Importance of Storage for the Grid

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Director, Office of Science
Department of Energy

Trans-Atlantic Workshop on Storage Technologies for Power Grids

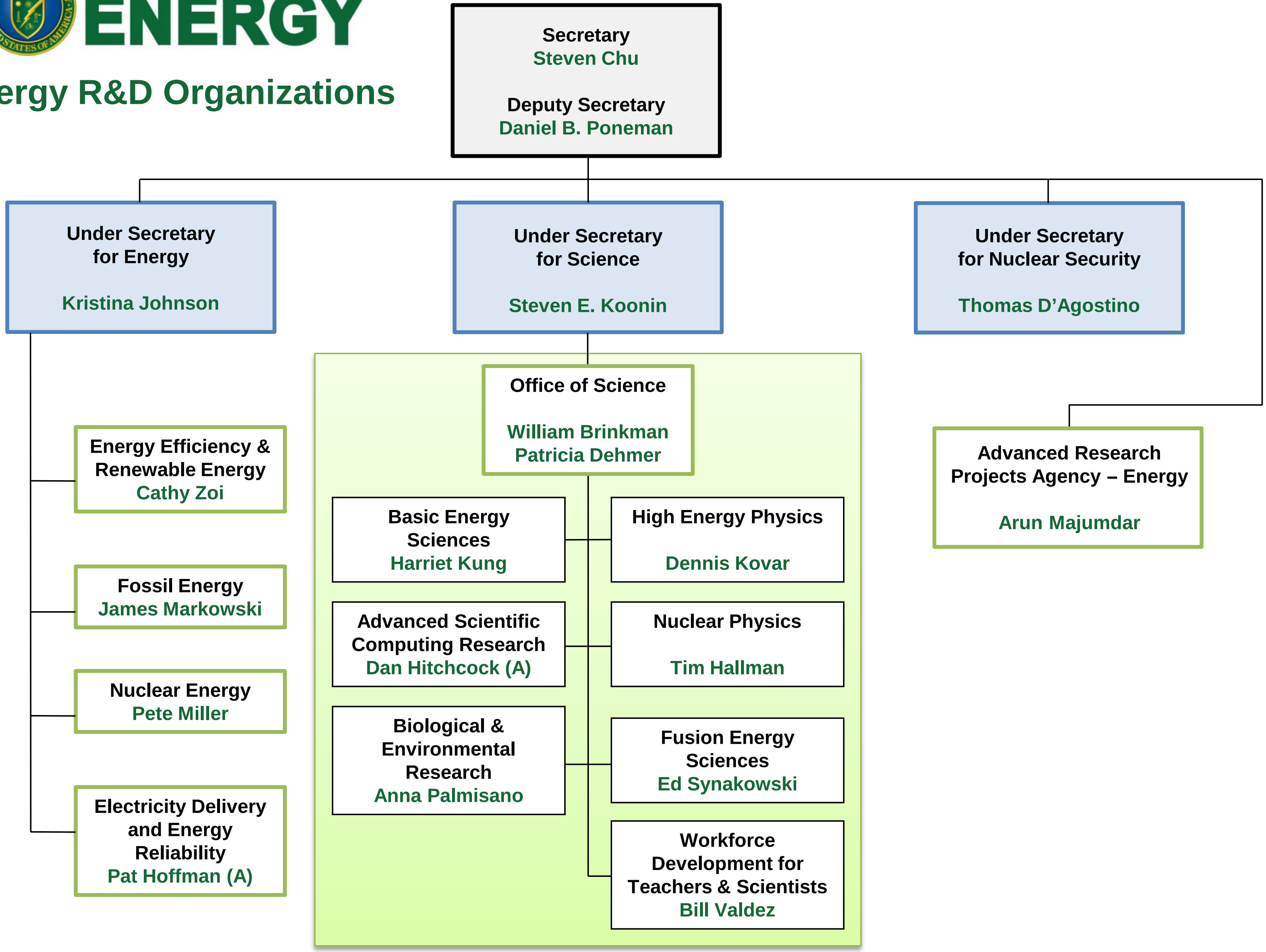
Washington, D.C. Convention Center
October 19, 2010

Department of Energy Strategic Plan

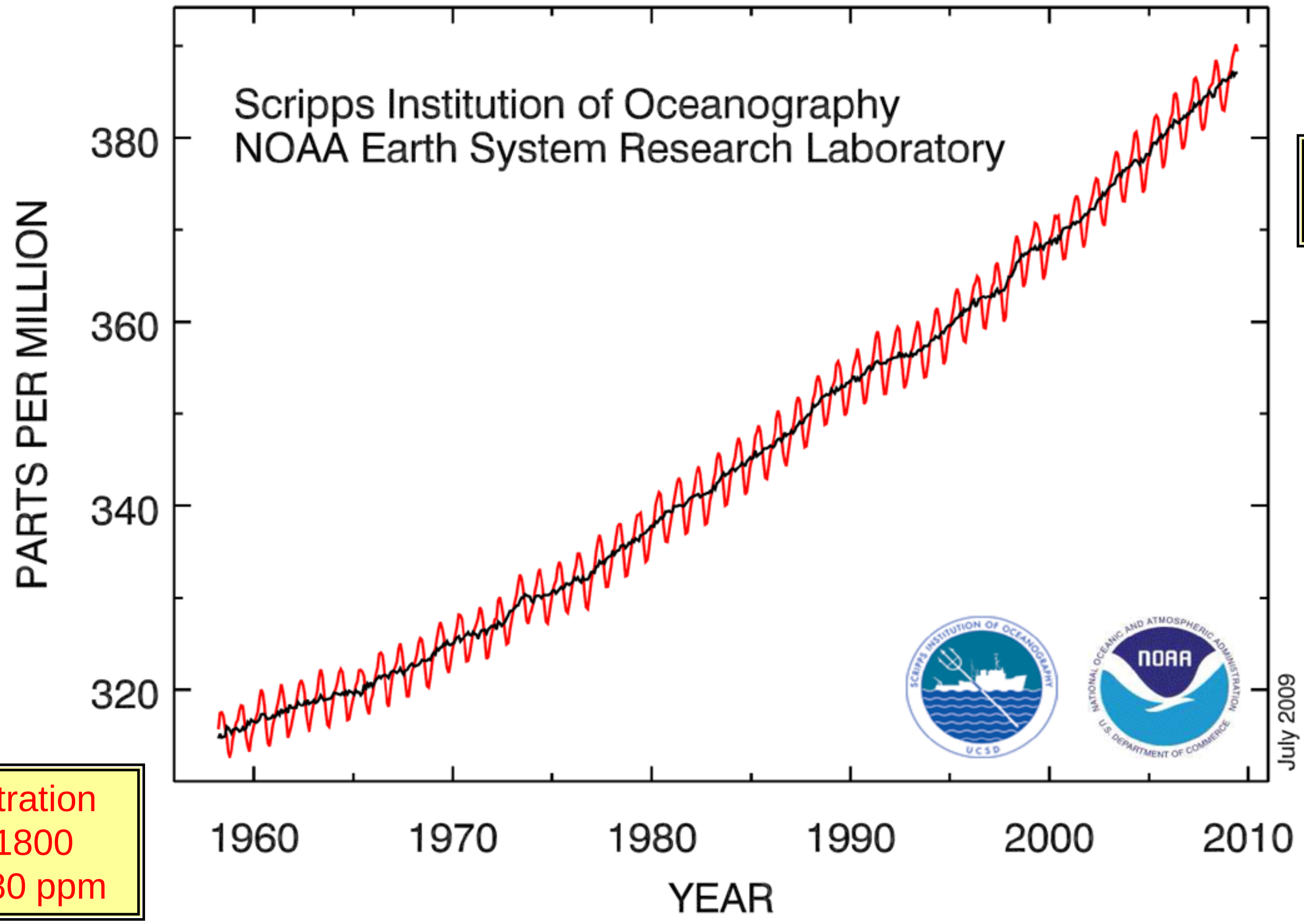
- **Transforming our Energy Systems**
  - Deploying the Technologies We Have
  - Discovering the New Solutions We Need
  - Driving the National Conversation on Energy
- **The Science and Engineering Enterprise**
  - Extending Our Knowledge of the Natural World
  - Delivering New Technologies to Advance Our Mission
  - Sustaining a World-Leading Technical Workforce
- **Securing our Nation**
  - Supporting the U.S. nuclear stockpile and future military needs
  - Reducing global nuclear dangers
  - Applying DOE's capabilities for other critical national security missions
  - Supporting responsible civilian nuclear power development and fuel cycle mgmt
  - Completing environmental remediation of our legacy and active sites

U.S. DEPARTMENT OF ENERGY

Energy R&D Organizations



Atmospheric CO_2 at Mauna Loa Observatory



Concentration now ~388 ppm

Concentration prior to 1800 was ~280 ppm

Greenland Ice Mass Loss – 2002 to 2009

Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE (Gravity Recovery and Climate Experiment) satellite:

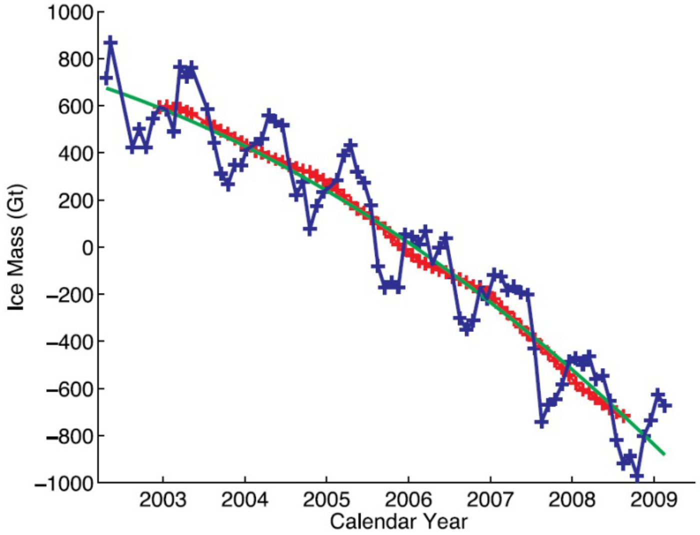
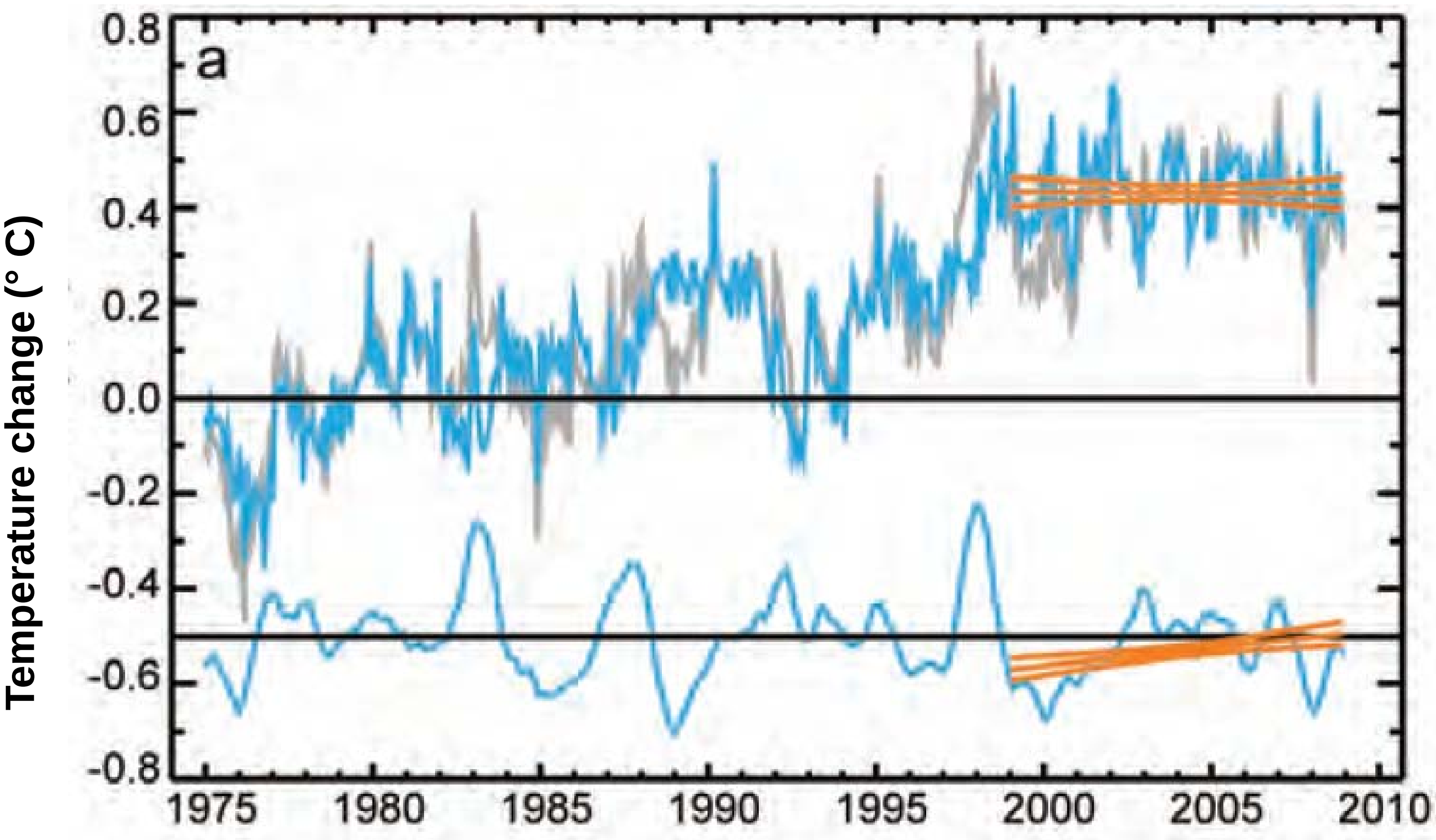


Figure 1. Time series of ice mass changes for the Greenland ice sheet estimated from GRACE monthly mass solutions for the period from April 2002 to February 2009. Unfiltered data are blue crosses. Data filtered for the seasonal dependence using a 13-month window are shown as red crosses. The best-fitting quadratic trend is shown (green line). The GRACE data have been corrected for leakage and GIA.

- In Greenland, the mass loss increased from 137 Gt/yr in 2002–2003 to 286 Gt/yr in 2007–2009
- In Antarctica, the mass loss increased from 104 Gt/yr in 2002–2006 to 246 Gt/yr in 2006–2009

I. Velicogna, *Geophysical Research Letters*, VOL. 36, L19503, 2009

Accounting for Stagnation of Global Average Temperature: The Role of Climate Model Variability



J. Knight et al., *Bull. Amer. Met. Soc.*, "State of the Climate" Supplement, August 2009

Major Changes are Required to Reduce Greenhouse Gas Pollution

To prevent global average surface temperature from rising more than 2.5 C by 2050 . . .

. . . we must emit less than 1000 GT of CO_2 between 2000–2050 . . .

. . . but our emissions rate from 2000–2010 was 33 GT per year . . .

. . . so we must reduce our emissions by a factor of 8 between 2010-2050.

Batteries and Energy Storage
Cross-Cutting Challenge that Impacts Energy Technologies

The Administration's Energy Plan has two goals that rely heavily on improvements in the science and technology of energy storage:

- Solar and wind providing over 25% of electricity consumed in the U.S. by 2025
- 1 million all-electric/plug-in hybrid vehicles on the road by 2015

- Grid stability and distributed power require innovative energy storage devices
  - Grid integration of intermittent energy sources such as wind and solar
  - Storage of large amounts of power
  - Delivery of significant power rapidly

- Enabling widespread utilization of hybrid and all-electric vehicles requires:
  - Substantially higher energy and power densities
  - Lower costs
  - Faster recharge times

Basics: Energy Storage Technologies

Energy

- **Pumped Hydro**
- **Compressed Air Energy Storage (CAES)**
- **Batteries**
  - Sodium Sulfur (NaS)
  - Flow Batteries
  - Lead Acid, Lead Carbon
  - Lithium Ion
  - NiMH
  - NiCad
- **Flywheels**
- **Electrochemical Capacitors**

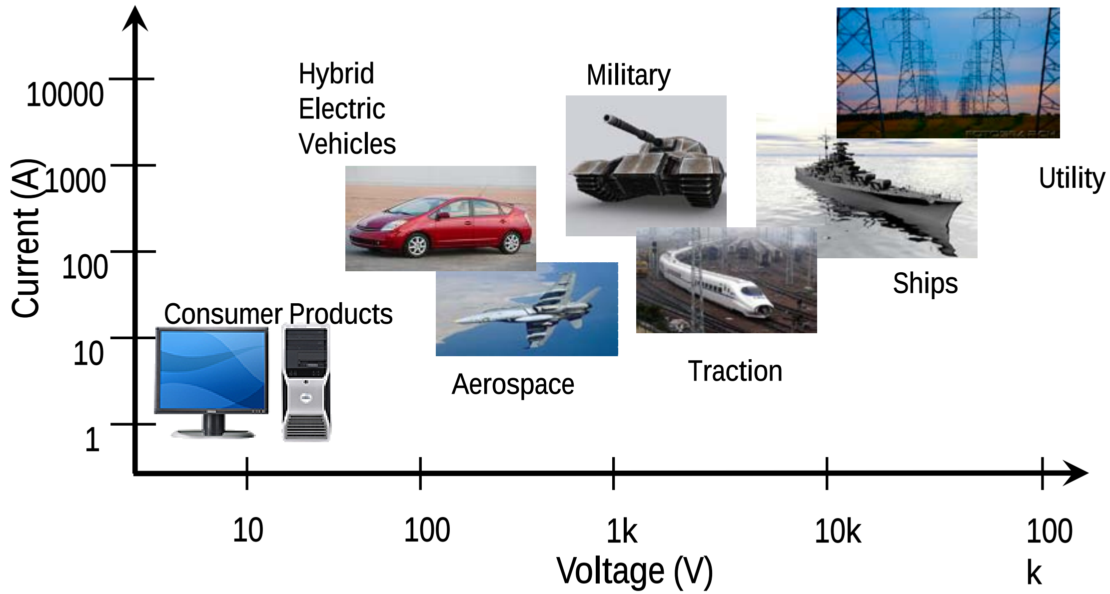
Power

Pumped Hydro (Taum Sauk) 400 MW

Sodium Sulfur Battery 2 MW

Flywheels 1 – 20 MW

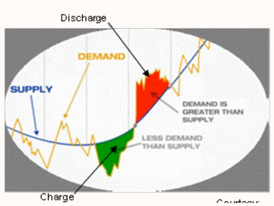
Energy Storage: Scales of Power & Time



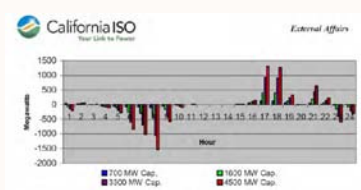
Different power requirements and time regimes will require different storage solutions

Seconds to Minutes — **Minutes - one Hour** — **Several Hours - one Day**

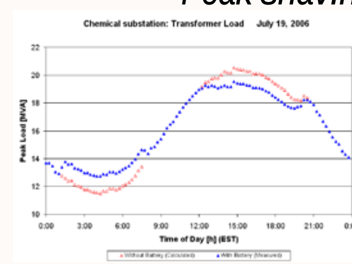
Regulation

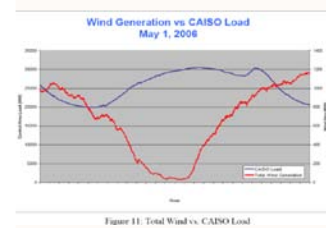


Ramping



Peak shaving, load leveling





Energy Storage Challenges – Energy/Power Density and Cost

Comparisons of “theoretical” and “practical” energy and power density involve several factors

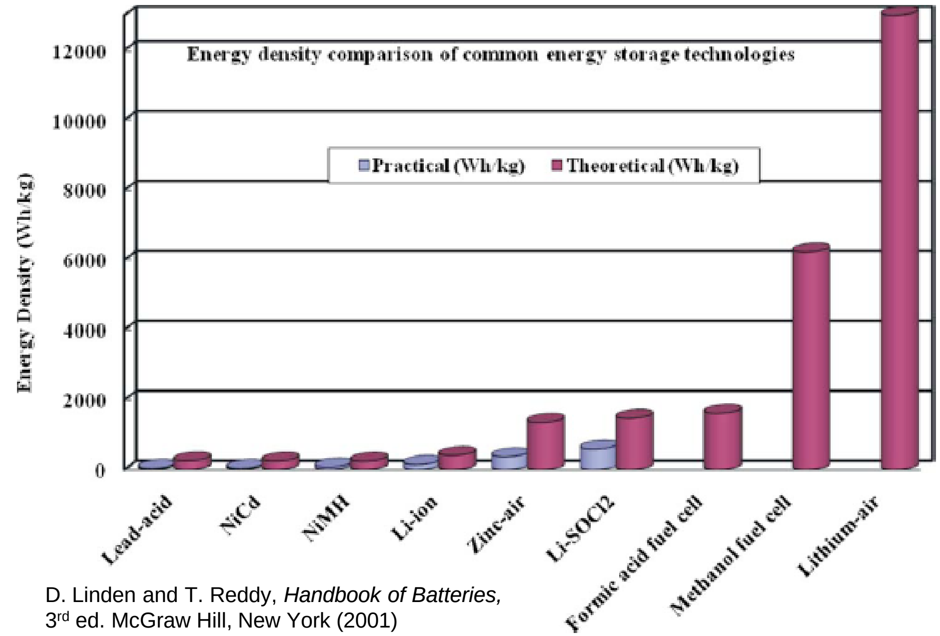
- Energy density of a $LiFePO_4$ battery is **595 Wh/kg** in theory but typically **120 Wh/kg** at the pack level

High quoted power densities are often associated with low cycle life, high cost and reduced safety (e.g., runaway thermal events)

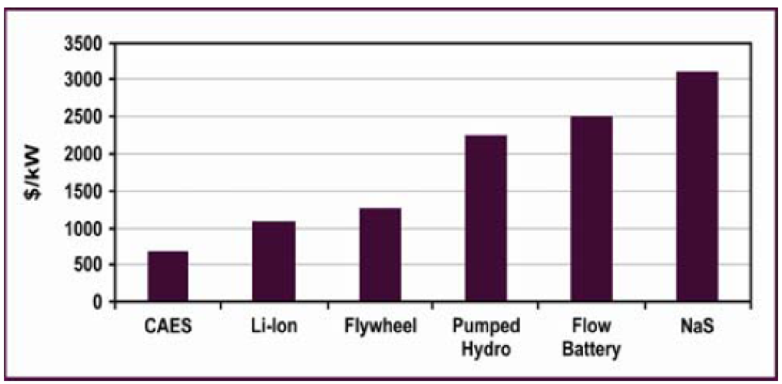
Cycle life for batteries vary widely but are poor for the high-energy density systems

- Li-Air (40 cycles versus a desired level of >1,000)

Reduce cost and weight of both active and non-active components



D. Linden and T. Reddy, *Handbook of Batteries,* 3rd ed. McGraw Hill, New York (2001)



Source: Figure created for *Bottling Electricity: Storage as a Strategic Tool for Managing Variability and Capacity Concerns in the Modern Grid* by EAC Energy Storage Technologies Subcommittee 2008

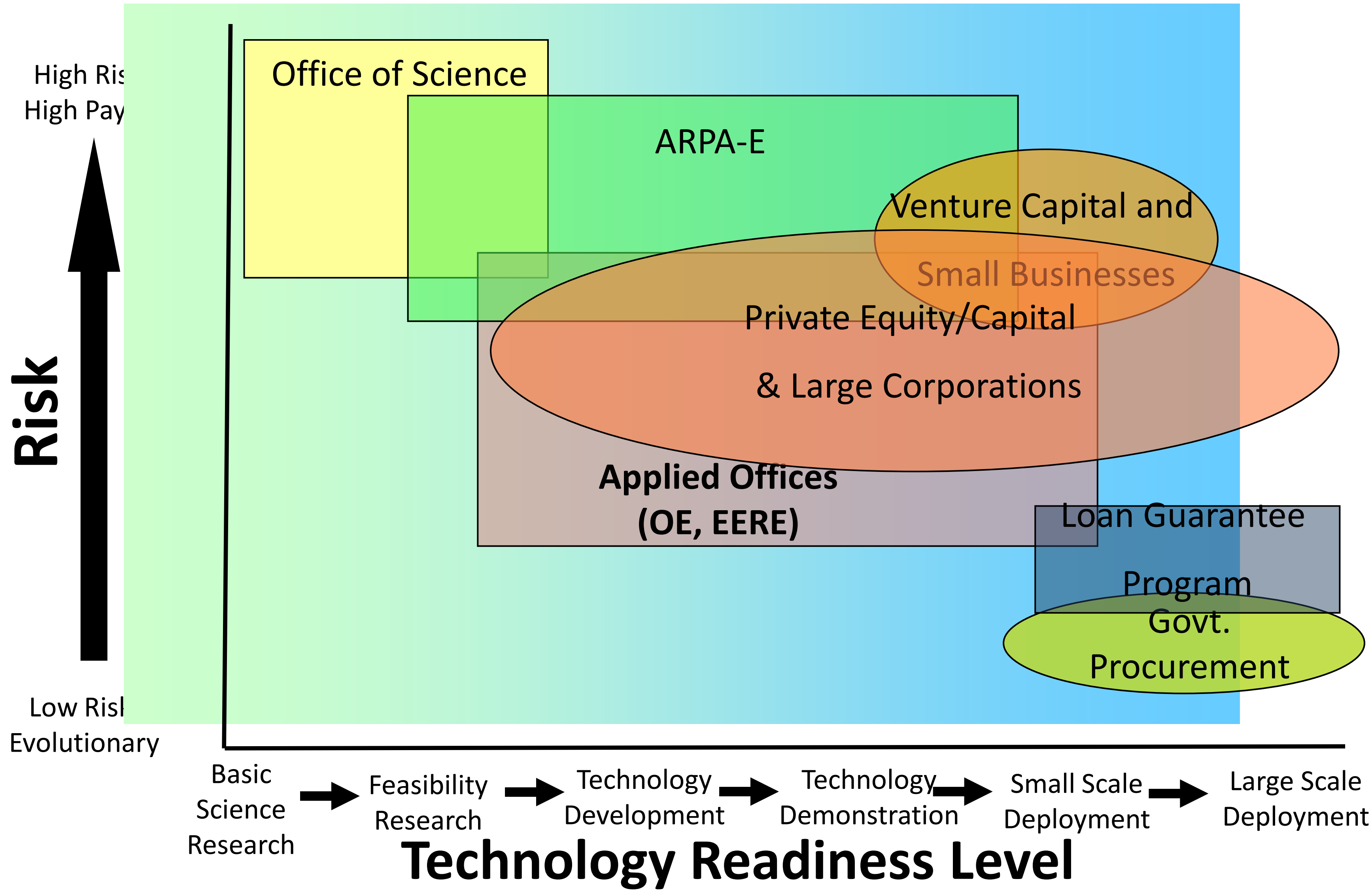
Battery Cell Specific Energy Density, Wh/kg

	Theoretical	***Practical***
Lead Acid	252*	35*
Nickel-Metal Hydride	240*	75*
Lithium-ion	410*	150*
Lithium-sulfur	2500#	350#

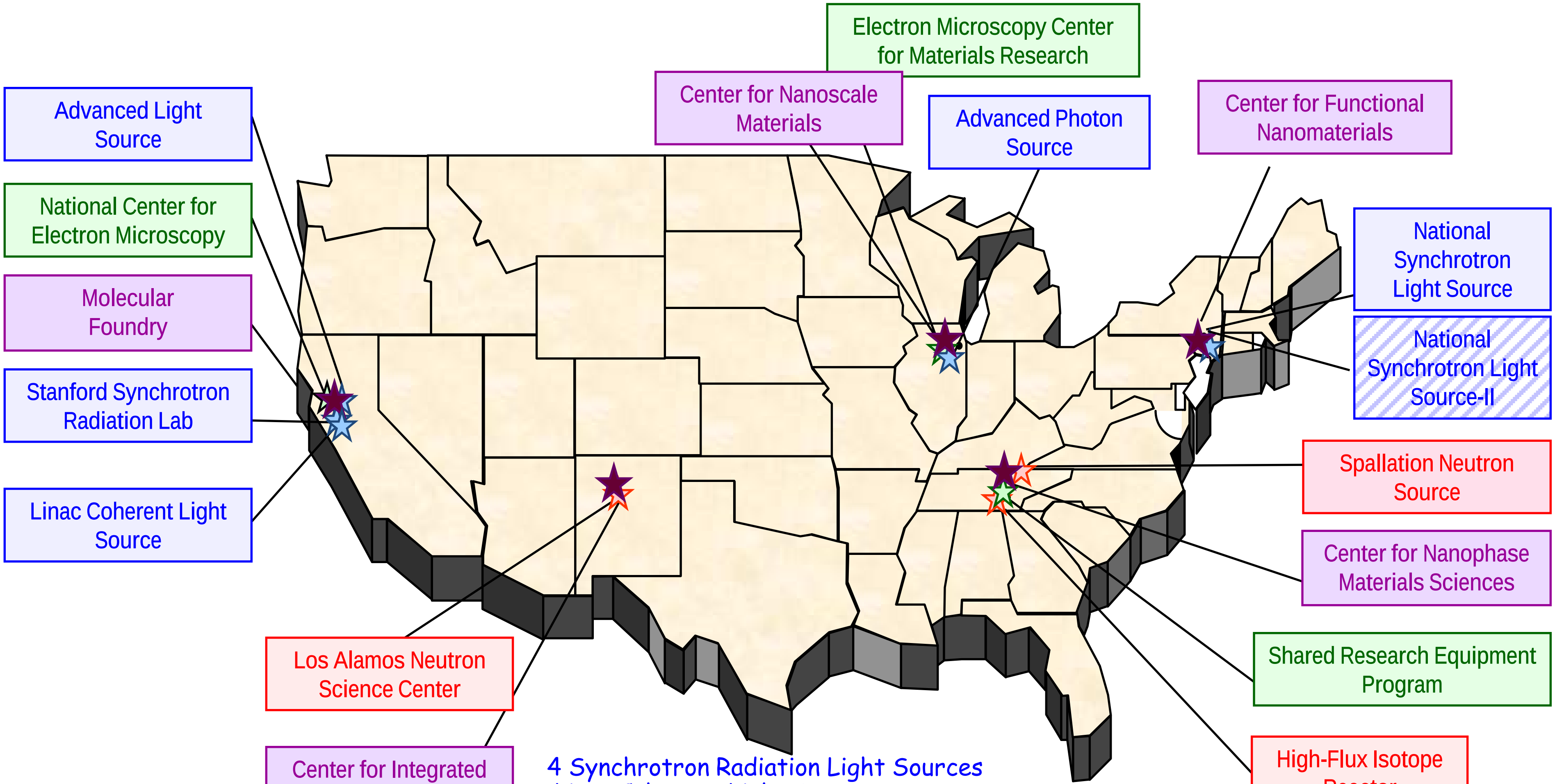
Source: *Handbook of Batteries,3rd Edition, pp. 1.12-1.13
Sion Power Corporation Literature

Safety: *The theoretical specific energy of a lithium thionyl chloride battery is 1420 Wh/L, comparable to the theoretical specific energy of TNT at 1920 Wh/L.*

DOE Roles in the Energy Innovation Profile



BES Scientific User Facilities: Resources for Energy Storage Research

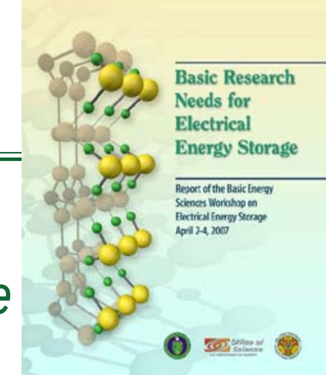


4 Synchrotron Radiation Light Sources
Linac Coherent Light Source
3 Neutron Sources
3 Electron Beam Microcharacterization Centers
5 Nanoscale Science Research Centers

DOE Inter-Office Integration for Grid Level Energy Storage

Office	Strategy/Funding Approach
OE	Energy storage technology research, development, modeling, demonstration and control of technologies that will increase the flexibility of the system (grid), from the generator to the consumer and everything in between, thereby allowing for grid integration of a greater diversity of technologies.
EERE	R&D and demonstrations of on-site energy storage technologies that enable penetration of EERE technologies (generation, efficiency, or transportation) into the current system (grid).
ARPA-E	High risk R&D to prove & prototype disruptive new energy storage technologies
BES	Fundamental research to (i) design and develop novel materials and concepts and (ii) probe physical and chemical phenomena associated with electrical energy storage. Operate User Facilities for Basic and Applied Research. Energy Frontier Research Centers and proposed Energy Innovation Hub.

Batteries and Energy Storage: Critical Issues in Research



A Unified Research Framework for Transportation and Stationary End-use

How can we approach theoretical energy densities?

- Need to know how to design and control energy transfer
- Need to develop novel multi-electron systems
- Need to understand fluid behavior in nanopores

Increased Energy Density

How do we increase the rate of energy utilization and safe storage capacity?

- Need to improve ionic and electrical conductivity
- Need to design simple, stable nanostructures
- Need to understand energy transport

Higher Power

Can we create a system that is close to perfectly reversible?

- Need to understand interfaces and phase stability
- Need to understand system dynamics
- Need todesign new materials and structures

Longer Lifetimes

FY 2011 Energy Innovation Hub for Batteries and Energy Storage

Addressing science gaps for both grid and mobile energy storage applications

A FY 2011 SC/BES Hub for Batteries and Energy Storage ($34,020K) will address the critical research issues and will include:

- **Design of advanced materials architectures**: design of low-cost materials that are self-healing, self-regulating, failure tolerant, and impurity tolerant
- **Control of charge transfer and transport:** control of electron transfer through designer molecules; electrolytes with strong ionic solvation, yet weak ion-ion interactions, high fluidity, and controlled reactivity
- **Development of probes of the chemistry and physics of energy storage:** tools to probe interfaces and bulk phases with atomic spatial resolution and femtosecond time resolution
- **Development of multi-scale computational models**: computational tools to probe physical and chemical processes in storage devices from the molecular scale to system scale

Where Can a Battery and Energy Storage Hub Take Us?

- Move science and technology for energy storage forward at a rapid pace to enable transformative developments for reliable energy supply and transportation systems

- Provide a strong linkage between fundamental science, applied technology and end-use communities to create long- and short-term innovations that would not otherwise be achieved

Batteries and Energy Storage Hub:
A research framework for scientific discovery and transformational technologies

Alternate Slides

Basics: Why is Energy Storage Needed?

- **Key to greater Renewable Penetration**
  - Balance variability
  - Ramp rate control
  - Load shifting
  - Improve dispatchability

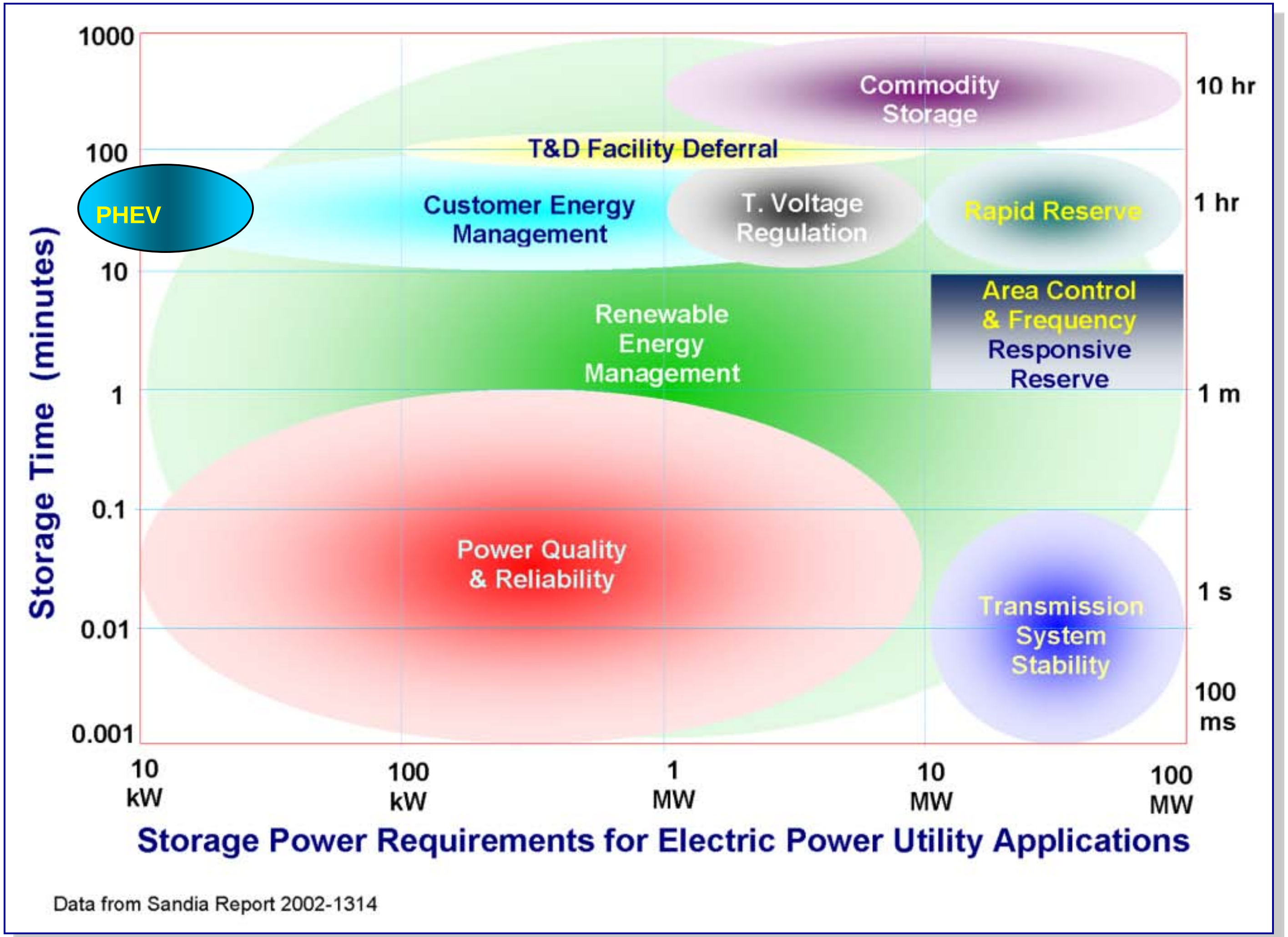
- **Reduce carbon footprint**
  - Minimize “peakers”
  - Expand renewables
  - Emissionless regulation

- **Provides Buffer for the Grid**
  - Reduces peak load
  - Reduces infrastructure requirements
  - Minimizes congestion
  - Improves duty factor

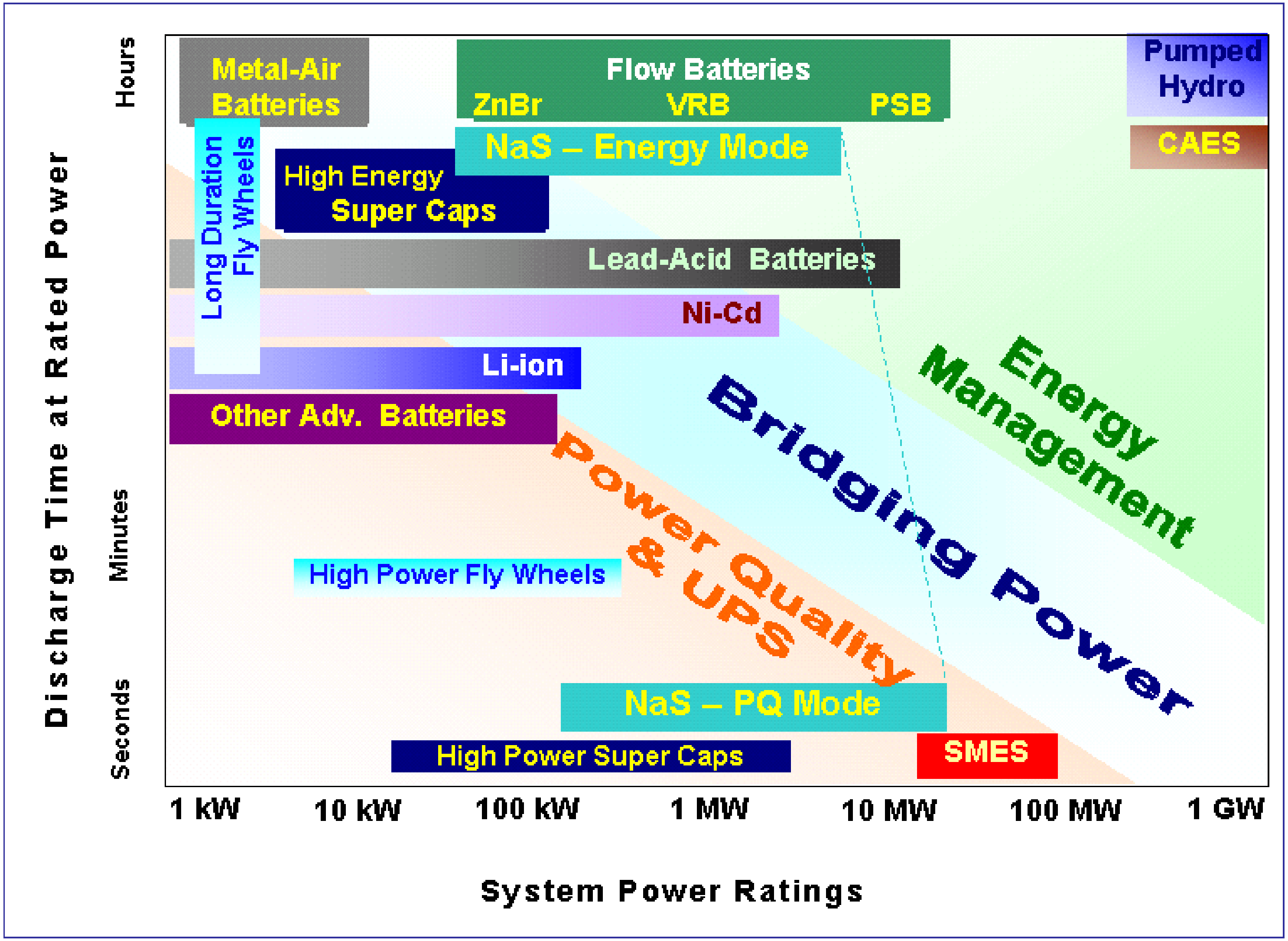
- **Smart Grid**
  - Integrating tool

- **Power Quality & Reliability**
  - For digitized technology

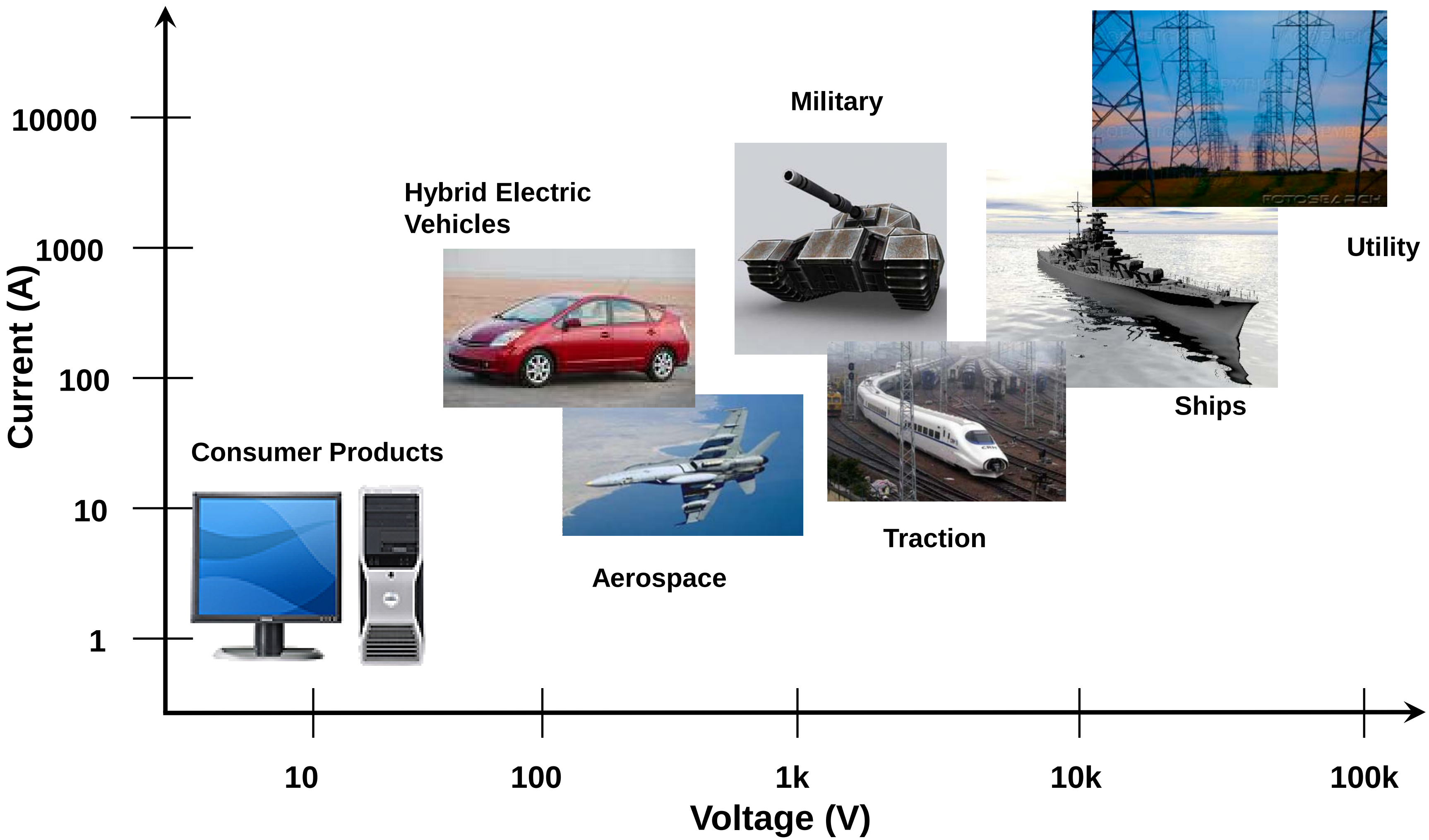
Basics: Regimes of Storage Application



Basics: Regimes of Storage Technologies



Basics: Scales of Power



DOE Batteries and Energy Storage Program Features

	Investigators and their institutions	Diversity of Disciplines Per Award	Period of Award and Management	Annual Average Award Amount	Core Motivation, Research Focus
Core BES Program	Single or small-groups of researchers led by Universities or National Laboratories	Few	3 –year renewable awards	~$300k	Fundamental research to understand the underlying science of materials and chemistry issues related to electrical energy storage. Current projects focus on electrode and electrolyte phenomena.
Energy Frontier Research Centers	Self-assembled group of ~6-12 investigators. Led by Universities, National Laboratories and Industry.	Several	Five years with 5-year renewal possible. Managed by DOE SC-BES.	~$3M	Fundamental research on electrical energy storage with a link to new energy technologies or technology roadblocks. The investigators are addressing subject matter from among a large set of scientific grand challenges and electrical energy storage-related topics based on the "Directing matter and Energy: Five Challenges for Science and the Imagination", and "Basic Research Needs in Electrical Energy Storage" reports, respectively.
Batteries and Energy Storage Energy Innovation Hub	Large set of investigators spanning multiple science and engineering disciplines and possibly including other non-science areas such as energy policy, economics, and market analysis. May be led by Labs or universities, nonprofit organizations or private firms.	Many	Five years with 5-year renewal possible; the "bar" is significantly higher for further renewals. Managed by DOE SC with broad DOE participation. A Board of Advisors consisting of senior leadership will coordinate across DOE.	~$25 million per year for R&D	Integrate from fundamental research through potential commercialization of electrical energy storage relevant to transportation and the electric grid. The breadth and emphasis of activities will be influenced by the nature of the selected Hub proposal. Some may place a greater emphasis on basic and applied research, while others may focus more on technology development. This Hub will be managed by SC with input from OE, EERE, and ARPA-E
ARPA-E	Single investigator, small group, or small teams.	Few	1-3 years Managed by ARPA-E, which reports to the Secretary of Energy	$1 -7M	High risk translational research driven by the potential for significant commercial impact in the near-term. Current solicitation open on Batteries for Electrical Energy Storage in Transportation which is focused on ultra-high energy density, low-cost battery technologies.
EERE and OE	Range of research teams, frequently involving industrial partners	Few	Varies, typically 1-3 years	Ranging from small teams ($300K+) to technology demonstrations (can be >$1M)	Developmental research and technology demonstration projects. EERE primarily focuses on mobile applications, OE on stationary and grid applications.

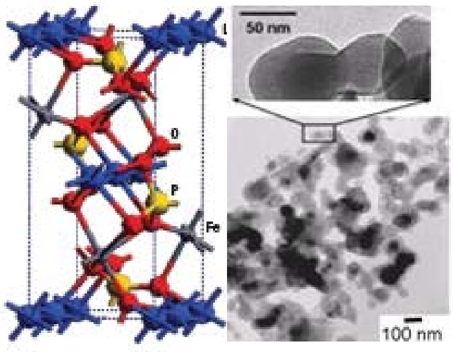
SC-BES FY 2011 Budget Request:
Energy Innovation Hub - Batteries and Energy Storage

Today's electrical energy storage approaches, such as batteries and electrochemical devices, suffer from limited energy and power capacities, lower-than-desired rates of charge and discharge, calendar and cycle life limitations, low abuse tolerance, high cost, and poor performance at high or low temperatures. An Energy Innovation Hub is planned to develop novel electrical energy storage concepts for transportation applications and for grid-scale stationary energy storage. Key scientific areas are:

- Efficacy of structure in energy storage: new approaches combining theory and synthesis for the design and optimization of materials architectures including self-healing, self-regulation, failure-tolerance, and impurity-sequestration; and based on abundant materials and low-cost manufacturing processes.
- Charge transfer and transport: molecular scale understanding of interfacial electron transfer, and electrolytes -- electrolytes with strong ionic solvation, yet weak ion-ion interactions, high fluidity, and controlled reactivity.
- Probes of energy storage chemistry and physics at all time and length scales: analytical tools capable of monitoring changes in structure and composition at interfaces and in bulk phases with spatial resolution from atomic to mesoscopic levels and temporal resolution down to femtoseconds.
- Multi-scale modeling: computational tools with improved integration of length and time scales to understand the complex physical and chemical processes that occur in electrical energy storage from the molecular to system scales

SC:BES Research in Electrical Energy Storage Leads to a Broad Range of Applications

- BES-sponsored basic research at MIT over a decade ago led to the discovery that nanostructuring of ceramics enhanced their conductivity
  - Doping of nanostructured $LiFePO_4$ increased the conductivity by eight orders of magnitude
- Based on the knowledge gained, the faculty member founded a high-tech start-up company, A123 Systems in Watertown, MA, to commercialize this new battery technology.
- Further developed by a DOE SC SBIR starting in 2002 and by a grant from the DOE Office of Energy Efficiency and Renewable Energy starting in 2006
- Today - A123Systems' batteries have reached the commercial marketplace in power tools, hybrid and plug-in hybrid electric vehicles, and grid-related applications.



$LiFePO_4$ structural model and nanostructure

Basic Research for Batteries and Energy Storage

Basic research in chemical and materials sciences is needed to surmount the significant challenges of electrical energy storage devices for stationary grid and distributed power applications to take advantage transient energy sources such as solar and wind and for hybrid and electric vehicles

- **Nanostructured electrodes with tailored architectures**

  Electrode composition (structure and chemistry) are key aspects of power density. Fundamental studies of the role of dopants, alloying and surface reactions of the mechanisms and to enhance performance.

- **The promise of higher battery power via conversion reactions**

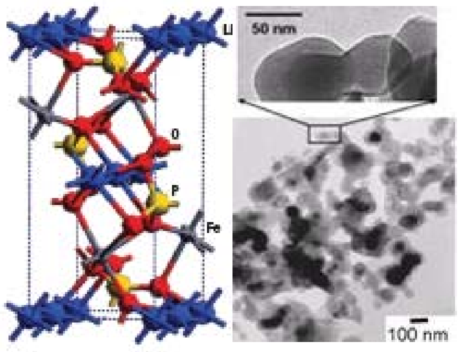
  Current batteries operate with slightly less than one electron per redox center with typical electrode materials. Research on conversion reactions with in situ studies and theory/modeling can provide insights to advance electrode design.

- **Multifunctional material architectures for ultracapacitors**

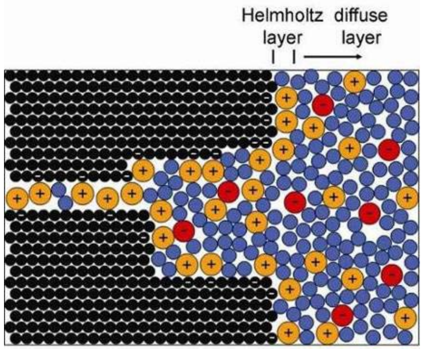
  Ultracapacitors complement battery power by allowing very rapid charge and discharge cycles and providing high charge storage capacity (high surface area). Investigations of charge storage mechanisms at surfaces through in-situ analytical studies in end use environments can overcome the shortcomings of this technology.

- **Understanding behavior in confined spaces**

  The behavior of electrolytes is a critical energy storage performance factor. As pores of nanostructured electrodes approach the size of the electrolyte molecules, new chemistry and physics will be needed to understand system behavior.



$LiFePO_4$ structural model and nanostructure



Ion solvation changes with pore size during electric double layer charging (electrode, black; solvent, blue; cation, orange; anion, red)

Metrics for Energy/Power Density in Batteries

Comparisons of "theoretical" and "practical" energy and power density involve several factors including the mass/volume of components.

- Energy Density of a LiFePO4 battery is 595 Wh/kg in theory but typically 120 Wh/kg at the pack level.

Different battery systems have different packaging requirements. High power densities are sometimes quoted but often are associated with low cycle life, high cost and reduced safety (e.g., runaway thermal events).

An electric vehicle with a 200 mile range with current technologies requires a battery that weighs almost 700 kg (compared to compact car weight of <1500kg) and is nearly 350 liters in volume (about the size of a trunk in a mid-sized sedan).

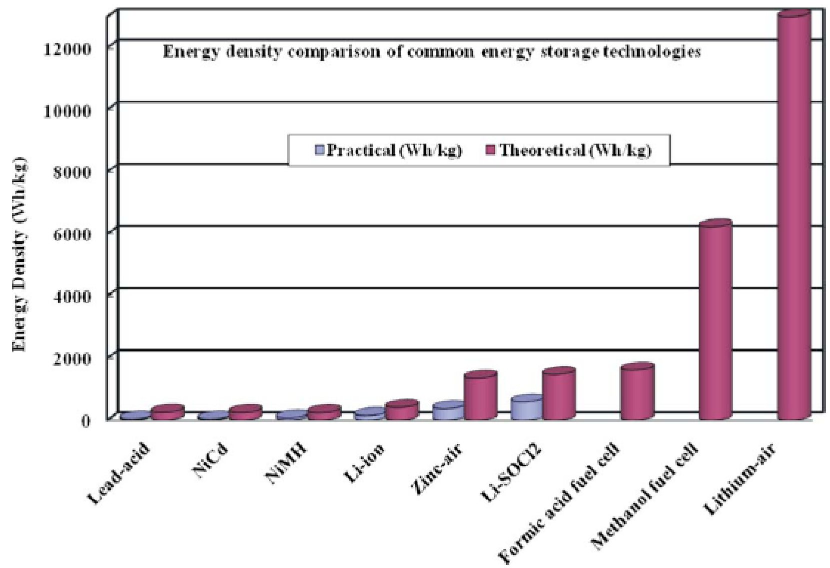
- Goal to reduce by a factor of five or more (to match current plug in hybrid system parameters – weight/volume, range, assoc. support systems).

Current status of specific energy at a c/3 discharge rate [3 hours to full discharge (or charge)] is 120 Wh/kg

- Long-term goal for a 40 kWh battery (all-electric vehicle but with limited range) is >200 Wh/kg (per EERE VT multi-year program plan).

Cycle life for electric vehicle batteries vary widely but are very poor for the high-energy density systems.

- Li-Air (40 cycles versus a desired level of >1,000)
- Li-S; though Sion (company that sells these) shows a high energy density they only guarantee it for 50 cycles



D. Linden and T. Reddy, *Handbook of Batteries*, 3rd ed. McGraw Hill, New York (2001).

Battery Cell Specific Energy Density, Wh/kg

	Theoretical	Practical
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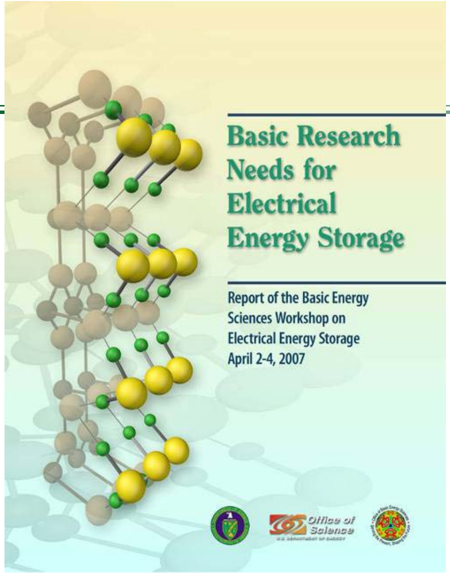
Source: *Handbook of Batteries,3rd Edition, pp. 1.12-1.13
Sion Power Corporation Literature

Batteries and Electrical Energy Storage
Enabling Transformational Solutions



Technology Gaps

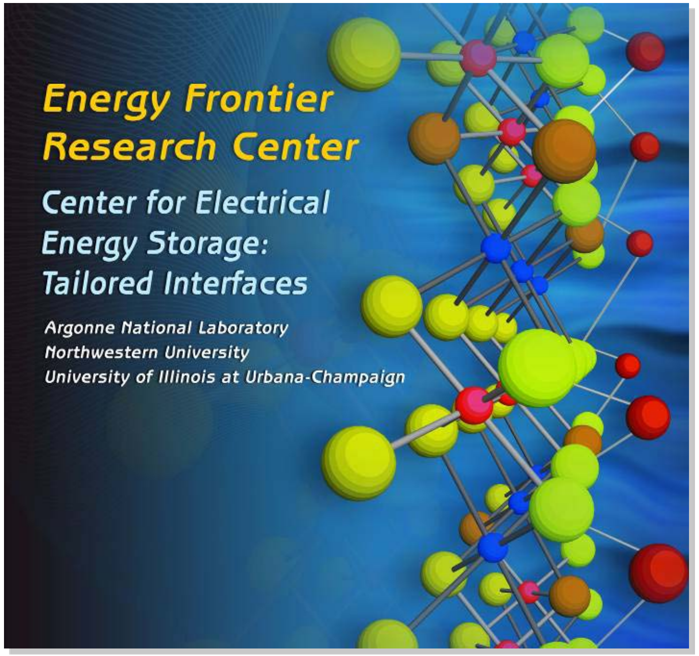
- Limited energy and power capacities
- Calendar and cycle life limitations
- Lower-than-desired rates of charge and discharge
- Poor performance at high or low temperatures
- High cost
- Low abuse tolerance

Fundamental Science: Enabling transformative solutions

- *How can we approach theoretical energy densities?*
- Materials Discovery: New materials that enable more than 1 charge per center
- Understand fluid behavior in nanopores
- *How do we increase the rate of energy utilization and safe storage capacity?*
- Determine how nanoparticles and nanocomposites increase power and energy
- Understand ion and electron transport and coupling between these
- *Cycle life: Can we create a perfectly reversible system?*
- Develop understanding of charge transport and chemical reactions at interfaces between electrodes and electrolyte
- Design and synthesize new electrolytes that are chemically inert and have high ion and electron conductivity.
- Acquire knowledge needed to design a SEI layer that is chemically and mechanically inert
- Identify the chemical reactions and dynamics that occur within electrodes and the electrolyte during charging and discharging

SC-BES: Center for Electrical Energy Storage
Michael Thackeray (Argonne National Laboratory)

The Center's overarching mission is to acquire a fundamental understanding of interfacial phenomena controlling electrochemical processes that will enable dramatic improvements in the properties and performance of electrical energy storage devices such as batteries and supercapacitors.

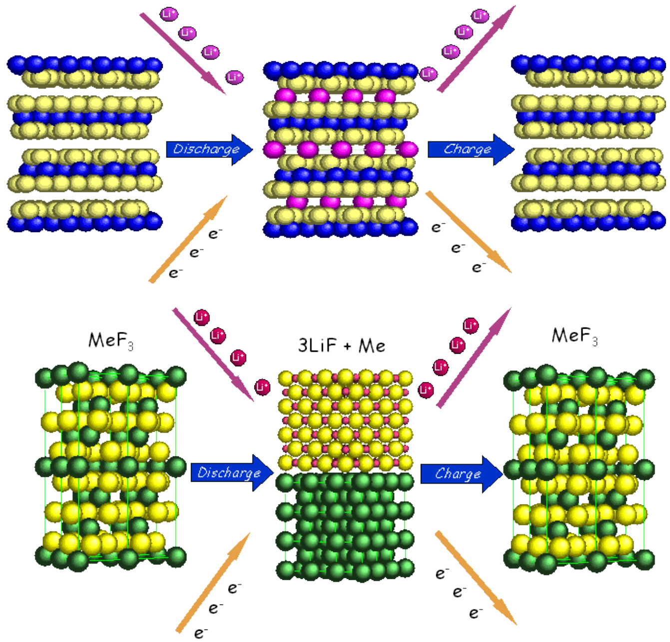


RESEARCH PLAN AND DIRECTIONS

Control of ionic and electronic transport and the stability of an electrified interface is central to the high energy and power output, lifetime, and safety of batteries and supercapacitors. Radical improvements will be sought through the synthesis and design of novel, stabilized architectures at the electrode-electrolyte interface and the characterization of electrochemical processes at the interface.

SC-BES Northeastern Center for Chemical Energy Storage; Clare P. Grey, Director (Stony Brook University)

Summary statement: A fundamental understanding of how key electrode reactions occur, and how they can be controlled will be developed, so as to identify critical structural and physical properties that are vital to improving battery performance; this information will be used to optimize and design new electrode materials.

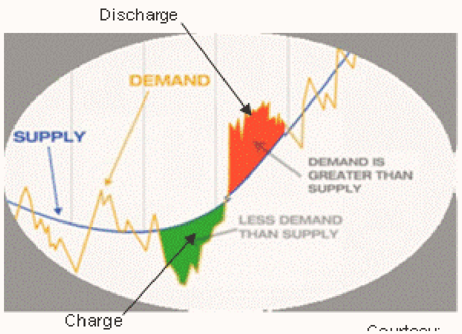


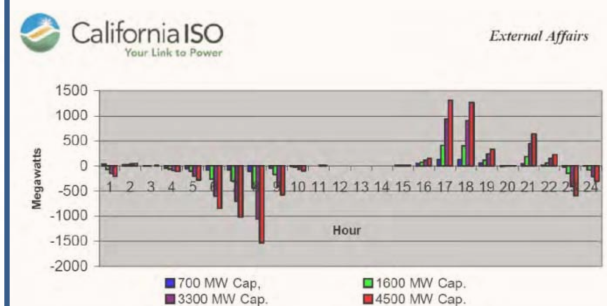
RESEARCH PLAN AND DIRECTIONS

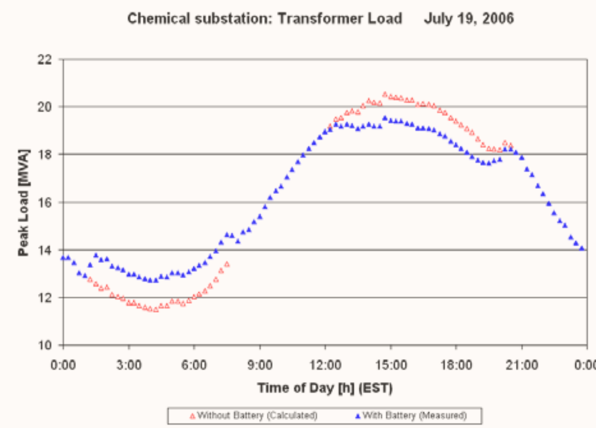
The processes that occur in batteries are complex, spanning a wide range of time and length scales. The assembled team of experimentalists and theorists will make use of, and develop new spectroscopy, scattering, imaging and theoretical methodologies to determine how electrodes function in real time, as batteries are cycled.

Basics: Energy Storage Time Scales

Seconds to Minutes	Minutes - one Hour	Several Hours - one Day
Regulation	*Ramping*	*Peak shaving, load leveling*







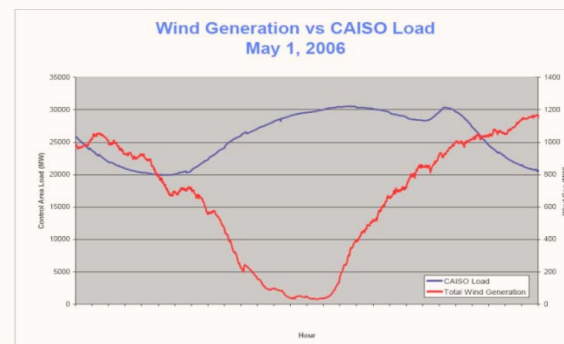


Figure 11: Total Wind vs. CAISO Load

Different Time Regimes will Require Different Storage Solutions