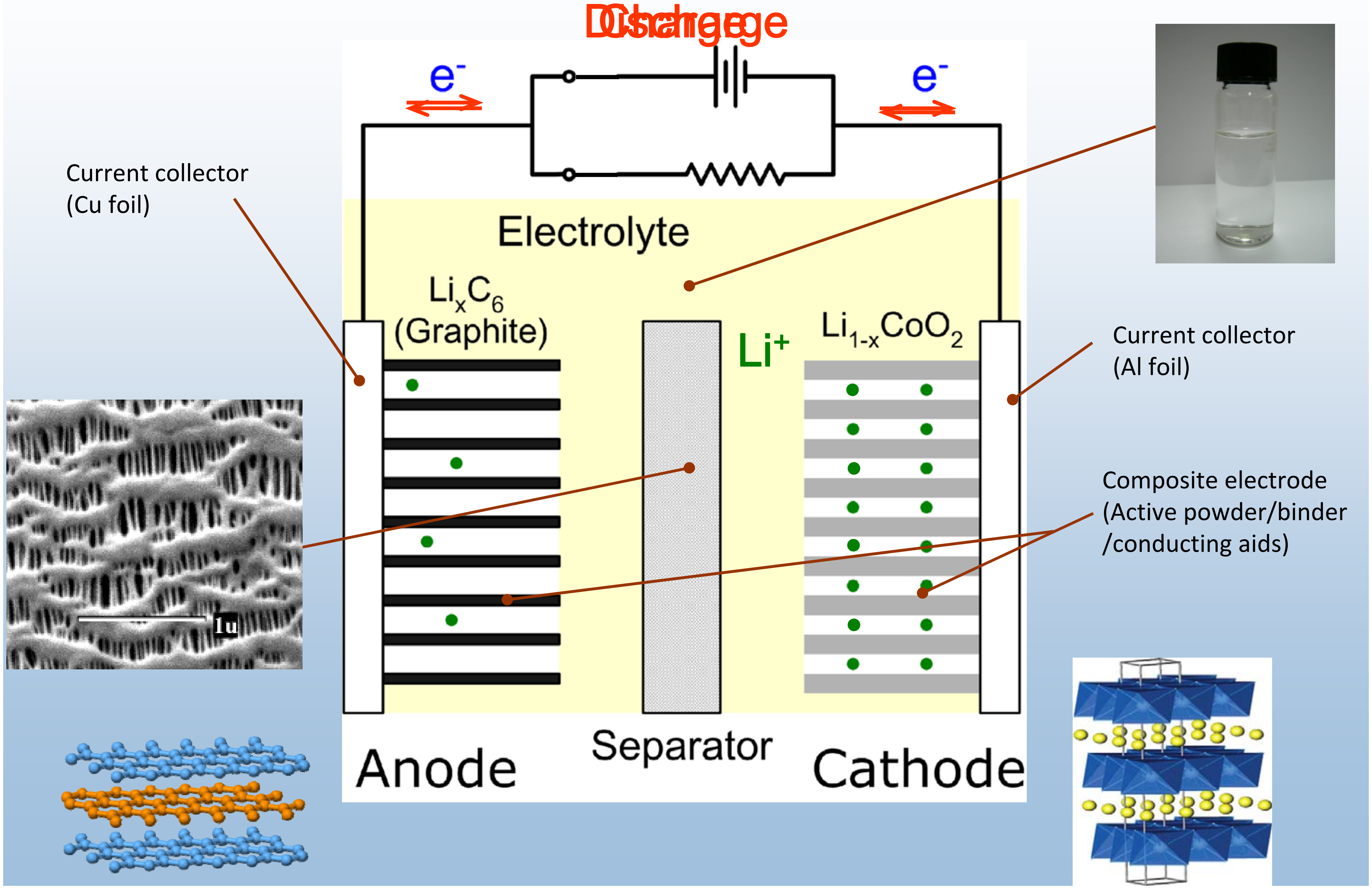
Miscellaneous (power tools, backup power, etc.)

Transportation

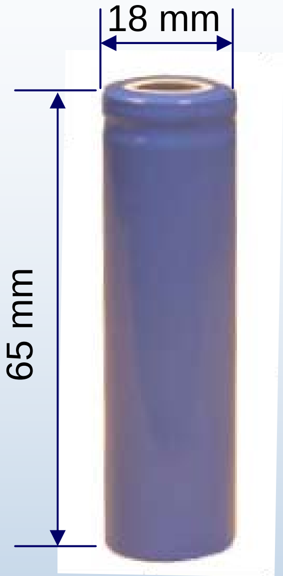
Spaceships and Satellites

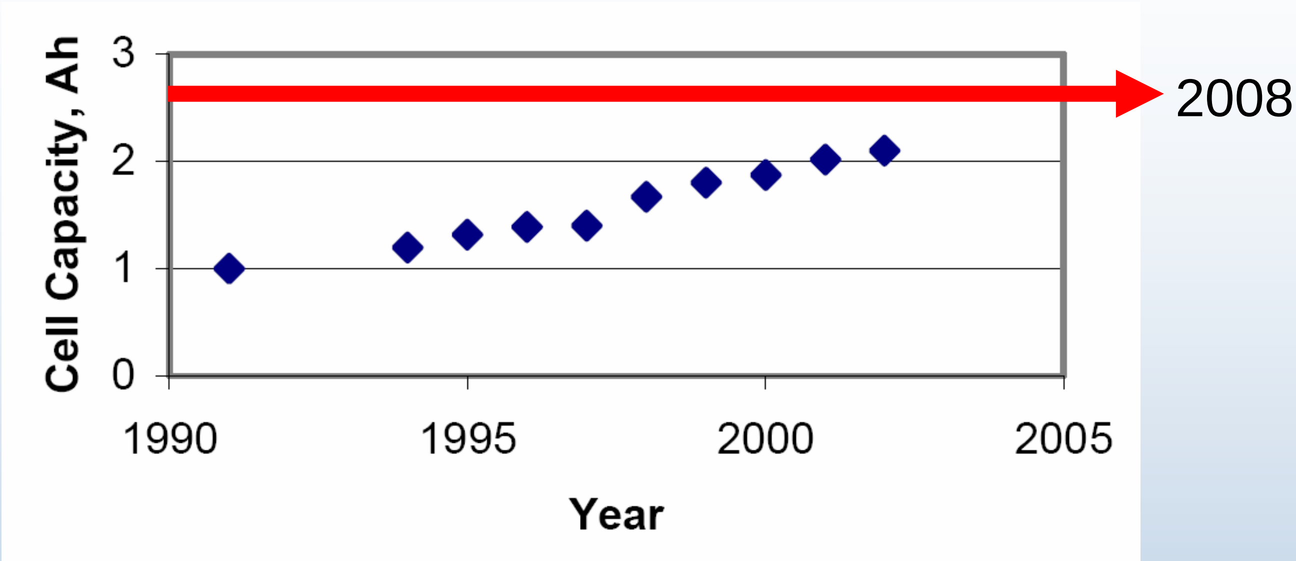
Li-ion secondary batteries ~ 3B cells/year world production

Lithium Ion Batteries (LIBs)



Capacity Increase of commercial 18650 Li-ion cells





www.electrochem.org/dl/ma/201/pdfs/0259.pdf

- In spite of the capacity increase, the cell chemistry (cathode and anode) remains similar: $LiCoO_2$- and carbon-based materials, respectively.
- A breakthrough is needed to further increase the cell capacity (and energy density) to meet the energy (and power) requirements for advanced portable electronics.

PHEV Battery Requirements

Characteristics at EOL (End of Life)		High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Reference Equivalent Electric Range	miles	10	40
Peak Pulse Discharge Power (2 sec/10 sec)	kW	50/45	46/38
Peak Regen Pulse Power (10 sec)	kW	30	25
Available Energy for CD (Charge Depleting) Mode, 10 kW Rate	kWh	3.4	11.6
Available Energy in CS (Charge Sustaining) Mode	kWh	0.5	0.3
CD Life / Discharge Throughput	Cycles/ MWh	5,000 / 17	5,000 / 58
CS HEV Cycle Life, 50 Wh Profile	Cycles	300,000	300,000
Calendar Life, 35°C	year	15	15
Maximum System Weight	kg	60	120
Maximum System Volume	Liter	40	80
System Recharge Rate at 30°C	kW	1.4 (120V/15A)	1.4 (120V/15A)
Unassisted Operating & Charging Temperature	°C	-30 to +52	-30 to +52
Survival Temperature Range	°C	-46 to +66	-46 to +66
Maximum System Production Price @ 100k units/yr	$	$1,700	$3,400

Source: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2007_energy_storage.pdf

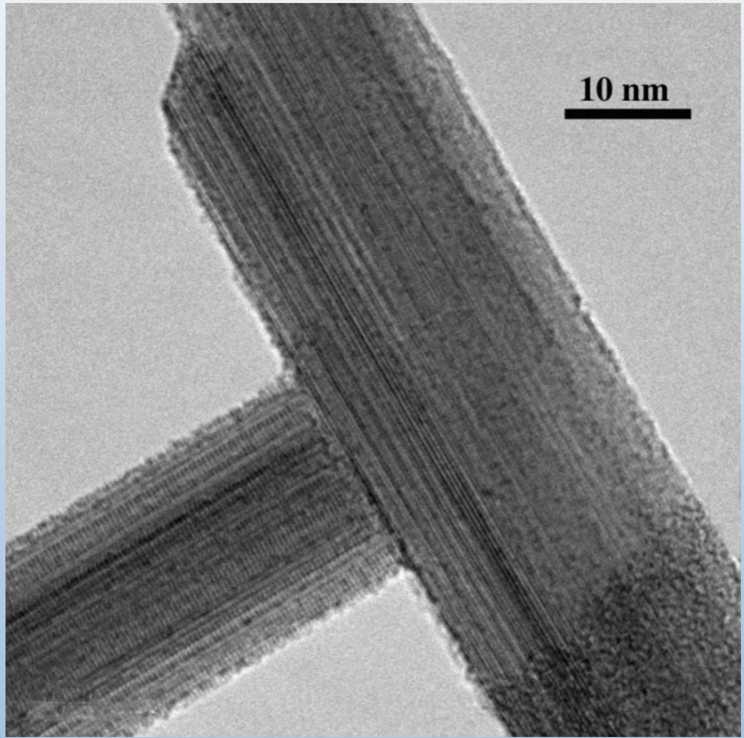
- New battery chemistries (cathode, anode, electrolyte, etc) are needed to achieve these goals!
  - Key issues: Energy, Power, Life, Safety, and Cost

Nanostructured Materials

•Nanotubes, Nanorods, Nanoshperoids, PDCs etc

•Nanocomposites:

- Inorganic-Inorganic: CNTs-Metal oxides, CNTs-PDCs, etc
  - Inorganic-Organic: Oxide-polymer multilayer, HPA-metal oxides, etc



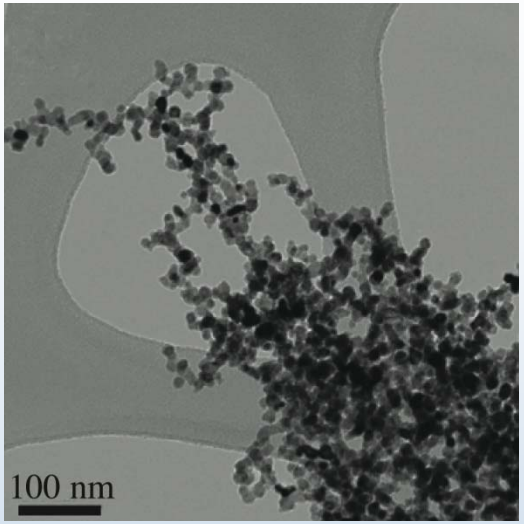
Crystalline WO_3 Nanorods

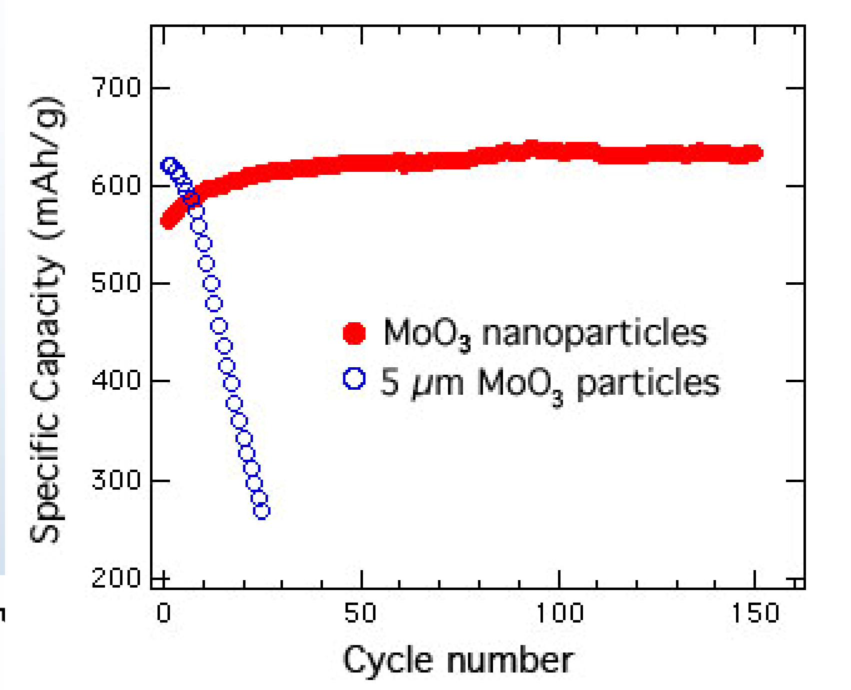
- **Nanostructured Materials** have a host of applications including high-energy-density Li^+ ion batteries, photoelectrochemistry, and electrochromic (EC) windows.
- Kinetics of the reaction is limited by solid-state diffusion of either ions or electrons.
- Time constant determined by diffusion coefficient (crystal structure) and length of diffusion path (microstructure).

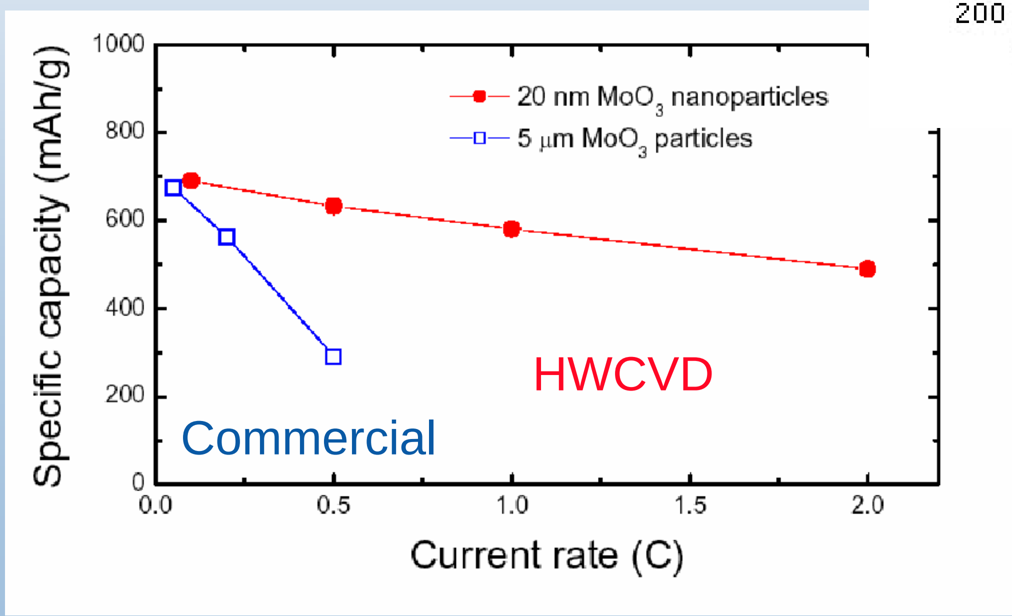
$$l \propto \sqrt{Dt}$$

- Short path lengths for Li^+ transport → higher power and faster response.
- Better accommodation of the strain of lithium insertion/removal → improved cycle life.
- Shorter electron transport distance → higher efficiency.

MoO_3 Nanoparticles by HWCVD





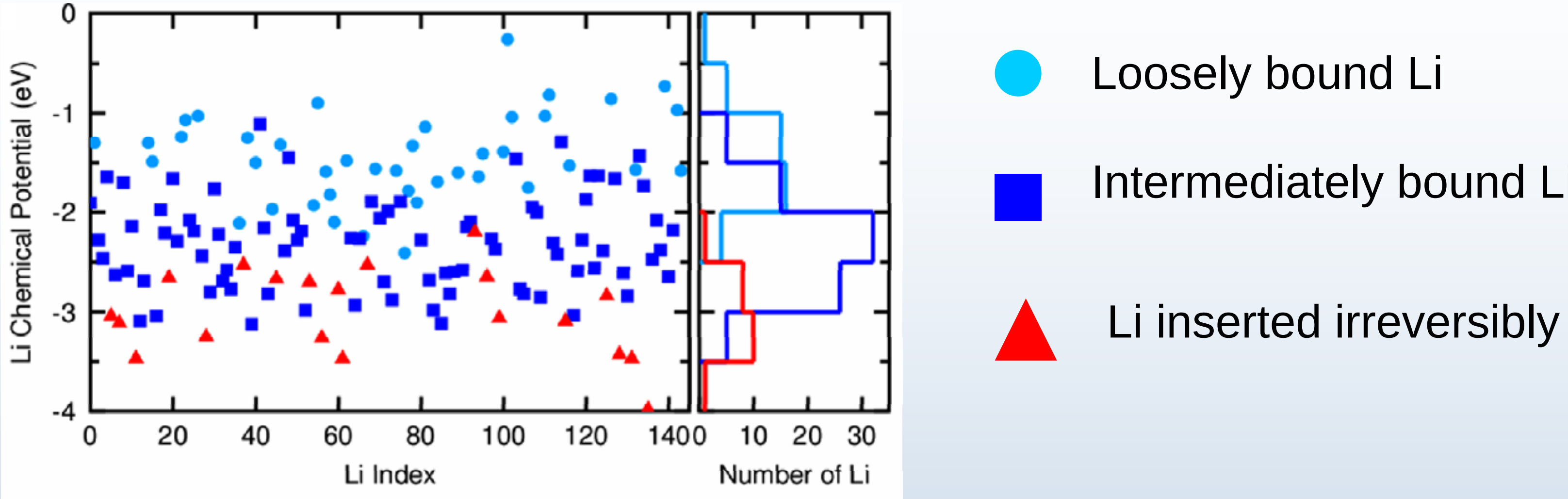


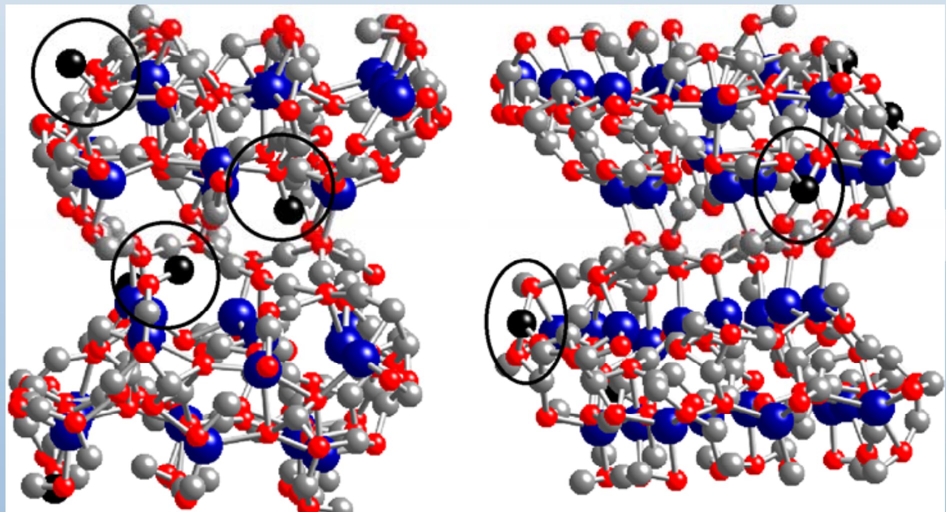
Nanoparticles exhibit 630 mAh/g reversible capacity for 150 cycles. At C/2 rate.

Capacity of commercially employed graphite is 350 mAh/g.

S.-H. Lee, et al Advanced Materials 20, 3627 (2008)

Theoretical Atomistic Energetics





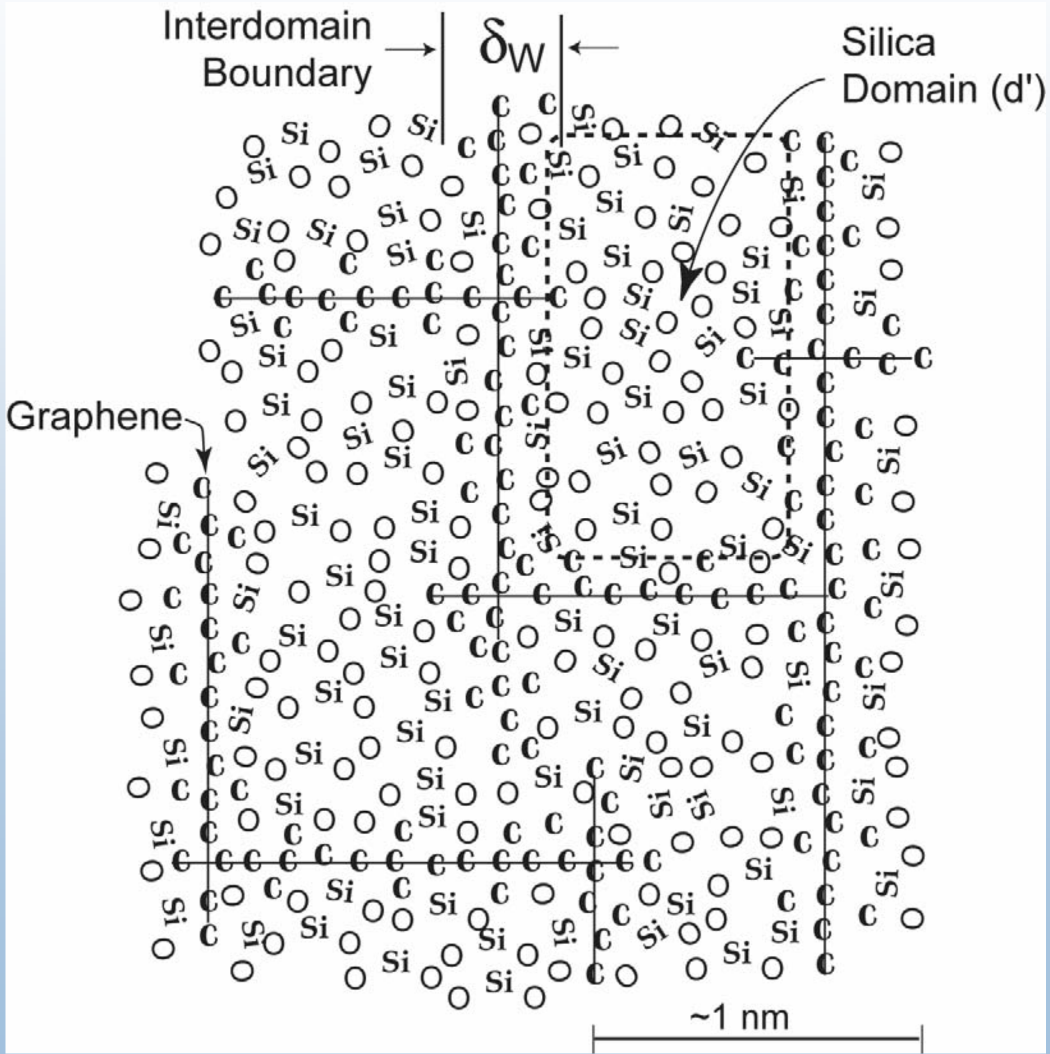
Li /one oxygen **Li / three oxygen**

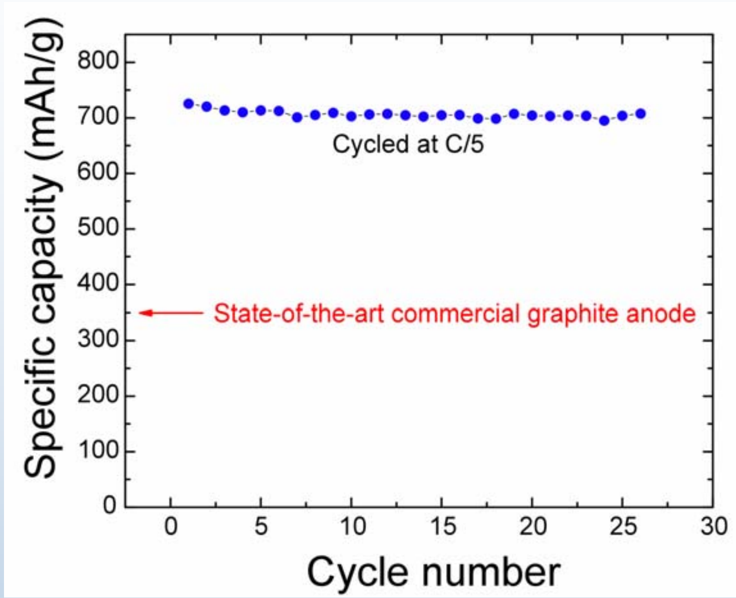
The Li that is inserted irreversibly interacts with three oxygen atoms. The reversible Li interact with either one (loosely bound) or two (intermediately bound) oxygen atoms.

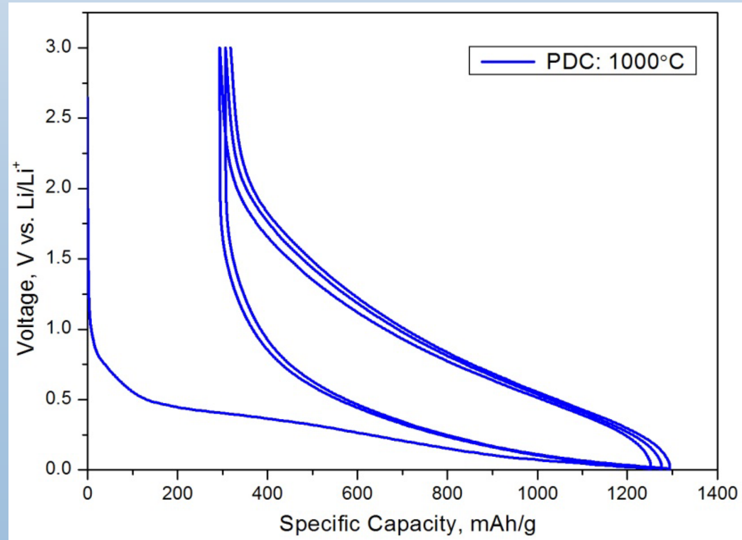
● Mo ● O ● Li

Polymer Derived Ceramics (PDCs)

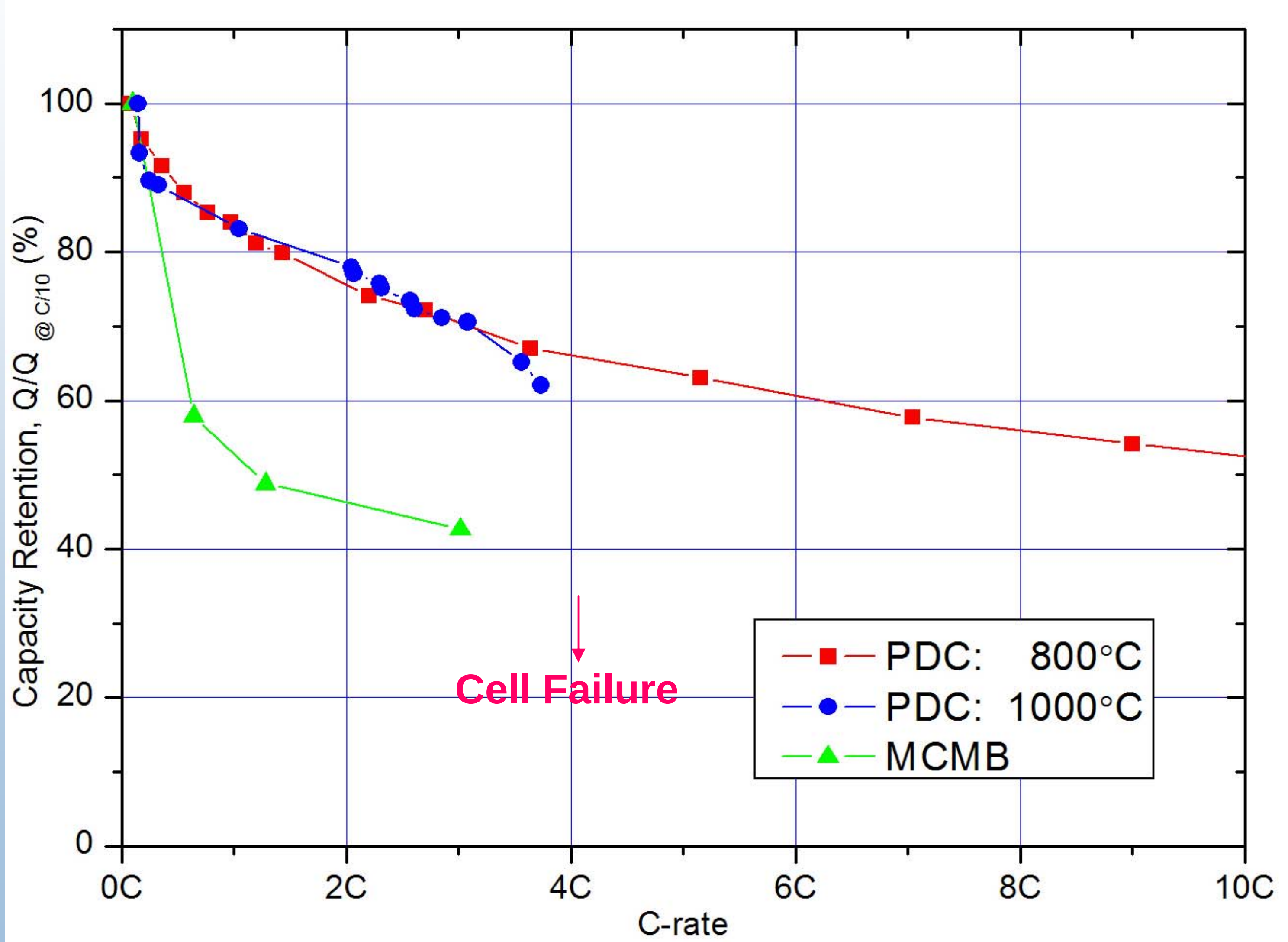
- Ceramic materials from organic polymers by pyrolysis



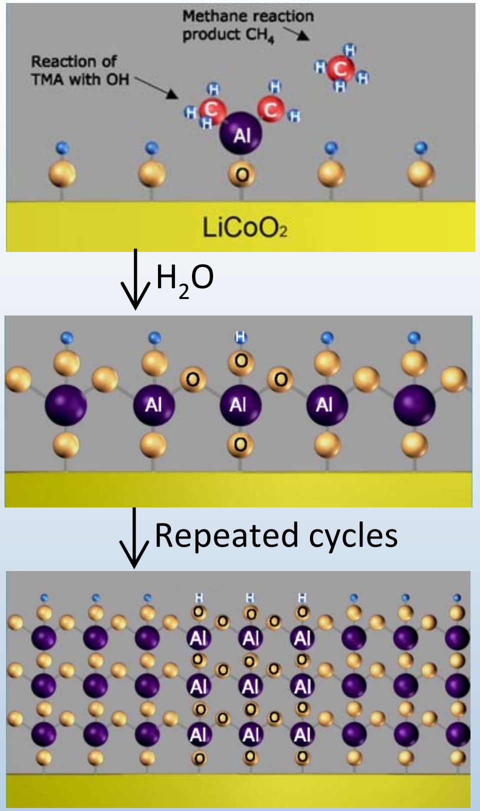


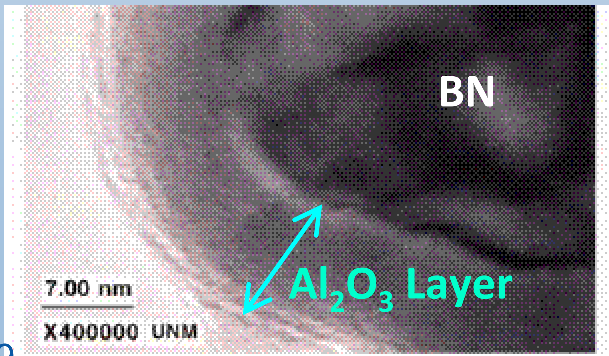


PDCs: Rate Capability

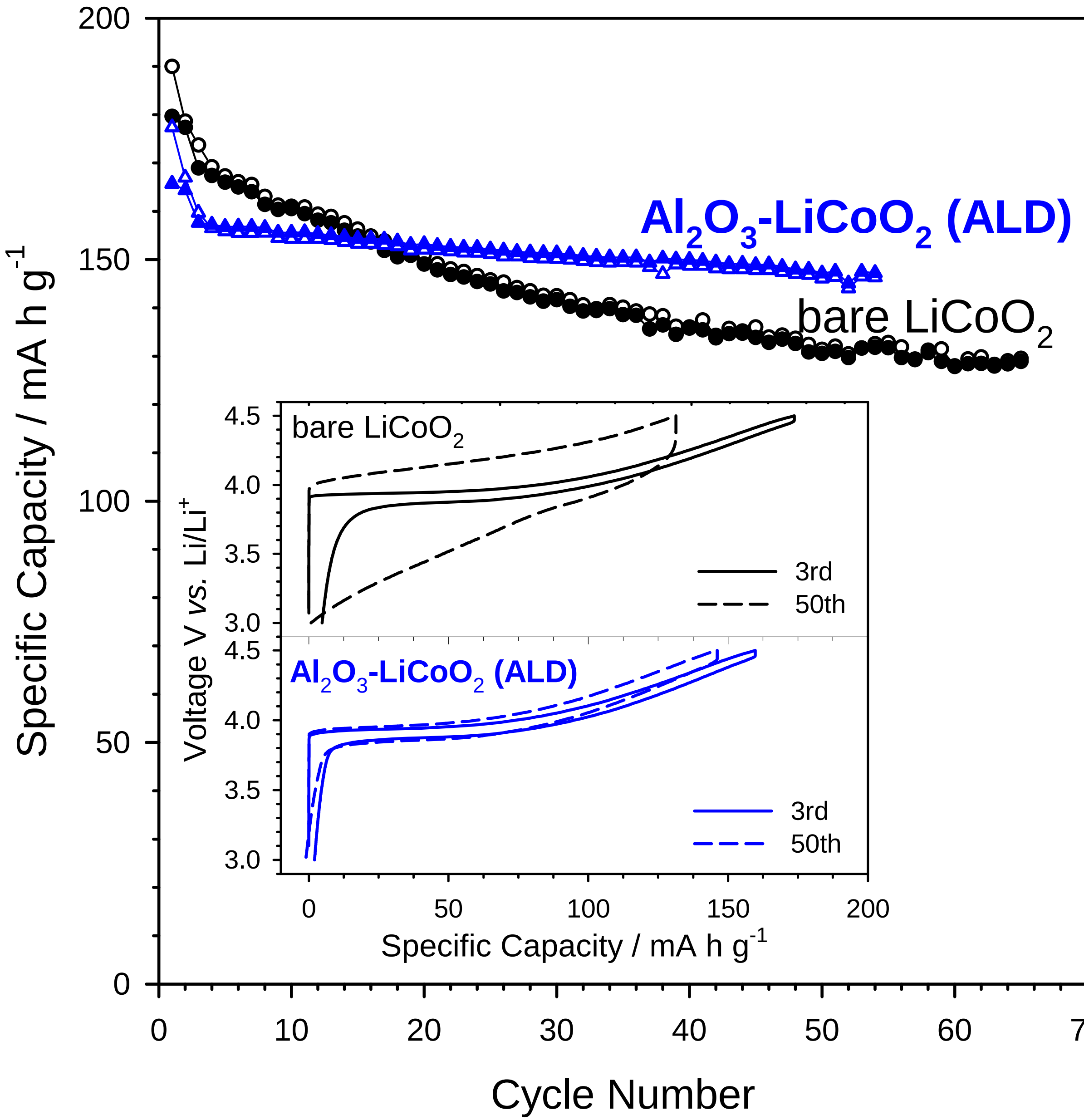


Surface-Coated Cathode by ALD (Atomic Layer Deposition)

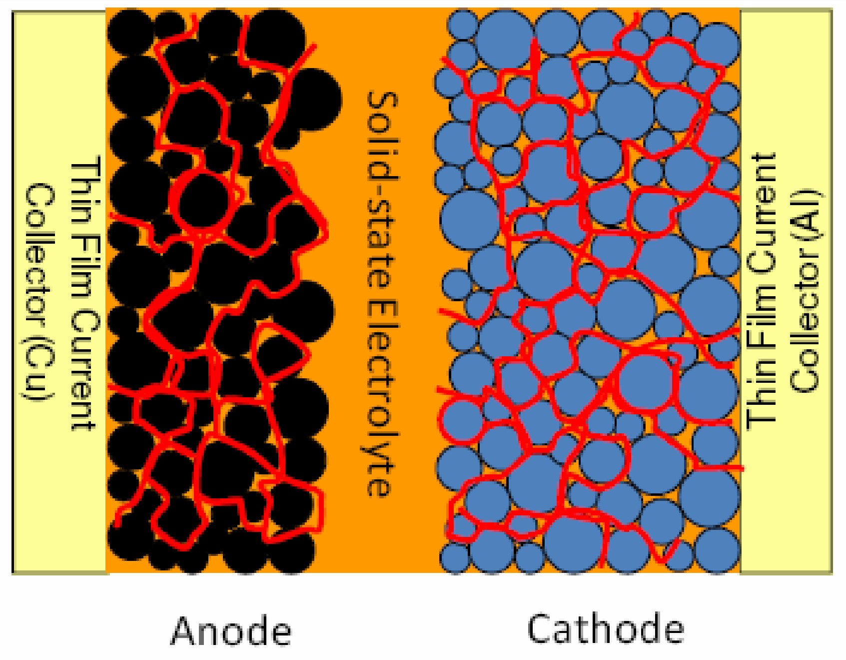


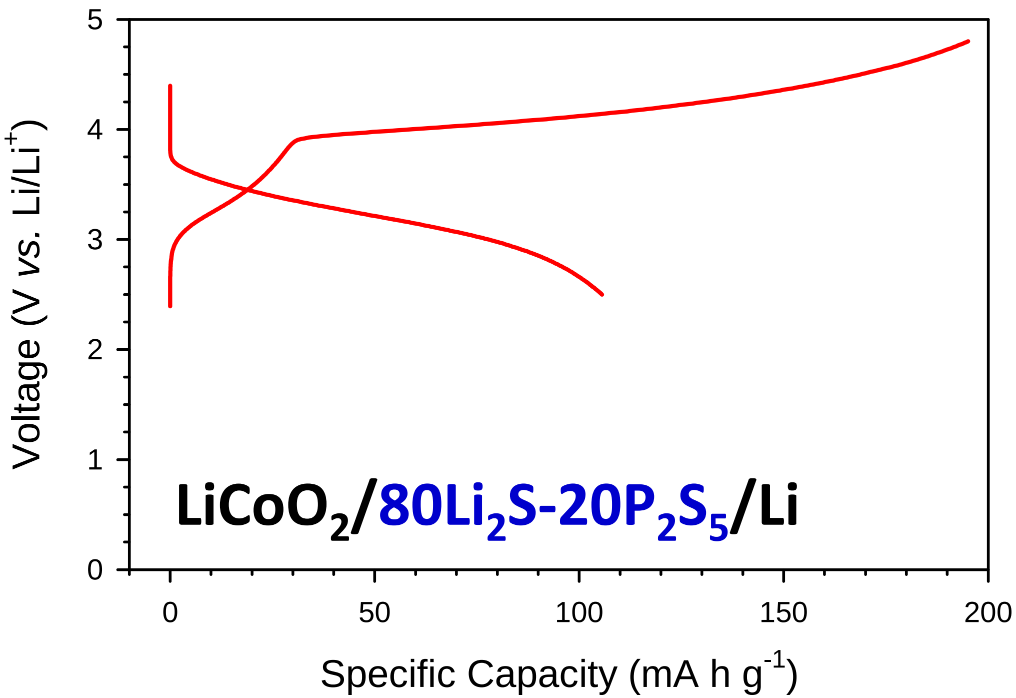


ALD by Prof. Steve George

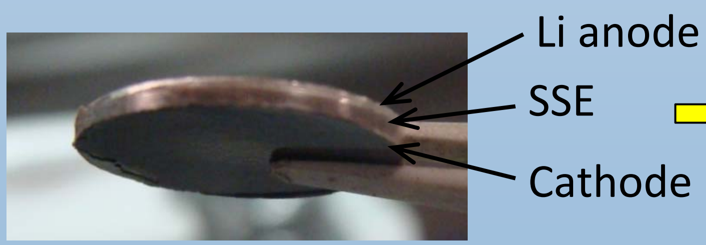


All-Solid-State Nanocomposite Li Batteries

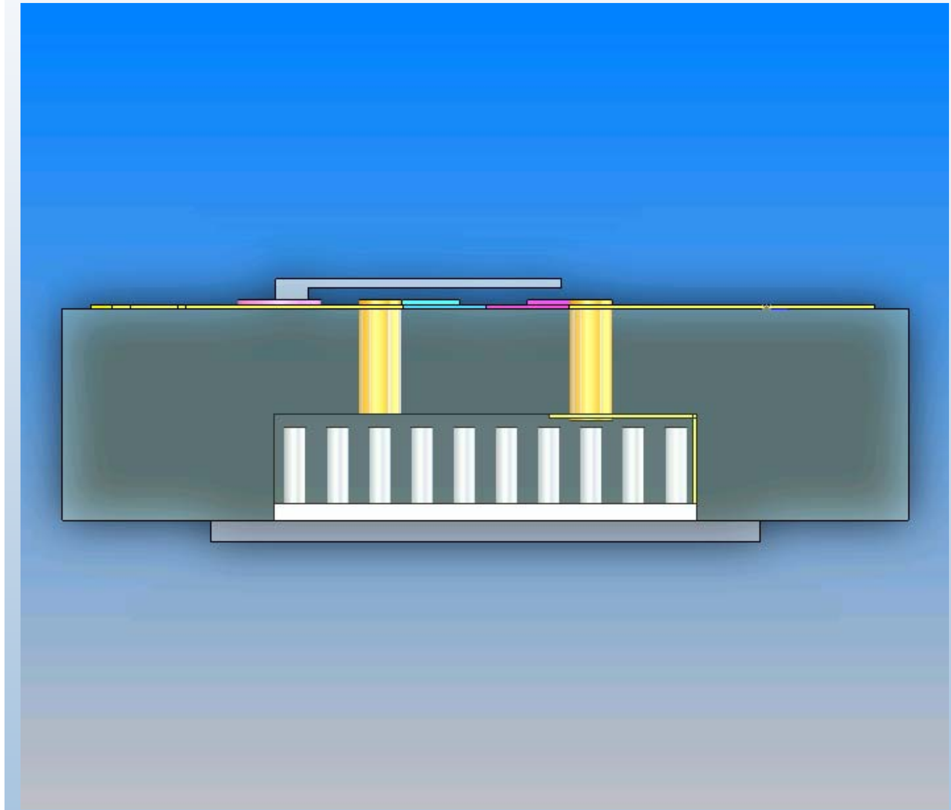


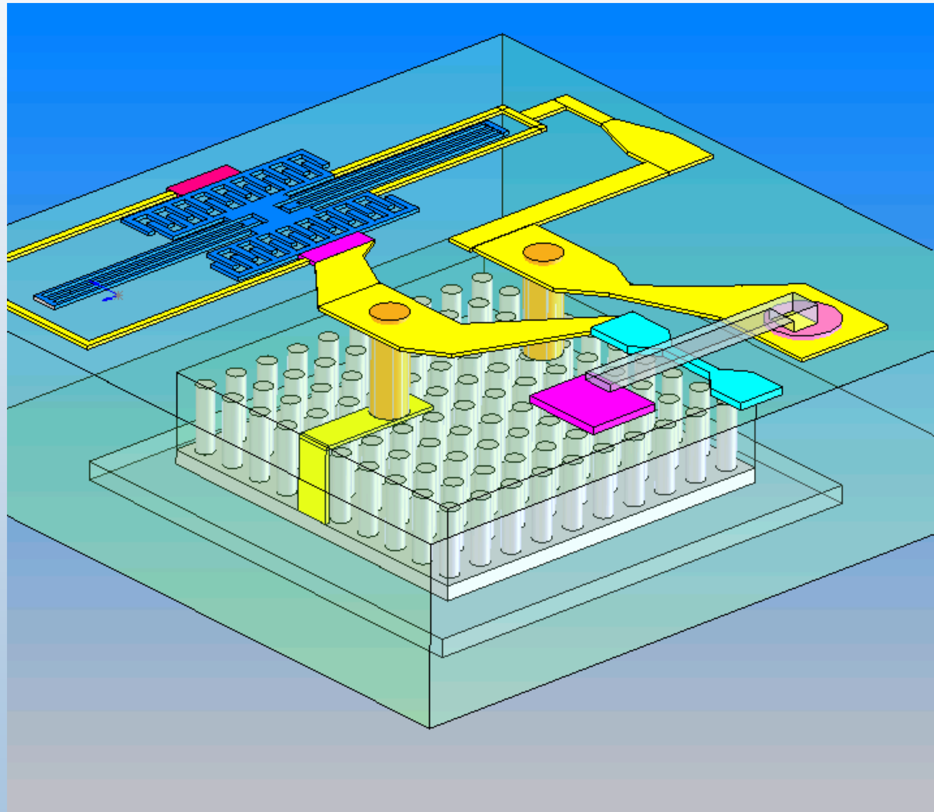


- **Energy density > 500 Wh/kg (vs. 150 Wh/kg)**
- **Power density > 2000 W/kg (vs. 260 W/kg)**



MEMS and/or CMOS electronic devices powered by on-chip solid-state battery





Summary

- High penetration of solar & wind now a reality
- Energy storage represents the "ultimate" solution to the problem of intermittent generation.
- Energy storage increases the usefulness of intermittent renewables.
- The combination of renewables and storage could effectively replace baseload generation, and thus increase the penetration of variable source generation in the system.
- High level of renewable energy penetration would truly require a raidical transformation of the current electricity system – from a centrally controlled to a highly distributed and interactive system.
- Li-ion batteries and enabling nanotechnologies

Acknowledgements:

DARPA/DSO, NREL, SRC, DOE-STTR, CU-IGP

Thank you!

Energy Density of Some Materials (kWh/kg)

- Gasoline ------------------------ 14
- Lead Acid Batteries -------------- 0.04
- Li-ion batteries ----------------- 0.15
- Hydrostorage --------------------- 0.3 (per cubic meter)
- Flywheel, Steel ------------------ 0.05
- Flywheel, Carbon Fiber ----------- 0.2
- Flywheel, Fused Silica ----------- 0.9
- Compress Air --------------------- 2 (per cubic meter)
- Hydrogen ------------------------- 38

Gasoline has one of the highest energy density storage capacities. This makes it very difficult to duplicate the convenience that gasoline has traditionally provided (e.g. 93 kg of Li-ion batteries is equivalent to 1 kg of gasoline !).