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Grid-Scale Energy Storage - Materials and Systems

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Agenda Overview

- Part 1
  - The Electric Grid
  - Role of Energy Storage in the Modern Grid
- Part 2
  - Energy Storage Technologies
  - Manufacturing of Grid-class Electrochemical Batteries
  - Systems Engineering
  - Energy Storage Safety and Reliability
- Part 3
  - Energy Storage Economics
  - Applications of Energy Storage

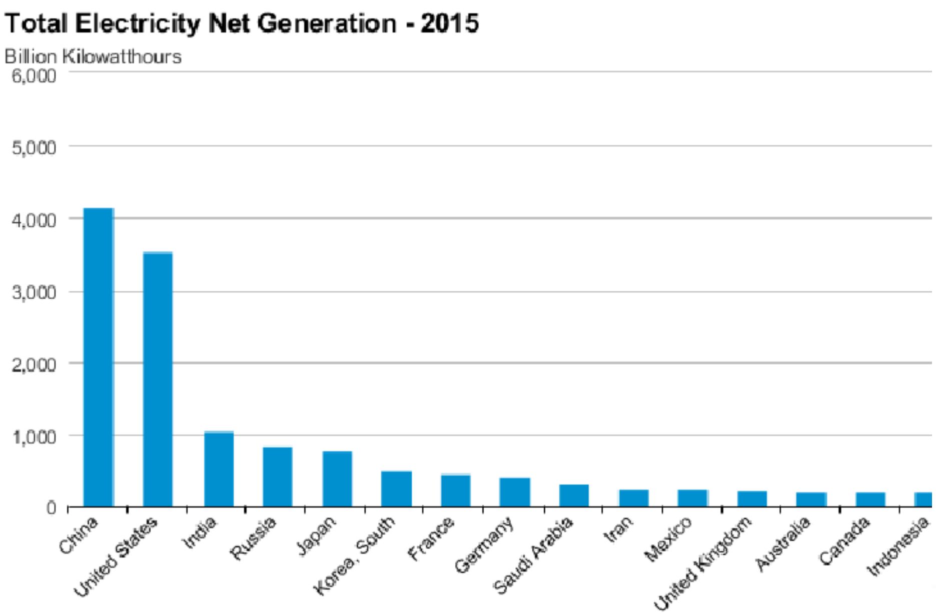
Questions We Will Address

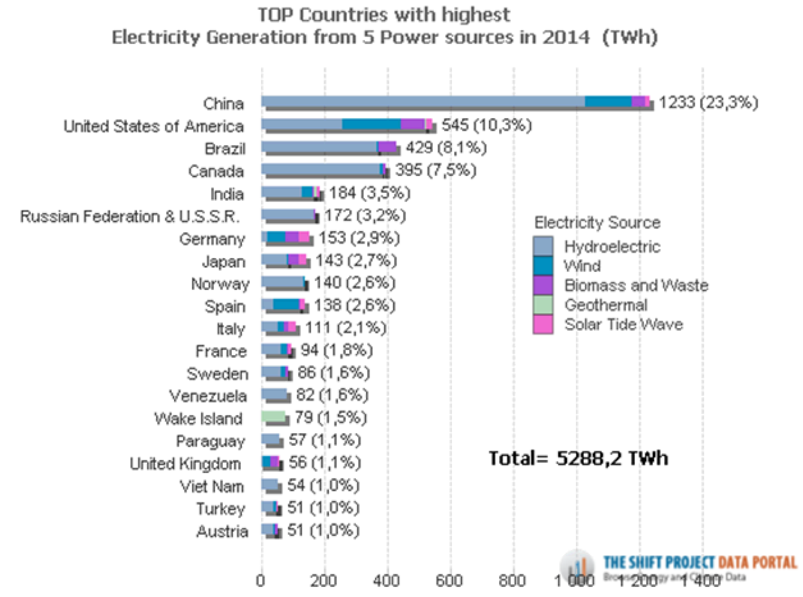
- How is the electric grid evolving?
- What is the role of energy storage systems on the grid?
- What are the drivers and challenges for integrating energy storage on a larger scale?
- What are the multiple energy storage technologies, and how do they work?
- On the role high volume manufacturing and scale on cost reduction?
- What are the reliability, safety, and other technical challenges for energy storage?
- What is the role of markets and economics of storage deployment?

The Electricity Grid

- Electrification is the greatest engineering achievement of the 20th century

Electricity Facts

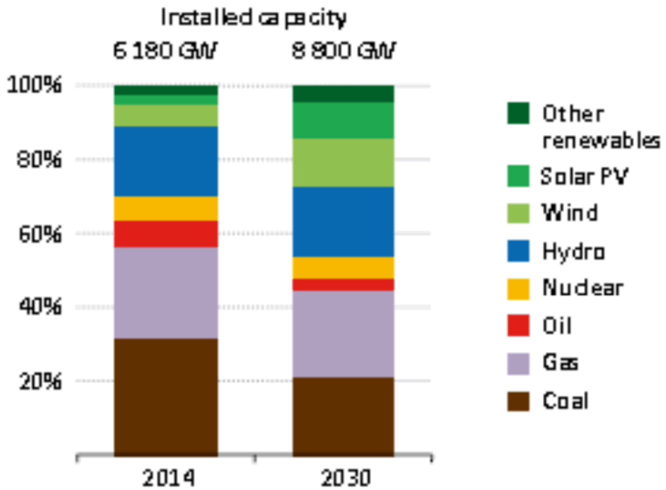


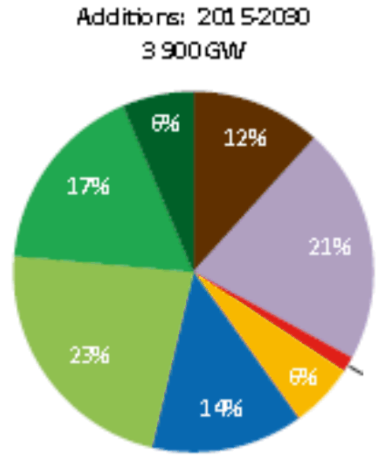


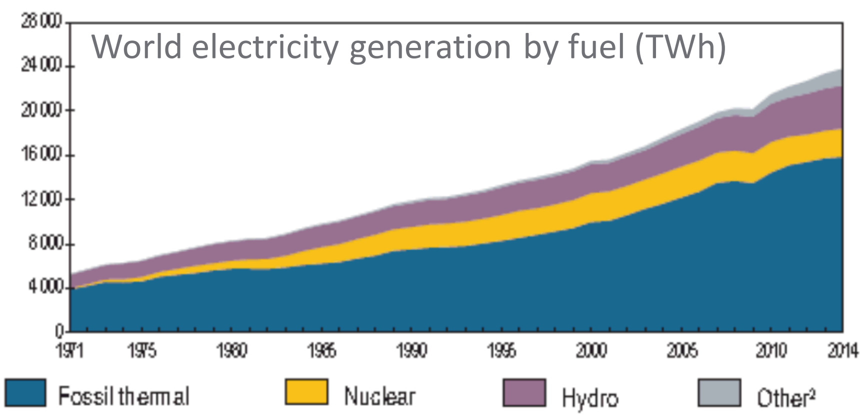
- 24 Trillion kWh of electricity generated annually (2014)

Source: US DOE, EIA (2016)

Worldwide Generation Capacity Mix and Future

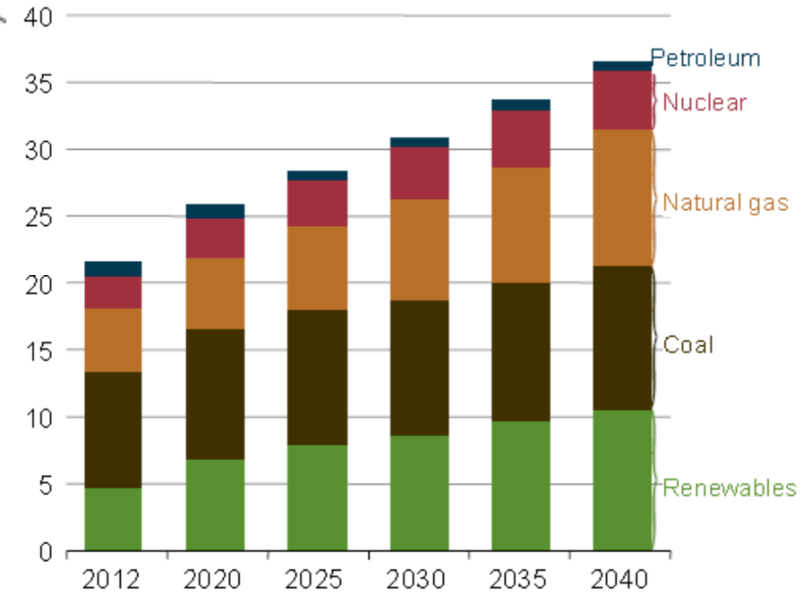




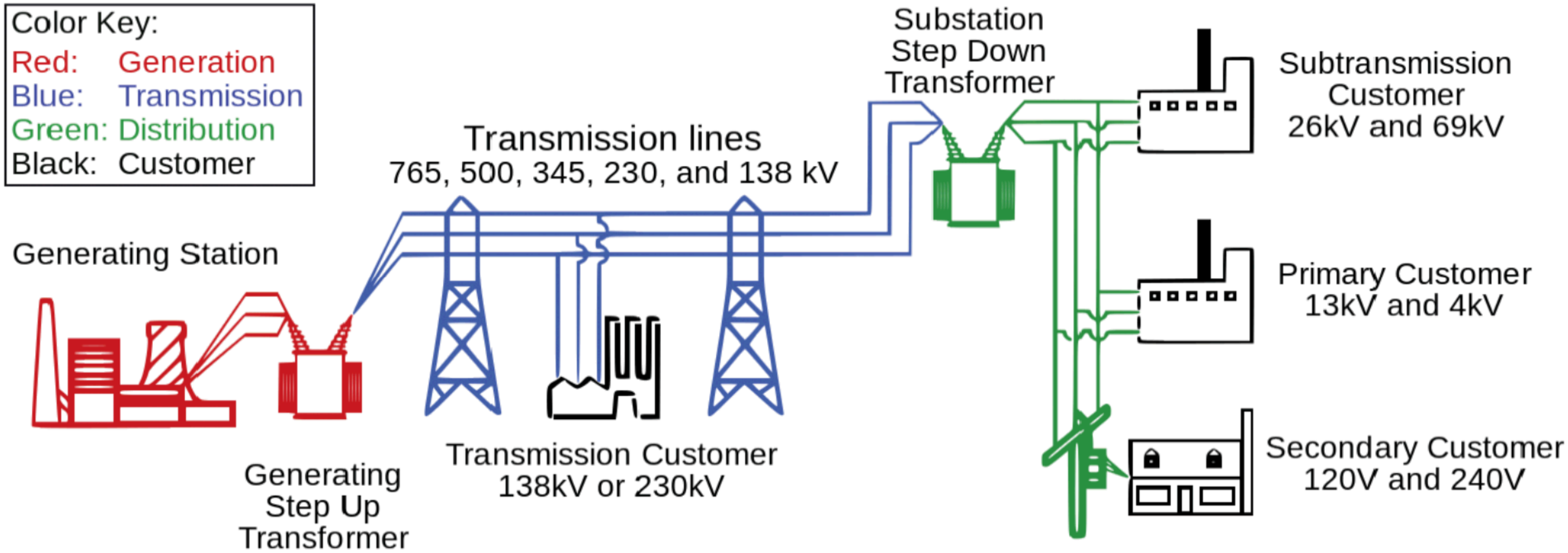


2016 International Energy Outlook, EIA 2016

World net electricity generation by energy source, 2012 in Trillion kWh (EIA, 2016)



The Grid Today

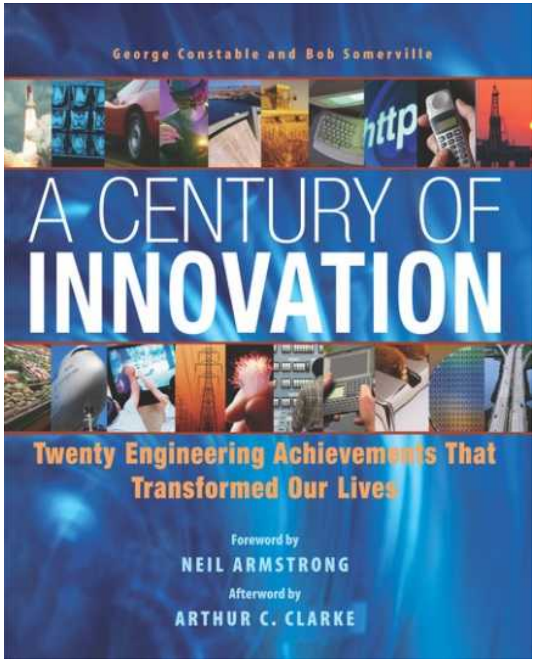


- Grid 1.0
  - One way energy flow
  - Generation and load must *always* be balanced

NERC

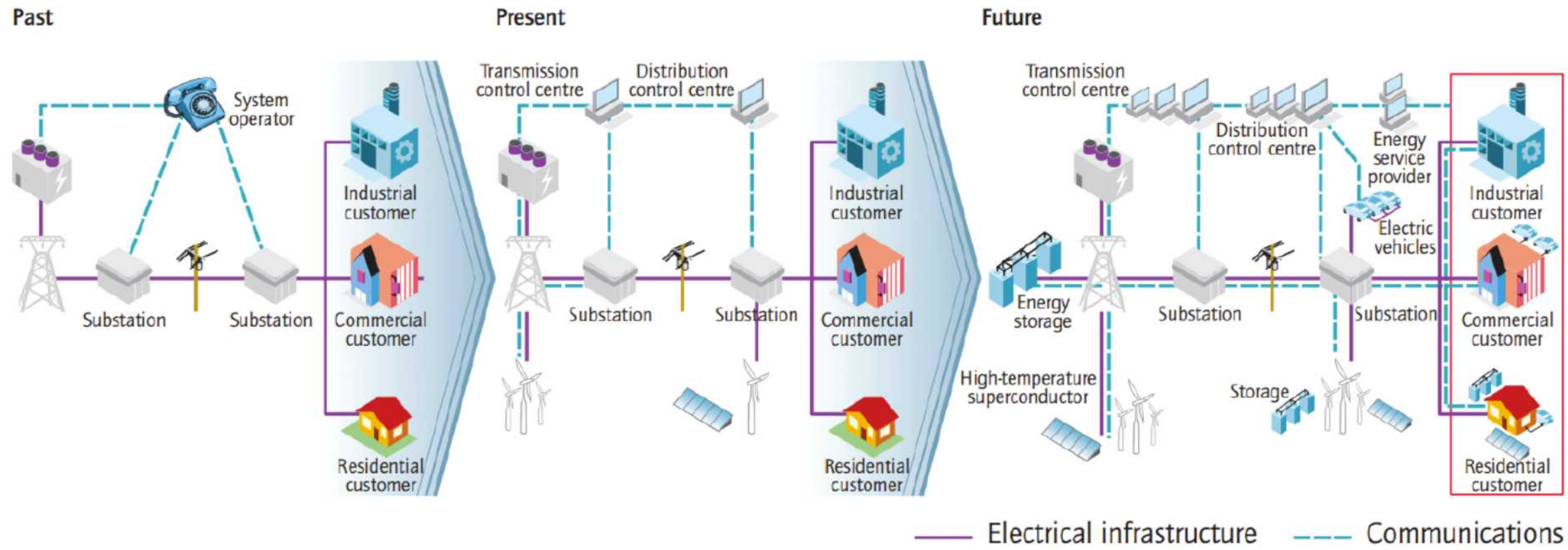
The Success of the Grid

- Remarkably reliable and efficient
  - Large interconnected network
  - Just-in-time production and consumption
  - Highly reliable 99.999%
- Success rests on two important principles
  - Diversity of aggregated loads
    - Aggregated loads change is predictable
    - Control over generation, throttled to provide power as needed



Electrification ranks as the most important engineering achievement of the 20th century
National Academy of Engineering, 2003

Grid Evolution and the Future Grid



Source: Quadrennial Technology Review
US DOE, 2015

Grid 2.0

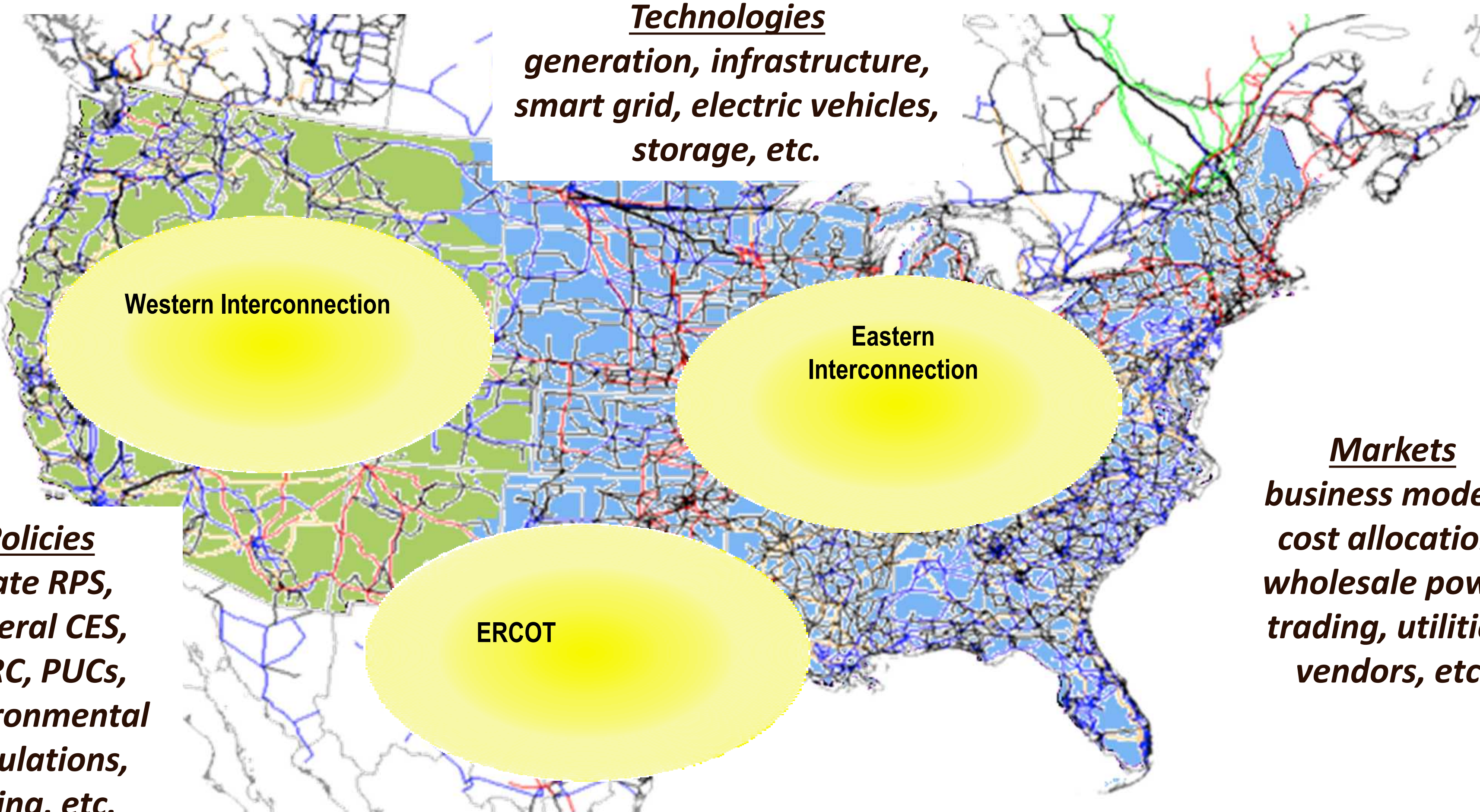
- Integration of renewables and distributed generation beginning to take off
- Minimal tools to manage grid instabilities

Future Grid

- Distributed generation and two-way energy flows
- Large scale renewable integration. Ability to manage diverse generation mix and intermittency

The U.S. Grid Today

Technologies
generation, infrastructure, smart grid, electric vehicles, storage, etc.



Policies
state RPS, federal CES, FERC, PUCs, environmental regulations, siting, etc.

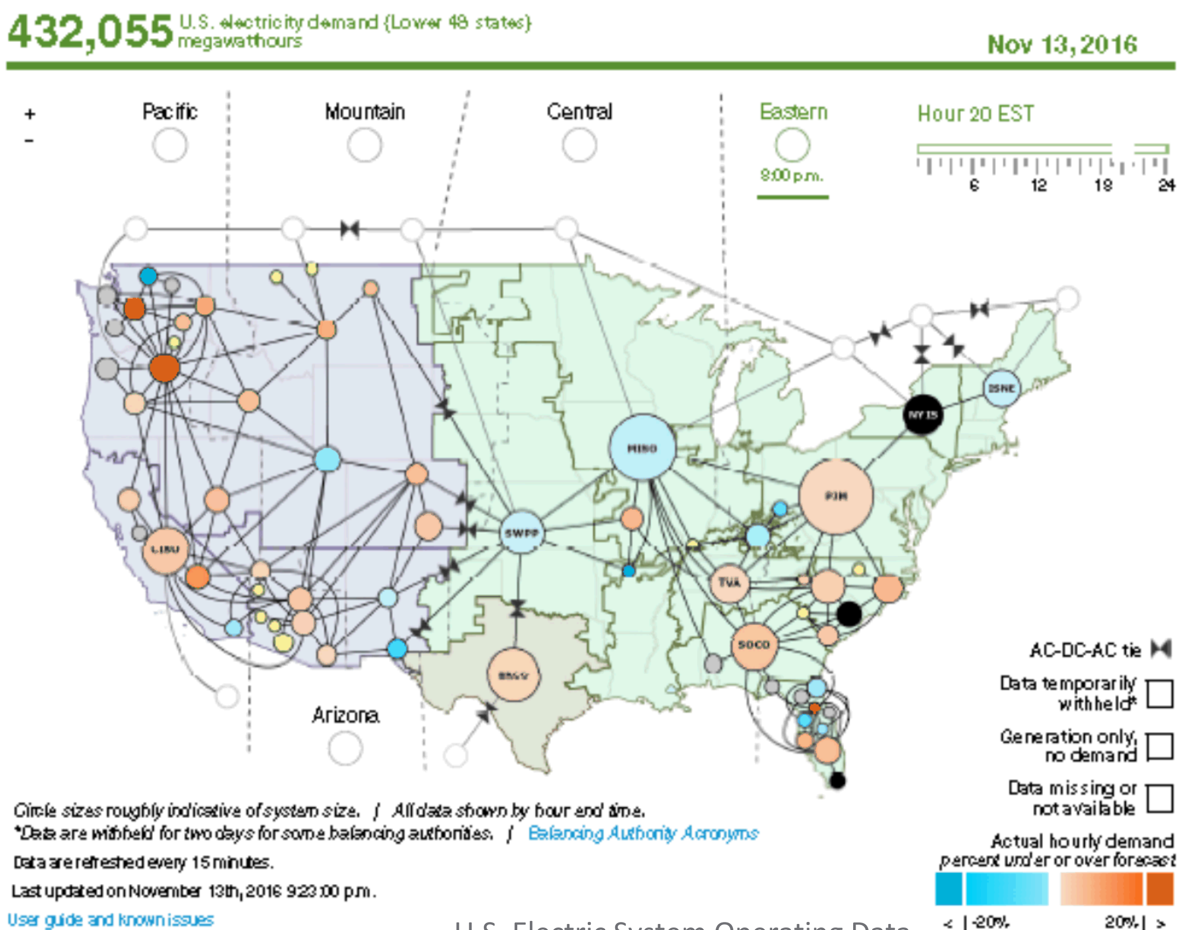
Markets
business models, cost allocation, wholesale power trading, utilities, vendors, etc.

U.S. Electricity Facts

- Over 3,200 utilities, 60,000 substations, 160,000 miles of high-voltage transmission lines, 7 million miles of distribution circuit
- As of Dec 31, 2015, generation capacity of 1,176,185 MW
- In 2015, total U.S. electricity generation was 4,087,381 GWh
  - U.S. investor-owned electric companies accounted for 1,489,472 GWh, or 36.4 percent, of total U.S. electricity generation
  - 13.4% of generation from renewables including 6.1% from Hydropower, 7.3% from other renewables including wind and solar.
- Total revenues of $388 billion, average revenue 10.42 cents/kWh

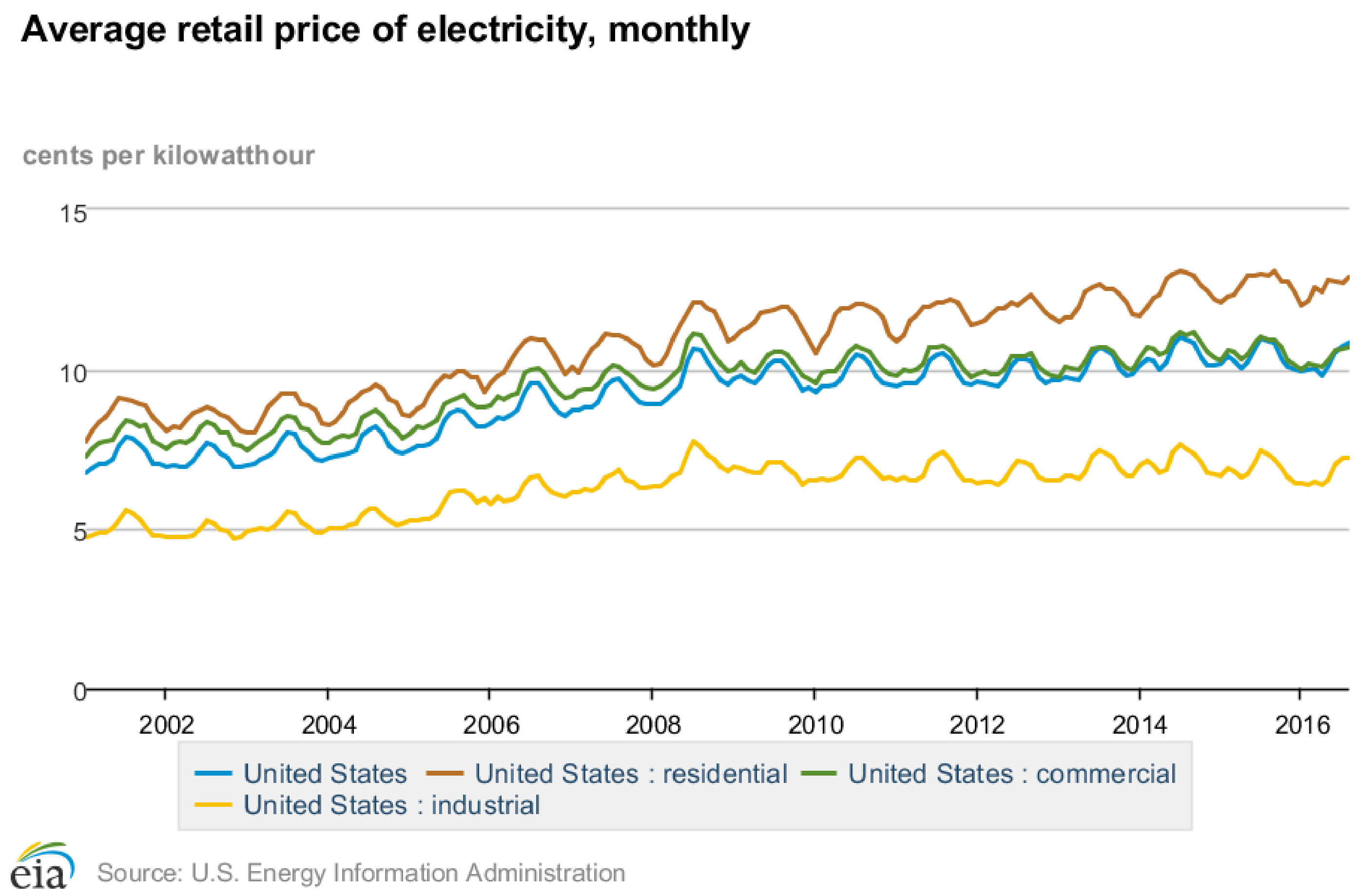
Sources: EIA, EEI

A Day in the Life of the U.S. Grid

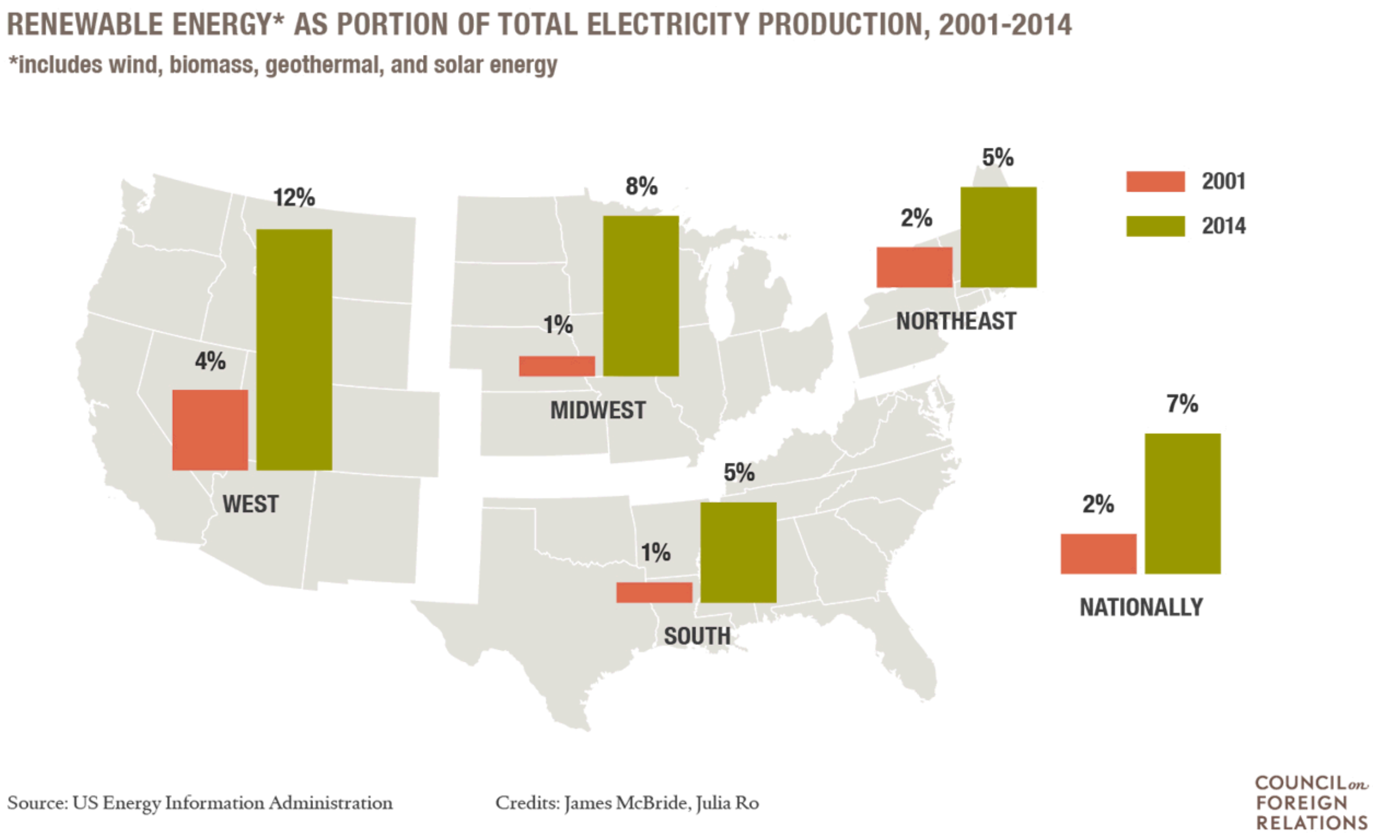


U.S. Electric System Operating Data
http://www.eia.gov/beta/realtime_grid/?src=-f2#/status?end=20161113T20

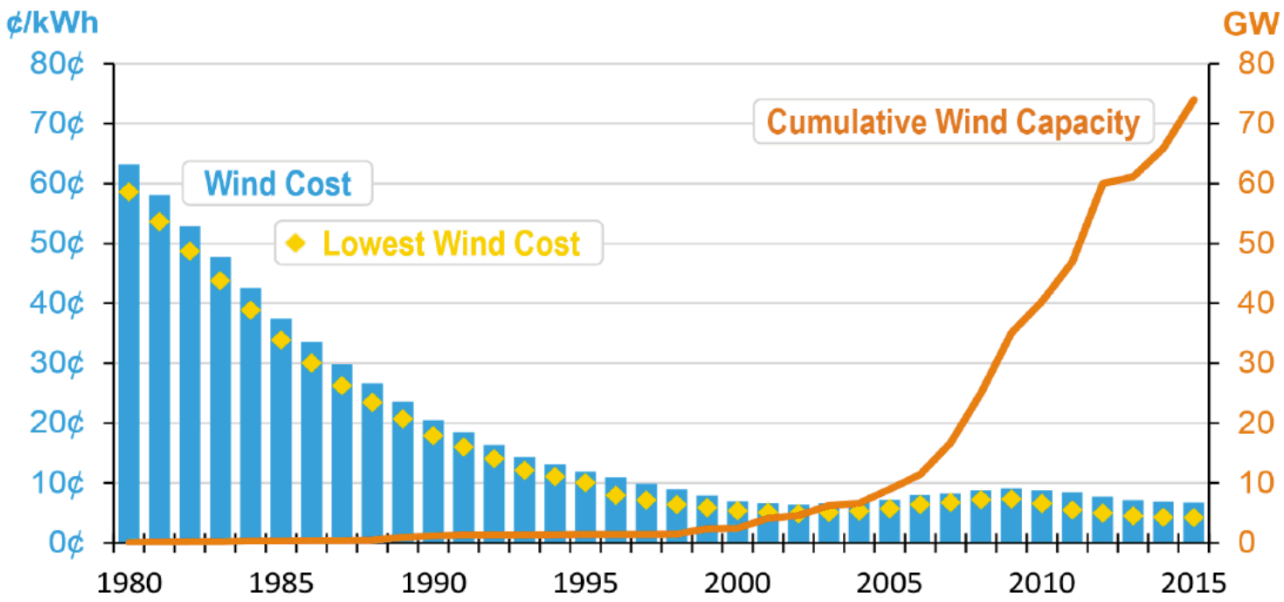
U.S. Electricity Prices



Growing Role of Renewables



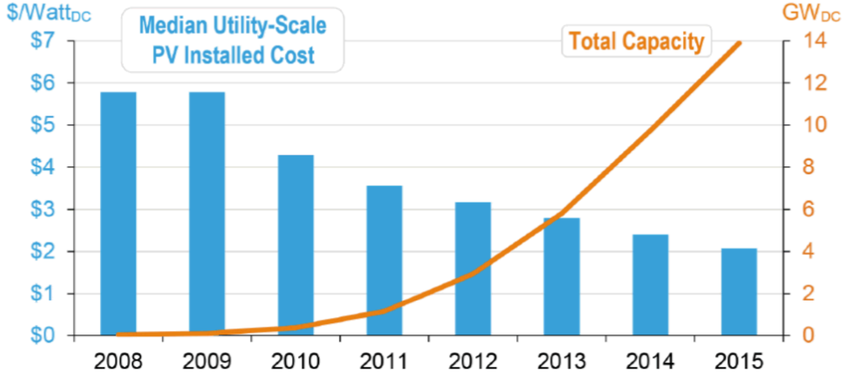
Growth of Wind Generation

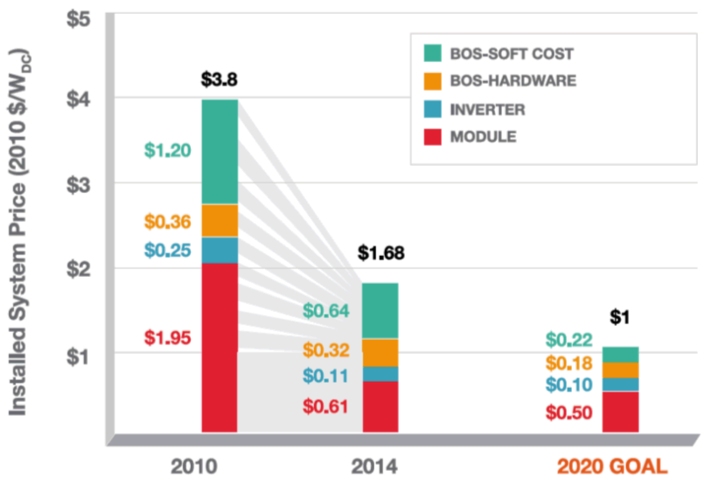


The Future Arrives for Five Clean Energy Technologies – 2016 Update, US DOE
http://energy.gov/eere/downloads/revolutionnow-2016-update

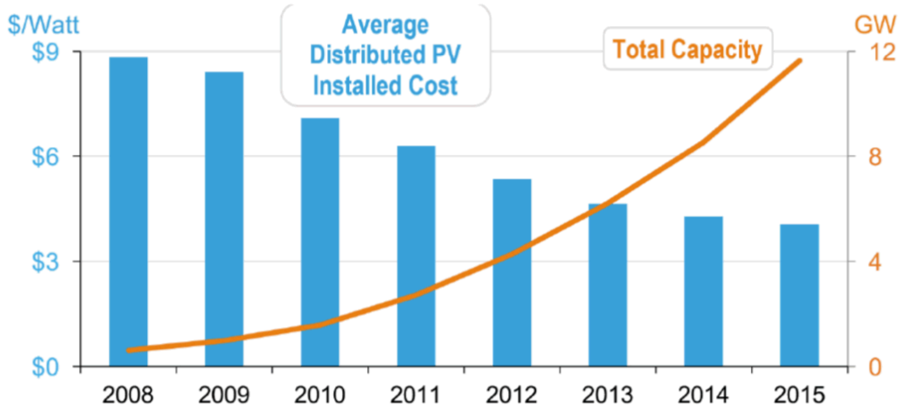
PV Deployments

Solar PV: Utility-Scale





olar PV: Distributed



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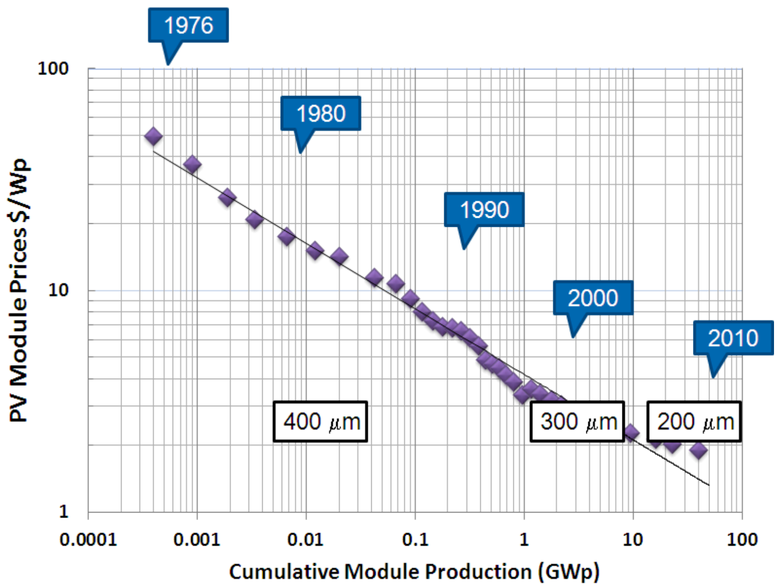
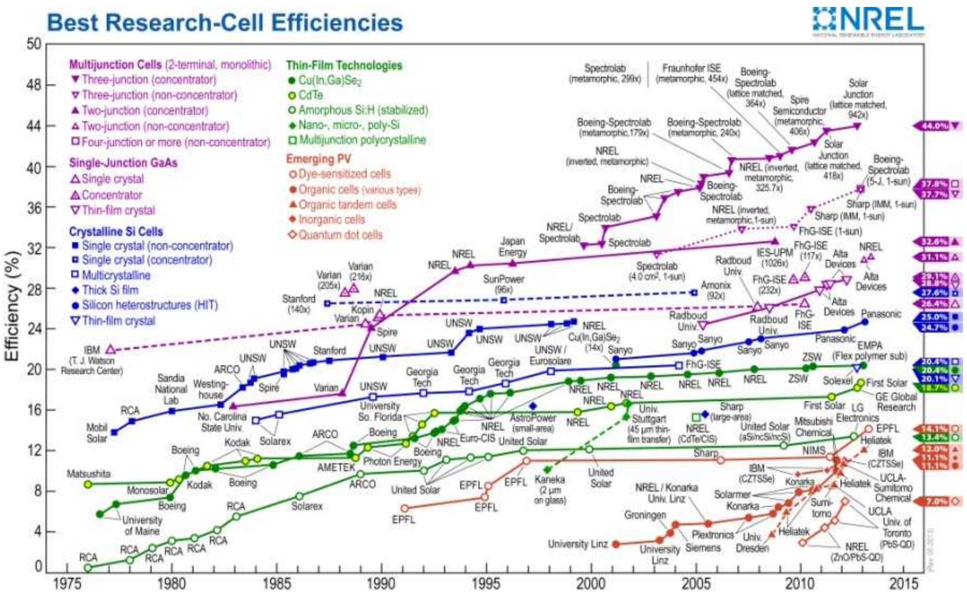
PV Learning Curve



Source: Fisher, Proc IEEE, May 2012

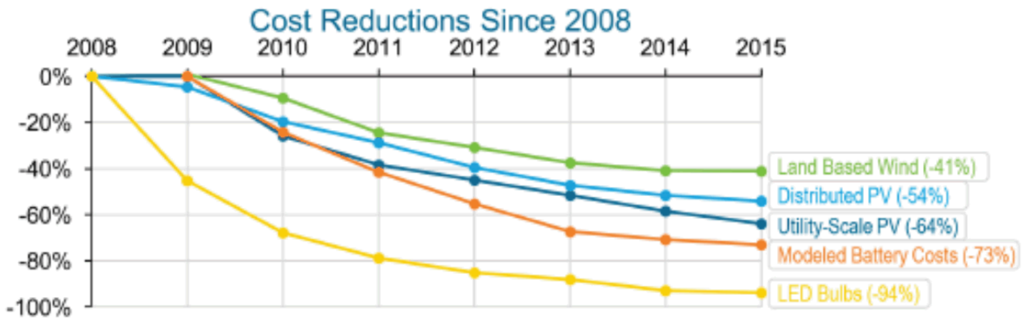


Data Sources: DOE SunShot & SunEdison

- Rapid growth in PV deployment driven by10X drop in $/kW and 50% increase in cell efficiency for c-Si in 20 years
- Cost reduction is the stronger driver
- 2015 PV production capacity: 60 GW

Cost Reduction through Manufacturing

- All driven by rapid reductions in costs through manufacturing at scale



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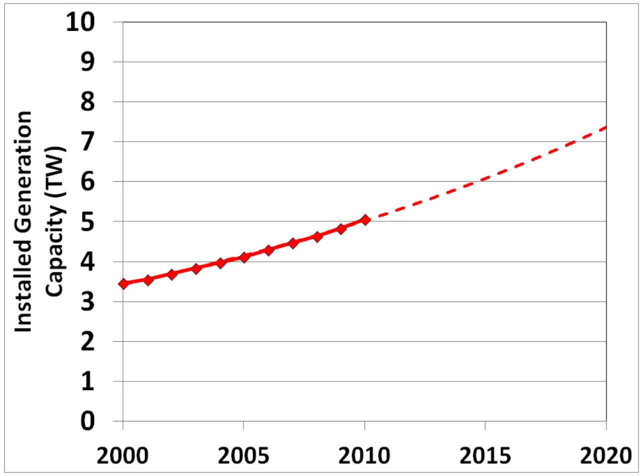
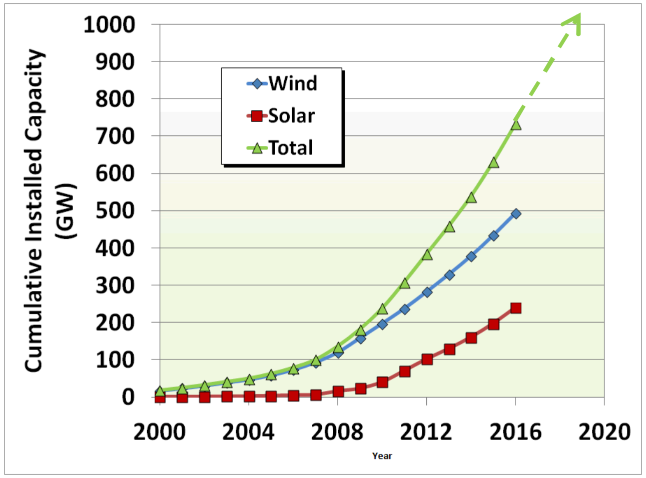
Global Trends in Energy

- Transition Towards a Renewable Electricity Regime
  - Distributed energy sources, improve resiliency, rapid adaption to climate and demographics change
- Electricity Infrastructure
  - Grid modernization needs major investments
  - Transition to a distributed generation model and technology needs for this transformation
- Smart Grids and High Level Systems Integration
  - Optimization distributed energy systems across multiple platforms and use regimes (residential, commercial and utility scale
  - Grid security and resiliency

Growth of Renewables is the Big Story

- Rapid transition towards a distributed generation model.
- Of the 6 TW of worldwide generation capacity, wind and solar are reaching the 5-10% range in many areas.
- By 2020, worldwide installed RE capacity will be ~ 1 TW, penetration levels may approach 30-40% in some markets.
- Are we really prepared to handle high levels of RE and the associated intermittency?
- Is the current grid ready for large amounts of renewables?
  - Handling intermittency is a key challenge
- Can we provide electricity to the 1.6B people who are have connected to the grid?



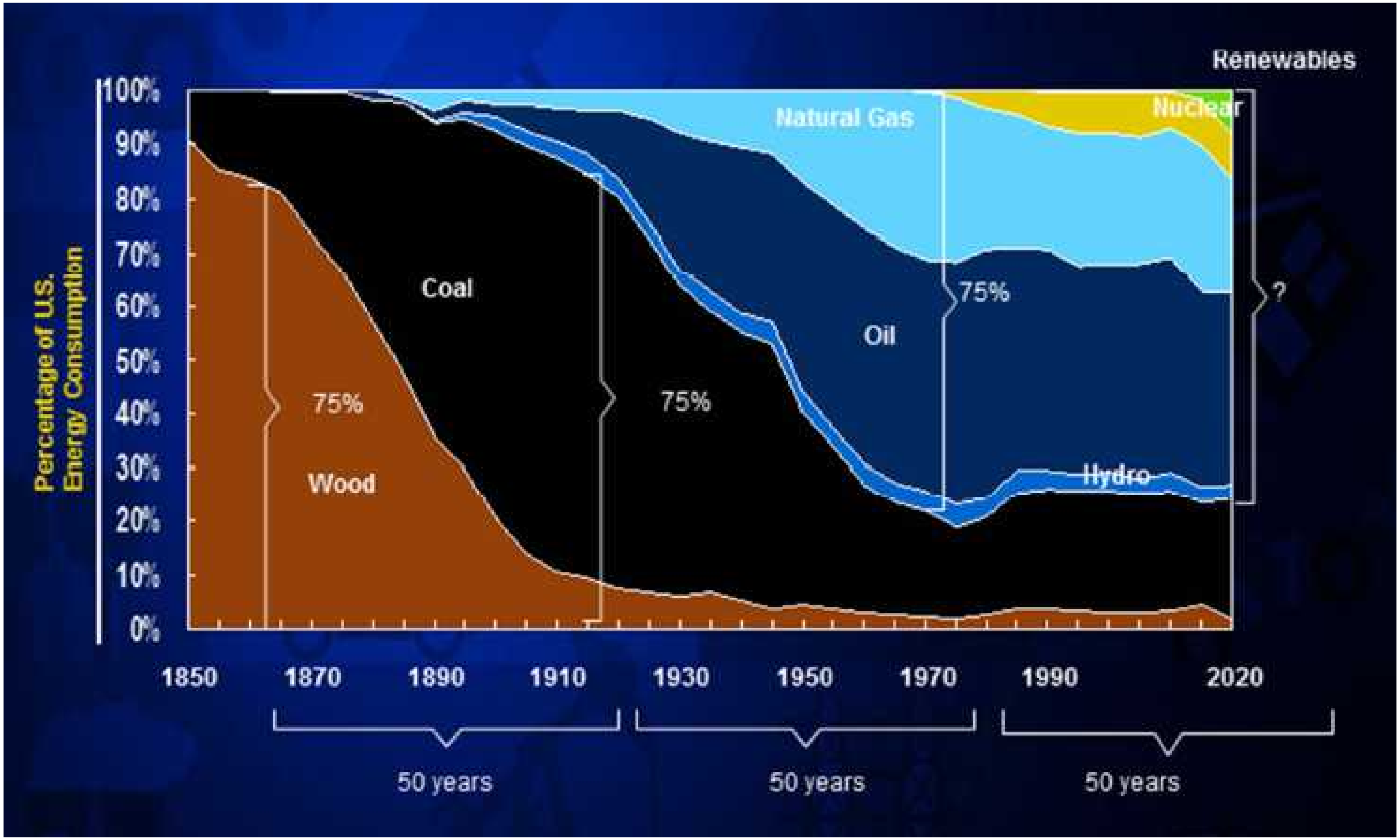


Data Sources: IEA, EPIA, Global Wind Energy Council, Earth Policy Institute, 2013

Energy Transformation

- Electricity Infrastructure
  - Grid modernization offers tremendous R&D opportunity
  - How do we make the transition to a distributed generation model and what does it to make this transformation?
    - Will take thirty or forty years and major investments. What are the opportunities to make major engineering contributions?
- Transition Towards a Renewable Electricity Regime
  - Distributed energy sources, improve resiliency, rapid adaption to climate and demographics change
- Smart Grids and High Level Systems Integration
  - How do we optimize distributed energy systems across multiple platforms (electricity, thermal, fuel) and use regimes (residential, commercial and utility scale
  - Grid security and resiliency

Technology Cycles – Energy, 50-Year Cycles

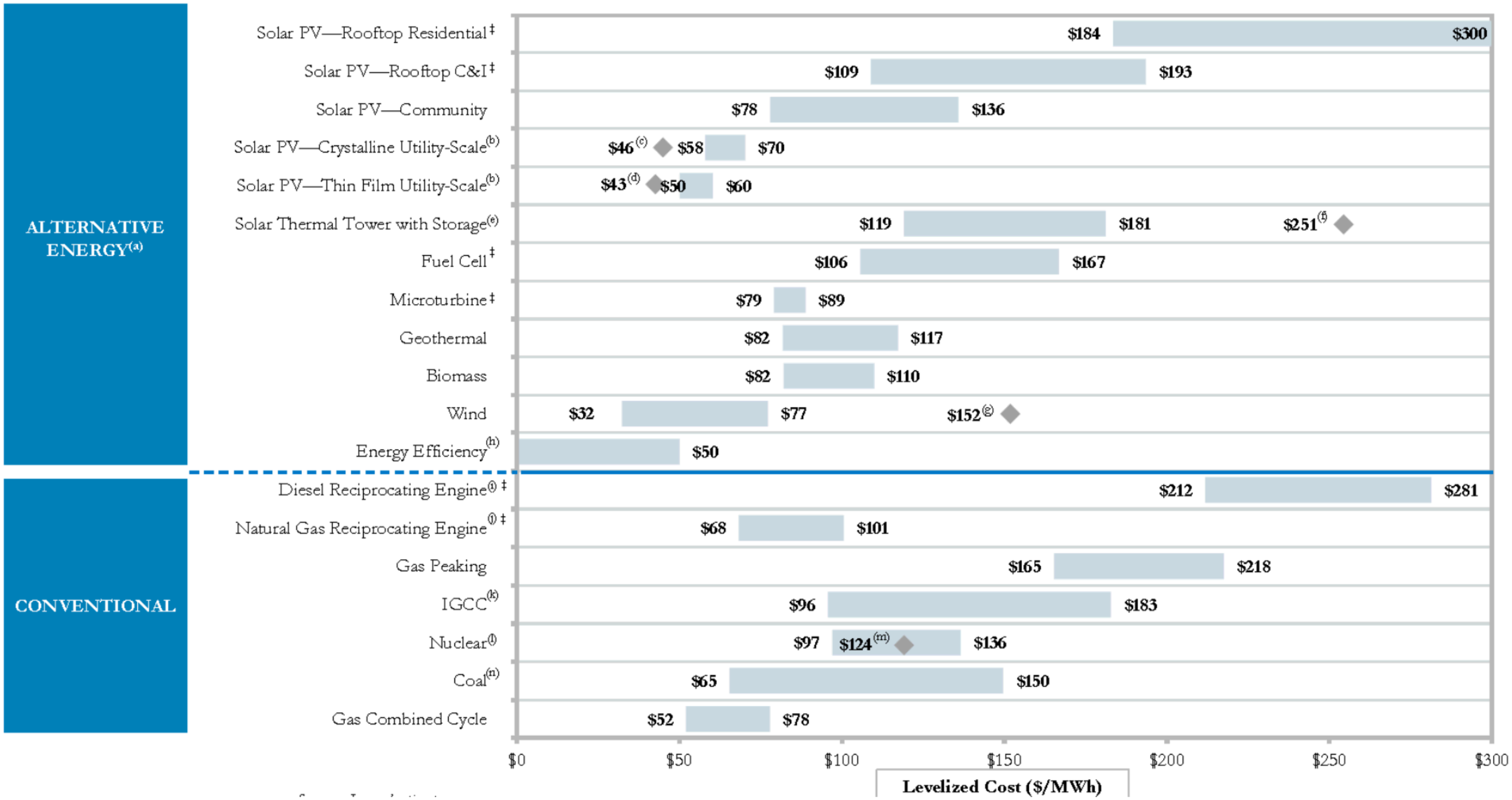


EIA Annual Energy Review 2008

Electricity Infrastructure

- Poised for major transformation driven by
  - Aging infrastructure
  - Making the grid adaptive and resilient
  - Growth of renewables and distributed energy
- Significant long term research opportunities
  - Methods to improve the resiliency of the electric grid infrastructure,
  - Adaptive electronics and software systems for improved grid security and reliability
  - Smart grids and advanced systems integration
- Technological Drivers
  - Advanced materials
  - Energy storage
  - Power electronics

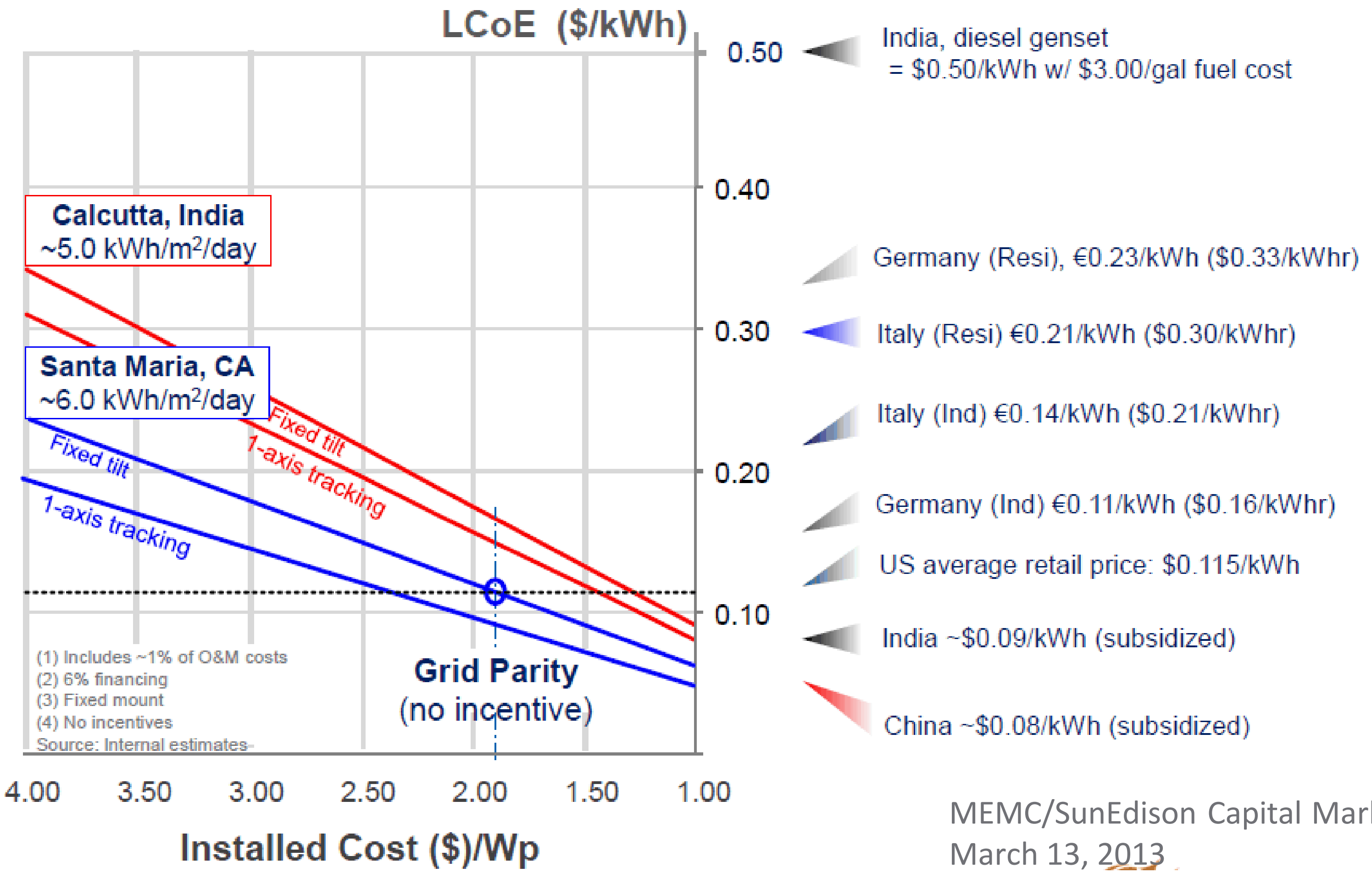
Unsubsidized Levelized Cost of Energy Comparison



Wind and solar PV have become increasingly cost-competitive with conventional generation technologies on an unsubsidized basis.

Data Source: Lazard, 2016

Renewables Transition to Incentive-Free Market



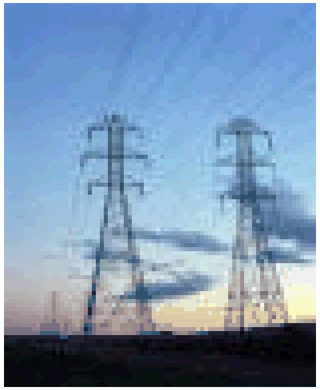
MEMC/SunEdison Capital Markets Day
March 13, 2013

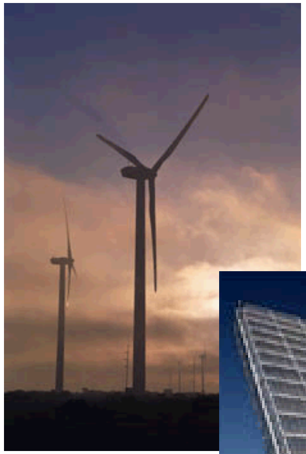
Making Renewable Ubiquitous

- Major challenges and research needs
  - For renewable to become ubiquitous, firm power is needed
  - Handling intermittency is a key challenge
  - Cost and reliability are significant metrics
- To make LCOE of firm renewables to be globally competitive (vs. fossil fuels, NG), need major advances in power electronics, BOS, and integration
- At system level, renewable energy systems need to become
  - Intelligent and highly adaptive systems (lot of local intelligence, forecasting, adaptive controls)
  - High level integration of energy storage and hybrids on a grand scale (imagine replacing 7TW of electric grid with renewables)
  - Remote integration with smart grids

Why Do We Need Energy Storage?

Energy Storage Mediates Between Variable Sources and Variable Loads





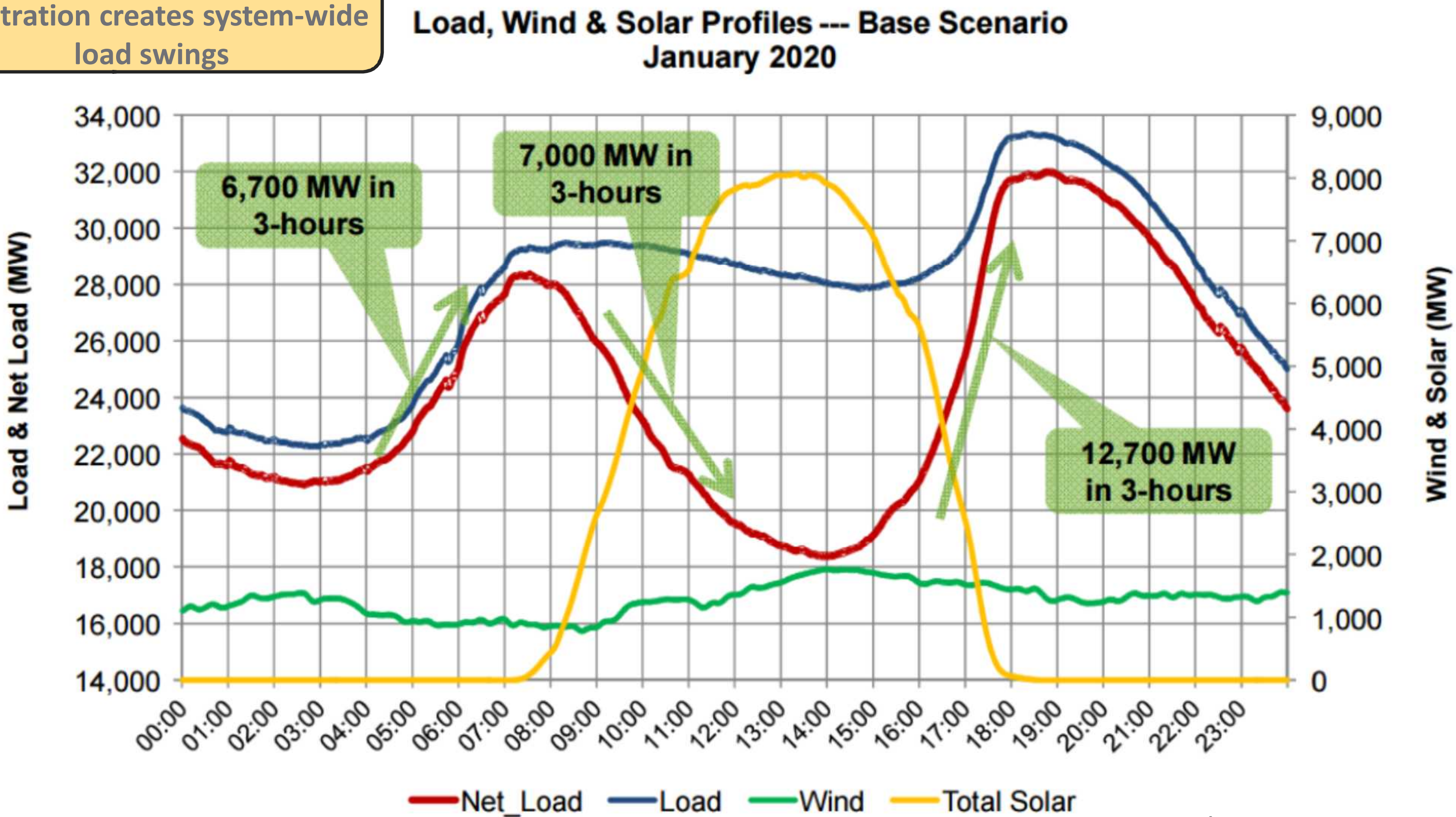
Without storage, energy generation must equal energy consumption.

Application Drivers for Energy Storage

- Renewable integration
- Transmission and Distribution upgrade deferral
- Power quality, e.g., UPS application, microgrids, etc.
- Improved efficiency of nonrenewable sources (e.g., coal, nuclear)
- Off-grid applications

Wind and Solar Load Balancing (CAISO)

Increased renewable penetration creates system-wide load swings



Source: Rob Cummings, NERC, 2016

Improved Efficiency of Existing Generation Assets

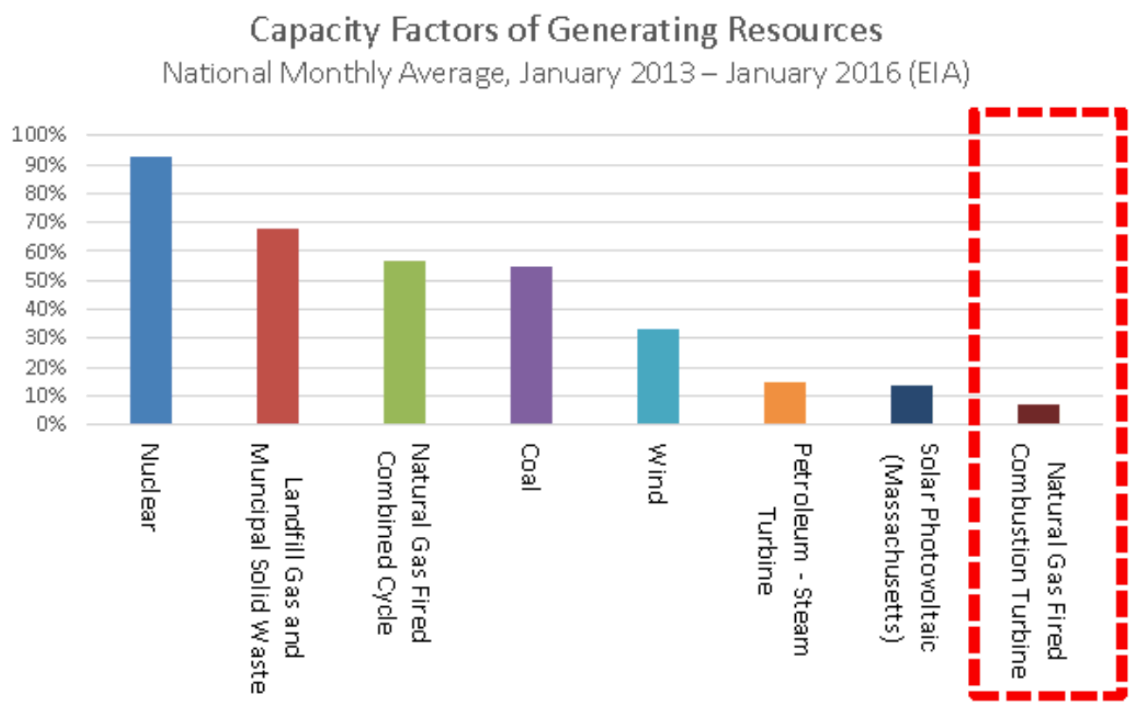


Figure 2-8: Average Monthly Capacity Factors[44]

EIA Electric Power Monthly, Table 6.7.A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels, January 2013-January 2016; https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_6_07_a

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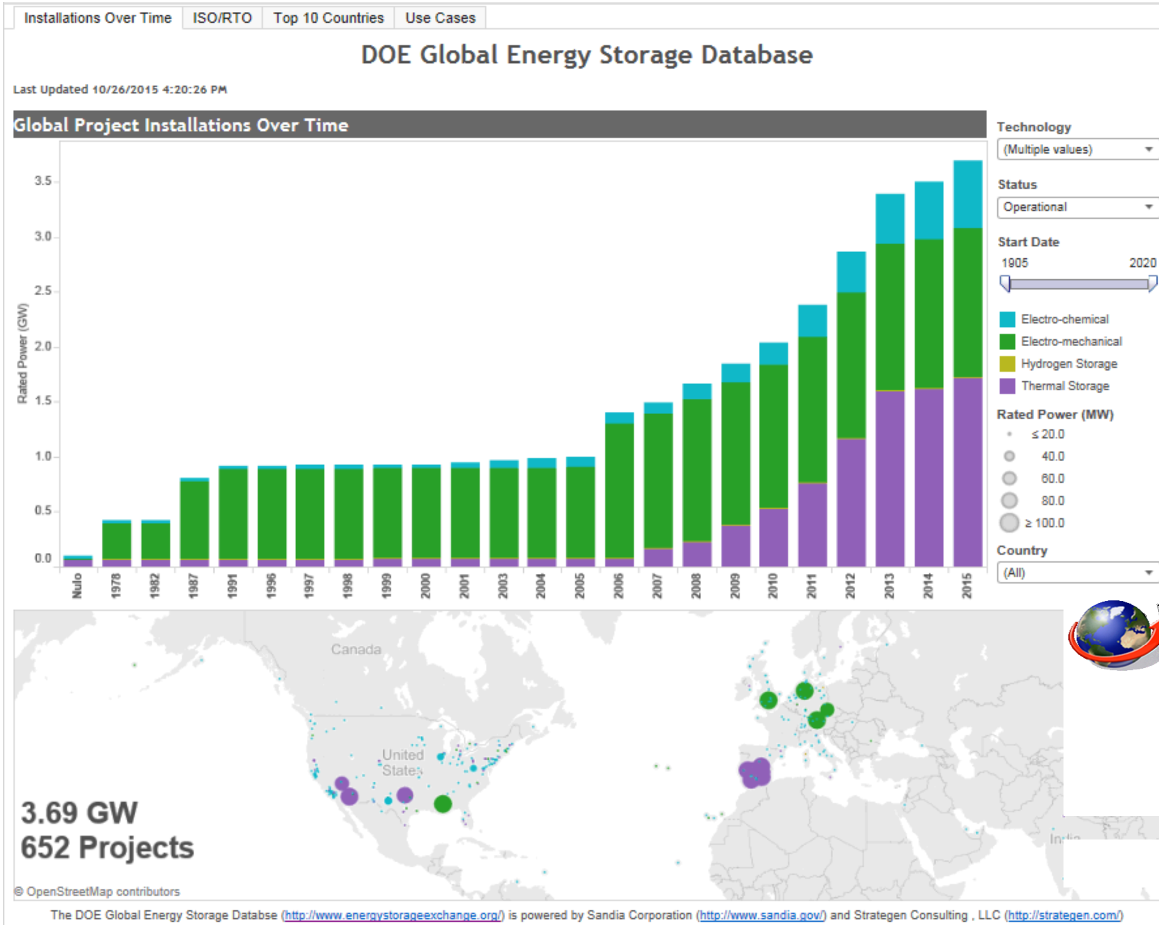
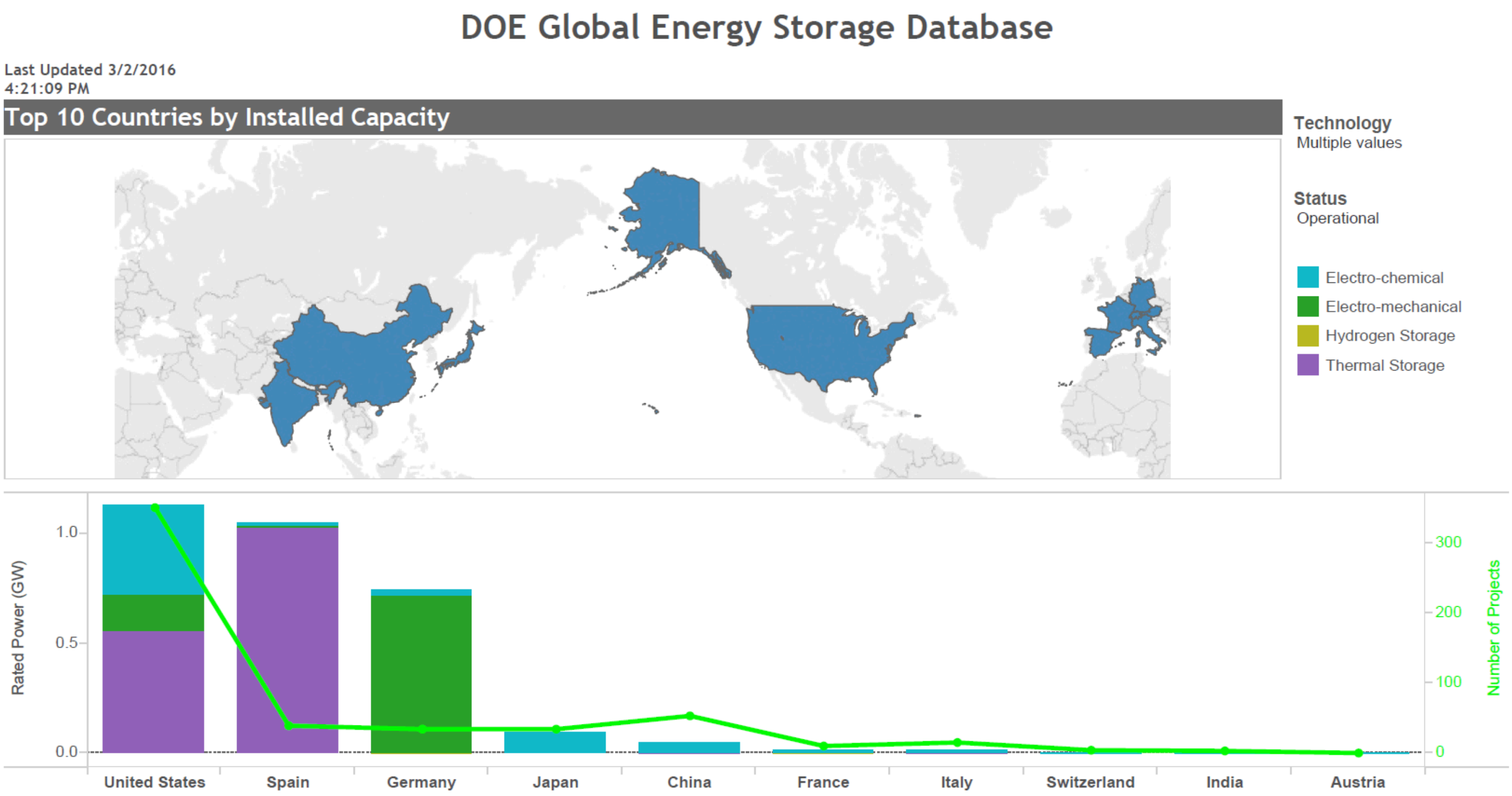
Energy Storage on the Grid Today



World-wide	**2.2%**
• **Japan**	**8.9%**
• **Europe**	**4.7%**
• **USA**	**2.2%**

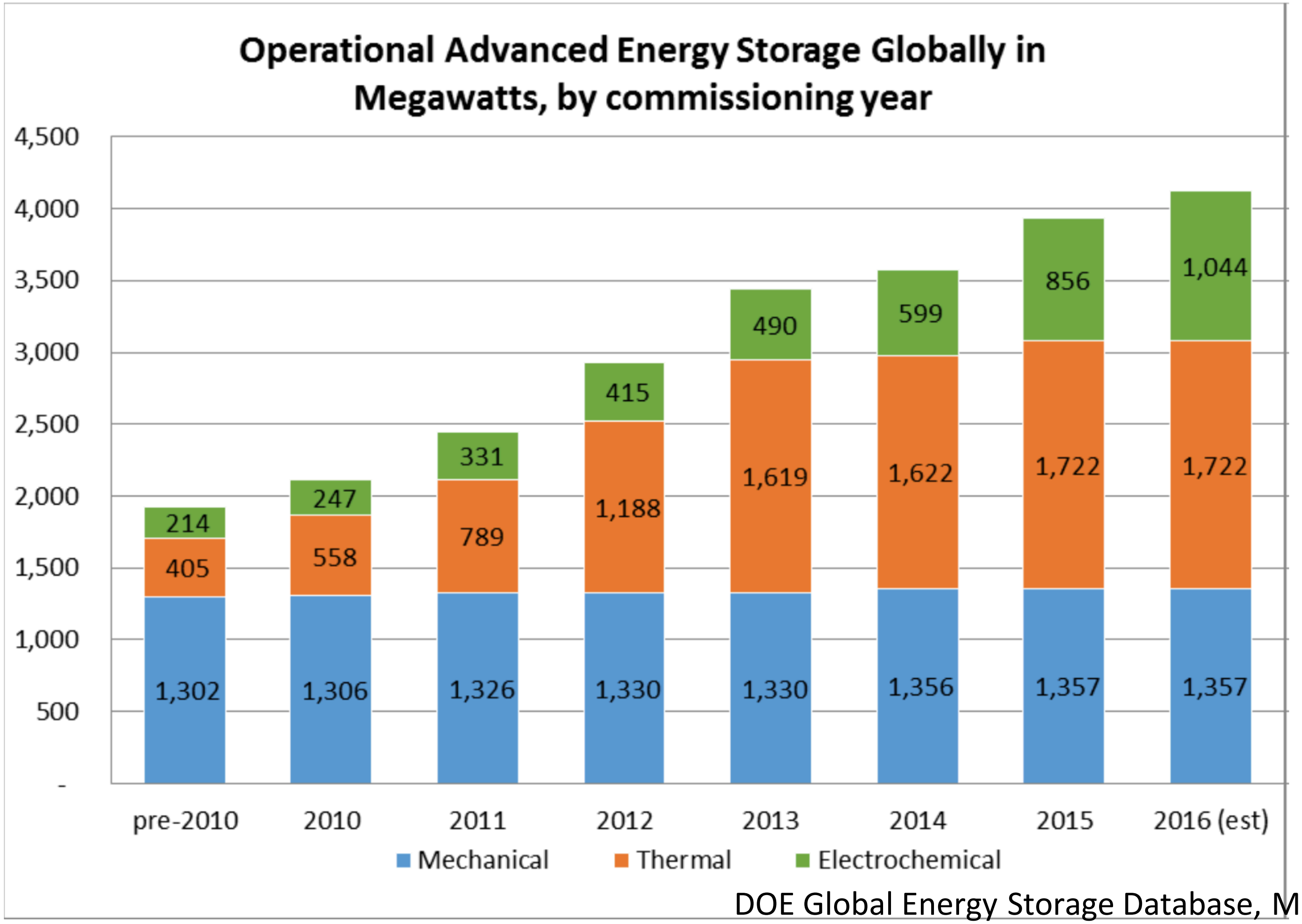
Source: DOE Global Energy Storage Database

Energy Storage on the Grid Today



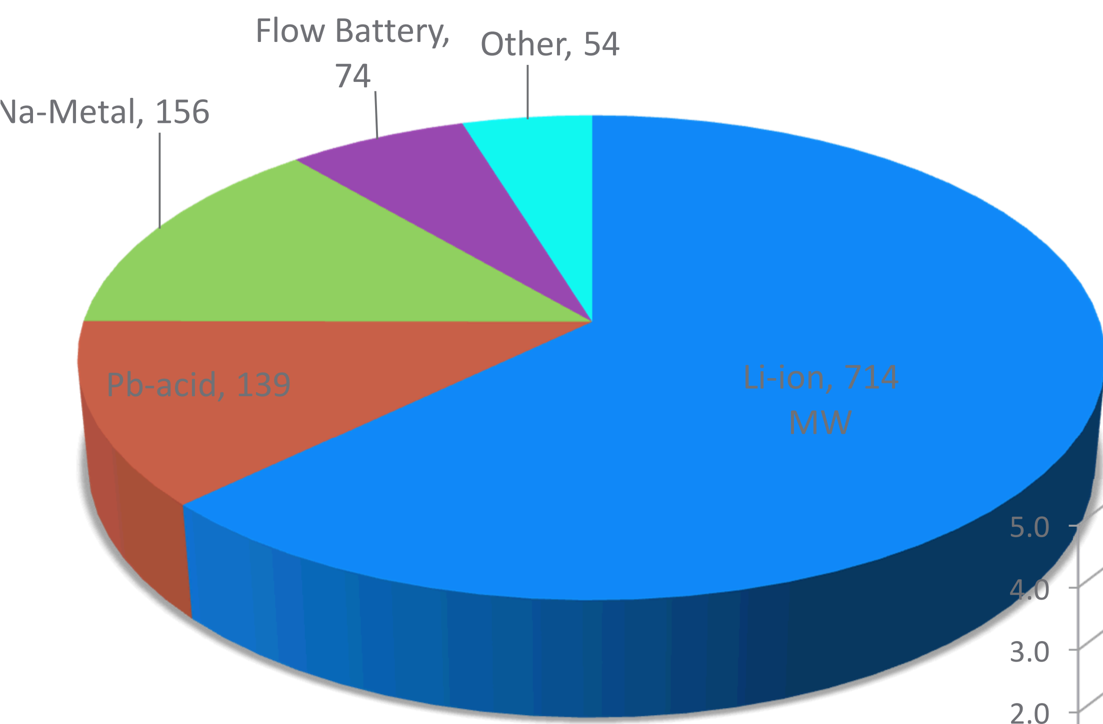
Source: DOE Global Energy Storage Database

Operational Advanced Energy Storage Globally in Megawatts, by Commissioning Year2



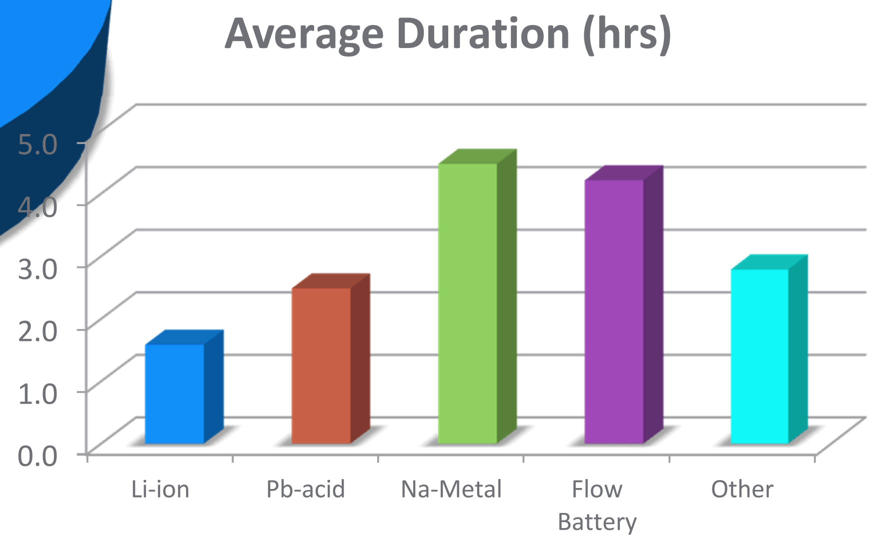
DOE Global Energy Storage Database, March 23, 2016:
www.energystorageexchange.org

Current Stationary ESS deployments (Battery Only)



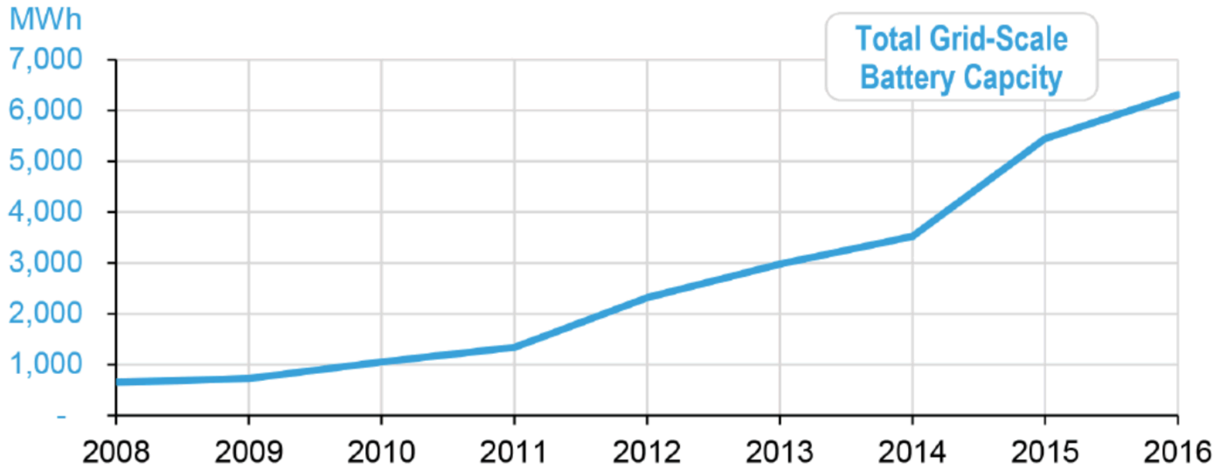
~ 1.1 GW of Battery Energy Storage

~110 GW of Pumped Hydro



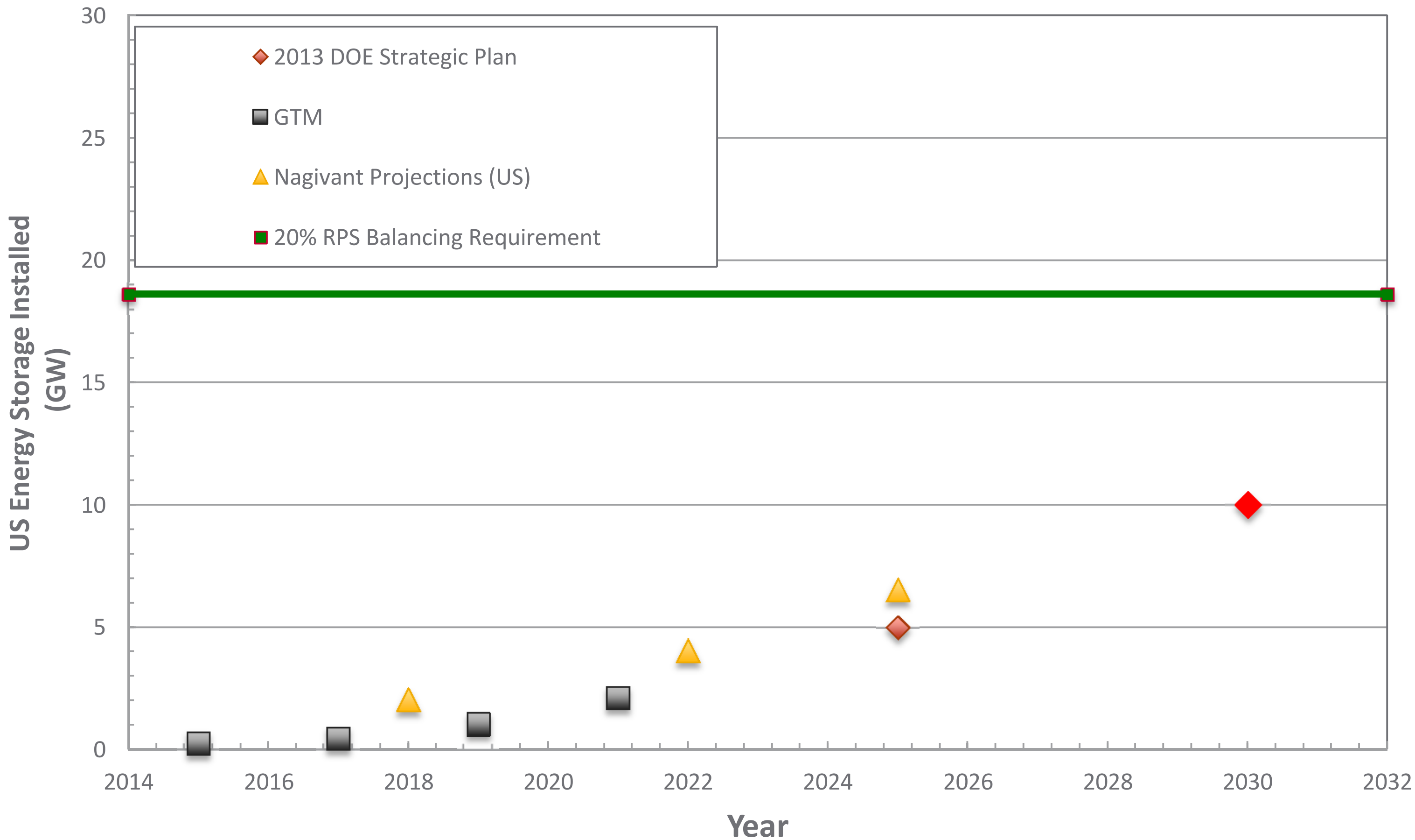
Source: *DOE Global Energy Storage Database*
http://www.energystorageexchange.org/
July 2015

Battery Storage in the Grid



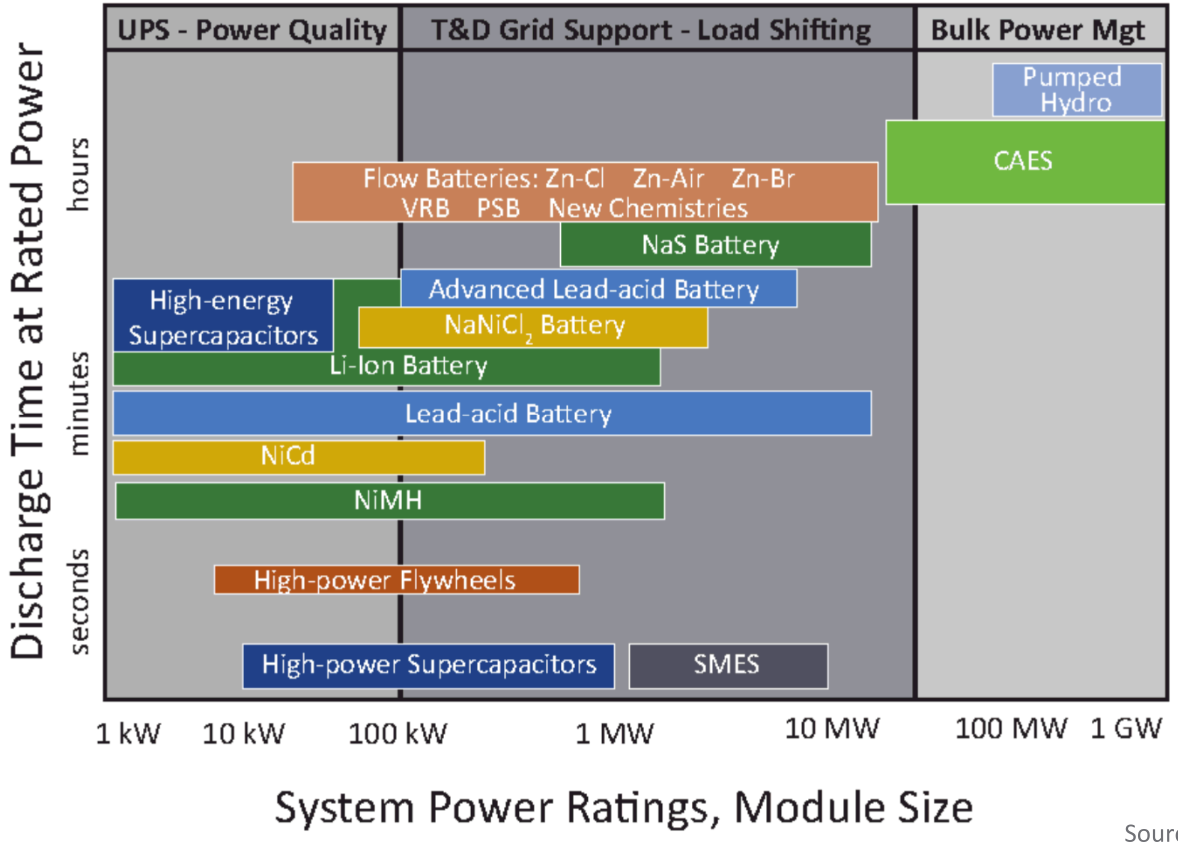
Source: DOE Global Energy Storage Database

How much storage can the grid handle?



US Energy Storage Market Forecasts

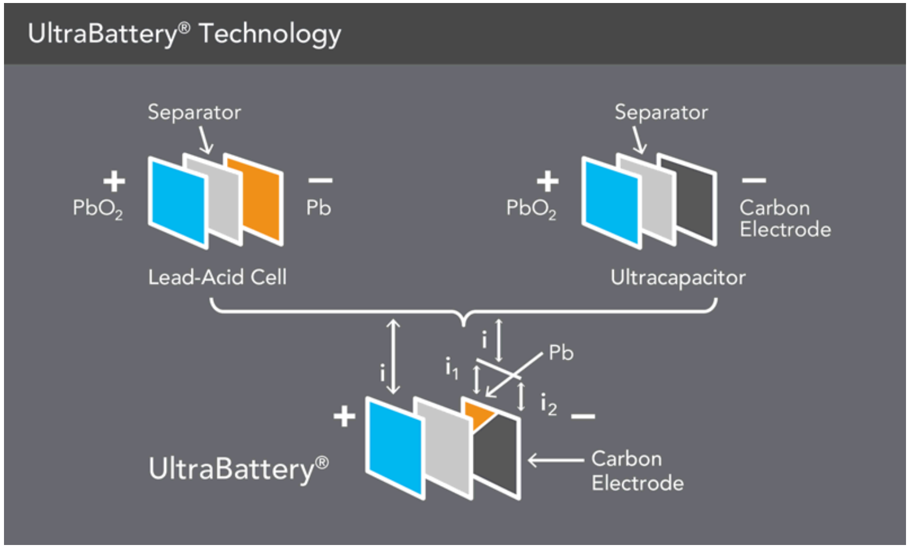
Storage Technology and Application Markets



Source: DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, 2013

Advanced Lead Acid – Ultra Batteries

- Advanced Lead Acid Energy Storage
  - High carbon batteries, in manufacturing at EastPenn, Furakawa, Axiom, ..
  - Carbon plates significantly improve performance
  - Mature technology
  - Low cost
  - High recycled content
  - Improved cycle life
- Applications
  - Load leveling
  - Frequency regulation
  - Grid stabilization
- Challenges
  - Low energy density
  - Limited depth of discharge
  - Large footprint

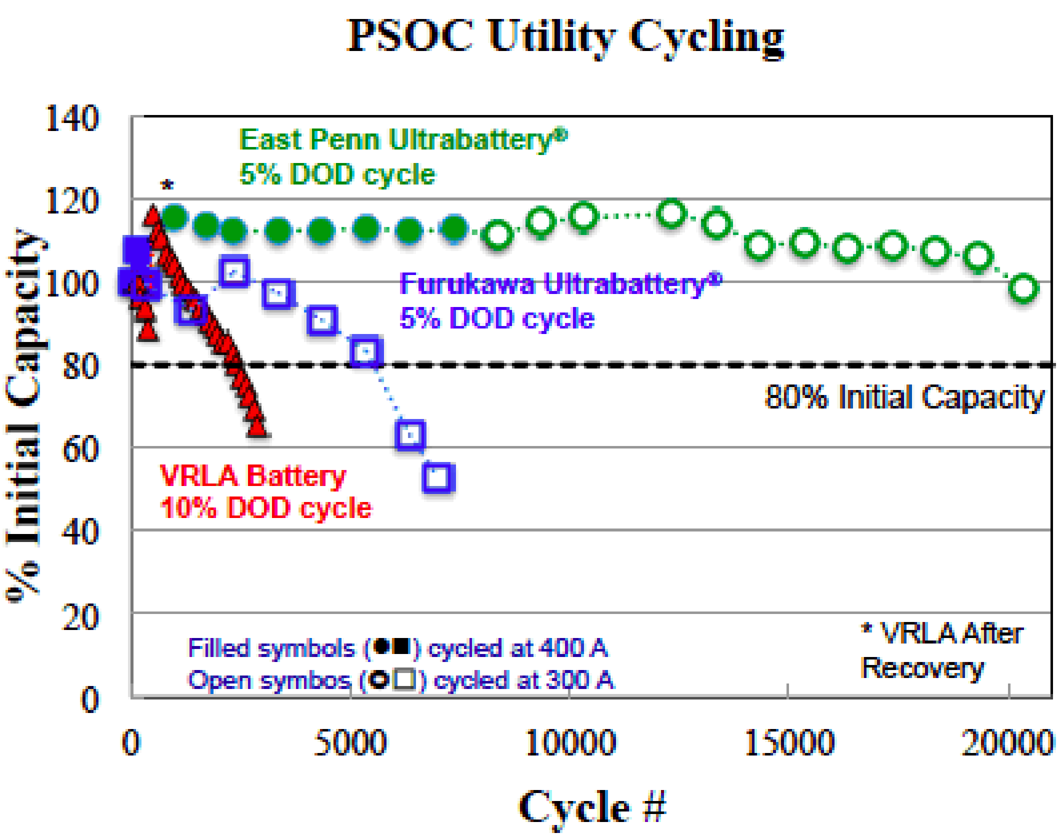


Albuquerque, NM

East Lyons, PA

Advanced Lead Acid: Cycle Life

East Penn



http://www.sandia.gov/batterytesting/docs/LifeCycleTestingEES.pdf

Li-ion Batteries

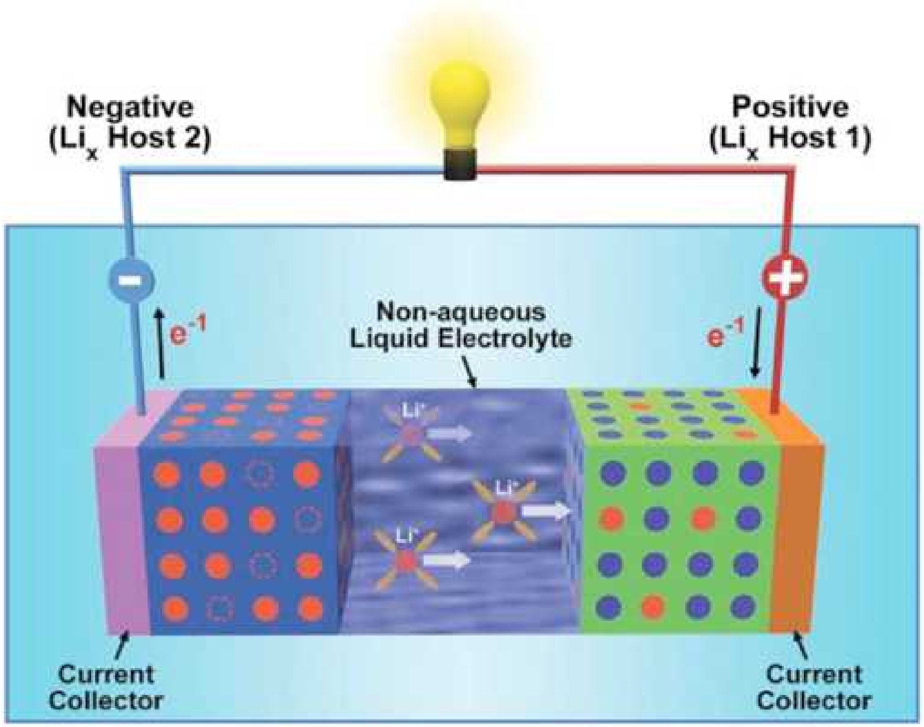
- Li-ion Energy Storage
  - High energy density
  - Good cycle life
  - High charge/discharge efficiency
- Applications
  - Power quality
  - Frequency regulation
- Challenges
  - High production cost
  - Extreme sensitivity to:
    - Over temperature
    - Overcharge
    - Internal pressure buildup
  - Intolerance to deep discharge

SCE Tehachapi plant, 8MW, 32MWh.

Lithium Ion Batteries

- First two generations driven by consumer electronics, newer chemistries geared for automotive applications
  - Li-Ion Chemistries, LiCoO2 - dominant technology for consumer electronics
  - 2nd Generation Li-Ion Chemistries
    - Better performance, up to 300 Wh/kg with fast recharge
    - Wider temp range, Improved safety and potentially lower cost
  - Spill off into Power applications, competitive for power applications in the grid. Several installations for power regulation (2-20 MW)
- Li ion chemistry
  - Safety and reliability continues to be significant concerns
  - Power control and safety adds significant cost to Li ion storage
  - Packaging and thermal management add significant costs
  - Deep discharge cycle life issues for energy applications (1000 cycles for automotive)

Li-ion Batteries: Basic Chemistry

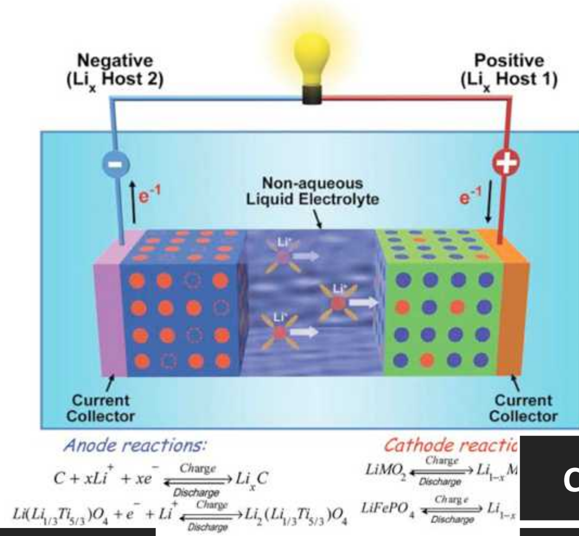


Anode: $$Li_xC_6 \xrightarrow{discharge} xLi^+ + xe^- + C_6$$

Cathode: $$Li_{1-x}CoO_2 + xLi^+ + xe^- \xrightarrow{discharge} LiCoO_2$$

Source: Z. Yang JOM September 2010, Volume 62, Issue 9, pp 14-23

Li-ion: Basic Chemistry



Anodes

Chemistry	Specific Capacity	Potential vs. Li^+/Li
Soft Carbon	< 700	< 1
Hard Carbon	600	< 1
$Li_4Ti_5O_{12}$	175 / 170	1.55
TiO_2	168 / 168	1.85
SnO_2	782 / 780	< 0.5
Sn	993 / 990	< 0.5
Si	4198 / < 3500	0.5 ~ 1

LTO

Cathodes

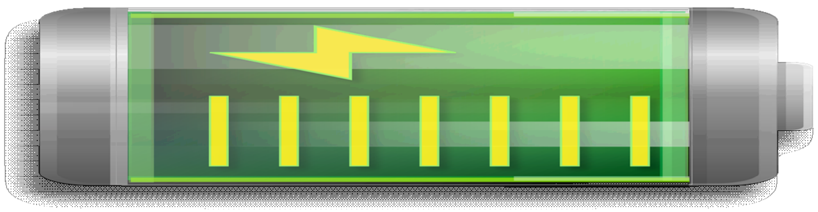
Chemistry	Specific Capacity	Potential vs. Li^+/Li
$LiCoO_2$	273 / 160	3.9
$LiNiO_2$	274 / 180	3.6
$LiNi_xCo_yMn_zO_2$	~ 270 / 150~180	3.8
$LiNi_xCo_yAl_zO_2$	~ 250 / 180	3.7
$LiMn_2O_4$	148 / 130	4.1
$LiMn_{1.5}Ni_{0.5}O_4$	146 / 130	4.7
$LiFePO_4$	170 / 160	3.45
$LiMnPO_4$	171 / 80~150	4.1
$LiNiPO_4$	166 / -	5.1
$LiCoPO_4$	166 / 60~130	4.8

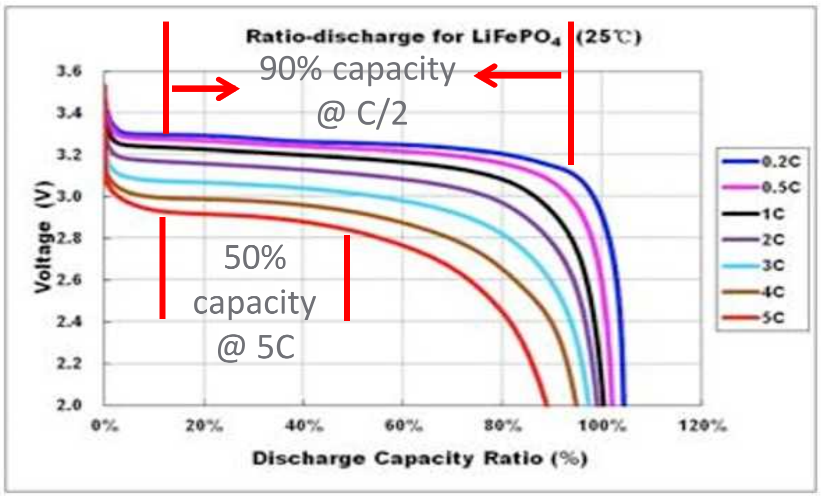
NMC

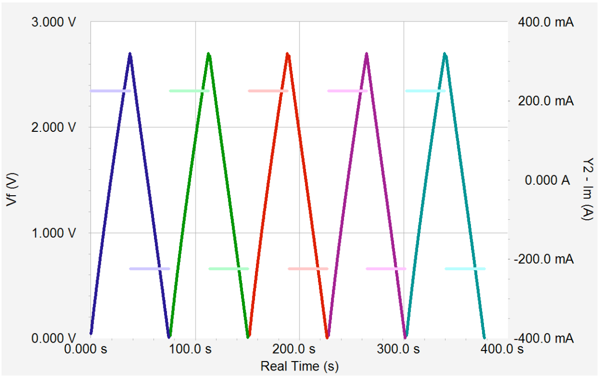
NCA

LFP

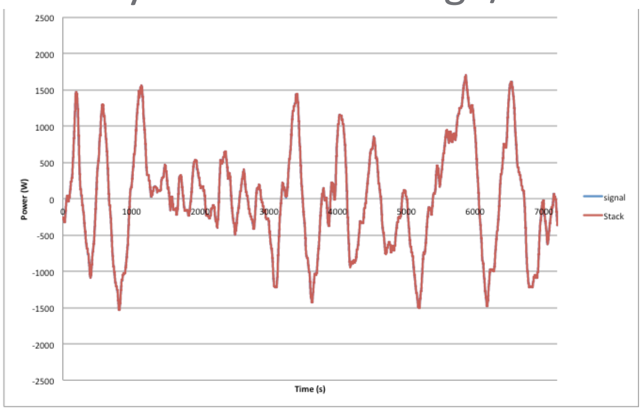
Lifetime and Capacity







Standard symmetrical Charge/Discharge



Average PJM Freq. Regulation signal

Li-ion: Advantages/Issues

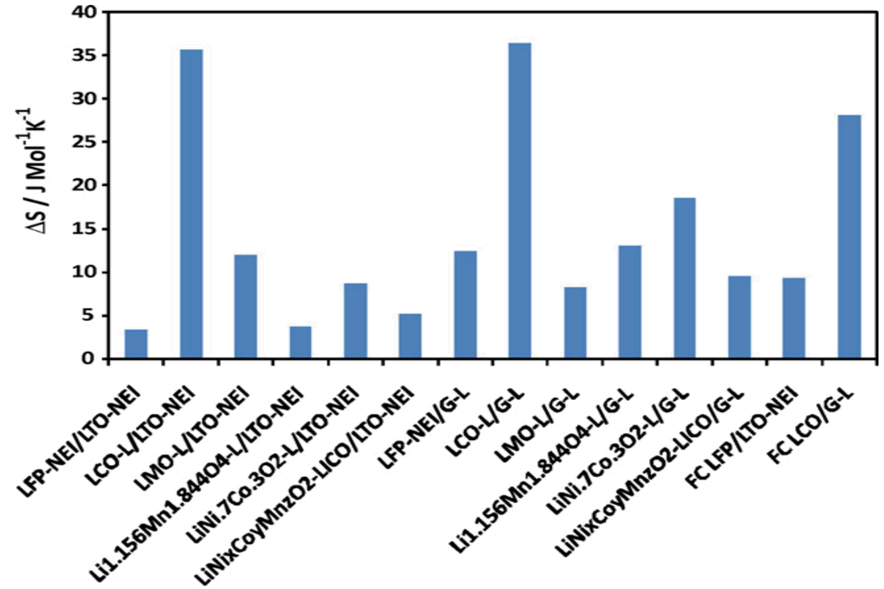
Advantages:

- Decreasing costs – Stationary on coattails of increasing EV.
- Ubiquitous – Multiple vendors
- Fast response.
- Higher efficiency

Issues:

- High Temperature
  - Typical operating window 0-50°C
  - Operation above this temperature can lead to organic electrolyte decomposition and flammable gas.
  - Different chemistries have different heat generation
  - Parasitic loads like HVAC often not included
- Overcharging
  - Max voltage depends on materials, overcharging can lead to Li metal plating on anode, potential for short

Inherent Heat Generation of Electrodes



Li-ion Batteries: SOA

- For grid applications
  - Costs coming down in LIB. However, BOM constitute ~70-80% of cell cost in a LiB.
  - Need lower manufacturing costa, currently in the $300-400M range for a 1GWh of manufacturing capacity
  - Grid batteries in addition to low BOM and cost of manufacturing
    - Reliability and Safety and Cycle life are significantly more serious
  - Excess capacity in the large format automotive batteries driving the market for applications in the grid

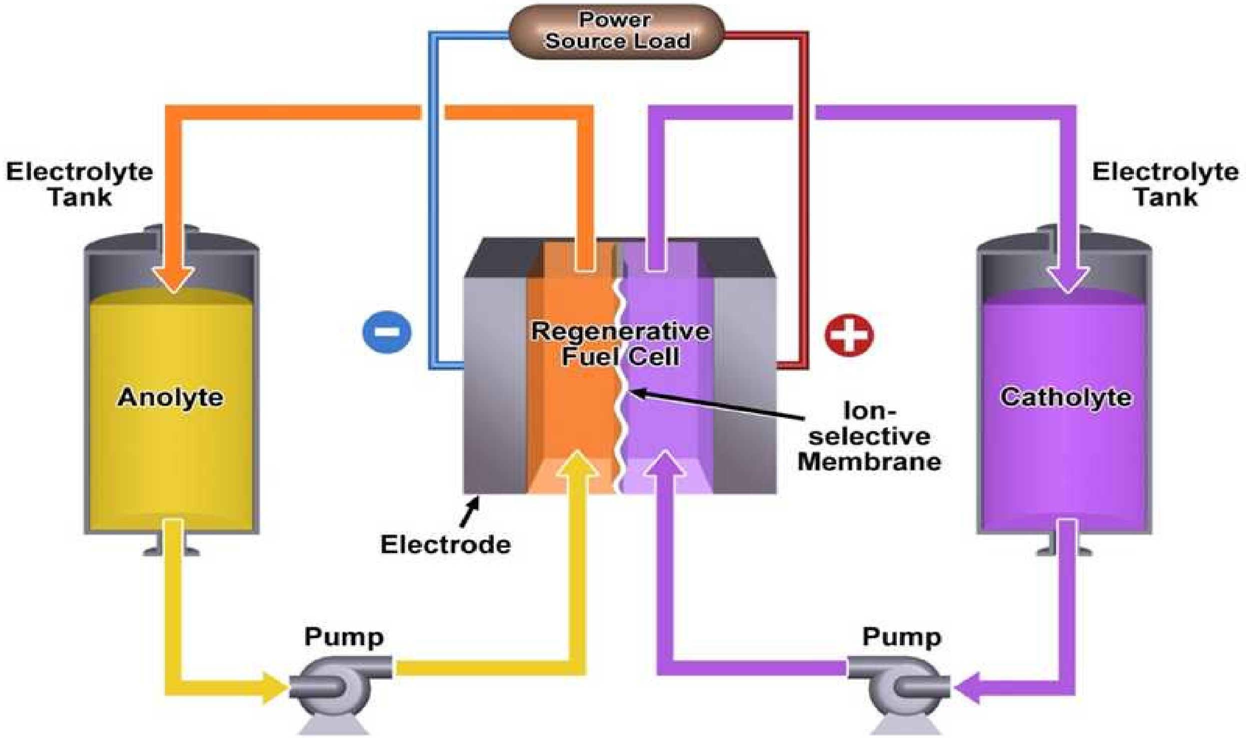
Flow Batteries

- Flow Battery Energy Storage
  - Long cycle life
  - Power/Energy decomposition
  - Lower efficiency
- Applications
  - Ramping
  - Peak Shaving
  - Time Shifting
  - Power quality
  - Frequency regulation
- Challenges
  - Developing technology
  - Complicated design
  - Lower energy density

Enervault plant, Turlock, CA. 250kW, 1 MWh.

Vionx Vanadium Redox Flow battery, 65kW, 390kWh

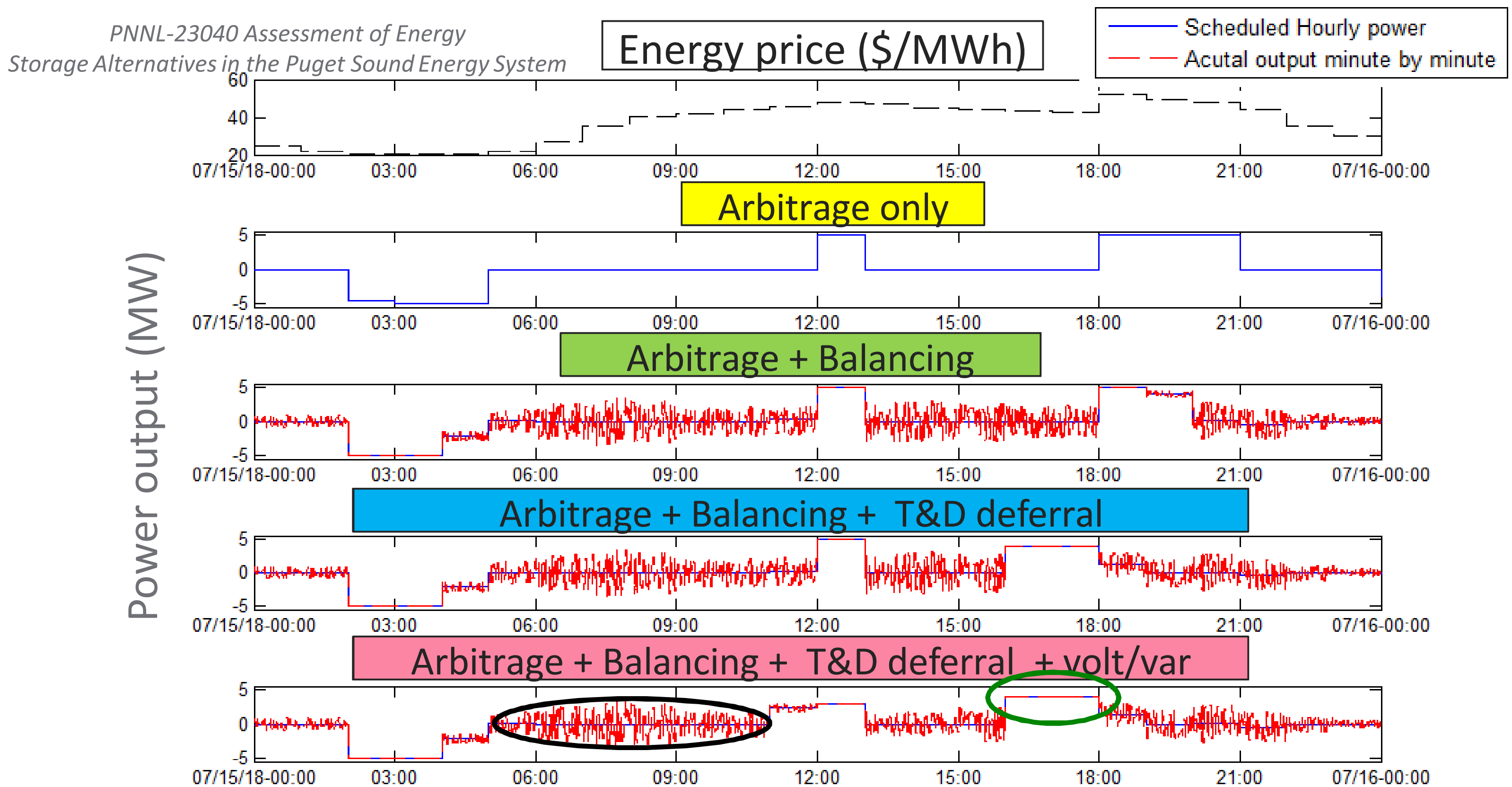
Why Redox Flow Battery?



Key Aspects

- Power and Energy are separate enabling greater flexibility and safety.
- Suitable for wide range of applications 10's MW to ~ 5 kw
- Wide range of chemistries available.
- Low energy density ~ 30 Whr/kg

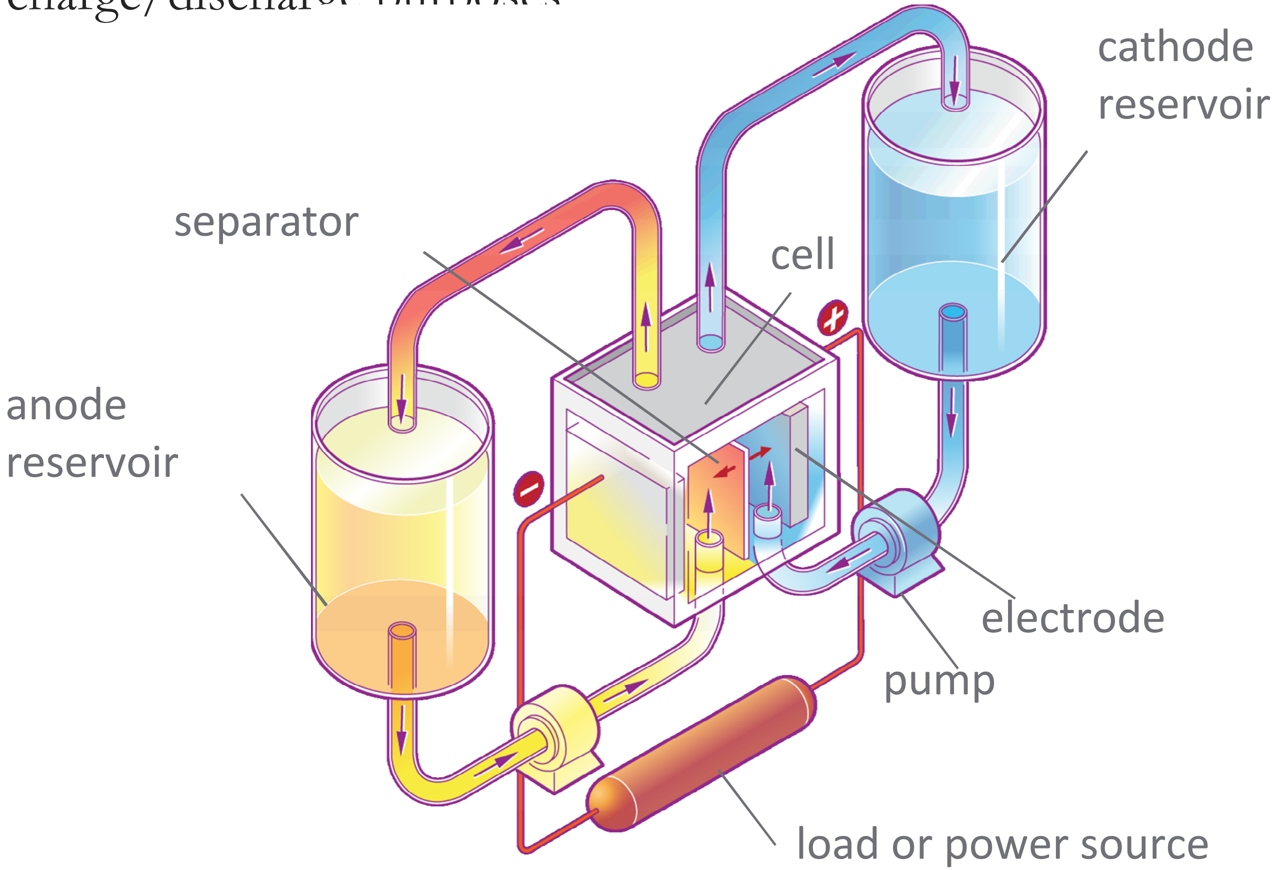
Bundled Services: High degree of Flexibility needed from Energy Storage?



- Want energy storage systems that can provide *for both*:
  - Fast response balancing services *and*
  - Longer duration (2^+ hr) deferral and outage mitigation.

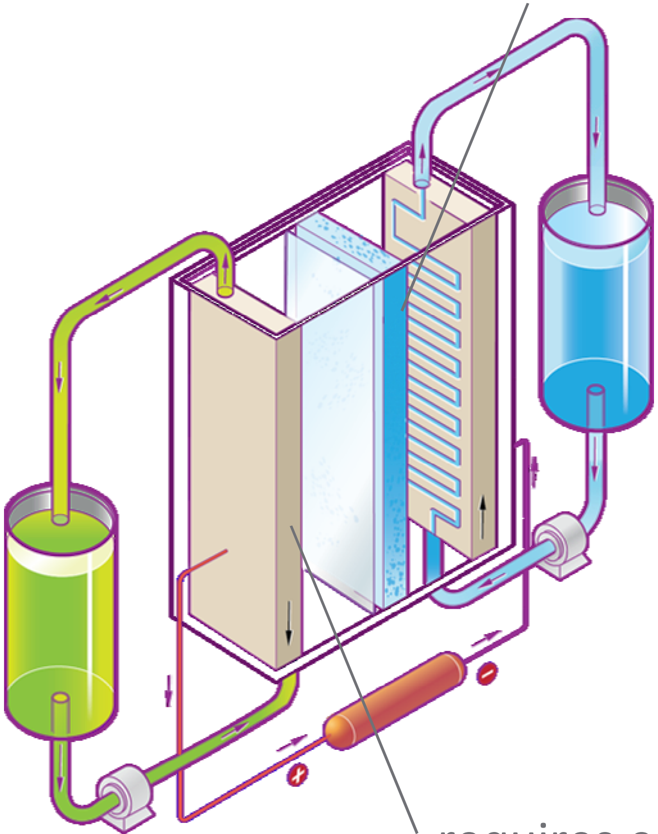
Flow Batteries

- Energy storage technology utilizing redox states of various species for charge/discharge purposes



Early Development

Open Circuit
Potential (OCP)
1.2 V



$Fe^{2+} \rightleftharpoons Fe^{3+} + e^{-}$

$Cr^{2+} \rightleftharpoons Cr^{3+} + e^{-}$

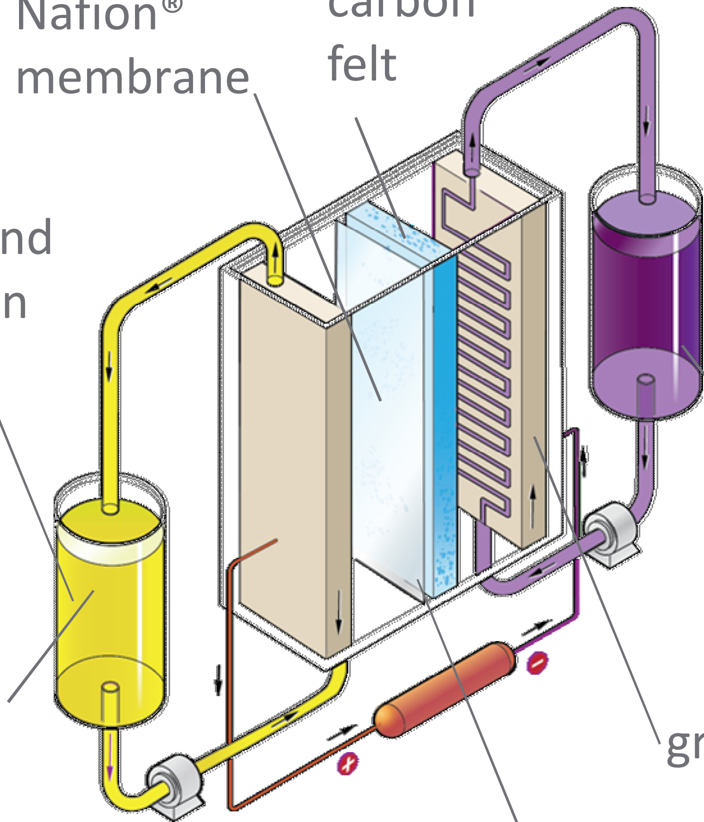
All-Vanadium Battery

Nafion® membrane

carbon felt

Open Circuit Potential (OCP) **1.5 V**

electrolytes influence temperature stability and vanadium concentration



$V^{2+} \rightleftharpoons V^{3+} + e^-$

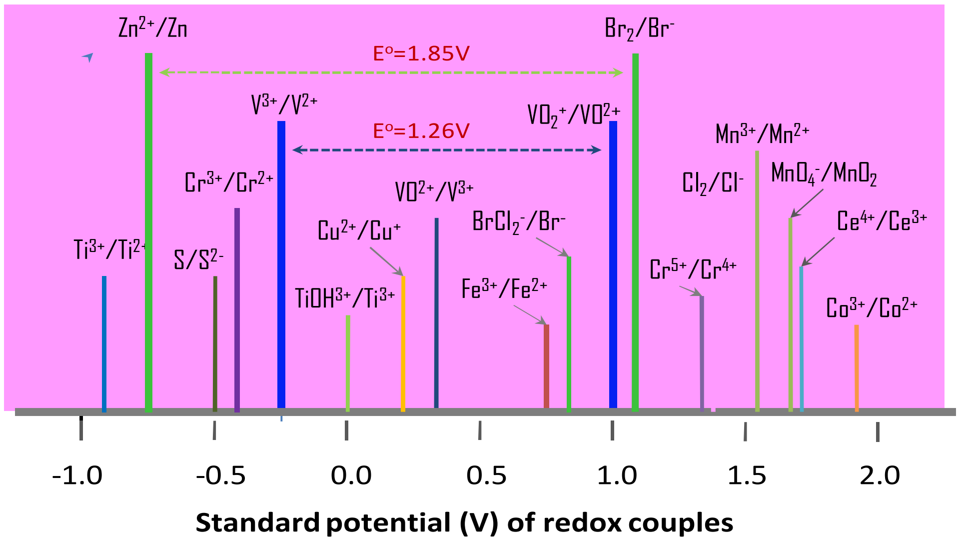
low vanadium concentration/low energy density

temperature sensitivity

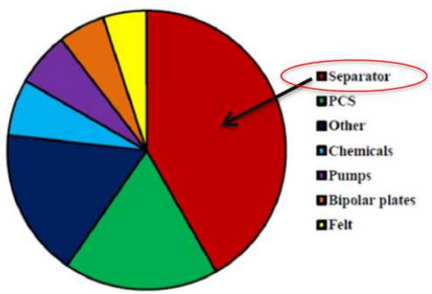
graphite

crossover is less of an issue

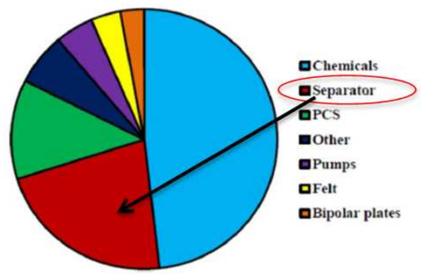
VRFB Mixed Acid



Vanadium Redox Flow Battery (VRFB) Total Costs



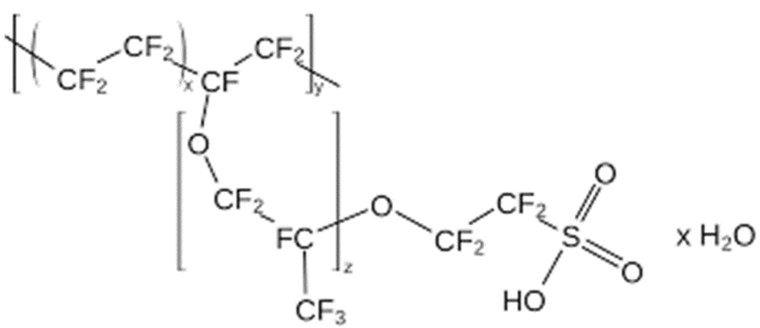
Power intensive case



Energy intensive case

Membrane separators account for between 1/2 to 1/3 the cost of VRFB stack depending on power out design

Perfluorosulfonic acid (PFSA) polymers current state of the art. High cost ($250-500/m^2$). Various suppliers. With no other challengers to the market cost remain high.



V. Viswanathan, et al, J. Power Sources, 247, 2014, 1040.

Company	Product type	Trade name
DuPont	Perfluorosulfonic acid membrane	Nafion
Asahi Chemical	Perfluorosulfonic acid membrane	Aciplex
Asahi Glass	Perfluorosulfonic acid membrane	Flemion
3M	Perfluorosulfonic acid membrane	3M MEA
Fumatech	Perfluorosulfonic acid	F-series
Gore	Reinforced perfluorosulfonic acid membrane	GoreSelect
DSM Solutech	Reinforced perfluorosulfonic acid membrane	Solupor

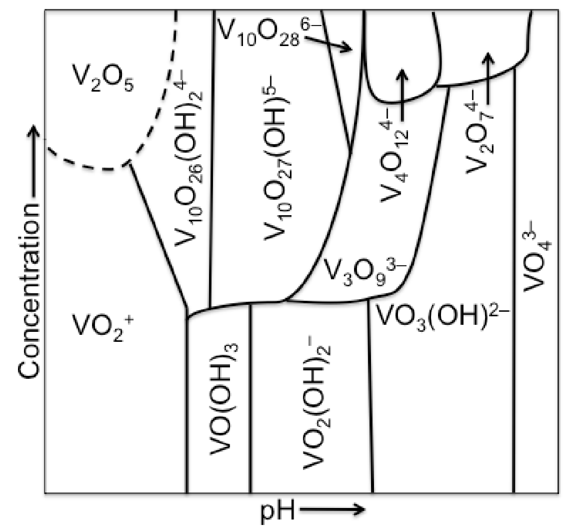
Redox Flow Batteries - Advantages/Issues

- Temperature
  - High/Low Temperatures can lead to precipitation of species
  - Typical range -10-60°C
- Charging
  - Overcharging can lead to evolution of hydrogen (H_2O electrolysis)
- Toxicity of Elements
  - Solutions are in pumped system, susceptible to leaks.
- Minimal Fire Hazard
  - Electroactive element in aqueous solution
- High Degree of Flexibility

Non-Aqueous Flow Chemistries

- Wider voltage window
- Higher charge cycle efficiency
- Decreased temperature sensitivity
- Increased cycle life
- Favorable cost projections

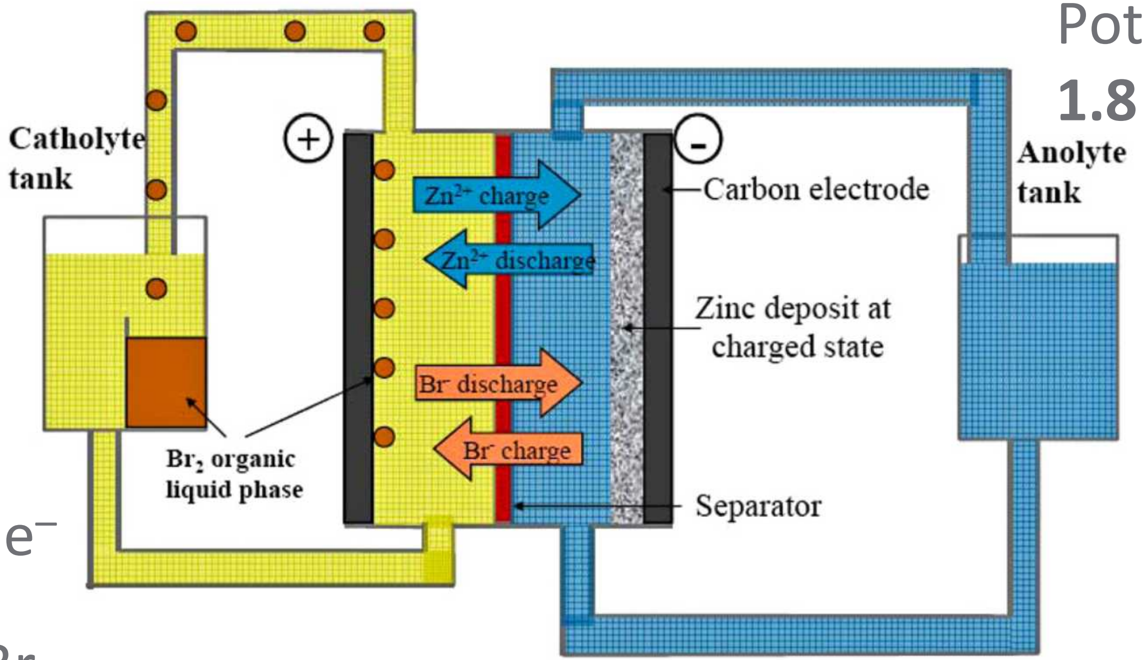
Aqueous vanadium (+5) speciation chemistry is **complex**!



Major Challenge: Getting high concentrations of redox active species.

Hybrid Flow Batteries

Open Circuit Potential (OCP)
1.8 V



$$2X^- \rightleftharpoons X_2 + 2e^-$$

X = Cl or Br

$$Zn^0(s) \rightleftharpoons Zn^{2+} + 2e^-$$

Bottom Line: Higher energy density than the all-vanadium system at the expense of toxicity, dendrite formation, higher self-discharge, and shorter cycle life.

Flow Batteries - SOA

Advantages

- Does not have the capacity limitations of LiB and LA, and scale is more and more economical
- No major IP issues, manufacturing currently not at scale, significant opportunity to scale up
- Opportunity to reduce material cost
  - New redox chemistries
  - Higher volumes of manufacturing

Disadvantages

- Manufacturing currently not at scale
- Low energy densities (15-30 Wh/L), limited voltage window of aqueous electrolyte solutions (< 1.5 V)

Flow Batteries – Challenges/Opportunities

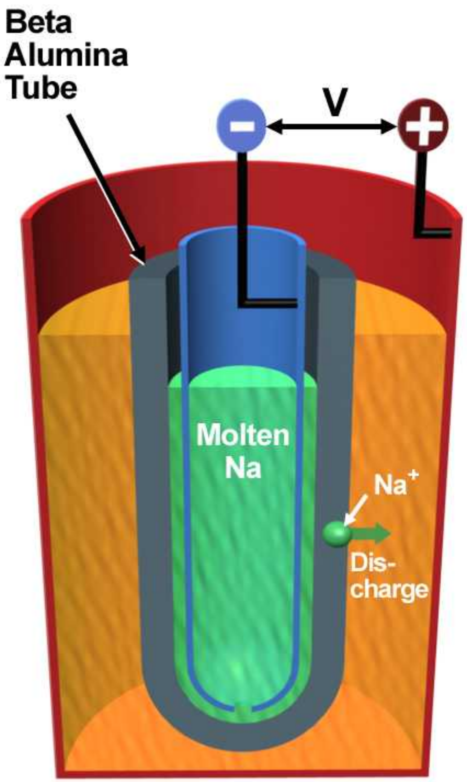
- Significant materials challenges, and opportunities for further improvement
  - Electrolytes relatively expensive (esp. Vanadium)
  - Low energy densities due to the limited solubility of V, Zn in aqueous electrolytes, need new electrolytes
  - Electrolyte is temperature sensitive
  - Membranes are relatively expensive (lower volumes)
- Potential opportunities to reduce materials cost
  - New redox chemistries, new electrolytes under development
  - Lower cost of membranes (moving beyond Nafion)
  - Increased current density and lower cost stack design

Molten Salt Batteries (NaS, $NaNiCl_2$..)

- Two primary chemistries
  - NaS, mature technology, deployed in grid applications
  - $NaNiCl_2$, mature, more stable than NaS
- NaS first developed by Ford Motor Co. in 1960's
  - Commercialized by NGK in Japan, most installed capacity
- $NaNiCl_2$ (Zebra) developed in South Africa in 1980's
  - GE, FIAMM in limited production
- Neither Na nor $NaNiCl_2$ are at high volumes of production for economies of scale

Na-Metal Batteries

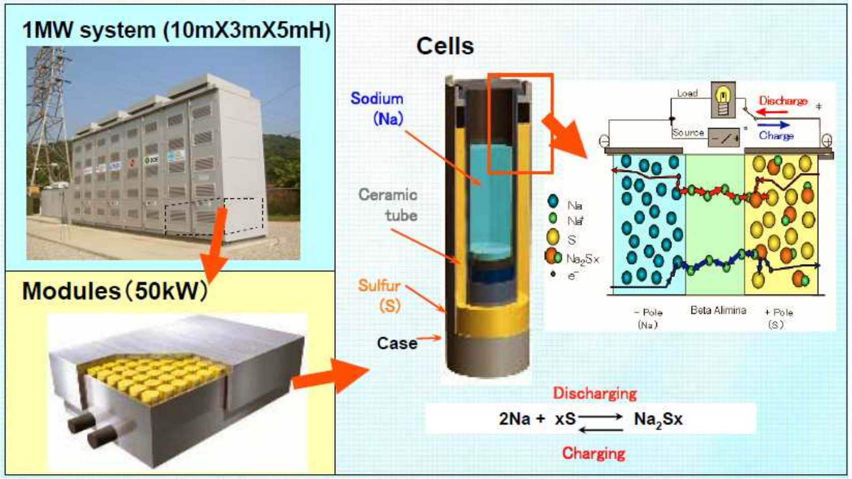
- Batteries consisting of molten sodium anode and β"-Al_2O_3 solid electrolyte (BASE)
  - Low cost starting materials
  - High specific energy density (120~240 Wh/kg)
  - Good specific power (150-230 W/kg)
  - Good candidate for energy applications (4-6 hrs discharge)
  - Operated at relatively high temperature (300~350°C)
- NaS battery
  - 2Na + xS → Na2Sx (x = 3~5)
    - E = 2.08~1.78 V at 350°C
- $NaNiCl_2$ (Zebra) battery
  - $2Na + NiCl_2 \rightarrow 2NaCl + Ni$
    - E = 2.58V at 300°C
    - Use of catholyte (NaAlCl4)



NaS Batteries

- NaS Batteries
  - High energy density
  - Long discharge cycles
  - Fast response
  - Long life
  - 221 sites globally, 190 sites in Japan, with 1800MWh of capacity
- Applications
  - Power quality
  - Congestion relief
  - Renewable integration
- Challenges
  - High operating temperature (250-300C)
  - Liquid containment issues

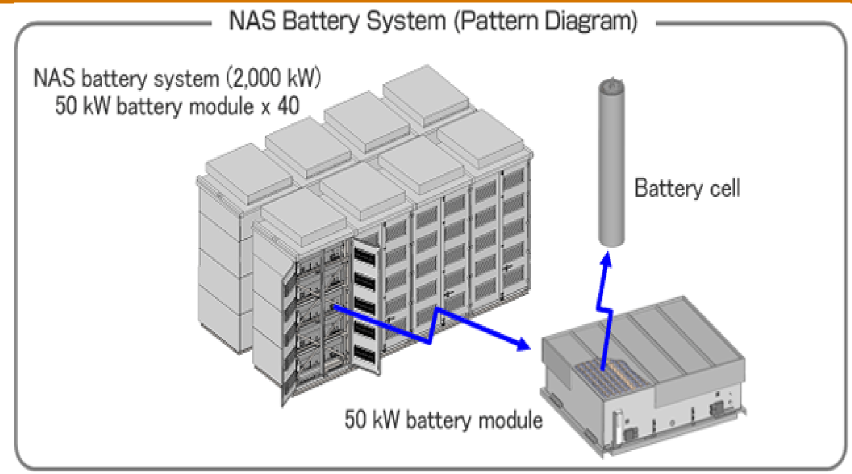
Los Alamos, NM. 1 MW, 6MWh

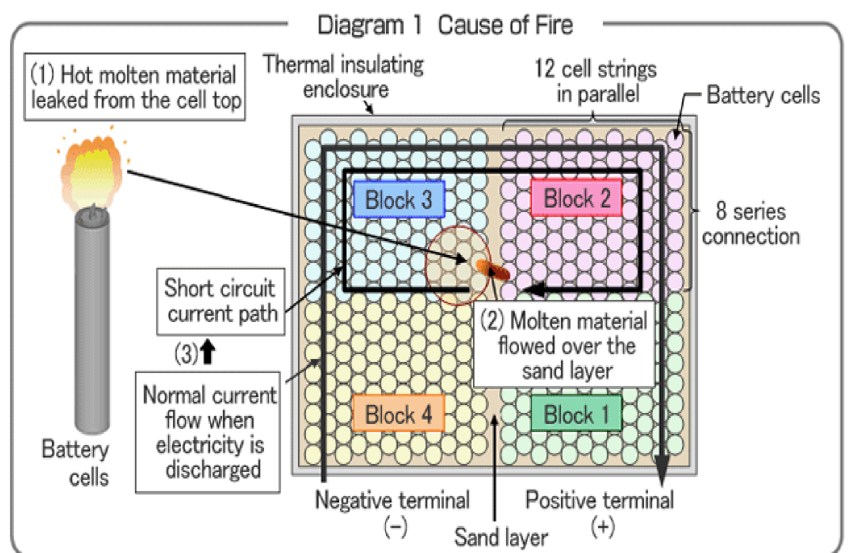


Source: NGK

NaS - Challenges

- NGK is the only committed manufacturer
- Battery is assembled fully charged, presents a major safety/handling issue
  - A major fire at Mitsubishi installation in 2011 resulted in shutdown of all NaS ESS for eight months
- Recent work on lower temp NaS utilizing NaSiCON solid electrolytes



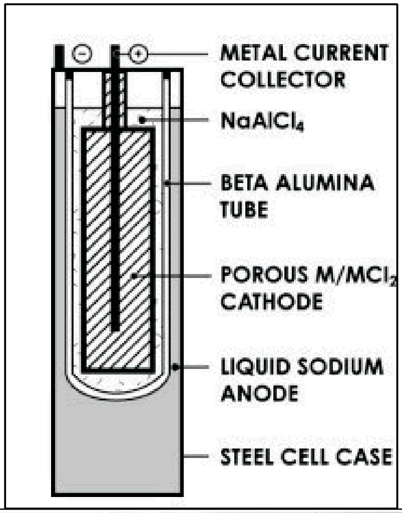


Na-Metal Batteries: Advantages/Issues

- **Temperature**
  - Less over temperature concerns, typical operating window 200-350°C. additional heaters needed when not in use.
  - At < 98°C, Na metal freezes out, degree of distortion to cell dictated by SOC of battery (amount of Na in anode)
- **Charging/Discharging Limitations**
- **Safety Concerns**
  - Solid ceramic electrolyte keeps reactive elements from contact. Failure in electrolyte can lead to exothermic reaction (Na-S)

NaNiCl2 (Zebra) Batteries

- Large cells and stable chemistry
  - Lower temperature than NaS
  - Cells loaded in discharge mode
  - Addition of NaAlCl4 leads to a closed circuit on failure
- High efficiency, low discharge
- Long warm up time (16 hr)
- Two major manufacturers
  - GE and FIAMM
  - Limited deployments



FIAMM 222-kWh System Duke Energy Rankin Substation

Lower Temperature Na-based Batteries

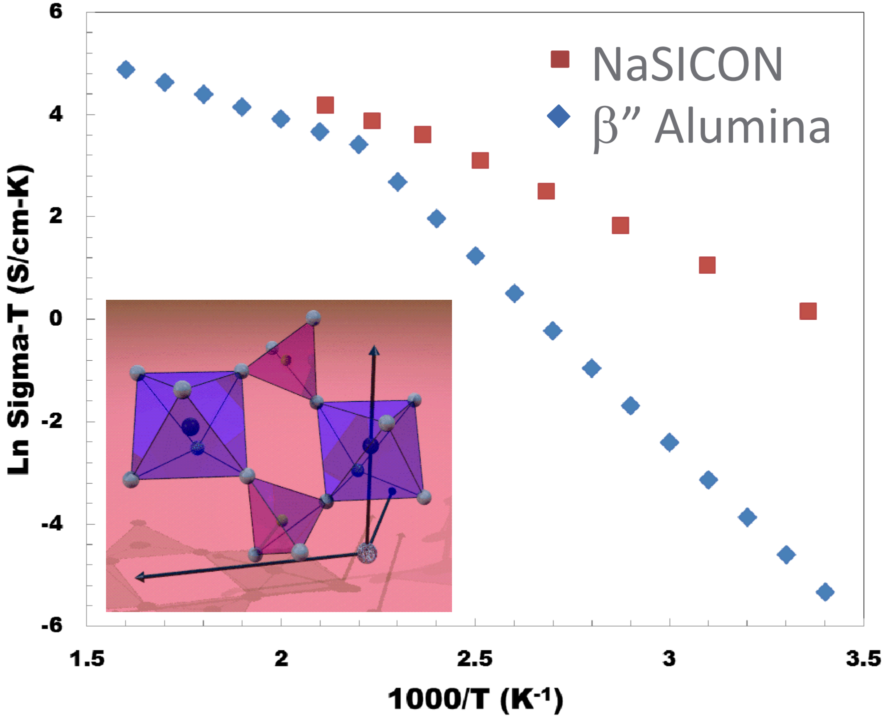
- Low temperature, safe, nonflammable alternatives to Na-S batteries.
- Enabled by low to intermediate temperature (<200°C) ceramic Na-ion conductor (NaSICON)
  - Robust physical barrier - no electrode crossover
  - Reduced operating costs
  - Lower cost materials/seals
  - Enables new cathode chemistries
- Engineered safe
  - Fully inorganic, no volatile organic electrolytes
  - Robust ceramic separator isolates anode and cathode
  - Cross-reaction generates benign byproducts

- Sodium-air
- Sodium-ion
- Aqueous Redox Flow
- Low temperature sodium-sulfur

- Sodium-bromine: $Na + ½ Br_2 \leftrightarrow Na^+ + Br^-$
- Sodium-iodine: $Na + ½ I_2 \leftrightarrow Na^+ + I^-$
- Sodium-nickel chloride: $Na + ½ NiCl_2 \leftrightarrow Na^+ + Cl^- + Ni(s)$
- Sodium-copper iodide: $Na + CuI_2^- \leftrightarrow Na^+ + 2I^- + Cu(s)$

NaSICON Lower Temperature Electrolyte

NaSICON (Na Super Ion CONductor): $Na_3Zr_2PSi_2O_{12}$

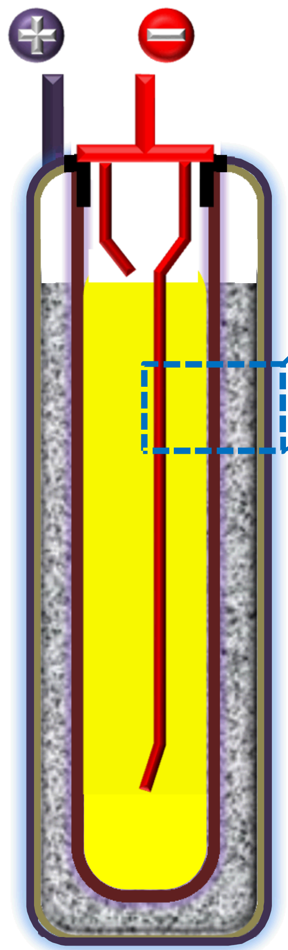


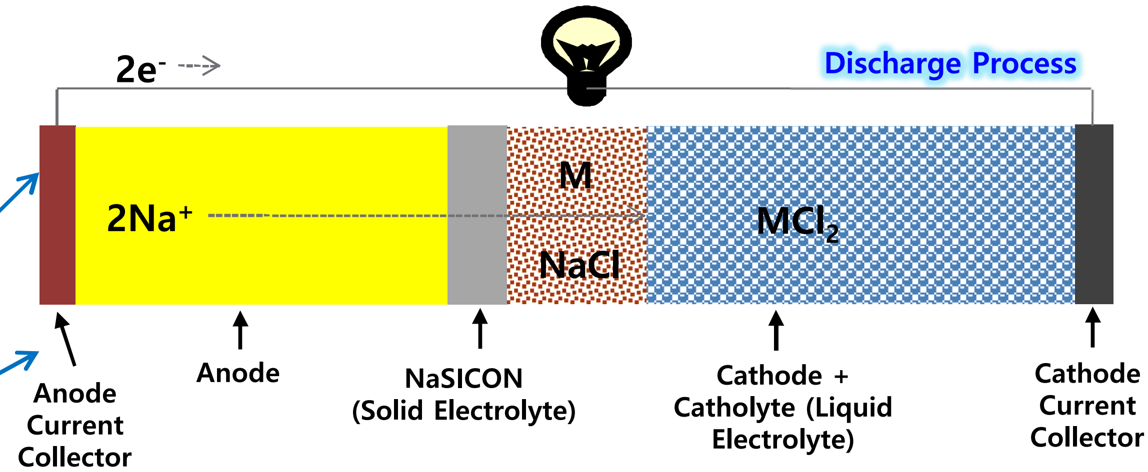
Engineered materials chemistry and advanced, scalable processing (Ceramatec, CoorsTek) make NaSICON a *chemically/mechanically stable, low temperature, high conductivity (>10^{-3} S/cm @RT)* separator technology.

CERAMATEC TOMORROW'S CERAMIC SYSTEMS

Poster: S. Bhavaraju

Na-$NiCl_2$ Batteries at T<200°C





$$NiCl_2 + 2Na^+ + 2e^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftharpoons}} Ni + 2NaCl$$

Features of Na-$NiCl_2$ Cell

- Open-circuit Voltage: 2.58 V
- Lower Operating Temperature: 195°C
- Less metal corrosion compared to NaS
- Safer reaction between Na and $NaAlCl_4$ in case of solid electrolyte fracture

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Stable Na-NiCl$_2$ Cell Performance

Nickel grain growth at high temperatures during cycling limits cycle life and charge-discharge kinetics for Na-NiCl$_2$ batteries.

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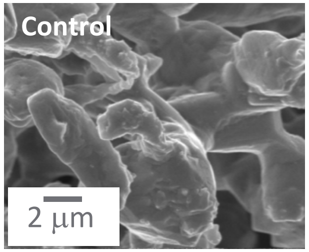
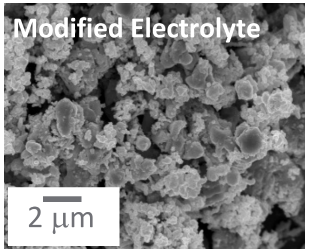
1 micrometer Ni Particle grows by more than 10X after multiple cycles

Using a NaSICON electrolyte allows us to lower temperature below 200^{o}C and adding Ni metal growth inhibitors.

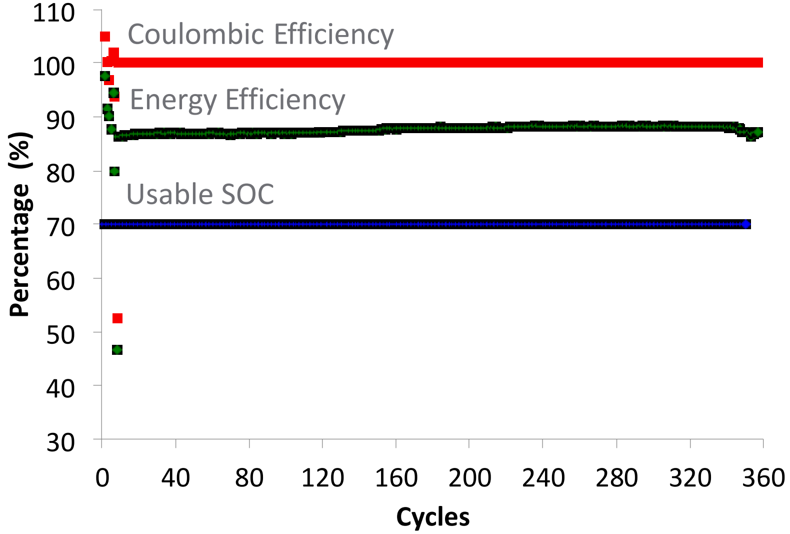
Together, these changes have allowed us to prevent Ni metal particle growth and preserve exceptional, stable battery performance over months (hundreds of cycles).





After electrochemical cycling, Ni-particle growth is suppressed using NaSICON and catholyte additives

Cycle test (Prototype cell)



13 Wh Na-NiCl$_2$ (NaX) Cell operation for 9+ months. 70% Depth of Discharge, >85% energy efficiency at 65 mA /cm^2 Charge/Discharge NaSICON current density

SK

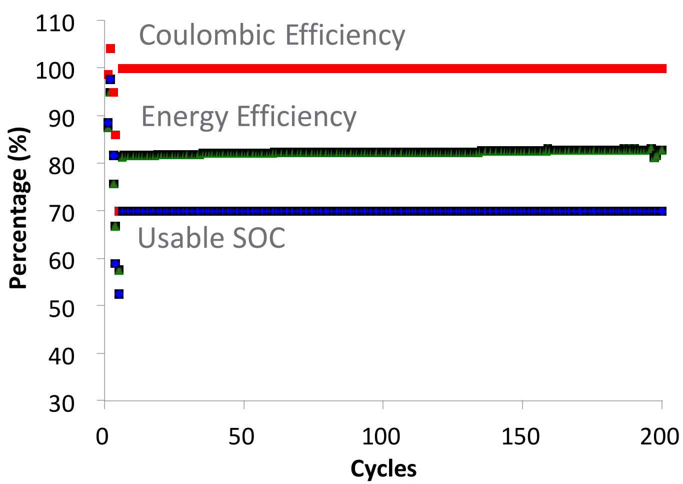
Cell Performance

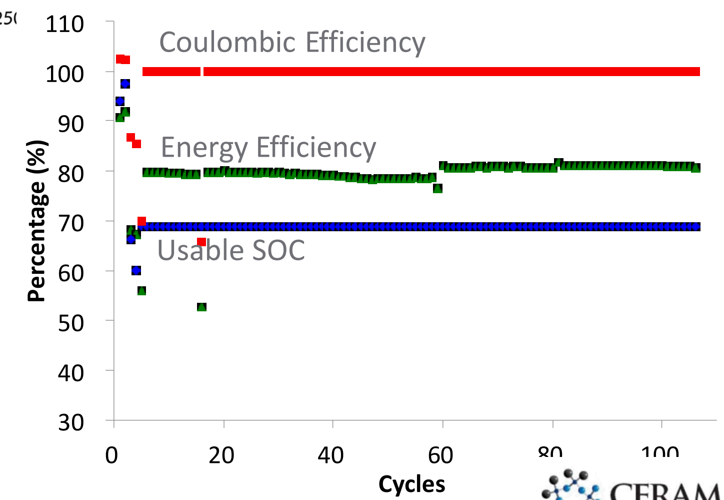
100 Wh pre-commercial Na-$NiCl_2$ unit cell:

- operational for 4+ months.
- 500+ cycles (70% DOD)
- coulombic efficiency ~100%
- energy efficiency 81.5 %
- 53 mA/cm^2 & C/7 rate

250 Wh pre-commercial Na-$NiCl_2$ unit cell:

- operational for 3+ months
- 110 cycles (70% DOD)
- coulombic efficiency ~100%
- energy efficiency 80 %
- 53 mA/cm^2 & C/7 rate





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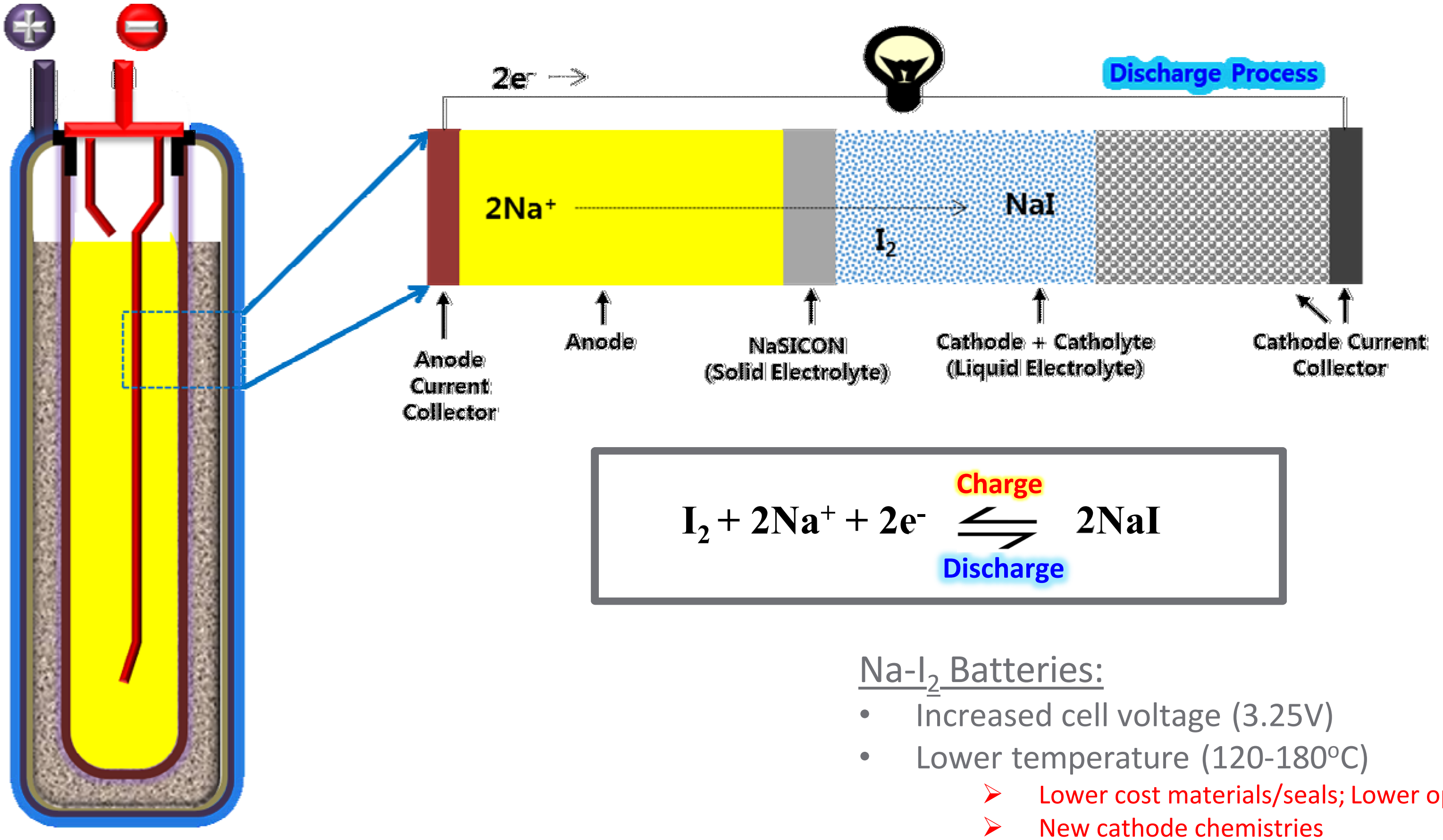
Na-I_2 Battery Technology



$$I_2 + 2Na^+ + 2e^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftharpoons}} 2NaI$$

Na-I_2 Batteries:

- Increased cell voltage (3.25V)
- Lower temperature (120-180°C)
  - Lower cost materials/seals; Lower operational costs
  - New cathode chemistries
- Liquid cathode increases feasible cycle life

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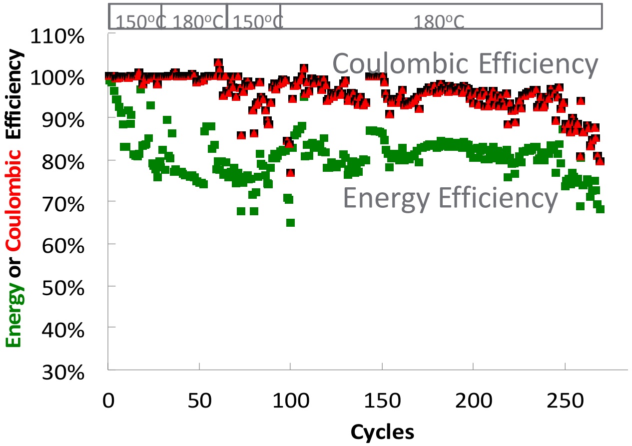
Na-I_2 Prototype Performance

Lab Scale Test Conditions

- 8.7 Wh lab-scale cell
- Graphite felt + tungsten wire current collectors
- NaI-$AlCl_3$ based molten salt catholyte
- 1" NaSICON tube (15 cm^2) glass sealed to α-alumina
- T = 150-180˚C



✓ Demonstrated long term performance

- More than 269 cycles @ 60% DOD Discharged 483Ah
- C/7 rate
- High energy efficiency of ~ 80%
- 28.5 mA/cm^2 current density

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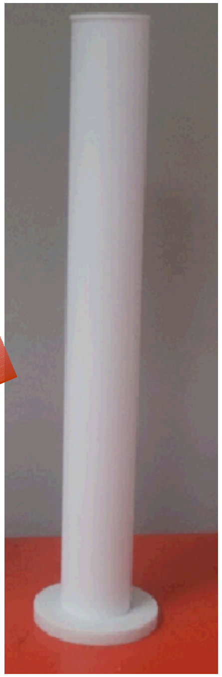
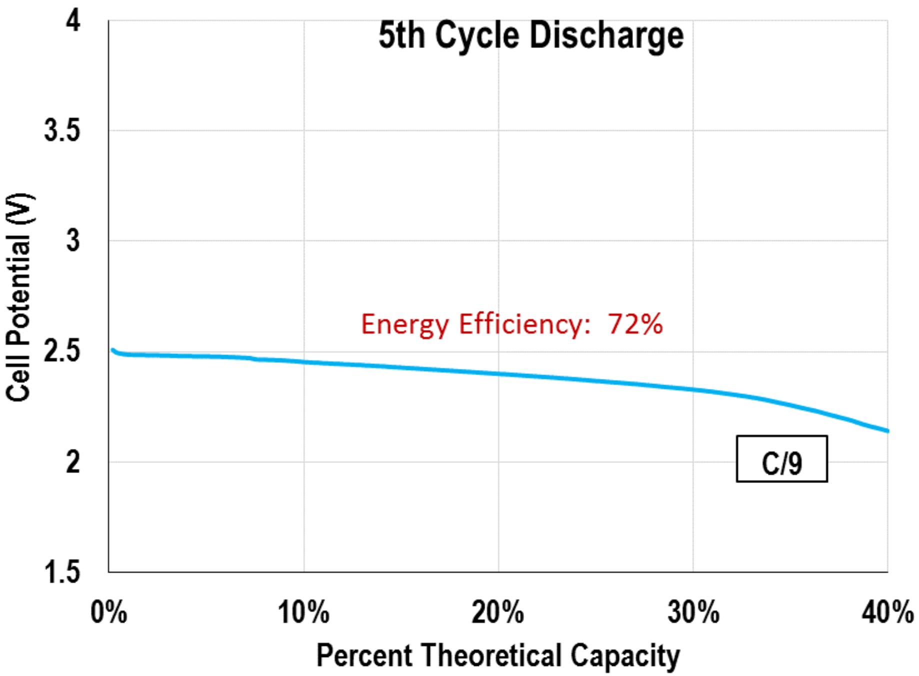
Preliminary Operation of 100 Wh Na-I_2 Battery





- The 100 Wh cell was built using Carbon felt/Tungsten mesh, infiltered with NaI.
- The majority of the cycling was done at 150 ºC, until the last 9 cycles where the temperature was raised to 165 C.
- The cell operated 360 hours (29 cycles) before failure.

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High Energy Density Li and Metal Air Batteries

- All metal air batteries (Li-air, Zn-air) have the potential to deliver high energy densities at low cost, challenges with recharging have so far precluded commercialization of the technology
  - Lot of startup activity in Metal-Air batteries
  - Technology not mature, decade or more away
  - Potential fundamental problems
- Li-Air combines difficulties of air and lithium electrodes
  - Breakthroughs needed in cheap catalysts, more stable and conductive ceramic separators
  - Developing a robust air electrode is a challenge, need major breakthroughs
- Li-S suffers from major problems of self discharge and poor life
  - breakthroughs needed for life of Li electrode, low cost separator

Further Away: Other Li-like Chemistries

- Na/NaxCoO2 and Na/NaxMnO2 attracting a lot of attention
  - Na/NaxCoO2: 440 Wh/kg, 1600 Wh/l
  - Na/NaxMnO2: 420 Wh/kg, 1410 Wh/l

- Na and Mg Chemistries potentially lower cost
  - Intercalation chemistry similar to Li ion
  - New class of electrolytes, separators needed
  - Very early stage, metal anodes vs. insertion materials

Zn-MnO_2 Batteries

Advantages of Zn/MnO2 alkaline batteries:

- Traditionally primary batteries at ~$18/kWh with long shelf life
- Lowest bill of materials cost, lowest manufacturing capital expenses
- Established supply chain for high volume manufacturing
- Readily be produced in larger form factors for grid applications
- Do not have the temperature limitations of Li-ion/Pb-acid
- Are inherently safer, e.g. are EPA certified for landfill disposal.
- The ultimate challenge in Zn/MnO2 batteries is reversibility

History of Rechargeable Zn-MnO_2 Batteries

- Long history of research on making Zn-MnO_2 rechargeable.
  - Several commercial products based on cylindrical formats (Rayovac, BTI).
  - All focused on cylindrical designs for consumer markets.

Cylindrical cells

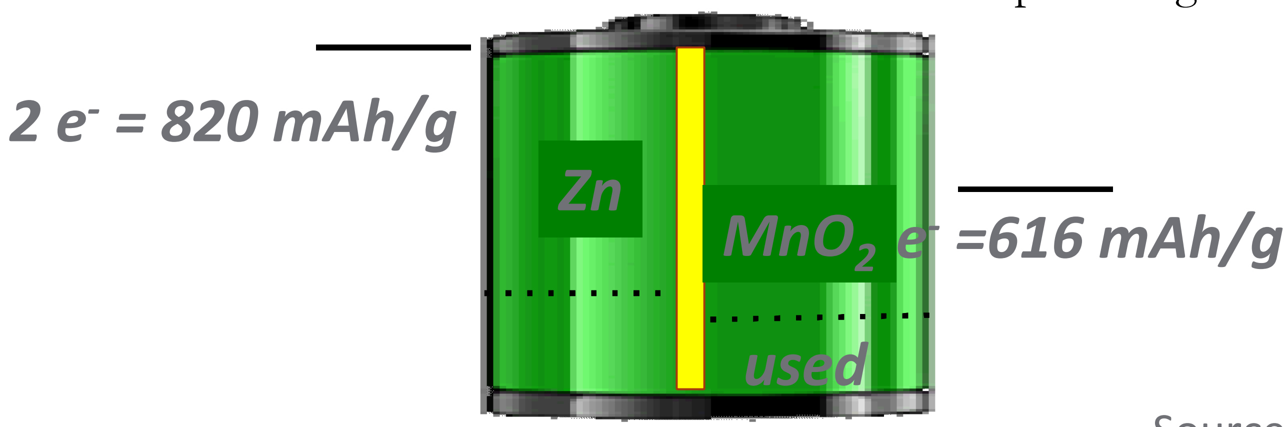
No flexibility to change critical parameters.

Year	Event
1882	Probably first description of an alkaline MnO_2 cell in German patent 24552 of G. Leuchs
1903	Description of another "wet alkaline cell" in US Patent 746,227 of S. Yai
1912	First alkaline "dry cells" described in German patent 261,319 of E. Aschenbach
1952	W.S. Herbert introduced first commercial alkaline MnO2 "crown" cell for low drain
1960	US patent 2,960,558 of K. Kordesch, P. Marsal and L. Urry describes the invention of the "modern" alkaline cell w/ sleeve type pelletized cathode on the outside in contact w/ the can
1962	US patent 3,024,297 of L. Urry describes a method of forming a cathode depolarizer mix for a rechargeable alkaline cell
~1970	First commercial rechargeable alkaline cells introduced by Union Carbide Corp. and Mallory Corp., but soon withdrawn.
~1980	Research on rechargeable alkaline manganese chemistry was intensified at the TU Graz under the leadership of Prof. Dr. K. Kordesch
1981	Kordesch et al studied the rechargeability of 12 International Common Samples
1983	US patent 4,384,029 of K. Kordesch and J. Gsellman describes a new cell design w/ the cathode constrained by a metal cage.
1985	Titanium doped electrolytic manganese dioxide for improved cycle life described in German patent 3,337,568 of K. Kordesch and J. Gsellman
1986	Battery Technologies Inc. (BTI) founded w/ the mission to commercialize rechargeable alkaline manganese (RAM™) technology
1990	US patent 4,925,747 of K. Kordesch and K. Tomantschger describes the internal pressure management of sealed cells via hydrogen recombination by catalytic means
1991	Ph.D. Thesis of J. Daniel-Ivad on Rechargeable Alkaline Manganese Cells focusing on mercury-free designs
1992	US patent 5,108,852 of K. Tomantschger and C. Michalowski describes a basic rechargeable alkaline cell w/o constraining the cathode
1993	US patent 5,108,852 of R. Flack describes an improved separator bottom seal
1993	Rayovac Corporation launched BTI licensed RAM™ cells manufactured and sold under their trademark RENEWAL™ in the United States
1994	US patent 5,281,497 of K. Kordesch, J. Daniel-Ivad and R. Flack describes a mercury-free rechargeable cell w/ an anode having gas release properties and a hydrogen recombination system to limit in-cell gas pressure
1994	Pure Energy Battery Corporation launched BTI licensed RAM™ cells manufactured under their trademark PURE ENERGY™ in Canada. Cells are mercury-free.
1995	US patent 5,424,145 of J. Daniel-Ivad, J. Book and K. Tomantschger describes a basic rechargeable cell w/ specific anode to cathode Ah-balance to achieve satisfactory performance in consumer use/misuse.
1995	Rayovac's RENEWAL™ cells become mercury-free
1996	US patent 5,626,988 of K. Tomantschger, J. Book and J. Daniel-Ivad describes a mercury-free rechargeable cell w/ a special anode process for reliable performance
1996	Young Poong Corporation launched BTI licensed RAM™ cells manufactured under their trademark ALCAVA™ in South Korea
1997	AccuCell started to sell BTI licensed RAM™ cells in Germany
1998	Grand Batteries Technologies launched BTI licensed RAM™ cells manufactured under their trademark GRANDCELL™ in Malaysia
1998	Single-use alkaline cell producers introduce cells capable of higher drain rates
1999	BTI released 1st Generation High-Rate RAM™ cell specifications for production
1999	Endurance cycling breakthrough of RAM™ cells in Cordless Phone test: 6500 cycles for 5 minute call, then recharge in cradle
2000	"Marathon" RAM™ cell research to extend the deep discharge stability from 25 to 50 cycles initiated
2000	US patent 6,099,987 of J. Daniel-Ivad, J. Book and E. Daniel-Ivad describes a cylindrical cell w/ a cup seal for improved cumulative performance
2001	BTI acquired the Dema Group, a Swedish distribution company, and launched Demacell™ RAM™ cells in an effort to promote a European expansion of the technology

J. Daniel-Ivad and K. Kordesch, "Rechargeable Alkaline Manganese Technology: Past-Present-Future," ECS Annual Meeting, May 12-17, 2002

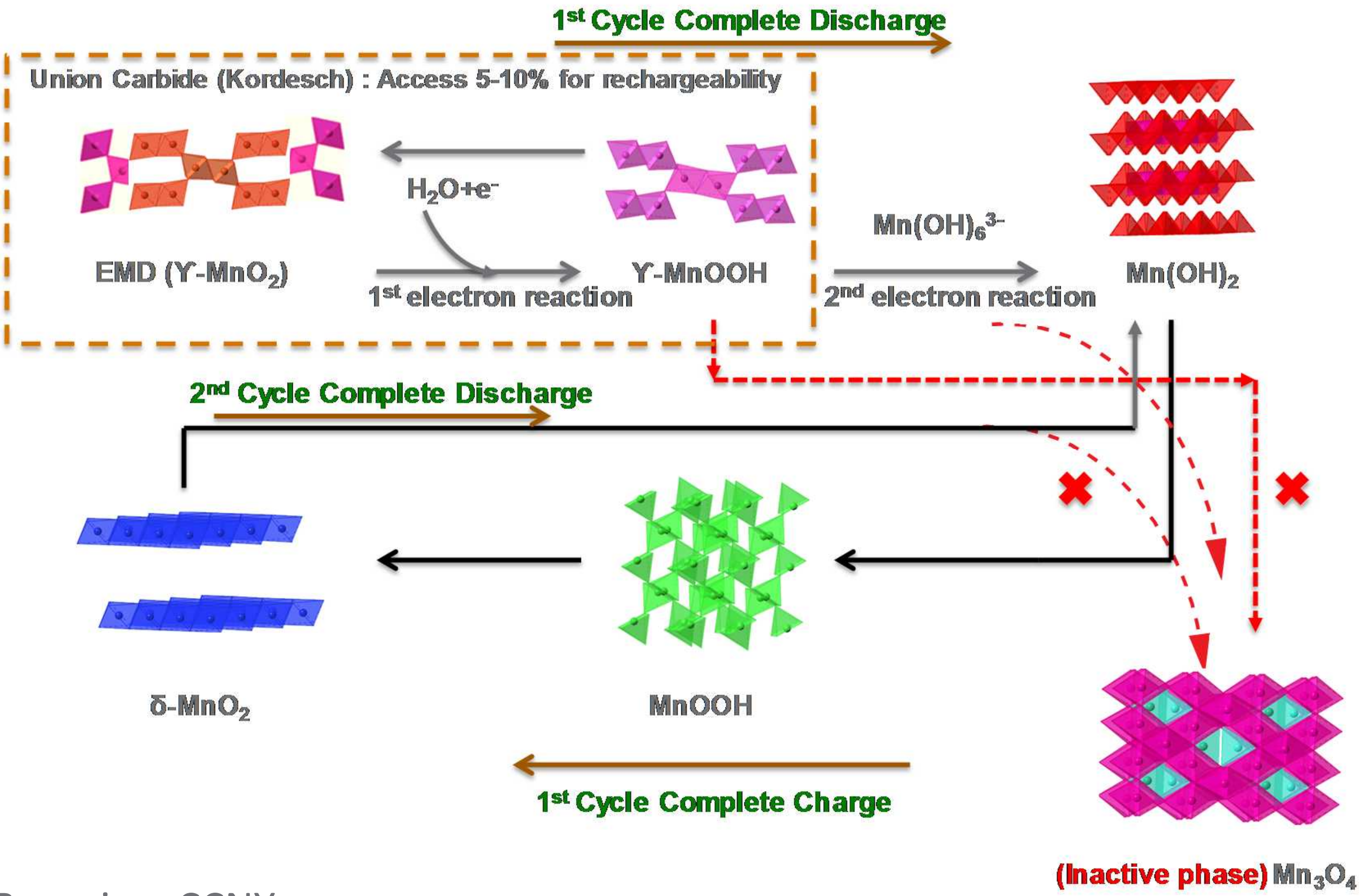
Making Zn-MnO_2 Rechargeable

- Anode issues
  - < 10% of total capacity is used
  - Shape Changes
  - Passivation
  - Dendrite Formation
- Cathode issues
  - Only 5-10% of total capacity is used
  - Crystal Structure Breakdown
  - Inactive Phase(s) formed
  - Zinc poisoning



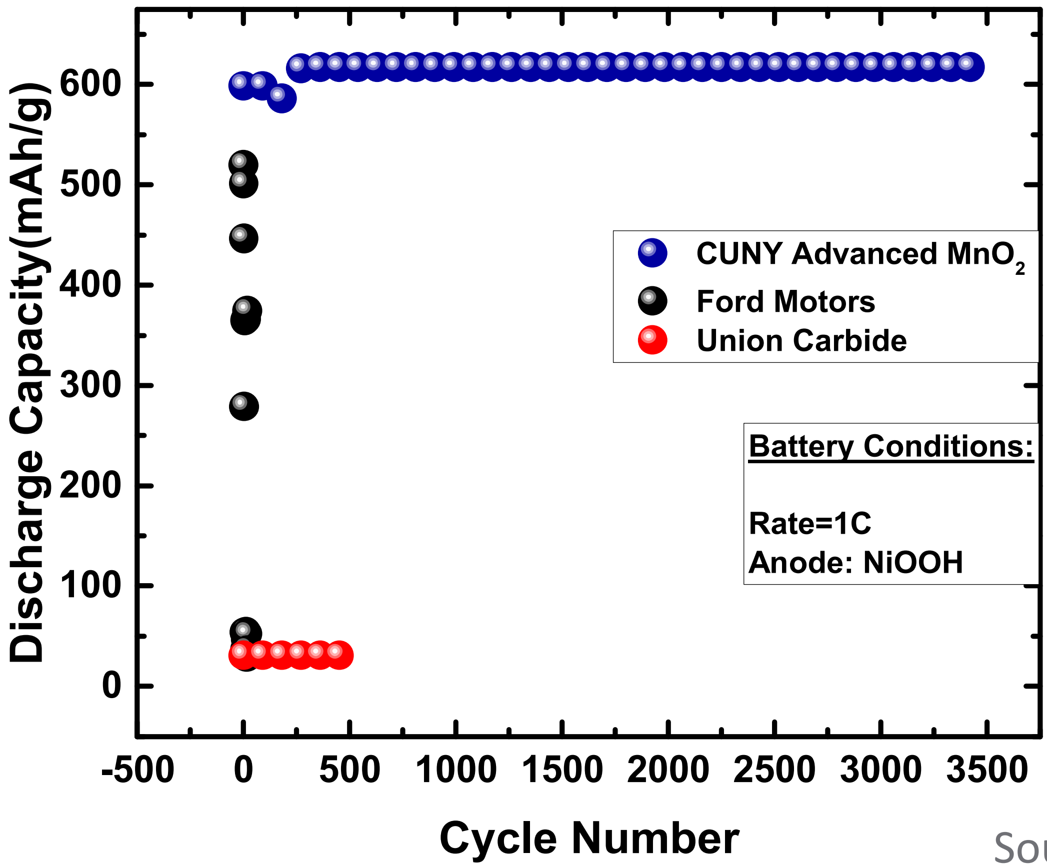
Source: S. Banerjee, CCNY

MnO_2 Reaction Mechanisms



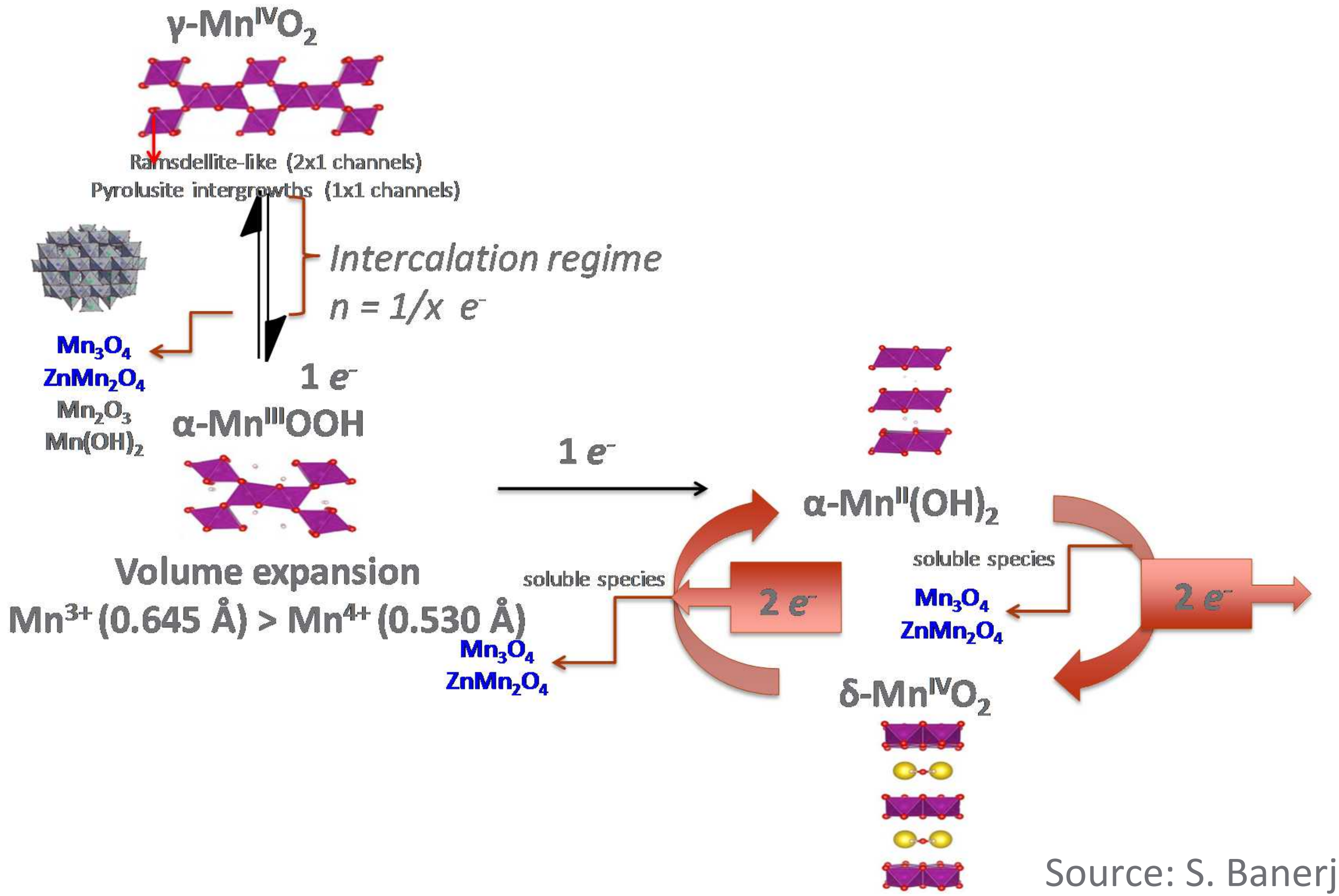
Source: S. Banerjee, CCNY

CUNY Breakthrough Advancement



Source: S. Banerjee, CCNY

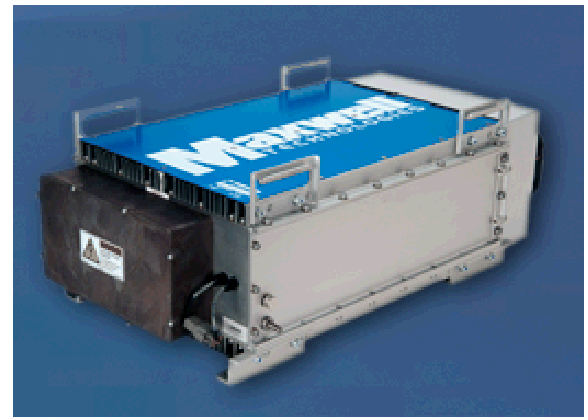
Enabling Zn-MnO_2 to Reach Li-ion in Energy Density



Source: S. Banerjee, CCNY

Super Capacitors

- Capacitor Energy Storage
  - Very long life
  - Highly reversible and fast discharge, low losses
- Applications
  - Power quality
  - Frequency regulation
  - Regenerative braking (vehicles)
- Challenges
  - Cost



Ultra capacitor module, designed for vehicle applications (e.g., buses, trains)

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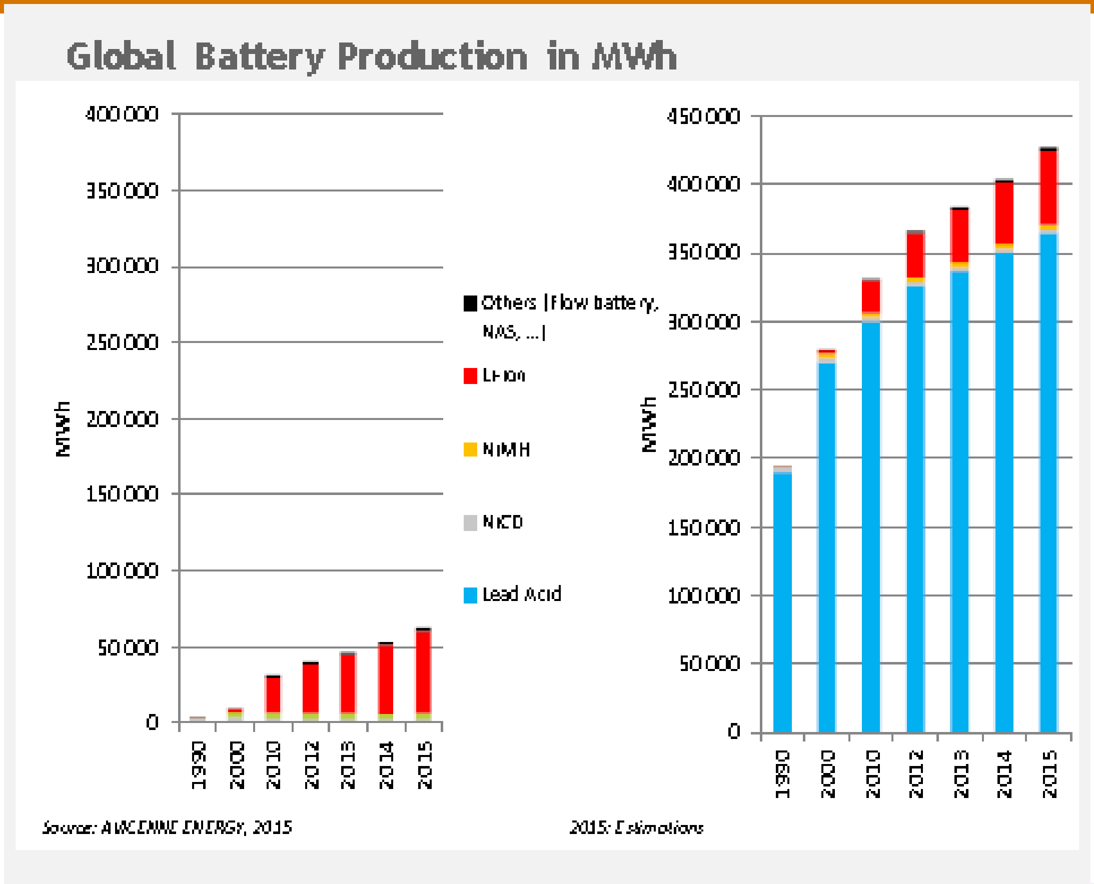
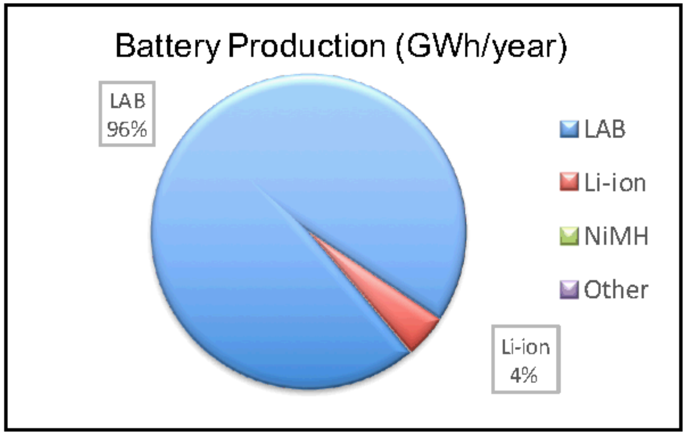
Battery Technologies

Mature Technologies				
	World Wide Capacity (GWh/y)	**Cost and Performance Improvements**	**Key Challenges for Energy Storage**	**Major Suppliers**
Lead Acid Batteries (LAB)	300	2%/year ((30 year data). $150/kWh	Cycle life. Advanced lead acid cycle life on par with EV grade LIB	JCI, GS Yuesa, EastPenn, EnerSys, Exide, Hagen, Amara Raja
Lithium Ion Batteries (LIB)	50	8%/year (20 year data). Cell level price reaching $200/kWh	Cycle life for deep discharge. Safety. Thermal management	Panasonic, Samsung, LG Chem, BYD, GS Yuesa (Nissan, Honda JVS), Lishen, JCI, A123, Toshiba. EV Batteries: Converging to NMC chemistry
Emerging Technologies				
NaS and NaNiCl	300 MWh	No economies of scale	High temperature chemistry. Safely, Cost	NGK, GE, FIAMM
Flow Batteries	<200 MWh	Not fully mature. Potential for lower cost. $400/kWh. Reach $270/kWh	Not mature. Has not reached manufacturing scale.	Sumitomo, UET, Rongke Power, ZBB, Gildenmeister. Only Sumitomo provides 18 yr. warranty
Alkaline chemistries (Na, Zn-MnO2,..)	<100 MWh	Not fully mature. Lowest cost BOM	Has not reached manufacturing scale.	Aquion (Na), UEP (Zn-MnO2), Fluidic Energy (Zn-air)

Global Production Volumes



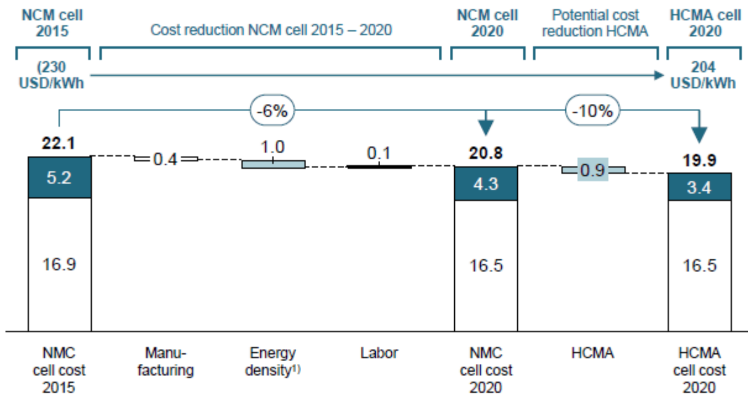


Source: Avicenne (2015), DOE

Lead Acid Battery business continues to be highly profitable
Li-ion struggling with low factory utilization rates of ~10-20%

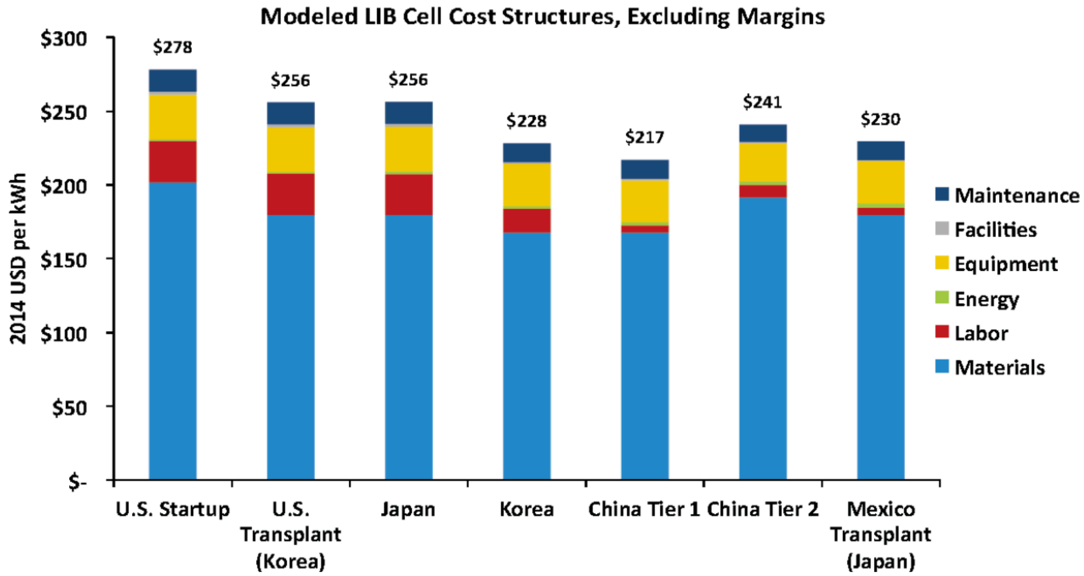
Manufacturing Capex and Starting Materials

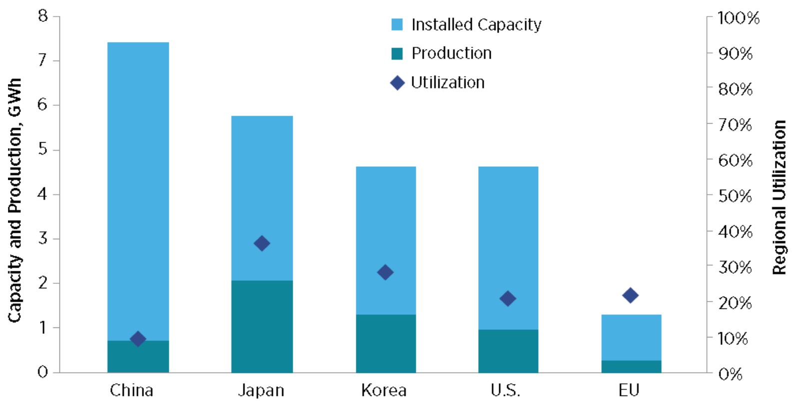
- Capex for GWh/yr production capacity
  - Lead acid: $50-60M
  - LIB: $300-400M
- For lead acid and Li-ion, BOM is 80-85% of the cell cost
  - Large format LIB: BOM $180-200/KWh
- For flow batteries, electrolyte cost ~30-40% overall cost
- For comparison, primary alkaline batteries: $18-20/KWh



Source: Roland Berger, 2013

Large Format LIB Manufacturing



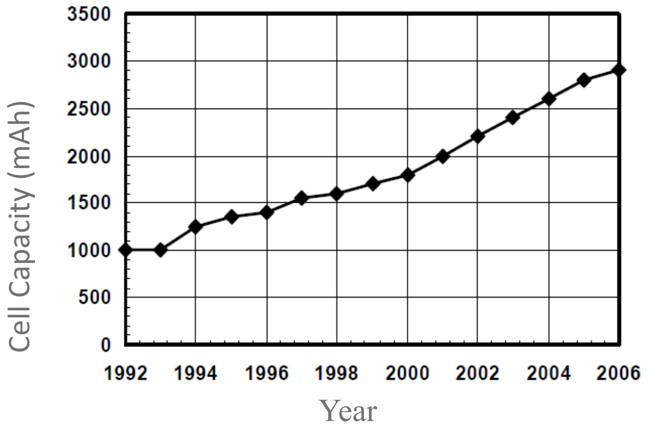


Source: D. Chang, et al, Automotive Li-ion Battery (LIB) Supply Chain and U.S. Competitive Considerations, NREL/PR--6A50--63354, June 2015

Capex intensive $300-400M /GWh capacity addition
Continued consolidation in the Automotive Li Battery business
Excess capacity driving the need for applications beyond EVs

Li-ion – Cycles of Learning

- Capacity improvements are incremental
  - 8% for LIB (1992-2007); 2% for Lead acid
  - Capacity improvements are incremental
- Continued reduction in cost/performance
  - Materials cost can not be scaled down much lower, BOM is 80-85% of cell costs
  - Need significant improvement in electrolytes, membranes, anode and cathode materials
  - Engineering larger cells (>100 Ah) is not still economical
- For MWh applications
  - Improve safety and control electronics
  - Thermal management is a bigger issue

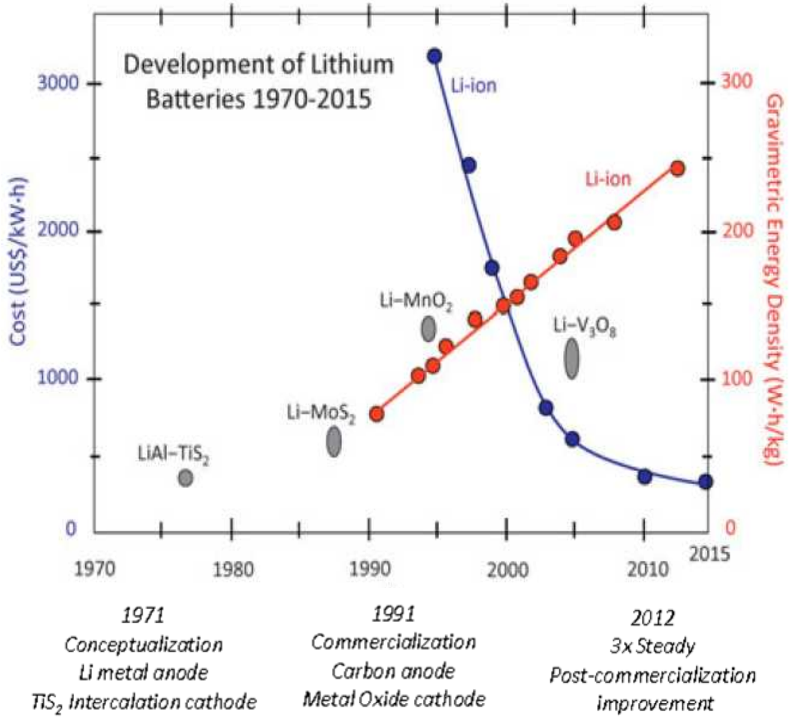


18650 cell capacity improvement of 8% per year
Source: Proc. IEEE, vol. 95, pp. 2106 – 2107, 2007

2015 LIB manufacturing capacity: 50 GWh

2015 LAB manufacturing capacity: 300 GWh

Capacity Scaling is Volumetric



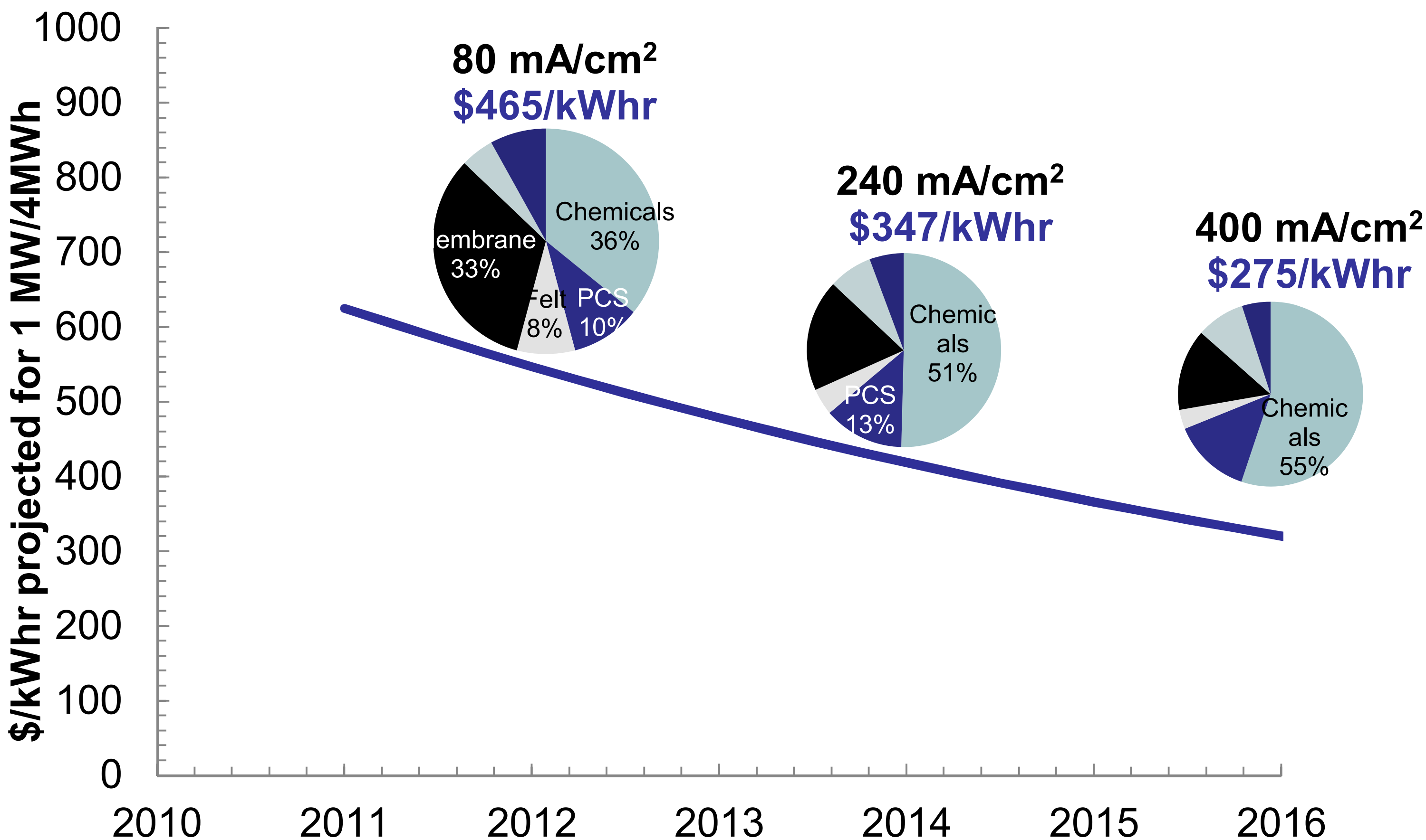
Source: Crabtree, Kocs, Trahey, MRS Bulletin, Dec 2015

- There is no equivalent of Moore's law in battery technology. Microelectronics scaling laws don't apply. Storage is based on volumetric material properties.
- Major improvements will be based on increased cycle life, reliability, and safety of batteries.

Industrial lead acid: \$150/KWh (high volume)

Large format LIB: cell level cost reaching the \$200/kWh range

Redox Flow System Component Cost Analysis



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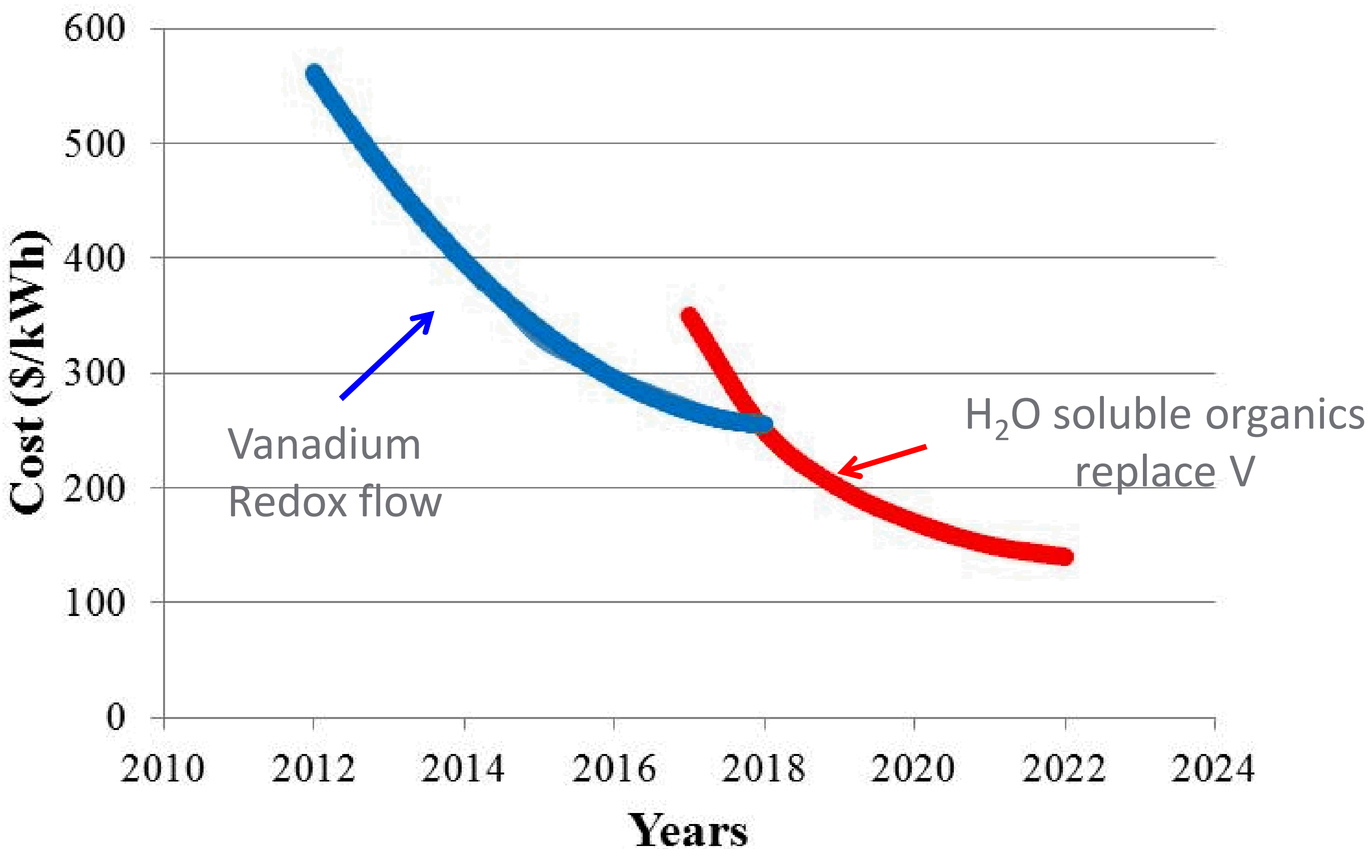
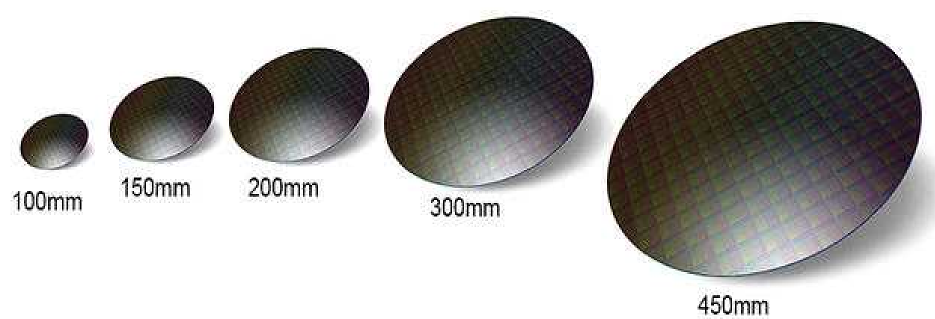
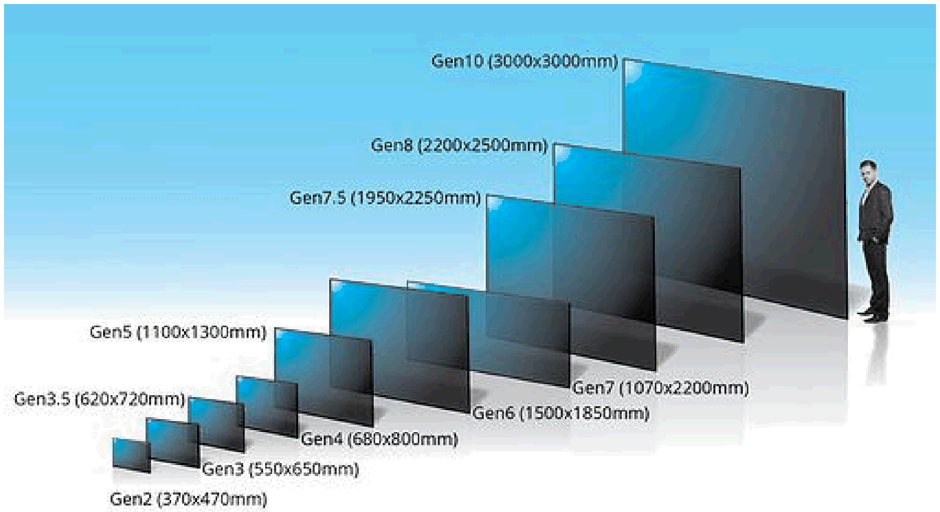
Future Redox Battery Development

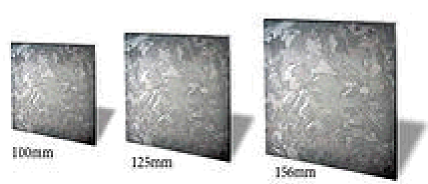


- Utility scale Vanadium flow battery systems approaching $350/kWh. Further reductions in cost requires improved chemistry, lower stack costs.

Scaling (size, volume, and performance)







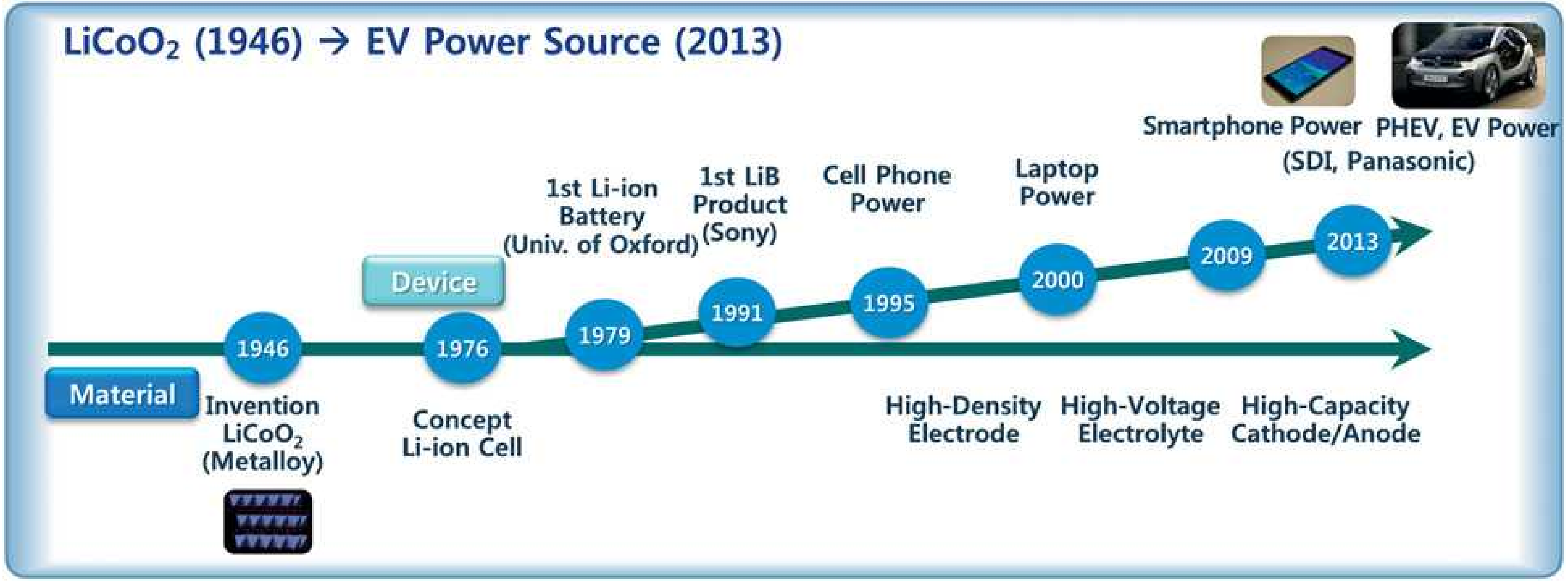
Microelectronics
Si Substrates
20x scaling (30 yr)
50, 100, 150, 200, 300 mm

Flat Panel Displays
Glass Substrates
50x scaling (30 yr)
Gen1 (370x470mm)
Gen 8 (2200x2600 mm)

Solar Panels
Si Substrates
100 mm to 150 mm
2x scaling (20 yr)

Source: Brad Mattson, Sivapower
D. Mitzi, Solution Processing of Inorganic Materials, 2010

Li-ion Commercialization



Manufacturing and Process Technologies

- Ability to reach high volume and scale is key for global impact

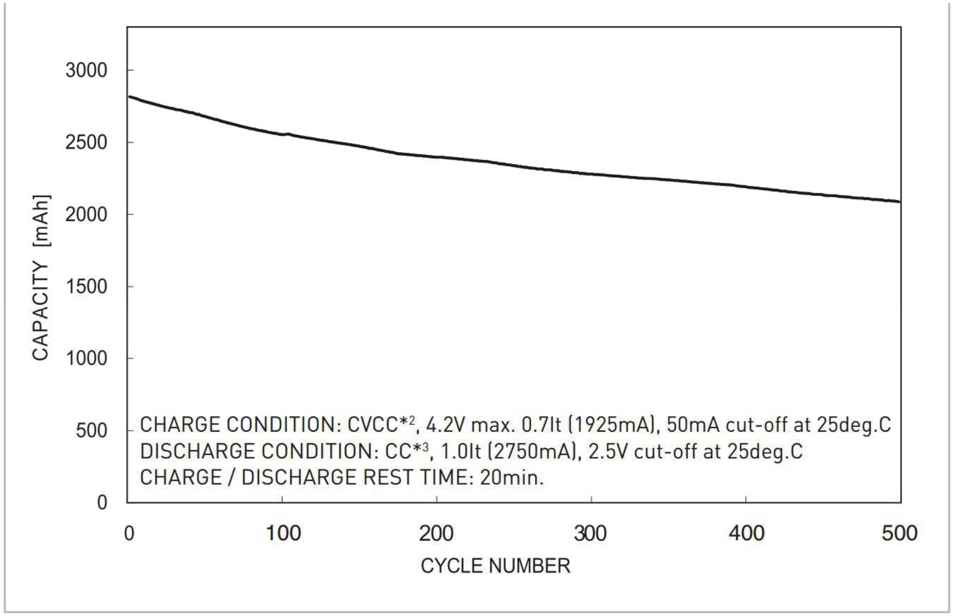
"Abandoning today's 'commodity' manufacturing can lock you out of tomorrow's emerging industry."

- Andy Grove, co-founder, former CEO, Intel

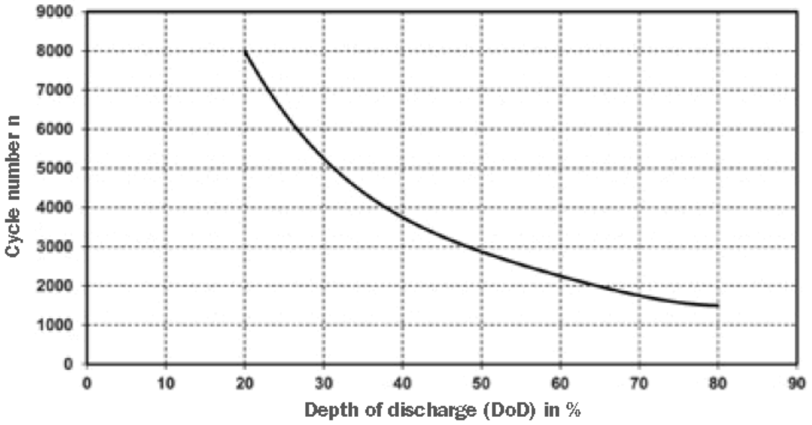
intel

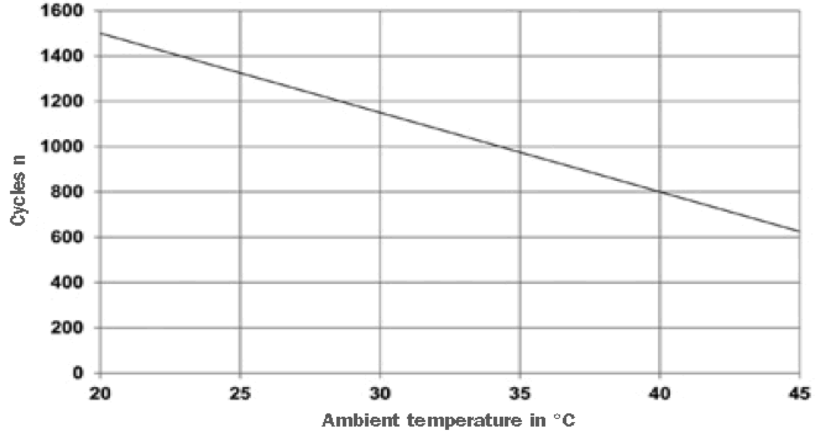
- Technologies that can drive cost reduction and performance enhancement
- Manufacturing and process technologies with broader impact across multiple areas

Cycle Life is a Major Challenge



Panasonic NCR18650 cell – cycle life





Hoppecke Lead Acid Batteries
Cycle life with DOD and Temperature

Materials and Manufacturing

- Volume manufacturing is critical to get economies of scale
- Low cost materials (BOM), established supply chain
  - Storage is volumetric, GWh needs lot of raw materials
  - BOM of $50/KWh and fully manufactured cost of <$100/kWh (cell)
- Scalable to large format cells, and simpler BMS
- Scalable for large volume manufacturing in GWh
- Low manufacturing capex and low BOM is critical

Materials and Manufacturing Challenge

- Critical challenges for energy storage are high system cost and cycle life
  - Existing storage solutions are too expensive
  - Deep discharge and longer cycle life
  - Safe and reliable chemistry
  - Scalable technology to cover all markets
- To make storage cost competitive, we need advances across all major areas:
  - Batteries, power electronics, PCS
  - BOS and Integration
  - Engineered safety of large systems
  - Codes and Standards
  - Optimal use of storage resources across the entire electricity infrastructure

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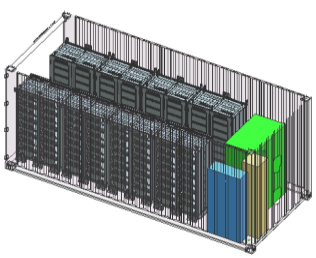
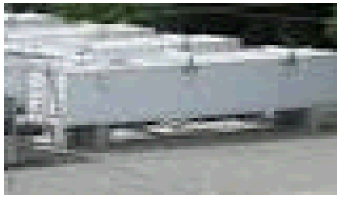
Energy Storage Systems

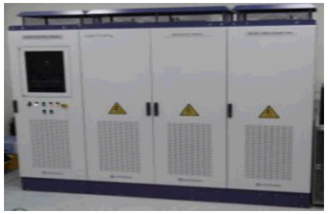
- The process of making batteries into energy storage requires a significant level of systems integration including packaging, thermal management systems, power electronics and power conversion systems, and control electronics.
- System and engineering aspects represent a significant cost and component, and system-level integration continues to present significant opportunities for further research.

Elements of an Energy Storage System

Storage	Integration	PCS	EMS
• Cell • Battery Management & Protection • Racking	• Container / Housing • Wiring • Climate control	• Bi-directional Inverter • Switchgear • Transformer • Skid	• Charge / Discharge • Load Management • Ramp rate control • Grid Stability

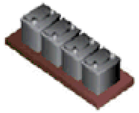






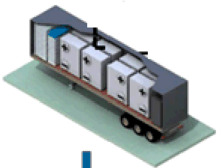
We need cost reductions across all areas, not just batteries

Cost Structure of Storage System in 2016



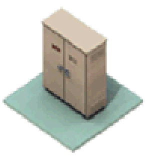
Storage
Racks+BMS

+



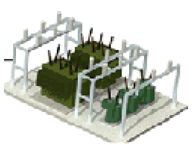
Product
Integration

+

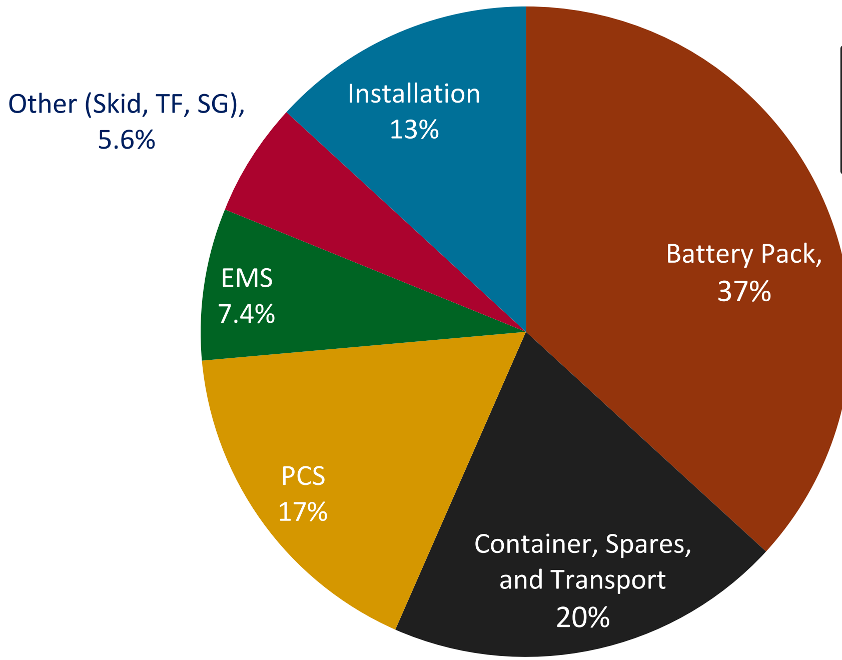


Power
Conditioning
(PCS)

+



Field EPC
Grid Integration



1MW/1MWh
LIB ESS

Data: Multiple industry sources

Projected cost line items for a 1MW/1MWh Li-ion energy storage system ($600/kWh and above depending on the system configuration)

Almost 60% of storage system cost is outside the Battery Pack

Battery to ES System

Battery

- $/kWh
- Efficiency (%)
  Self Discharge
- Cycle life (#)

PCS/BOS

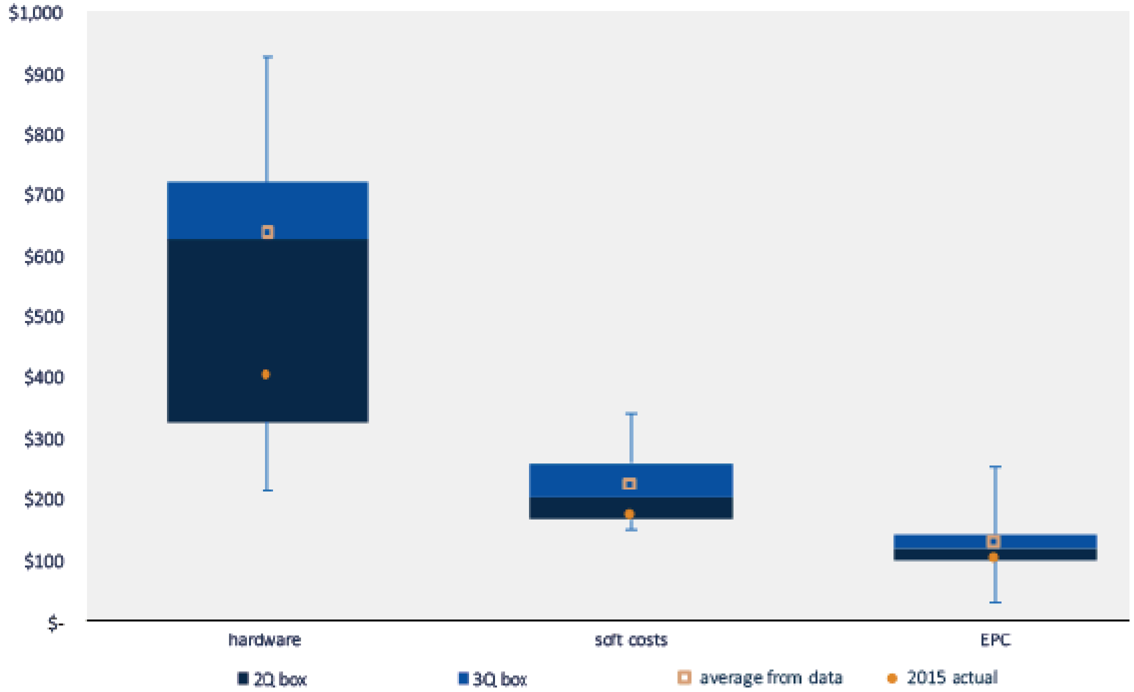
- Power Electronics
  $/kW
- BOS (Container, Safety, Thermal Management)

Softcosts

- Interconnection
- Permits
- O&M

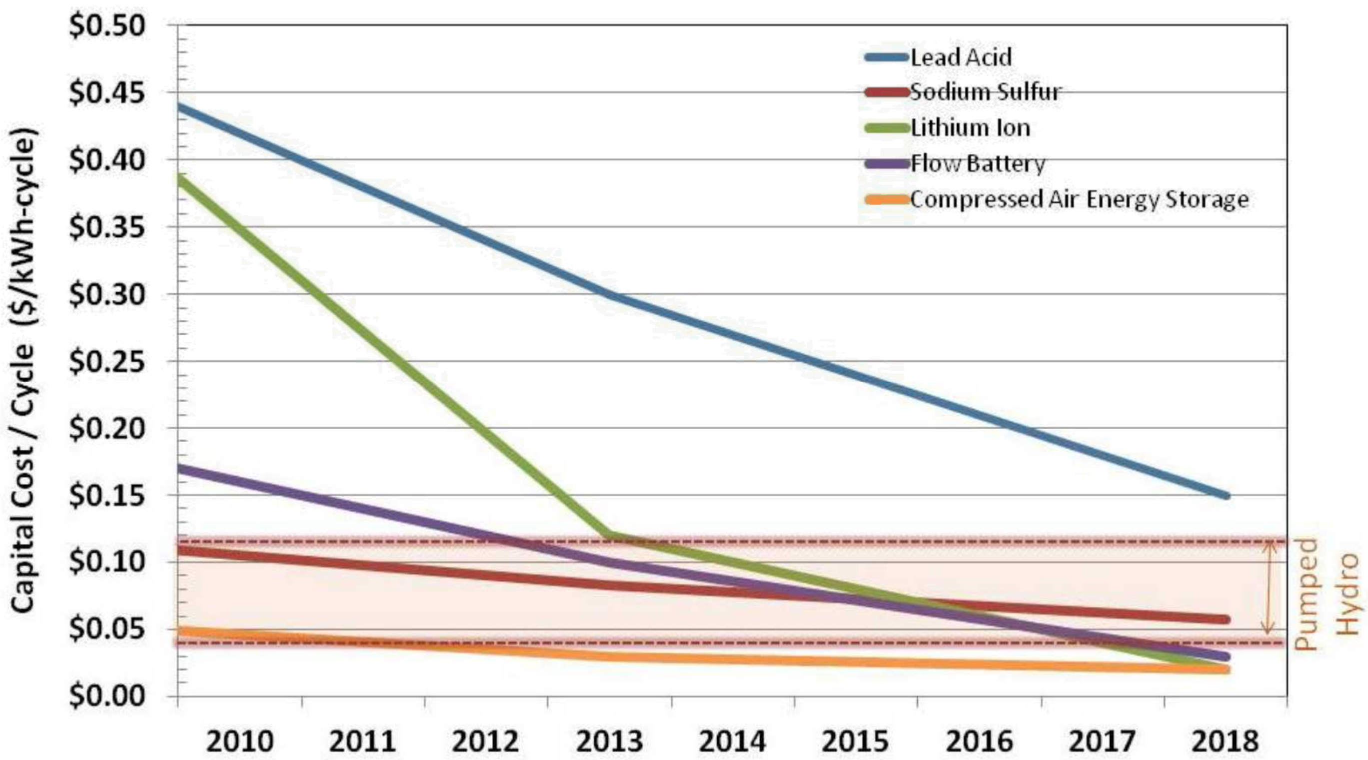
Battery to a Storage System: doubling in cost,
$500/kWh battery ⇨ $1000/kWh Storage System

Balance of System Costs



GTMResearch, Grid-Scale Energy Storage Balance of Systems 2015-2020: Architectures, Costs and Players, January 2016; http://www.greentechmedia.com/research/report/grid-scale-energy-storage-balance-of-systems-2015-2020

Estimated Capital Costs by Technology and Type



Source: Customized Energy Solutions and IESA
(State of Charge Report, MassCEC, 2016)

Making LCOE of Energy Storage Competetive

- For large scale deployment, levelized cost of energy stored (LCOES) need to be competitive with combined cycle NG plants

- Storage LCOES needs to reflect cycle life, efficiency, depth of depth, and other long term performance metrics.

$$LCOES = \frac{System\ Cost}{Cycle\ Life \times DOD \times RTE}$$

How to Lover LCOES on a kWh-cycle basis?

- Major variables
  - System cost, Round trip efficiency, DOD, and Cycle life

$$LCOES = \frac{System\ Cost}{Cycle\ Life \times DOD \times RTE}$$

System Cost ($/KW)
BOM, Manufacturing Costs
1-2X drop

Cycle Life ($/kWh)
Most important parameter
500 to 5000 - 10000 cycles
10 to 20x increase in cycle life

Modest improvements

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Safety and Reliability

- Unlike batteries for consumer electronics and battery packs for electric vehicles, the scale and complexity of large stationary applications in the electric grid impose a complex set of requirements on the safety and reliability of grid-scale energy storage systems.
- Safety aspects of grid energy storage and how this safety is connected to the electrochemistry of materials, cell-level interactions, packaging and thermal management at the cell and system level, and the overall engineering and control architecture of large-scale energy storage systems.

Energy Storage Hazard Identification

The risk of safety incidents will increase as a function of ESS deployment

Damage to Facilities

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

- There were two fires in a year at the Kahuku Wind Farm
- There was significant damage to the facility
- Capacitors in the power electronics are reported to be associated with the failure

Impact to First Responders

2013 Storage Battery Fire, The Landing Mall, Port Angeles WA

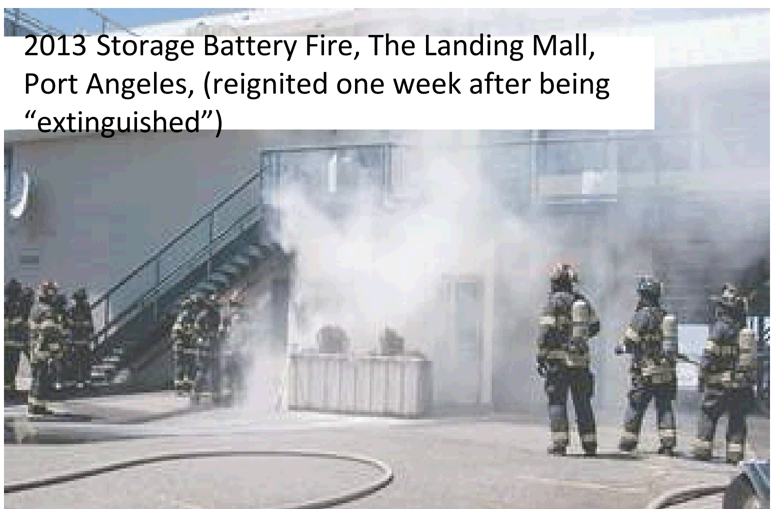
- First responders were not aware of the best way to extinguish the fire
- The fire reignited a week after it was thought to be extinguished

Energy Storage Safety

2011 Beacon Power Flywheel Failure

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

2011 NGK Na/S Battery Explosion, Japan (two weeks to extinguish blaze)



2013 Storage Battery Fire, The Landing Mall, Port Angeles, (reignited one week after being "extinguished")

2012 GM Test Facility Explosion, Warren, MI

Properties in Battery Systems that Can Develop Hazards

Voltage

Arc-Flash/Blast

Fire

Combustion

Toxicity

Voltage

- *The number of battery cells per string in grid energy storage can be higher than in mobile applications, resulting in higher DC voltage and a need for additional precautions.*
- *In the voltage range 100-1000V DC, the NFPA Standard 70E on electrical safety in the workplace establishes a limited approach boundary for unqualified workers at 1.0m.*
- *This boundary is to prevent those who are unable to avoid hazards from coming within arms reach of the exposed electrical conductors.*

Source: NFPA70E

Properties in Battery Systems that Can Develop Hazards

Voltage

Arc-Flash/Blast

Fire

Combustion

Toxicity

Arc-Flash/Blast

High string voltage affects both the potential for shock and the potential for arc-flash/blast. The equations below show the maximum power point method for calculating the incident energy in DC arc-flash. Incident energies calculated by this equation are described as "conservatively high" and other methods are being explored for calculating and classifying the potential harmful energy in a DC arc-flash. Arc-blast results from explosive components of an electric arc (e.g. vaporized copper) and depends greatly on the equipment and environment involved in the arc. Common controls to prevent injury from arc flash include increasing separation between positive and negative conductors, regular maintenance to prevent equipment failure, and arc-rated PPE for electrical workers.

$$I_{arc} = 0.5 I_{bf}$$

$$IE = 0.01 V_{sys} I_{arc} T_{arc} / (D^2)$$

Source: NFPA70E

Where:
Iarc = Arcing current (amps)
Ibf = System bolted fault current (amps)
IE = incident energy at a given working distance (cal cm□2)
Vsys = System voltage (volts)
Tarc = Arcing Time (sec)
D = working distance (cm)

Properties in Battery Systems that Can Develop Hazards

- Voltage
- Arc-Flash/Blast
- Fire
- Combustion
- Toxicity

Fire

As a Fuel Source

- *Plastic burns, some electrolytes are flammable.*

Thermal Runaway

- *Thermal runaway is chemical process where self-heating in a battery exceeds the rate of cooling causing high internal temperatures, melting, off-gassing/venting, and in some cases, fire or explosion.*
- *Thermal, mechanical, and electrical abuse can lead to thermal runaway; internal short circuit from manufacturing defects; or the development of metallic dendrites that form an internal short over time.*

Source: David Rosewater, Adam Williams, Analyzing system safety in lithium-ion grid energy storage, Journal of Power Sources, Volume 300, 30 December 2015, Pages 460-471, ISSN 0378-7753

Properties in Battery Systems that Can Develop Hazards

- Voltage
- Arc-Flash/Blast
- Fire
- Combustion
- Toxicity

Combustion

Hydrogen buildup from charging

- *Charging aqueous batteries can crack water into hydrogen and oxygen.*
- *Without proper ventilation this hydrogen can build up in an enclosed space.*
- *The Lower Explosive Limit (LEL) for hydrogen is 4% concentration in air.*
- *Battery system with this hazard must be equipped with alarm systems.*

Vent gas combustion from thermal runaway

- *Lithium-ion batteries undergoing thermal runaway can vent their internal contents in the form of gas.*
- *Without proper ventilation a combination of gases can build up in an enclosed space.*
- *The LEL for this mixture can very.*
- *Oxygen starvation fire suppression in lithium-ion battery systems is not recommended.*

Properties in Battery Systems that Can Develop Hazards

- Voltage
- Arc-Flash/Blast
- Fire
- Combustion
- Toxicity

Toxicity

Smoke

- *Smoke can be toxic and smoke from batteries is no exception.*
- *Use of a positive pressure breathing apparatus is recommended whenever responding to battery system fires.*

Liquid Electrolyte

- *Some flow-batteries contain electrolyte which can be toxic to the environment or to people.*
- *The MSDS should provide proper safety measures for handling and exposure.*
- *Liquid electrolyte can also be corrosive so avoid contact with the skin or eyes.*

Safety through Codes and Standards

- Many ESS safety related issues are identical or similar to those associated with other technologies
- Some safety issues are unique to energy storage in general and others only to a particular energy storage technology
- Current codes and standards provide a basis for documenting and validating system safety
  - prescriptively
  - through alternative methods and materials criteria
- Codes and standards are being updated and new ones developed to address gaps between ESS technology/applications and criteria needed to foster initial and ongoing safety

Safety-Related Issues

- ESS ‘product’ configuration and how safety validation is addressed
- New versus existing systems and new versus existing building/facility applications
- Siting (location, loads, protection, egress/access, maximum quantities of chemicals, separation, etc.)
- Ventilation, thermal management, exhausts (when necessary, flow rates, etc.)
- Interconnection with other systems (electrical, any non-electrical sources)
- Fire protection (detection, suppression, containment, smoke removal, etc.)
- Containment of fluids (from the ESS and from incident response)
- Signage

Materials R&D for Energy Storage System Safety

- Major research areas
  - Materials origin of safety and reliability
  - Device level failures
  - Cascading failures
- Advanced simulation and modeling of energy storage systems
- Further
  - Software's role as a critical safety system
  - Better control of cell behavior through power electronics

Impact and Consequence of Scale on Safety

The Lack of Safety:

Endangers Life
Loss of Property
Damages Reputation
Decreases Confidence in Storage

Consumer Cells (0.5-5 Ah) → Large Format Cells (10-200 Ah) → Transportation Batteries (1-50 kWh) → Utility Batteries (MWh)

www.ford.com www.samsung.com www.saftbatteries.com

Safety issues carry greater weight with increasing battery size

Improving Storage Safety

Development of Inherently Safe Cells →

- Safer cell chemistries
- Non-flammable electrolytes
- Shutdown separators
- Non-toxic battery materials
- Inherent overcharge protection

Safety Devices and Systems →

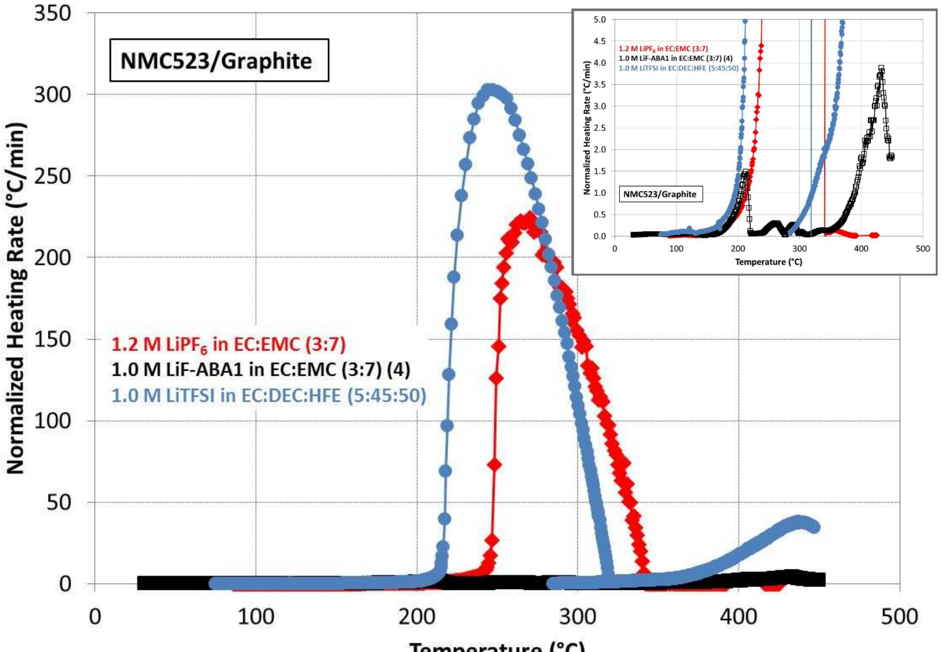
- Cell-based safety devices
  - current interrupt devices
  - positive T coefficient
  - Protection circuit module
- Battery management system
- Charging systems designed

Effective Response to Off-Normal Events →

- Suppressants
- Containment
- Advanced monitoring and controls

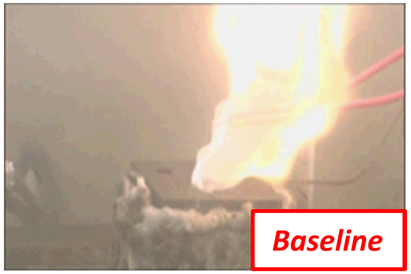
Abuse Tolerance of Li-ion Cells

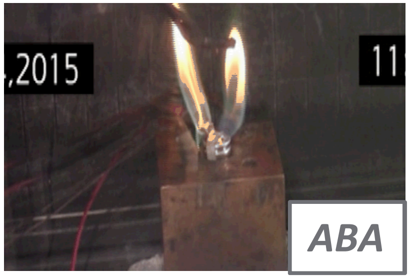
Accelerating Rate Calorimetry (ARC)



- ***Significant reduction in the thermal runaway free energy of NMC cells with LiF/ABA electrolytes***
- ***HFE electrolytes are measured to be nonflammable in a cell vent failure scenario***

Cell Vent Flammability Measurements

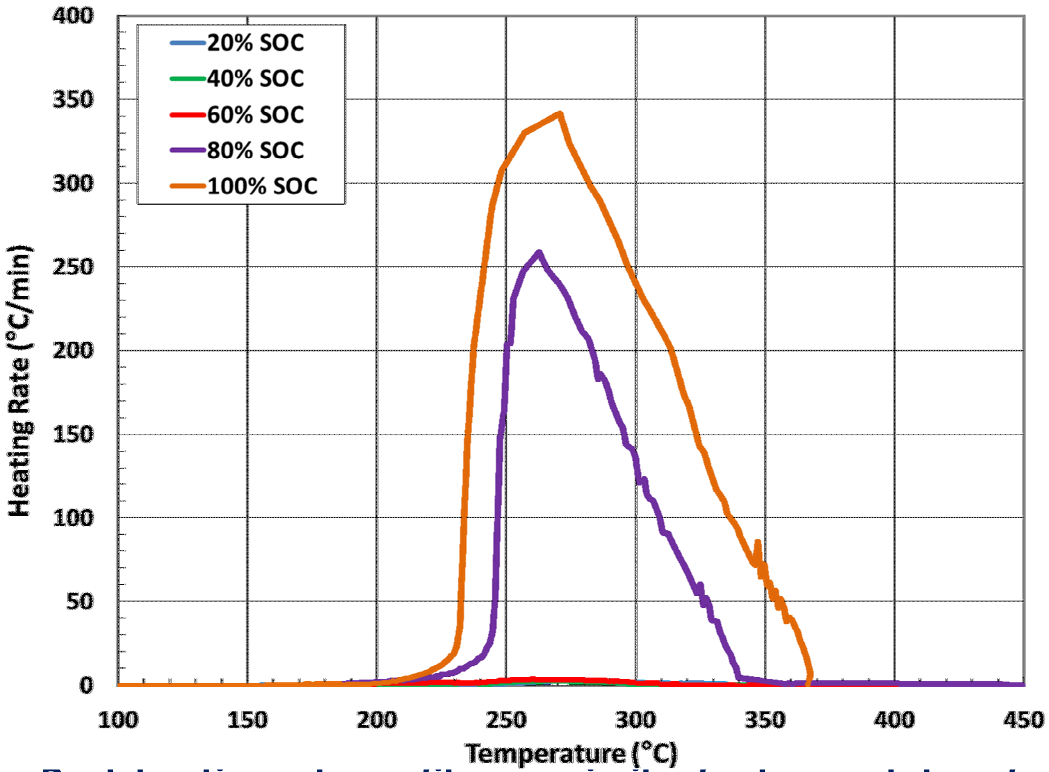




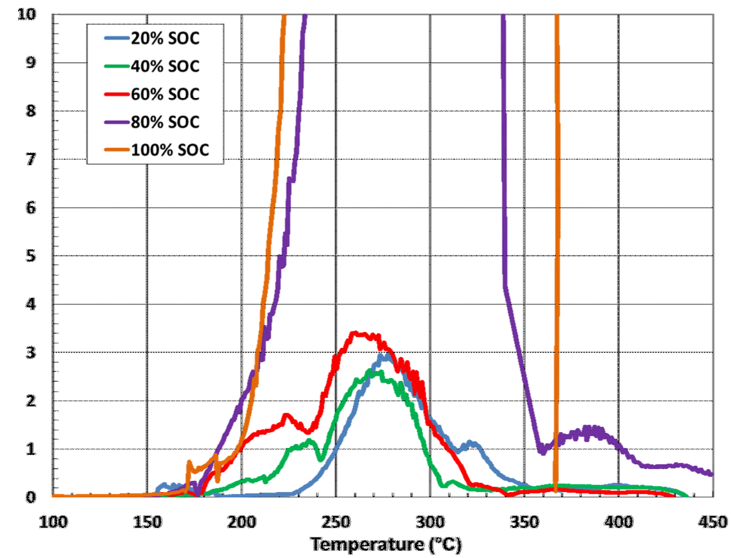
Chris Orendorff, John Lamb and Leigh Ann Steel

Role of SOC on Thermal Runaway

18650 cells 20-80% SOC (80-20%DOD)



Similar response observed in 18650

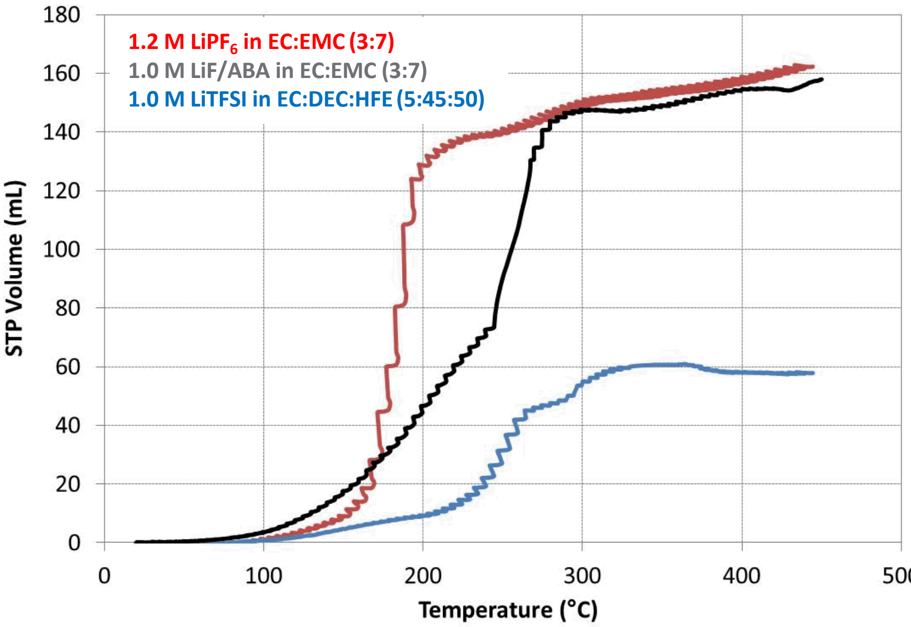


- **Peak heating rate profiles are similar for lower states of charge (20-60%) then drastically increase at 80% and 100% SOC. The onset of thermal runaway increases as the %SOC decreases**

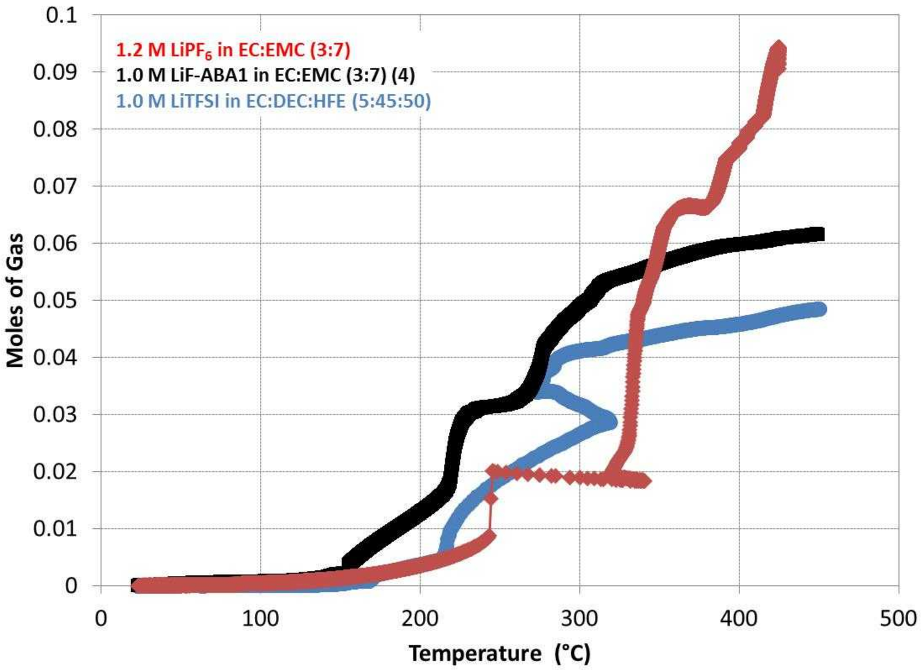
Chris Orendorff, John Lamb and Leigh Ann Steel

Electrolyte Gas Generation

Electrolyte ARC bomb gas volume



Cell ARC gas volume



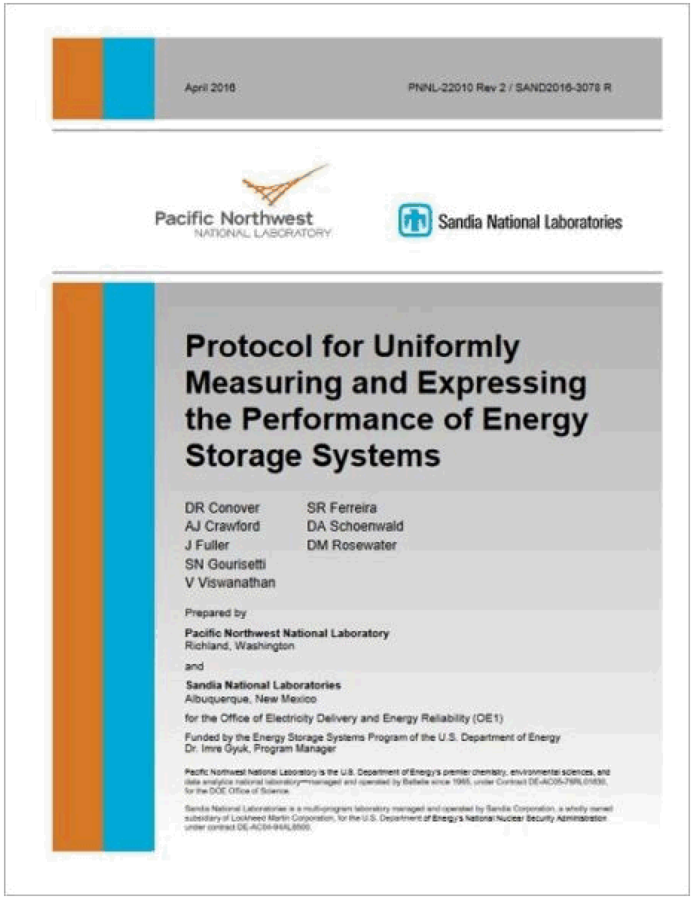
~60% reduction in gas volume between baseline and HFE electrolyte
~40% reduction in gas volume at the cell-level between baseline and HFE electrolyte
~30% reduction in gas volume at the cell-level between baseline and LiF/ABA electrolyte

Standards: SNL & PNNL Protocol for Evaluation ES Systems

Companies looking for an accurate method to gauge how well large batteries and other grid-scale energy storage systems work now have a new set of evaluation guidelines, called the Energy Storage Performance Protocol, at their disposal. The guidelines currently evaluate three energy storage performance uses:
Peak shaving, Frequency Regulation, and Islanded Microgrids

Additional Lab Protocols:

- **Duty Cycle for ESS Firming**
- **Duty Cycle for PV Smoothing**


April 2016

PNNL-22010 Rev 2 / SAND2016-3078 R

Pacific Northwest NATIONAL LABORATORY

Sandia National Laboratories

Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems

DR Conover
AJ Crawford
J Fuller
SN Gourisetti
V Viswanathan
SR Ferreira
DA Schoenwald
DM Rosewater

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and

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Albuquerque, New Mexico

for the Office of Electricity Delivery and Energy Reliability (OE1)

Funded by the Energy Storage Systems Program of the U.S. Department of Energy
Dr. Imre Gyuk, Program Manager

Agenda

- Part 1
  - The Electric Grid
  - Grid Modernization and Energy Storage
- Part 2
  - Energy Storage Technologies
  - Manufacturing of Grid-class Electrochemical Batteries
  - Systems Engineering
  - Energy Storage Safety and Reliability
- Part 3
  - Energy Storage Economics
  - Applications of Energy Storage

Energy Storage Economics

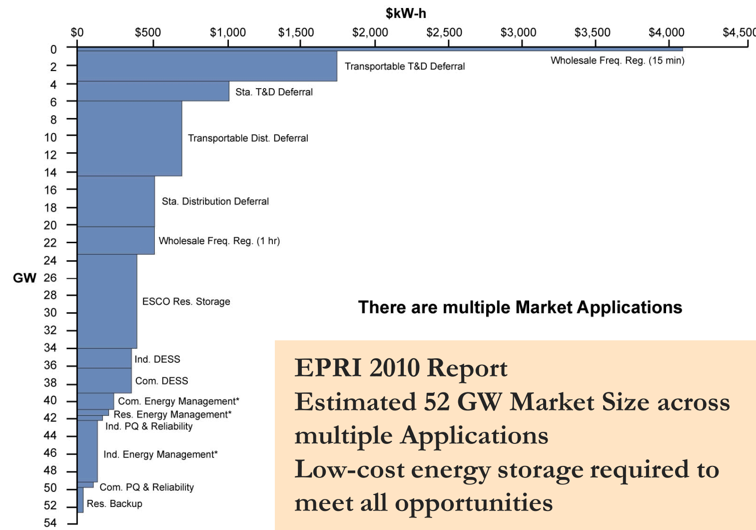
- The grid needs energy storage – right now there are several barriers
  - Storage is expensive
  - Electricity markets/utilities do not properly allocate payments/costs for services provided
    - Voltage support
    - Inertia
    - Renewable integration
    - Reliability
- The future ….
  - Greater penetration of renewables – storage becomes essential;
  - Higher energy prices – storage starts looking better
  - Lower technology costs – storage starts looking better
  - Efficient market design – helps pay for storage costs
- Potentially large market

Potentially Large Grid Energy Storage Market

#	Benefit Type	Discharge Duration* Low	Discharge Duration* High	Capacity (Power: kW, MW) Low	Capacity (Power: kW, MW) High	Benefit ($/kW)** Low	Benefit ($/kW)** High	Potential (MW, 10 Years) CA	Potential (MW, 10 Years) U.S.	Economy ($Million)[†] CA	Economy ($Million)[†] U.S.
1	Electric Energy Time-shift	2	8	1 MW	500 MW	400	700	1,445	18,417	795	10,129
2	Electric Supply Capacity	4	6	1 MW	500 MW	359	710	1,445	18,417	772	9,838
3	Load Following	2	4	1 MW	500 MW	600	1,000	2,889	36,834	2,312	29,467
4	Area Regulation	15 min.	30 min.	1 MW	40 MW	785	2,010	80	1,012	112	1,415
5	Electric Supply Reserve Capacity	1	2	1 MW	500 MW	57	225	636	5,986	90	844
6	Voltage Support	15 min.	1	1 MW	10 MW	400		722	9,209	433	5,525
7	Transmission Support	2 sec.	5 sec.	10 MW	100 MW	192		1,084	13,813	208	2,646
8	Transmission Congestion Relief	3	6	1 MW	100 MW	31	141	2,889	36,834	248	3,168
9.1	T&D Upgrade Deferral 50th percentile††	3	6	250 kW	5 MW	481	687	386	4,986	226	2,912
9.2	T&D Upgrade Deferral 90th percentile††	3	6	250 kW	2 MW	759	1,079	77	997	71	916
10	Substation On-site Power	8	16	1.5 kW	5 kW	1,800	3,000	20	250	47	600
11	Time-of-use Energy Cost Management	4	6	1 kW	1 MW	1,226		5,038	64,228	6,177	78,743
12	Demand Charge Management	5	11	50 kW	10 MW	582		2,519	32,111	1,466	18,695
13	Electric Service Reliability	5 min.	1	0.2 kW	10 MW	359	978	722	9,209	483	6,154
14	Electric Service Power Quality	10 sec.	1 min.	0.2 kW	10 MW	359	978	722	9,209	483	6,154
15	Renewables Energy Time-shift	3	5	1 kW	500 MW	233	389	2,889	36,834	899	11,455
16	Renewables Capacity Firming	2	4	1 kW	500 MW	709	915	2,889	36,834	2,346	29,909
17.1	Wind Generation Grid Integration, Short Duration	10 sec.	15 min.	0.2 kW	500 MW	500	1,000	181	2,302	135	1,727
17.2	Wind Generation Grid Integration, Long Duration	1	6	0.2 kW	500 MW	100	782	1,445	18,417	637	8,122

*Hours unless indicated otherwise. min. = minutes. sec. = seconds.
**Lifecycle, 10 years, 2.5% escalation, 10.0% discount rate.
[†]Based on potential (MW, 10 years) times average of low and high benefit ($/kW).
[††] Benefit for one year. However, storage could be used at more than one location at different times for similar benefits.

Jim Eyer and Garth Corey, Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide DOE ESS Program, SAND2010-0815, 2010



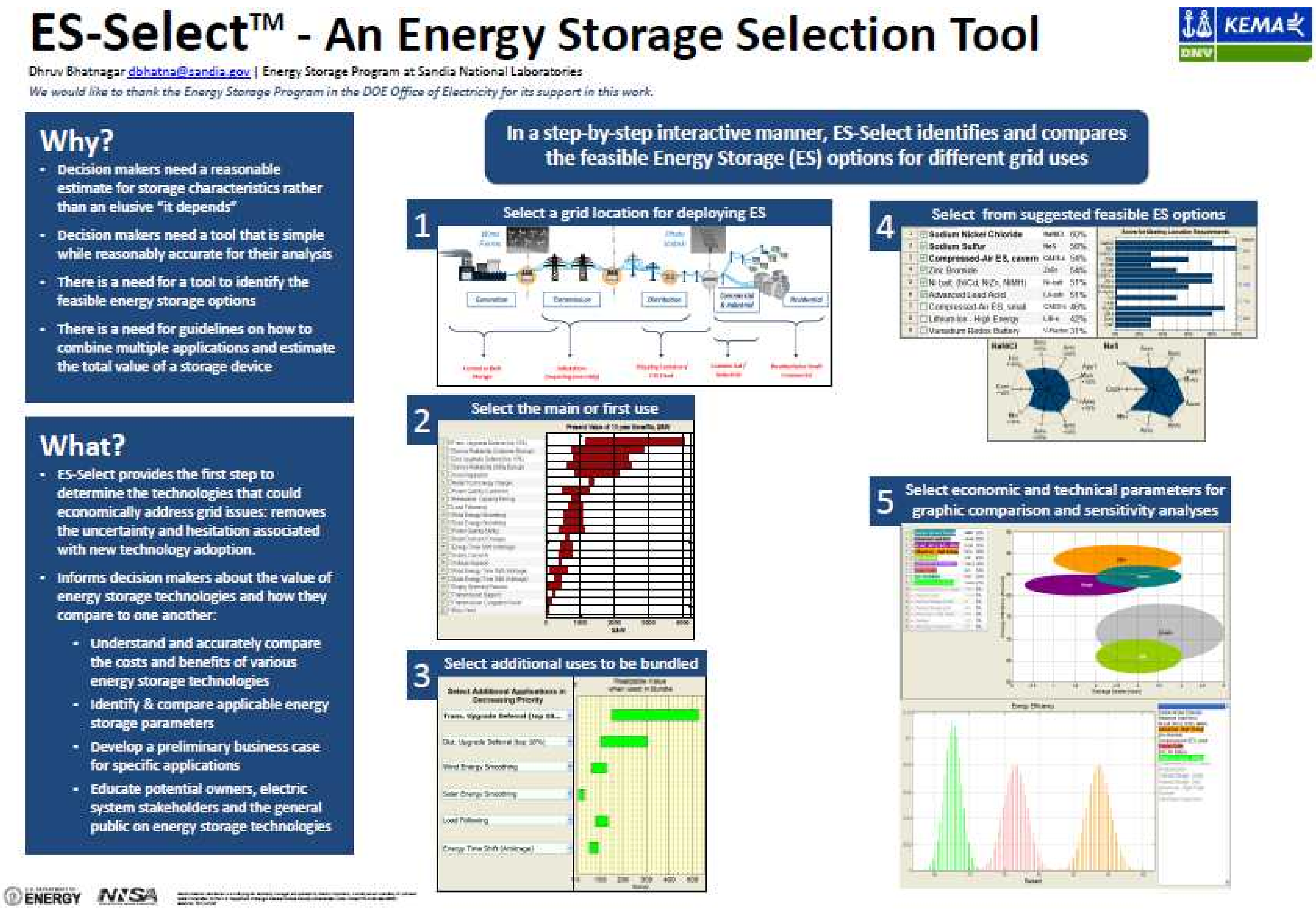
There are multiple Market Applications

EPRI 2010 Report
Estimated 52 GW Market Size across multiple Applications
Low-cost energy storage required to meet all opportunities

With permission from EPRI, Electric Energy Storage Technology Options; A Primer on Applications, Costs & Benefits, December 2010

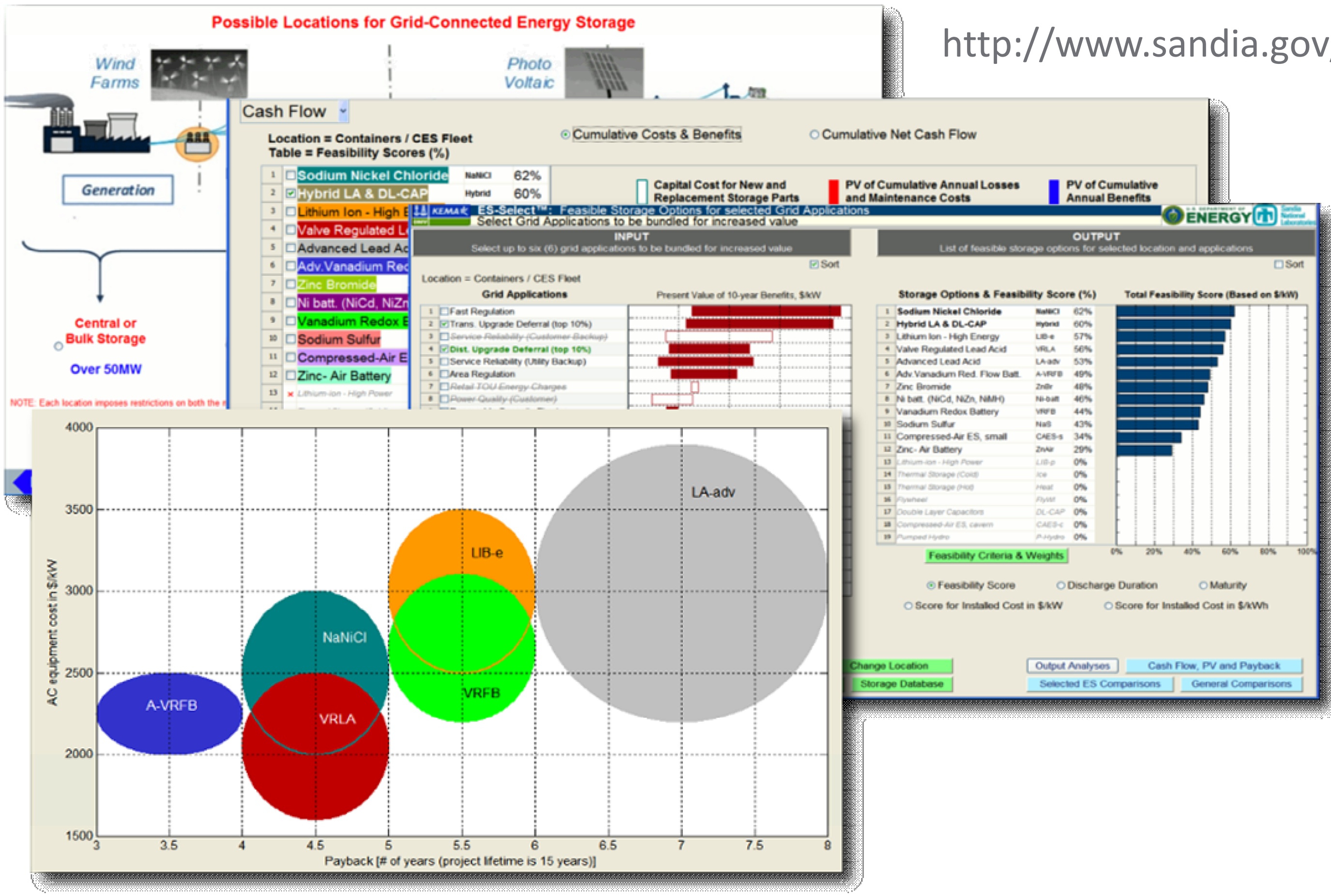
Duke/Dow/KEMA White Paper 2012
US Storage Requirements: 2012-22
Grid Reliability and Stability
150 GWh -300 GWh
Renewable Integration (Wind, PV)
4 GWh – 10 GWh
EV Charging and Grid Reliability
0.2 GWh – 2 GWh

EE-Select – An Energy Storage Selection Tool



EE-Select

http://www.sandia.gov/ess/tools/es-select-tool/

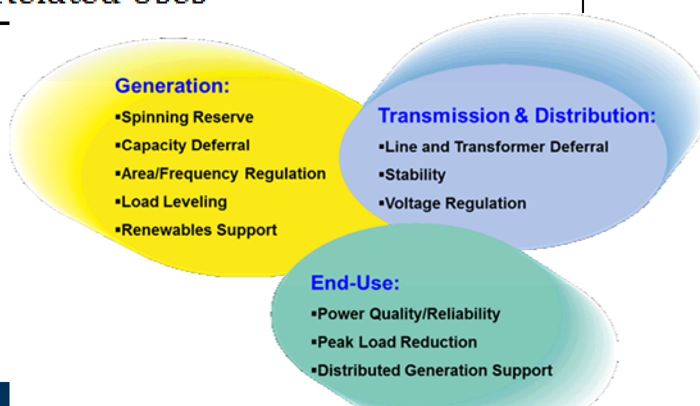


multiple applications and
: mutual compatibility. It then
f various storage technologies
;. It provides a graphical
comparison of the selected storage resource's technical and economic features.

Energy Storage Services

Bulk Energy Services	
	Electric Energy Time-Shift (Arbitrage)
	Electric Supply Capacity
Ancillary Services	
	Regulation
	Spinning, Non-Spinning and Supplemental Reserves
	Voltage Support
	Black Start
	Other Related Uses

Transmission Infrastructure Services	
	Transmission Upgrade Deferral
	Transmission Congestion Relief
Distribution Infrastructure Services	
	Distribution Upgrade Deferral
	Voltage Support
Customer Energy Management Services	
	Power Quality
	Power Reliability
	Retail Electric Energy Time-Shift
	Demand Charge Management



ource: DOE/EPRI Electricity Storage Handbook in
:ollaboration with NRECA, 2013
. Eyer and G. Corey, “Energy Storage for the Electricity Grid:
Benefits and Market Potential Assessment Guide”
ıttp://www.sandia.gov/ess/publications/SAND2010-0815.pdf

ES Policy and Market Implications (for the future)

- The Federal Energy Regulatory Commission (FERC), which oversees U.S. energy markets, is in the midst of re-evaluating several policies that could open up more of a market for storage.

- Currently, California and the regional grid PJM Interconnection (excluding New Jersey) together account for **92 percent of U.S. energy storage deployments.**

- There's a short-term frequency regulation market in PJM and incentives for self-generation in California.

- The storage industry is working to encourage FERC to apply changes such as these in services and benefits more broadly.

Reference: Julian Specter, "The Year Ahead for Energy Storage Policy", in Greentech Media; July 2016.

Why is Storage Valuation Difficult?

- Location/Jurisdiction
  - Market area, e.g., California ISO
  - Vertically integrated utility, e.g., PNM
  - Transmission and distribution deferral is very location specific
- Many applications require a combination of technical and financial analysis
  - Dynamic simulations (requires an accurate system model)
  - Production cost modeling (requires an accurate system model)
- Difficult to break out current cost of services, especially for vertically integrated utilities
- Identifying alternatives can be difficult
- Many storage technologies are not "off-the-shelf", proven technology (e.g., O&M costs, warranty????)
- Storage is expensive

Recent Storage Policy Breakthroughs

- American Recovery and Reinvestment Act (ARRA) of 2009 Energy Storage Demonstration Projects
  - 16 projects
  - Varying levels of technology maturity
  - 50% federal cost share ($600M for all 21 SGDPs)
- FERC order 755 and FERC order 784: “pay-for-performance”
  - More fairly compensates “fast responding” systems (e.g., storage)
  - Market redesign for frequency regulation compensation
    - Separate signals for “fast” devices
    - Mileage payment in addition to capacity payment
- California energy storage mandate (California Public Utilities Commission) 10/17/2013
  - 1.3 GW by 2020 (Note the units!)

California Energy Storage Mandate

Storage Grid Domain Point of Interconnection	2014	2016	2018	2020	Total
Southern California Edison					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
Subtotal SCE	**90**	**120**	**160**	**210**	**580**
Pacific Gas and Electric					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
Subtotal PG&E	**90**	**120**	**160**	**210**	**580**
San Diego Gas & Electric					
Transmission	10	15	22	33	80
Distribution	7	10	15	23	55
Customer	3	5	8	14	30
Subtotal SDG&E	**20**	**30**	**45**	**70**	**165**
Total - all 3 utilities	**200**	**270**	**365**	**490**	**1,325**

Energy Storage Value Streams - Grid Resiliency

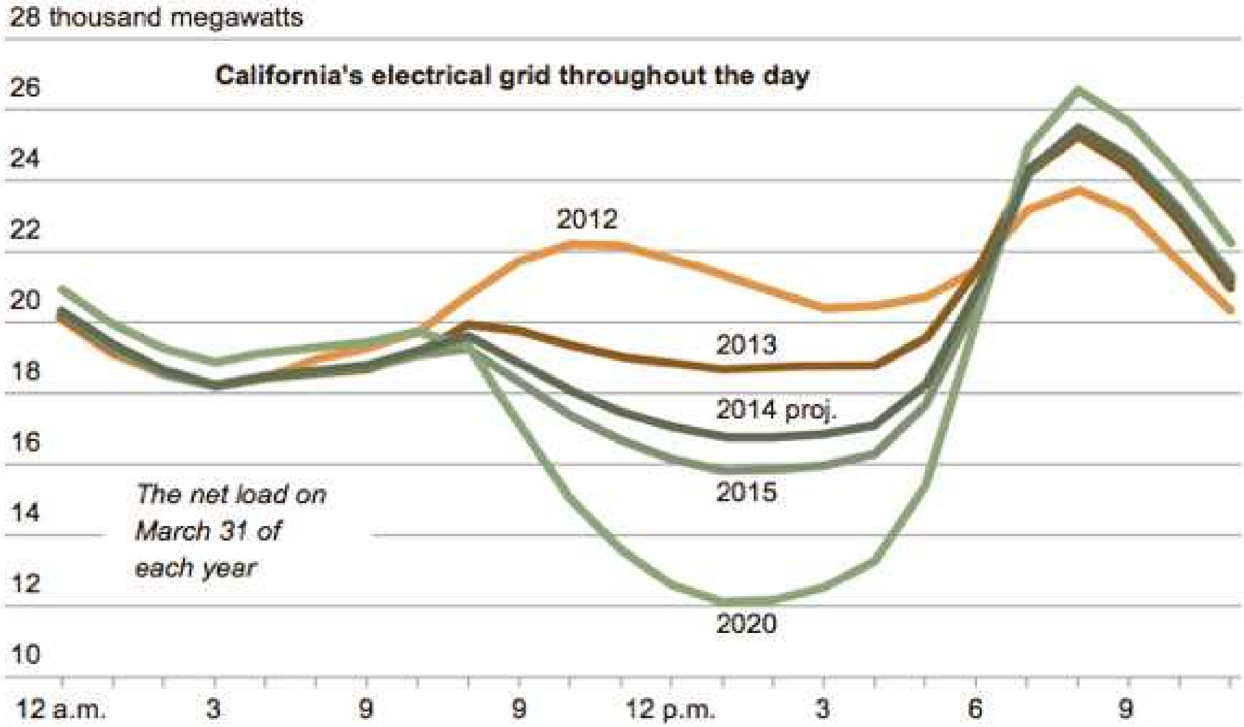
Energy Storage Value Streams

- Distribution level energy storage
  - Volt/VAR support
  - Islanding during outages
  - Frequency regulation
  - Renewable time shift
  - Peak shaving
  - Arbitrage

DTE ARRA energy storage demonstration project

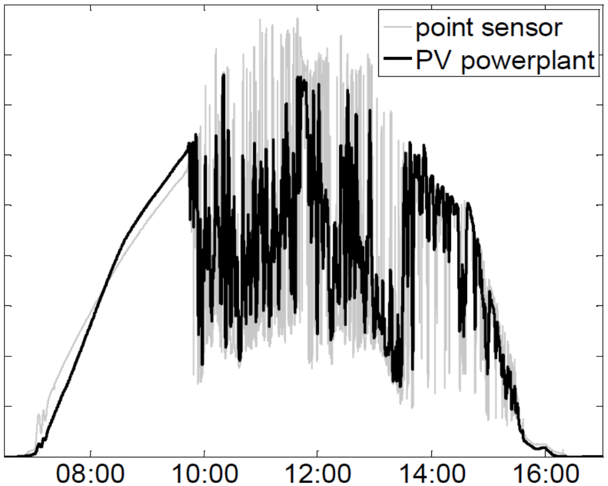
Energy Storage Value Streams – Renewable Firming

- Renewable firming
  - Puerto Rico is penalizing rapid ramp rates
  - Duck curve (CA is starting to be concerned)



Source: CallSO

CA "duck" curve

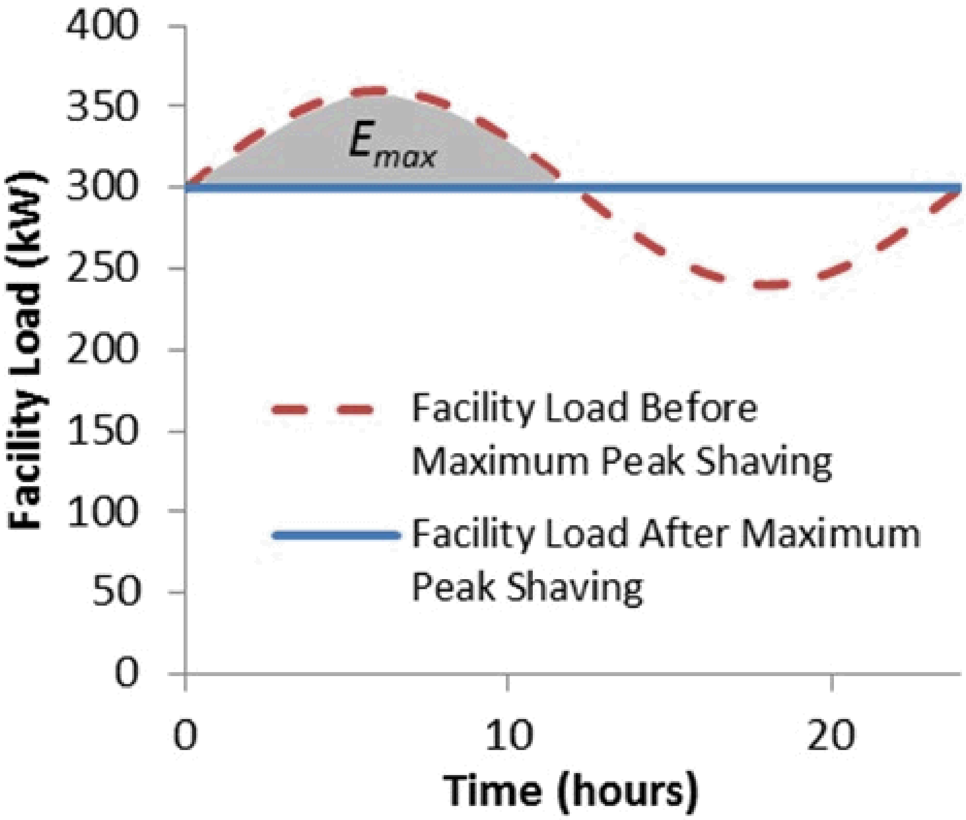


Solar variability

For vertically integrated utilities – increased regulating and spinning reserves. In market areas, adding ramping products.

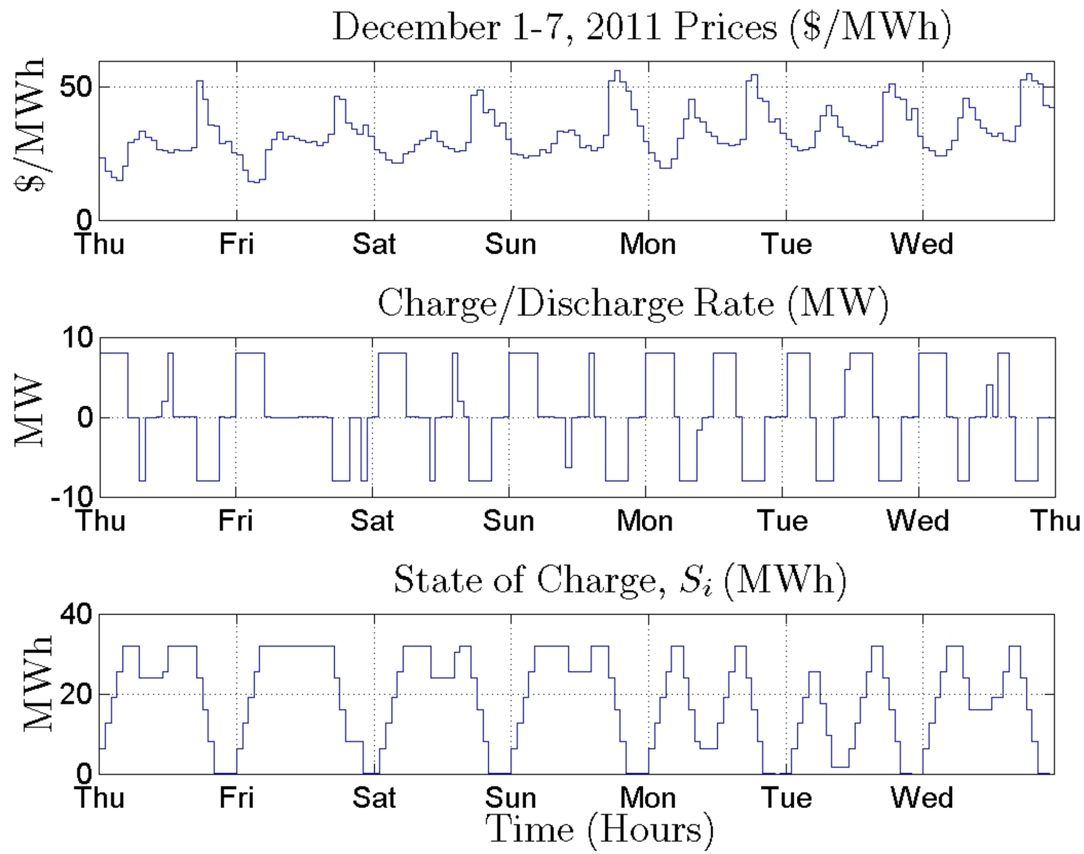
Energy Storage Value Streams – Demand Charge Reduction

- Reduction in demand charges (behind the meter)
- Large potential savings for industrial customers



Energy Storage Value Streams - Arbitrage

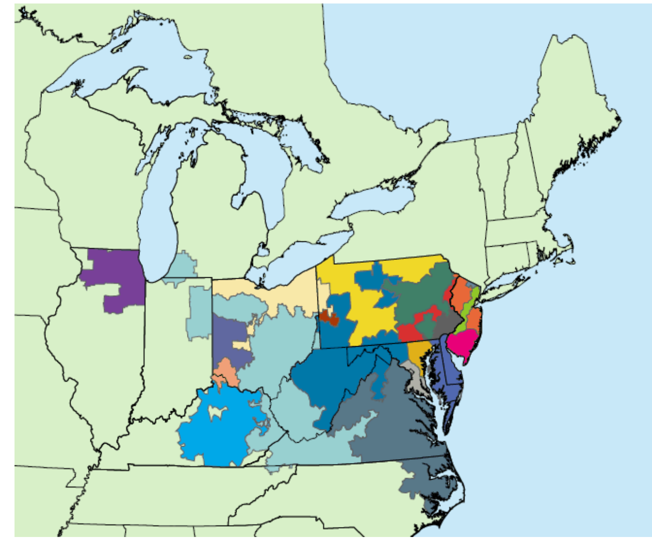
- Energy arbitrage – buy low, sell high
- Energy price swings must be larger than efficiency losses
- Rarely captures the largest value



Energy Storage Value Streams – Regulation Services

- Frequency regulation
  - Used to maintain 60 Hz grid frequency
  - Second by second dispatch
  - Typically the most valuable service

Month	Year	% q^R	% q^D	[illegible]	Revenue
Jun	2014	0.65	0.41	[illegible]	487,185.94
Jul	2014	1.22	0.38	[illegible]	484,494.90
Aug	2014	1.20	0.38	[illegible]	354,411.61
Sep	2014	1.23	0.52	[illegible]	401,076.97
Oct	2014	1.30	0.38	[illegible]	535,293.84
Nov	2014	1.71	0.58	[illegible]	431,106.41
Dec	2014	1.07	0.50	[illegible]	341,281.46
Jan	2015	0.80	1.10	[illegible]	443,436.10
Feb	2015	1.03	1.37	[illegible]	998,392.65
Mar	2015	0.87	0.71	[illegible]	723,692.29
Apr	2015	0.90	0.20	[illegible]	527,436.11
May	2015	1.02	0.37	[illegible]	666,290.70
				[illegible]	,394,098.97

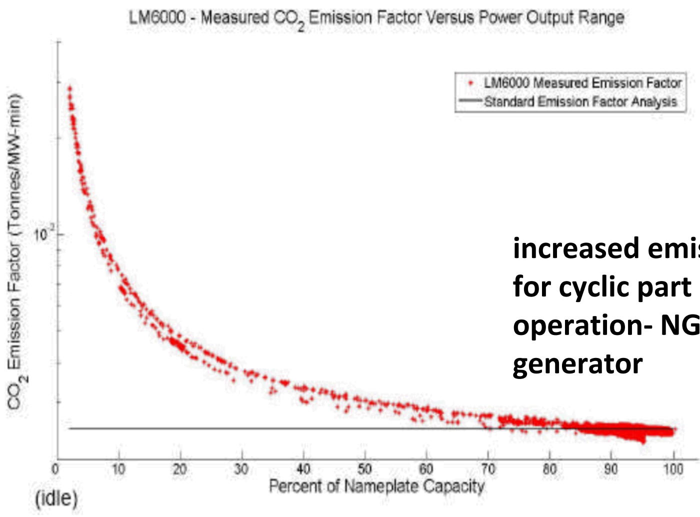


PJM results, 20MW, 5MWh 200-flywheel system

Beacon Power Flywheel

Energy Storage Value Streams – T&D

- Enhance asset utilization
- Defer upgrades
- Operate Fossil fuel generators at optimum set point– reduce emissions



increased emissions for cyclic part load operation- NG generator

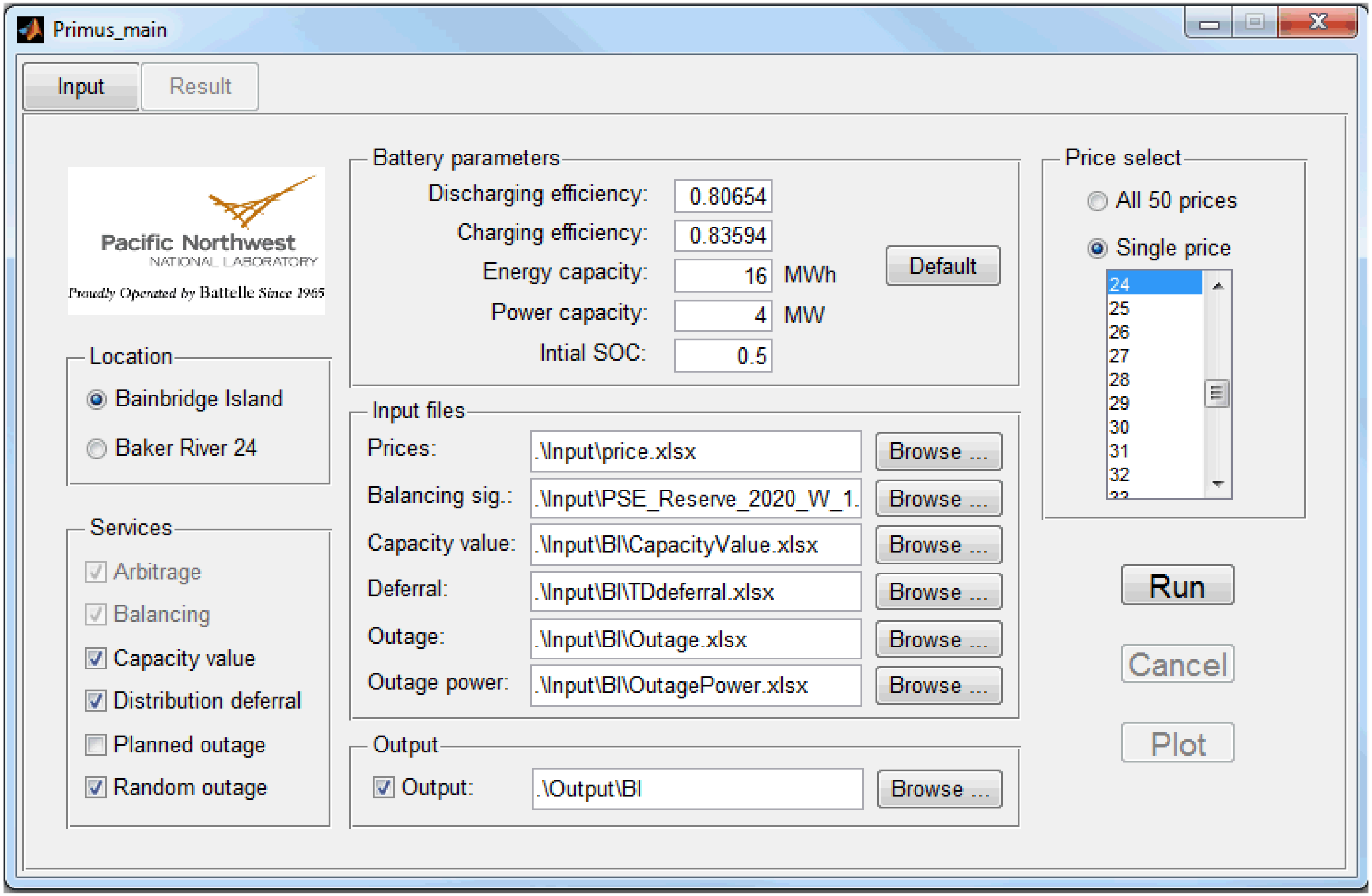
Source: EPRI/DOE Handbook of Energy Storage for Transmission and Distribution Applications - Wind Supplement update 2009

Case Study – Storage Valuation in Vertically Integrated Regions
Puget Sound Energy Storage Analysis

- 4 opportunities within PSE region analyzed. 2 eliminated in prescreen
- Bainbridge Island most suitable for storage application.
  - 2 radial substations (Winslow and Murden Cove) supply power for most of the island
- Potential Applications:
  - Distribution Values
    - Transformer upgrade deferral
    - Outage management
    - Volt/Var control
  - Transmission Values
    - Balancing
    - Economic energy dispatch
    - Capacity value system adequacy

145

Energy Storage Optimization Tool



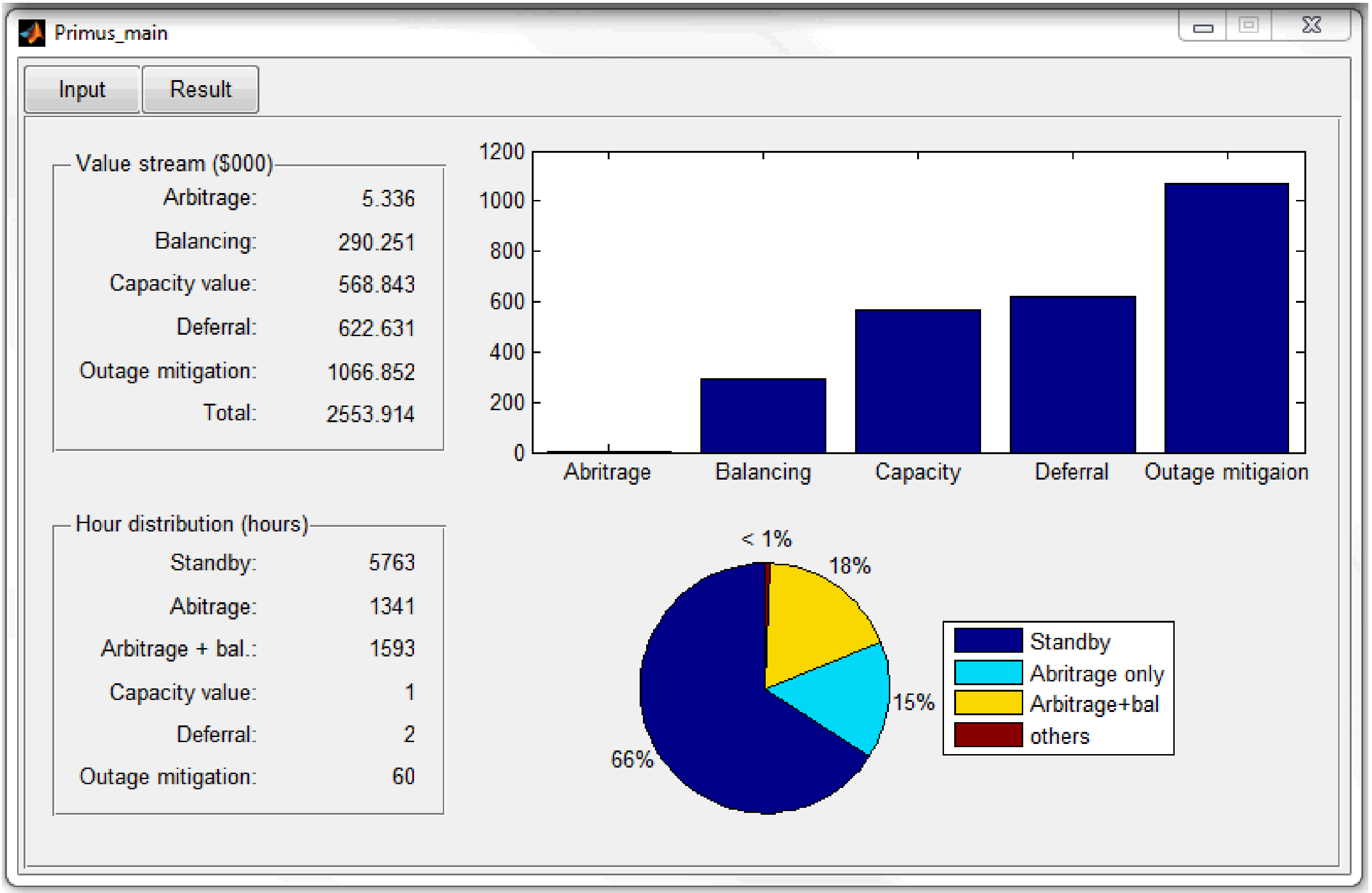
Energy Storage Optimization Tool

$$\max_{p_k^+, p_k^-, p_k, p_k^{\text{batt}}, l_k, r_k^+, r_k^-} \sum_{k=1}^{K} \left[\lambda_k p_k + \beta_k^+ r_k^+ + \beta_k^- r_k^-\right] \tag{3.6a}$$

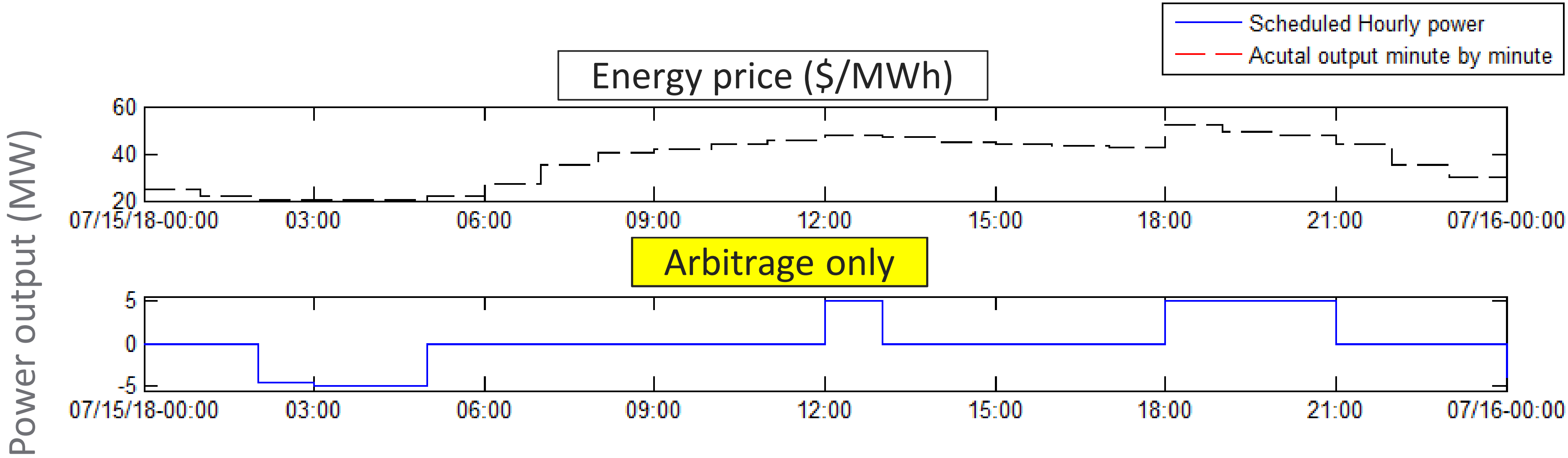
subject to:

Power injection limit:	$0 \leq p_k^+ \leq p_{\max}^+,$	$\forall k = 1, \cdots, K$	(3.6b)
Power withdrawal limit:	$0 \leq p_k^- \leq p_{\max}^-,$	$\forall k = 1, \cdots, K$	(3.6c)
Either charging or discharging (unnecessary):	$p_k^+ p_k^- = 0,$	$\forall k = 1, \cdots, K$	(3.6d)
Power transfer between battery and grid:	$p_k = p_k^+ - p_k^-,$	$\forall k = 1, \cdots, K$	(3.6e)
Power support requirement:	$P_k^{\text{req}} \leq p_k,$	$\forall k = 1, \cdots, K$	(3.6f)
Rate of change of energy in battery:	$p_k^{\text{batt}} = \dfrac{p_k^+}{\eta^+} - p_k^- \eta^-,$	$\forall k = 1, \cdots, K$	(3.6g)
State of charge level:	$l_k = l_{k-1} - \dfrac{1}{E_s} p_k^{\text{batt}},$	$\forall k = 1, \cdots, K$	(3.6h)
State of charge level limits:	$\underline{L}_k \leq l_k \leq \overline{L}_k,$	$\forall k = 1, \cdots, K$	(3.6i)
Balancing up capacity:	$r_k^+ \leq p_{\max}^+ - p_k,$	$\forall k = 1, \cdots, K$	(3.6j)
Balancing down capacity:	$r_k^- \leq p_k + p_{\min}^-,$	$\forall k = 1, \cdots, K$	(3.6k)
State of charge level limits including balancing up energy:	$\underline{L}_k \leq l_k - \dfrac{\epsilon_k^+ r_k^+}{\eta^+ E_s} \leq \overline{L}_k,$	$\forall k = 1, \cdots, K$	(3.6l)
State of charge level limits including balancing down energy:	$\underline{L}_k \leq l_k + \dfrac{\epsilon_k^- r_k^- \eta^-}{E_s} \leq \overline{L}_k,$	$\forall k = 1, \cdots, K$	(3.6m)
Desired SOC at the end of time horizon:	$l_{\text{set}} \leq l_K.$		(3.6n)

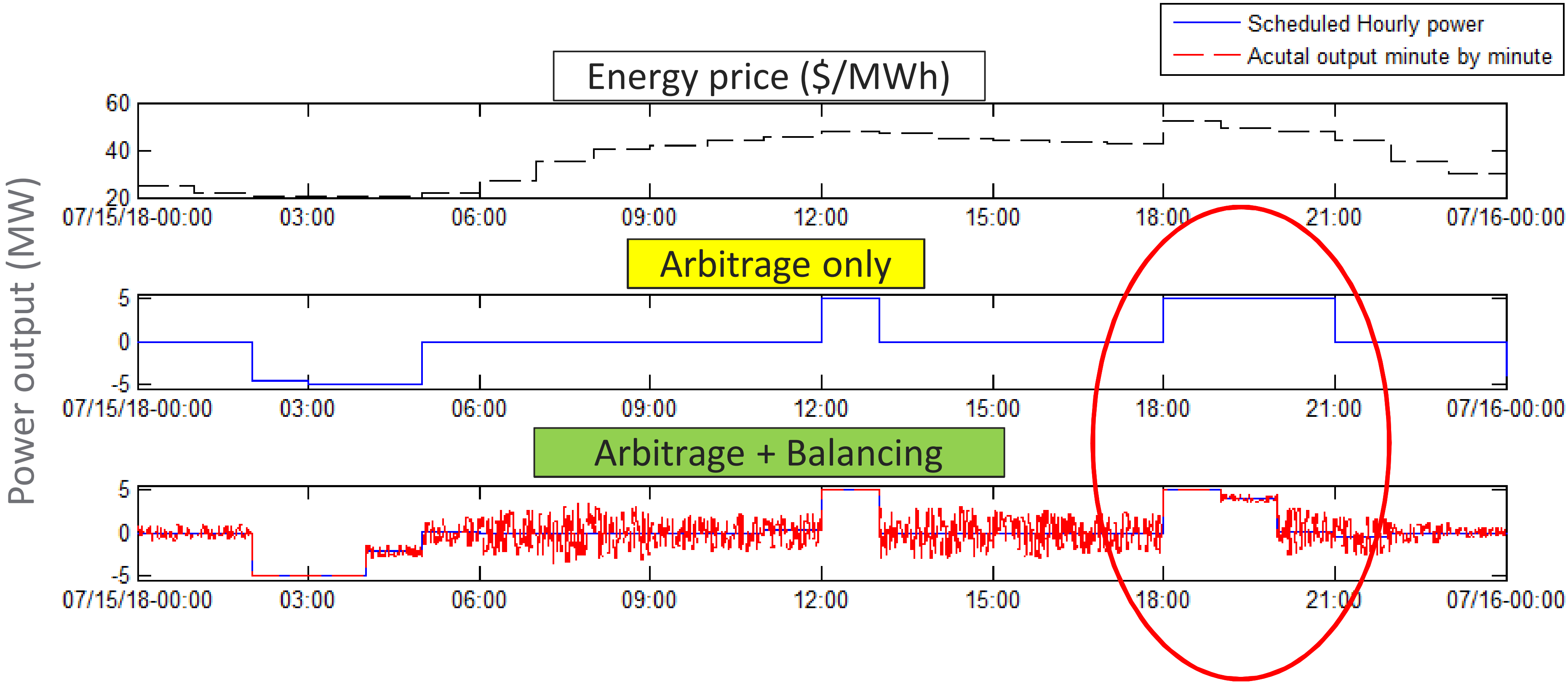
Energy Storage Optimization Tool Output



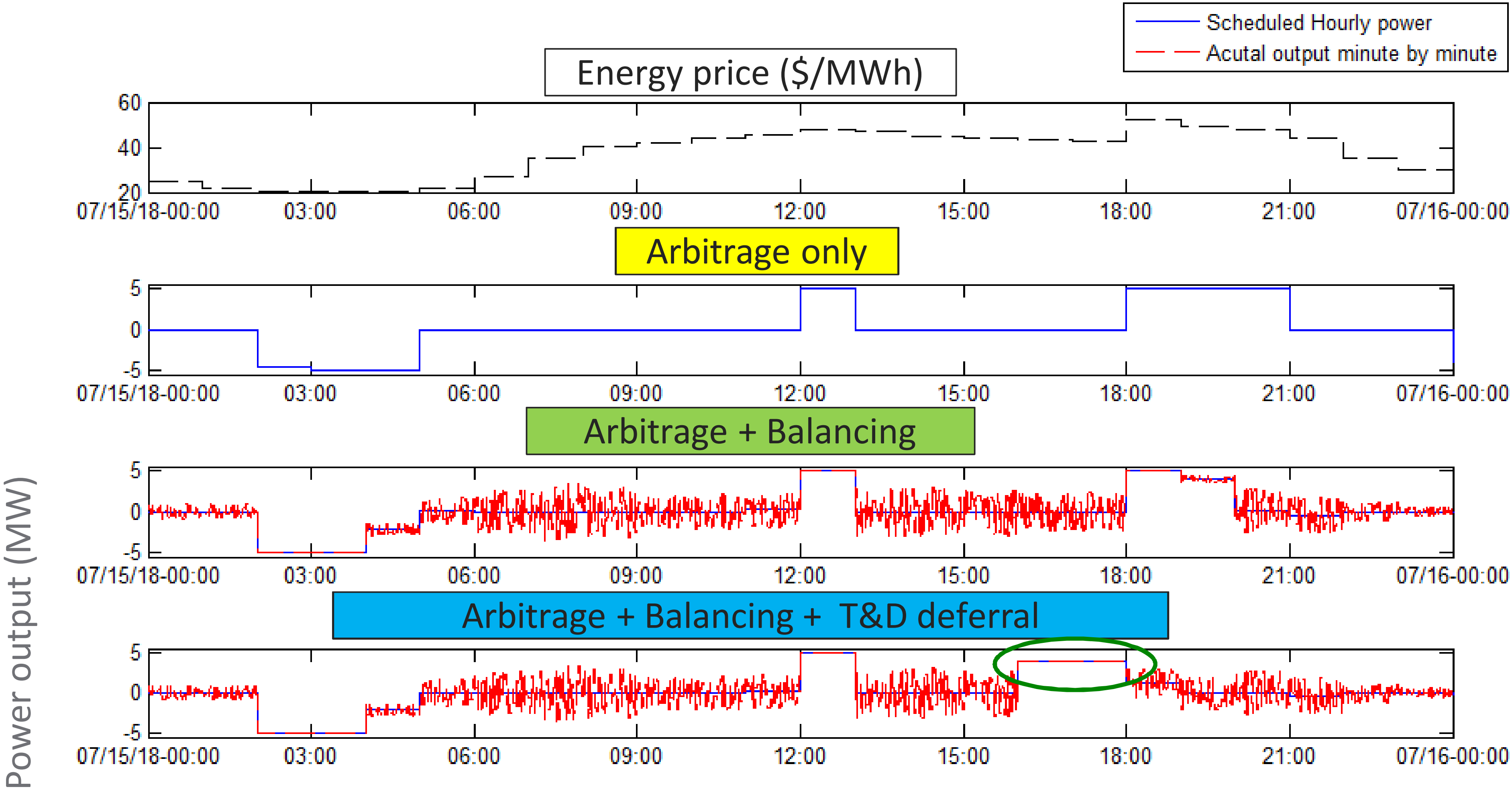
Bundling Services: how to do it optimally?



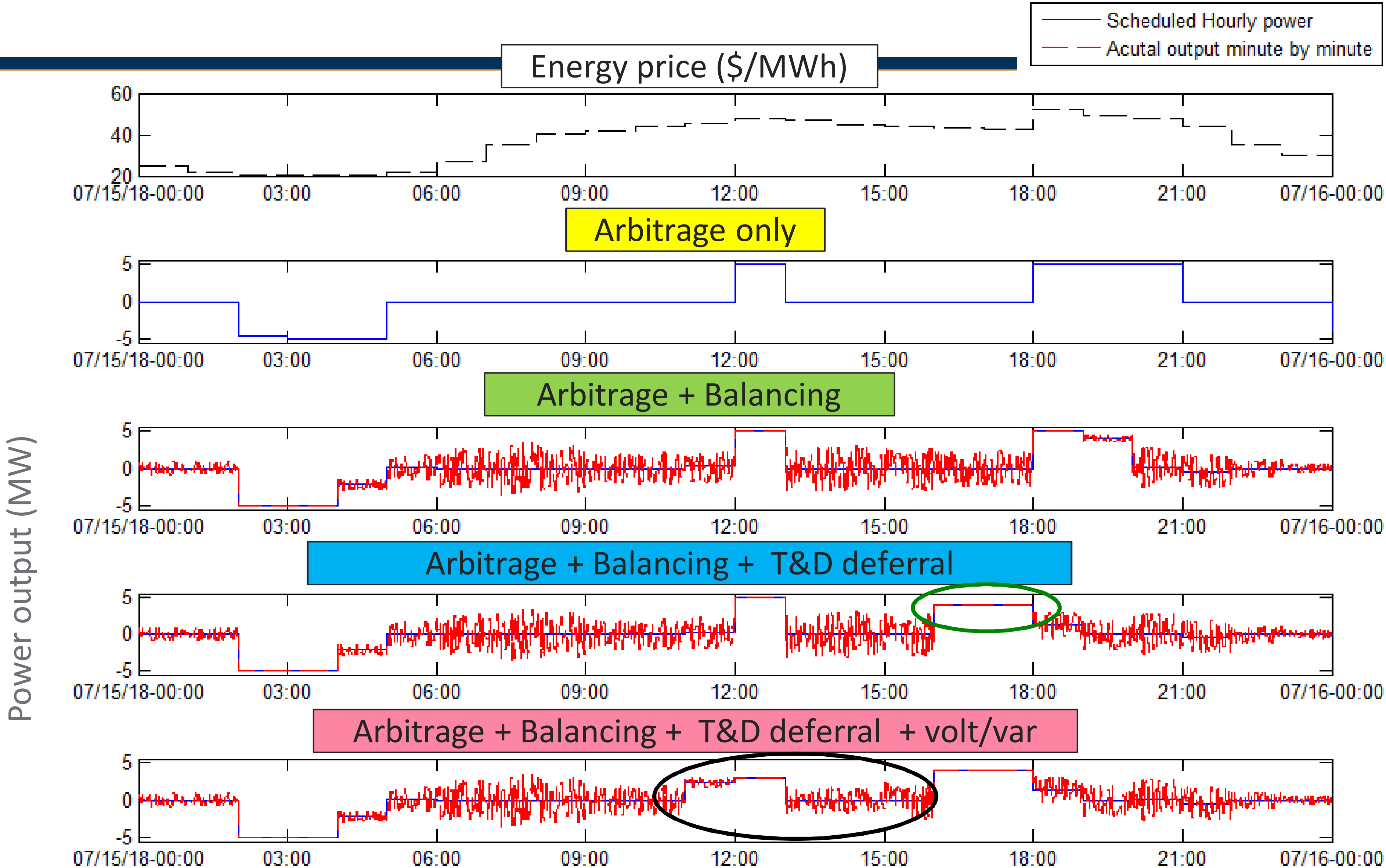
Bundling Services: How to do it optimally?



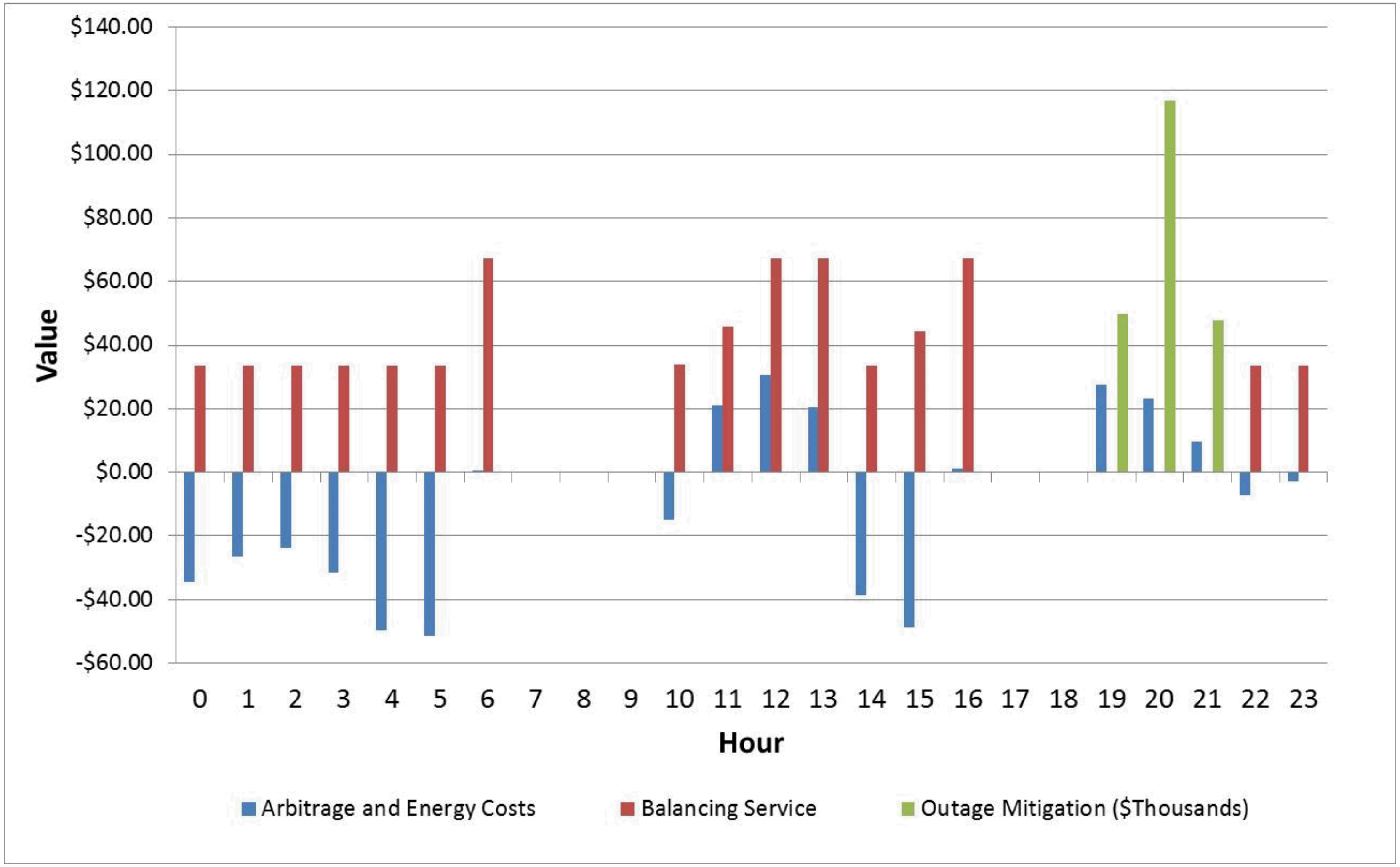
Bundling Services: how to do it optimally?



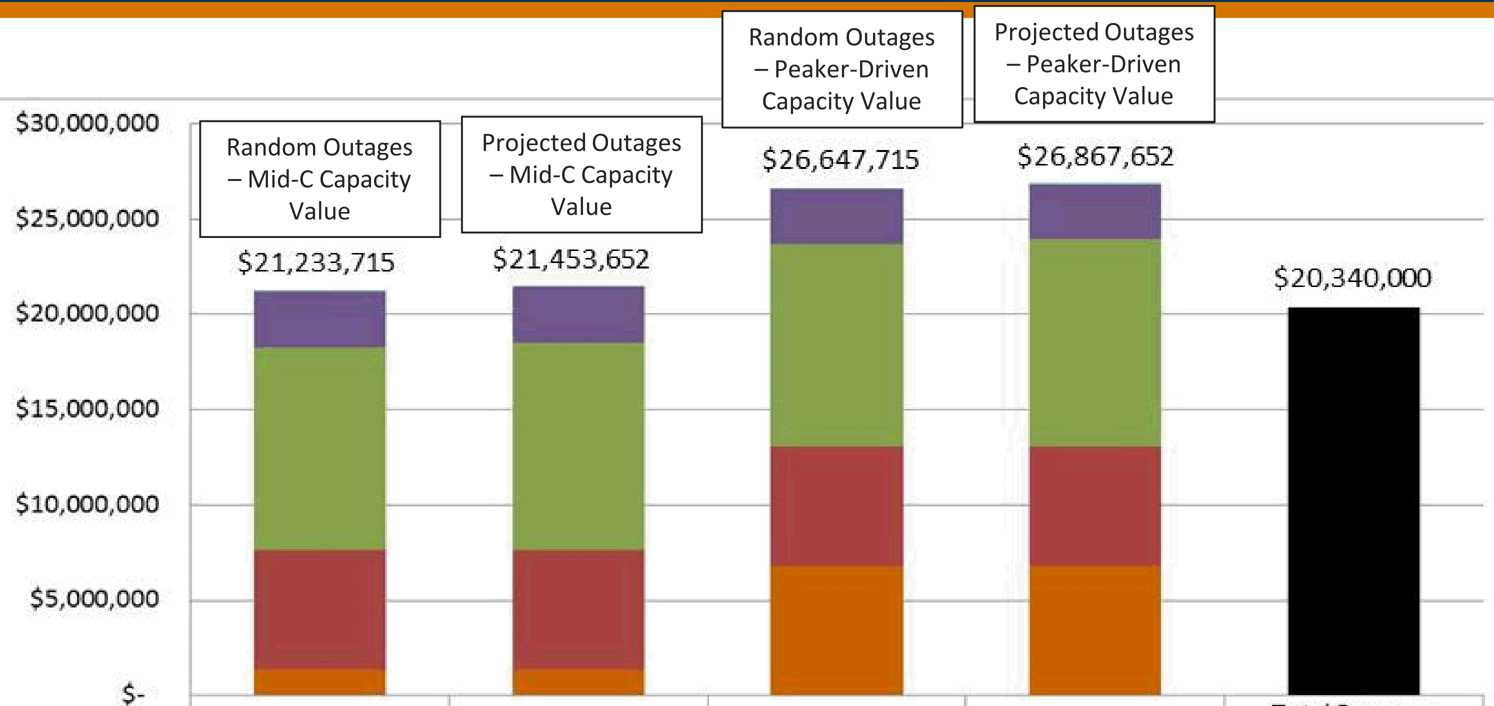
Bundling Services: how to do it optimally?



Example: Hourly value at Bainbridge Island for 24-hour period

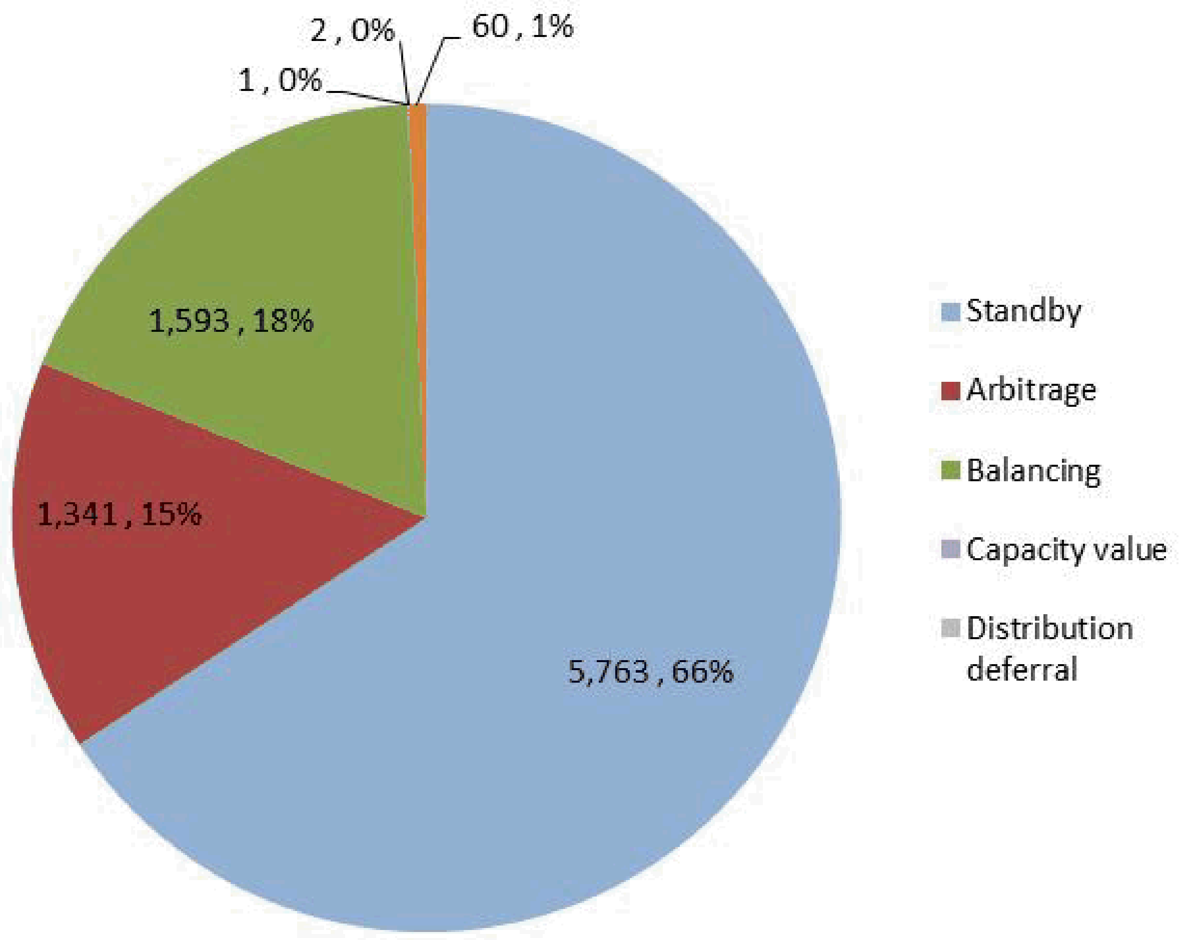


Summary of Results (NPV benefits and revenue requirements over 20-year time horizon) – Bainbridge Island



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Total Revenue Requirements
Revenue Requirements					$20,340,000
Arbitrage and Energy Costs	$53,299	$40,833	$53,299	$40,833	
Balancing Services	$2,899,171	$2,898,352	$2,899,171	$2,898,352	
Outage Mitigation	$10,656,246	$10,889,467	$10,656,246	$10,889,467	
Distribution Upgrade Deferral	$6,252,000	$6,252,000	$6,252,000	$6,252,000	
Capacity Value	$1,373,000	$1,373,000	$6,787,000	$6,787,000	

BATTERY USAGE (1 year) FOR APPLICATION



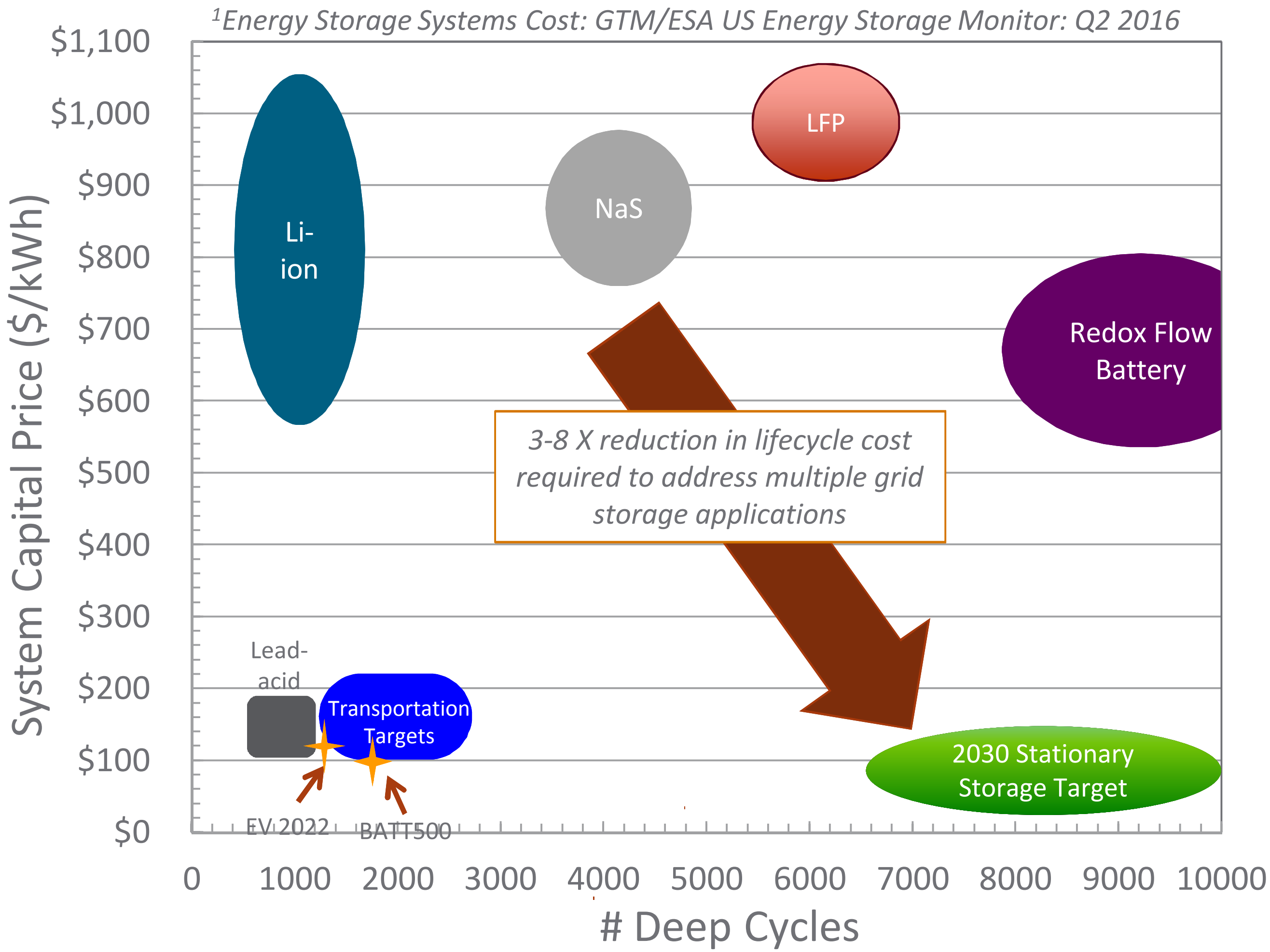
Case Study Summary

Revenue Breakdown

- **40% Outage Mitigation**
- **25% Capacity Value**
- **23% Upgrade Deferral,**
- **11% Balancing service**
- **< 1% Arbitrage**

- **BPA/PSE/Primus**
- **The Challenge**
  - Substations are capacity constrained
  - Reliability issues with radial transmission and distribution
- **The Solution**
  - Optimal energy storage is 3 MW and 9-12 MWh
  - Total Cost $3,690 per kW installed
  - Battery Cost $2300/kw
  - Net benefits of $6.5M
  - Total cost approx $11.8M

Reducing Cost is Key



- Grid Scale Energy Storage requires longer cycle life than EV systems
- Grid Scale Energy requires deeper discharge to serves multiple grid applications
- Lithium ion best suited to meet transportation requirements
- Many chemistries can compete for grid-scale applications

For Energy Storage to Become Ubiquitous

- LCOE on a $/kWh-cycle (energy delivered) needs to come down to <$0.05/kWh-cycle
- Got to look beyond bundling multiple benefit streams
- Better cost metrics – usable energy capacity in KWh-cycles.
- Greater attention to safety

Key Takeaways…

- **We will need much, much more storage on our grid** to accommodate increasing renewable penetration and the transition to a clean energy economy.
- Currently, the entire storage system (batteries to interconnection) is too expensive.
- Advances in several areas will make grid-based storage systems safer, more reliable, and cost-effective
  - Technology advances
  - Manufacturing and scale-up
  - Codes and standards
- Current demonstration projects are leading the way

DOE ESS Website Resource with Examples of Available Tools

- DOE / ESS Website:
  http://www.sandia.gov/ess/
- 2015 DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA
- DOE /Strategen Global Energy Storage Database
- Energy Storage Grid: Benefits & Market Guide
- ES Demonstration Projects Summary
- ES Strategic Safety Plan

SANDIA REPORT
SAND2010-0815
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Printed February 2010
Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide
A Study for the DOE Energy Storage Systems Program
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U.S. DEPARTMENT OF ENERGY

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