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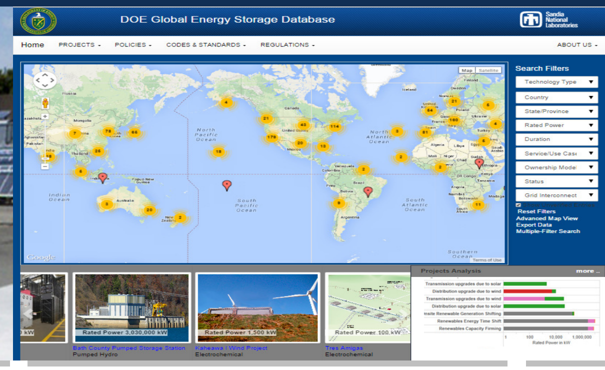

Energy Storage – The Future

Babu Chalamala, Ray Byrne and Dan Borneo

IEEE ESSB Winter 2017 Meeting

New Orleans, Jan 8, 2017

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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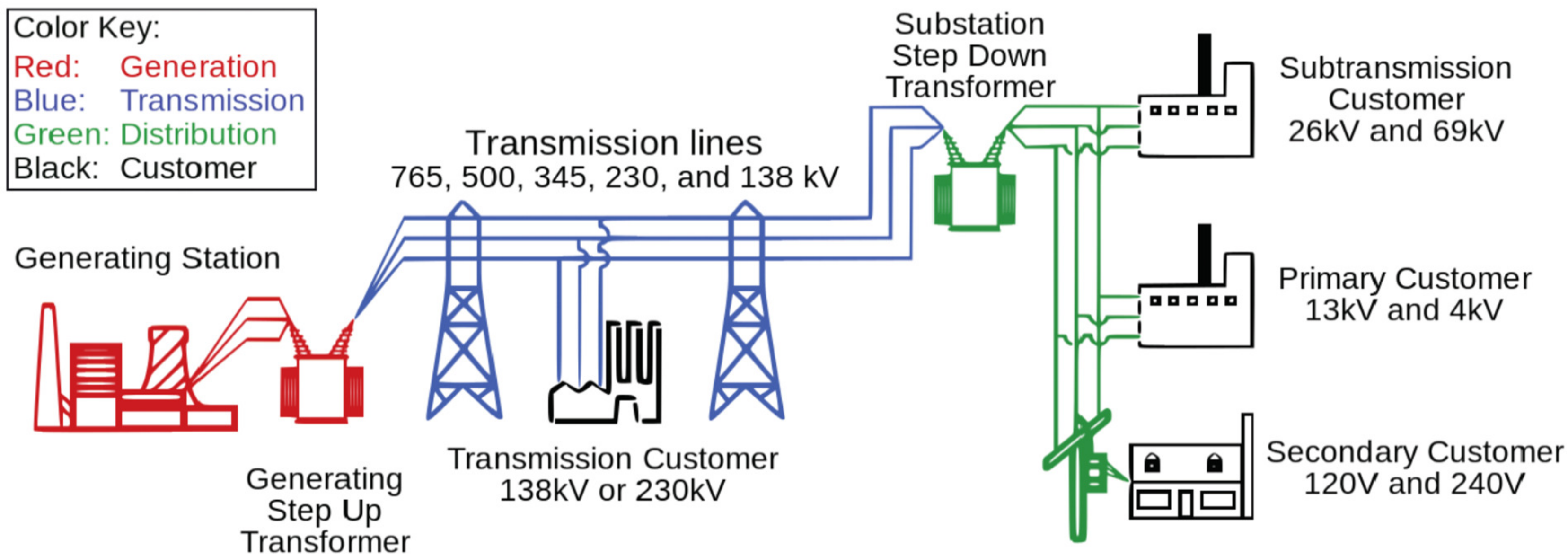
Agenda

- Grid Energy Storage Technologies Intro - Babu Chalamala
  - Review of drivers and challenges for integrating energy storage on a larger scale
  - Energy storage technologies and systems aspects
- Energy Storage Analytics and Storage Valuation - Ray Byrne
  - Role of markets and economics of storage deployment
  - Optimization of energy storage systems
- Development of Energy Storage Projects - Dan Borneo
  - Lessons learned from demonstration projects
  - Project guide and case studies

The Grid Today

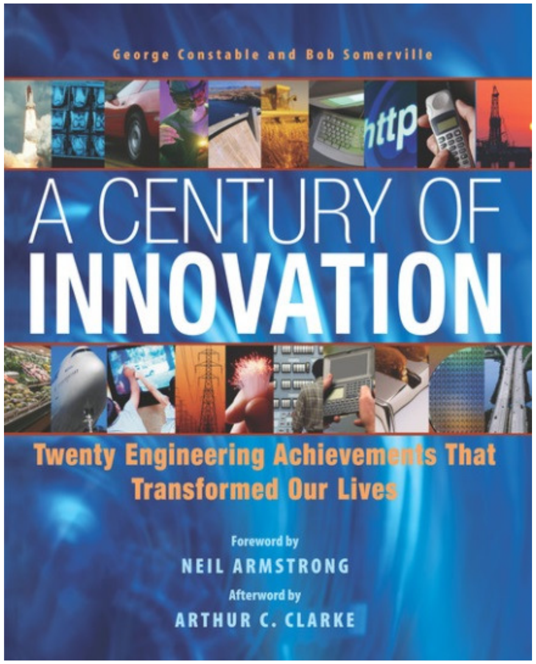


- Grid 1.0
  - One way energy flow
  - Generation and load must always be balanced

NERC

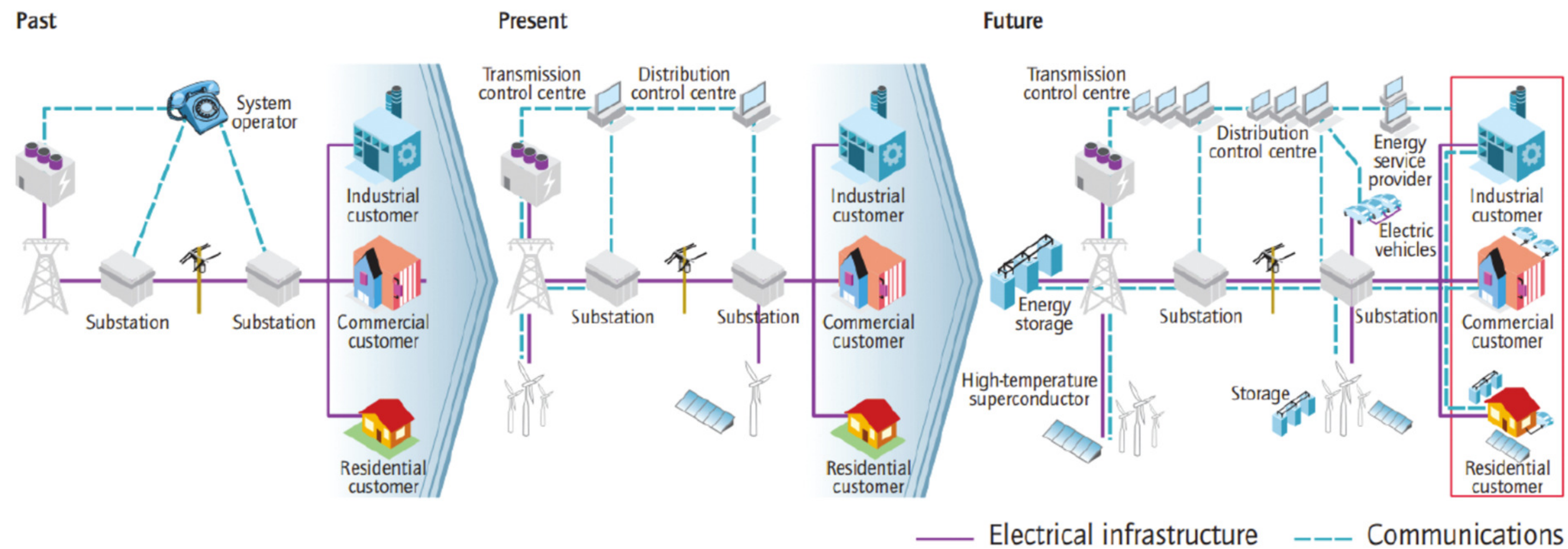
The Success of the Grid

- 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

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

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 Wind Generation

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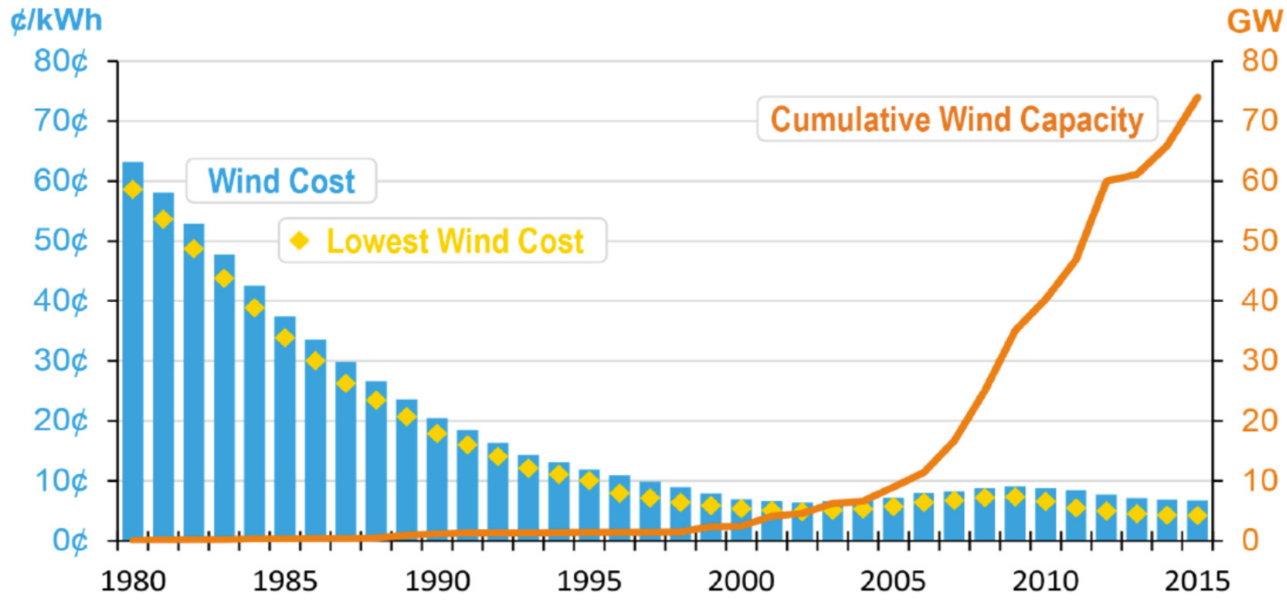
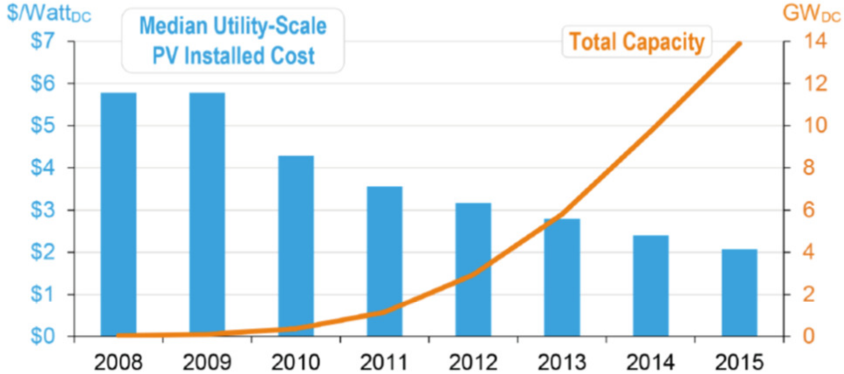
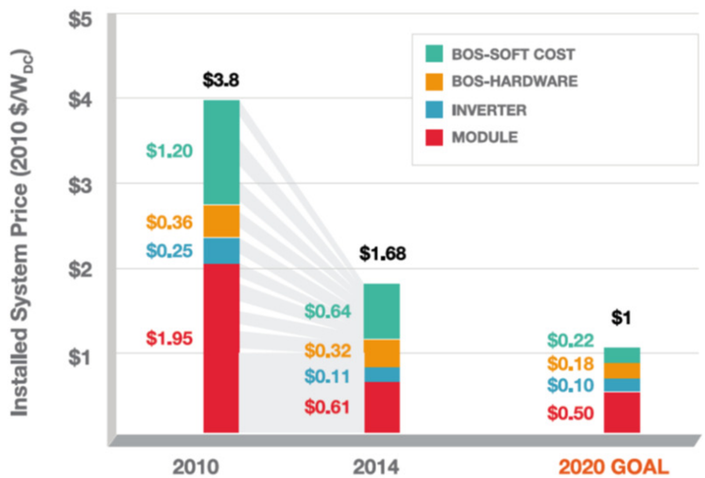


The Future Arrives for Five Clean Energy Technologies – 2016 Update, US DOE
http://energy.gov/eere/downloads/revolutionnow-2016-update

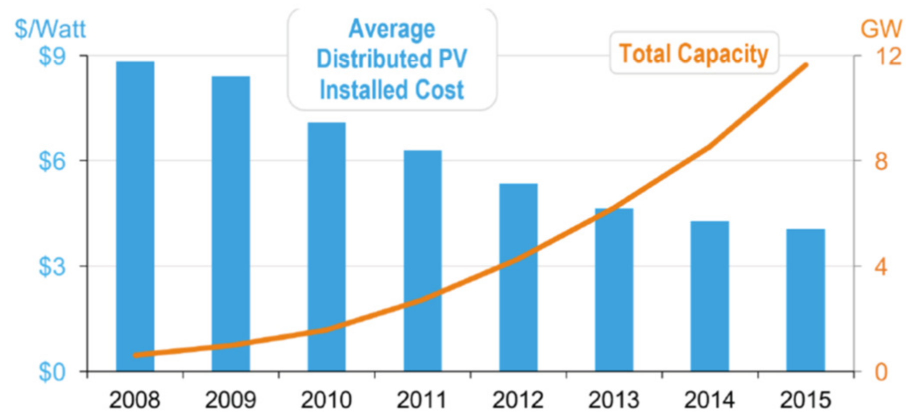
PV Deployments

Solar PV: Utility-Scale





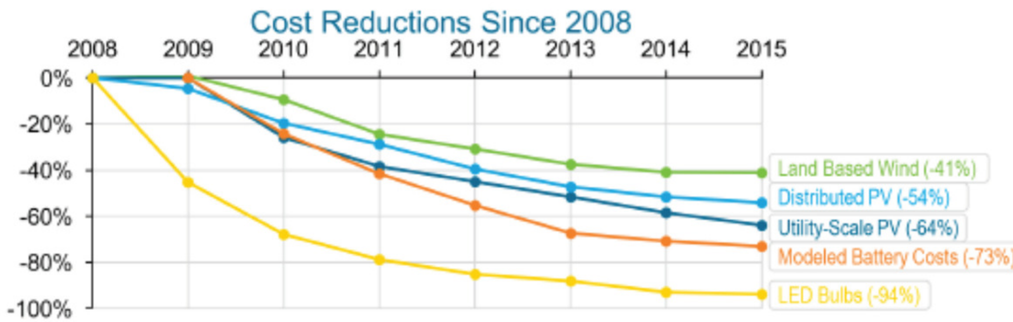
Solar PV: Distributed



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

Cost Reduction through Manufacturing

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



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Technology Cycles – Energy, 50-Year Cycles

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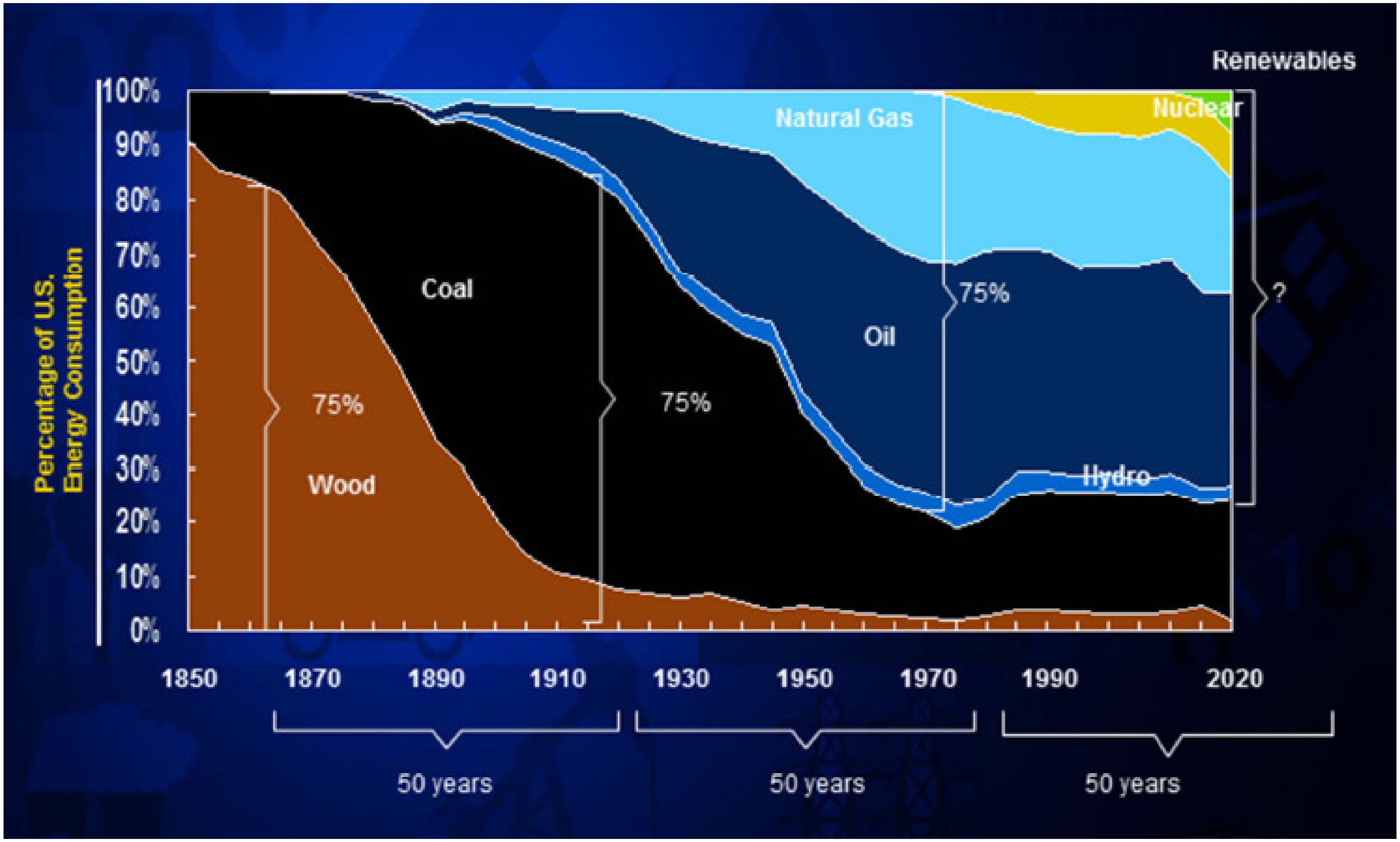

EIA Annual Energy Review 2008

Electricity Infrastructure

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- 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

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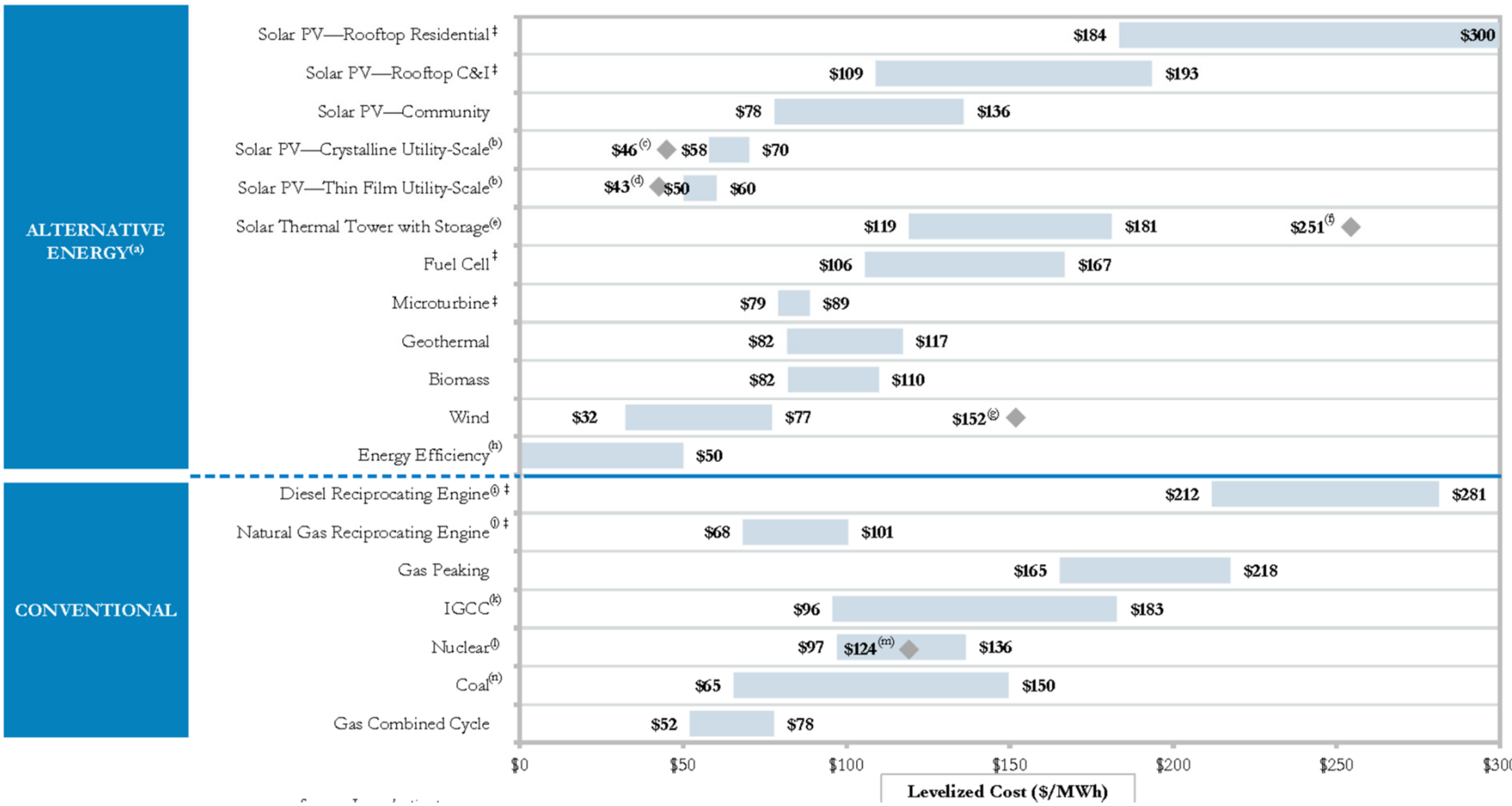

Wind and solar PV have become increasingly cost-competitive with conventional generation technologies on an unsubsidized basis. Data Source: Lazard, 2016

Why Do We Need Energy Storage?

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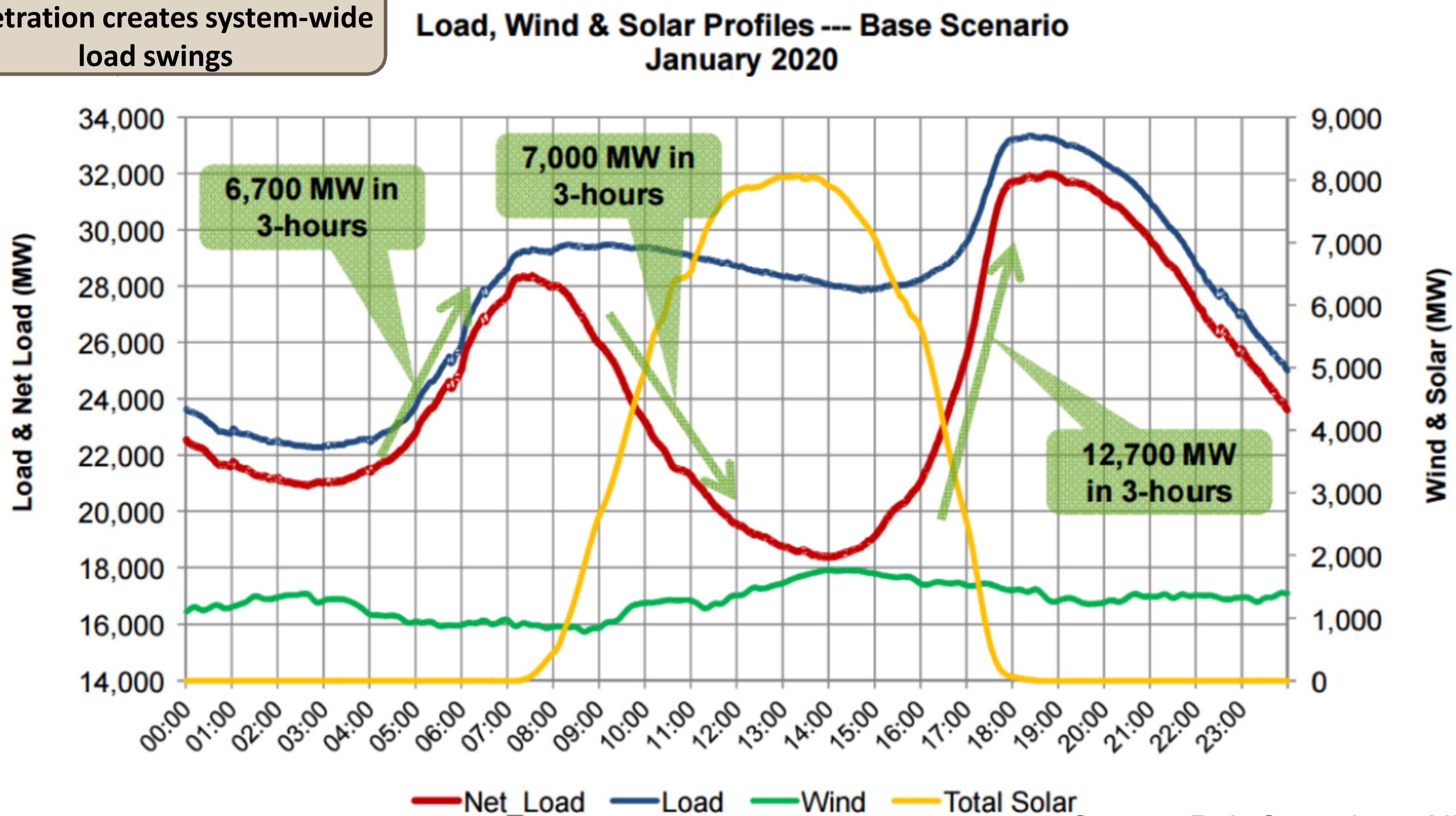
- Application drivers for large scale energy storage
  - Renewable integration
  - Transmission and Distribution upgrade deferral
  - Power quality, e.g., UPS application, microgrids, etc.
  - Improved efficiency of nonrenewable sources (e.g., coal, nuclear)
  - Off-grid applications

Energy storage mediates between variable sources and variable loads

Without storage, energy generation must equal energy consumption

Wind and Solar Load Balancing (CAISO)

Increased renewable penetration creates system-wide load swings



Source: Rob Cummings, NERC, 2

Improved Efficiency of Existing Generation Assets

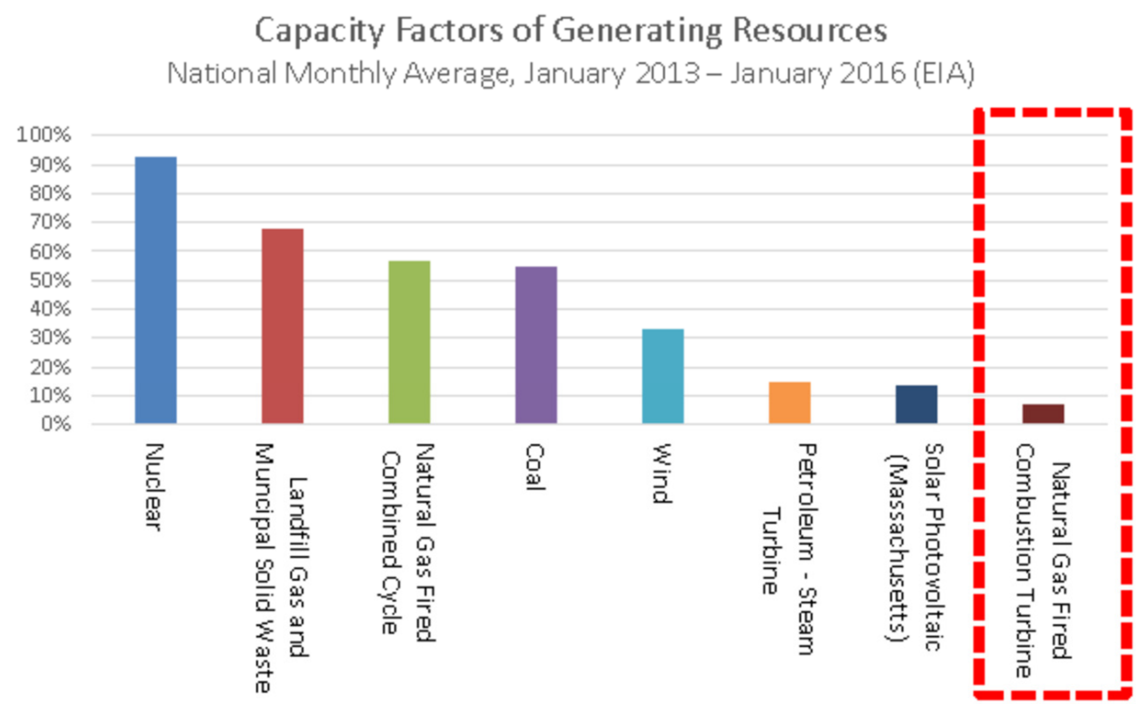


Figure 2-8: Average Monthly Capacity Factors[44]

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

Energy Storage on the Grid Today

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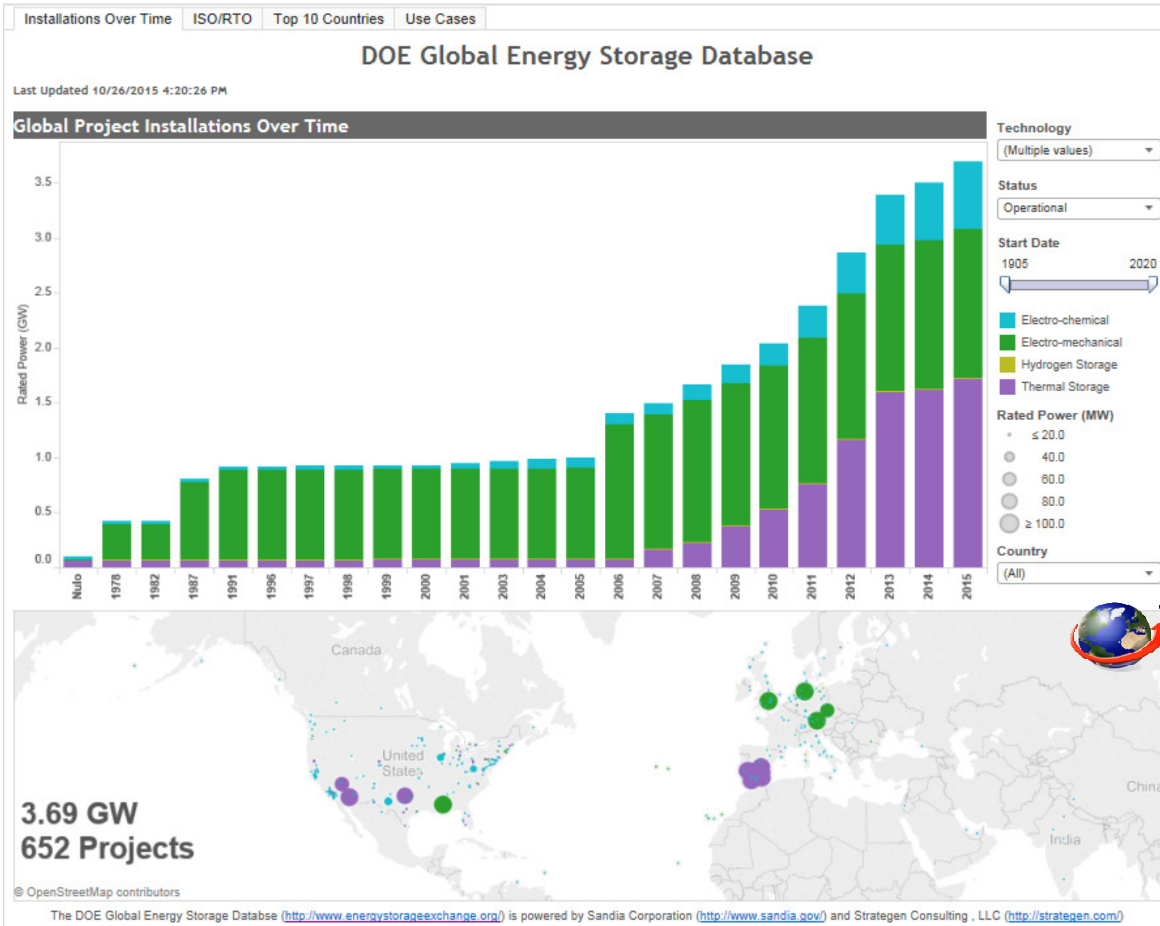
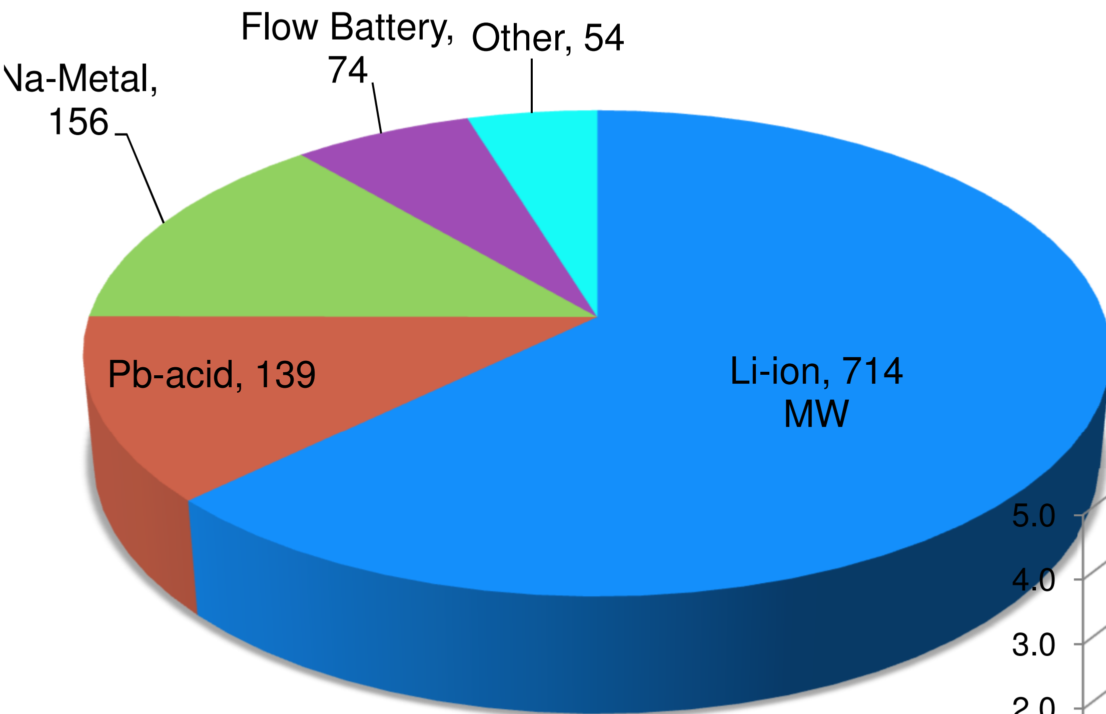


World-wide 2.2%

- Japan 8.9%
- Europe 4.7%
- USA 2.2%

Source: DOE Global Energy Storage Database

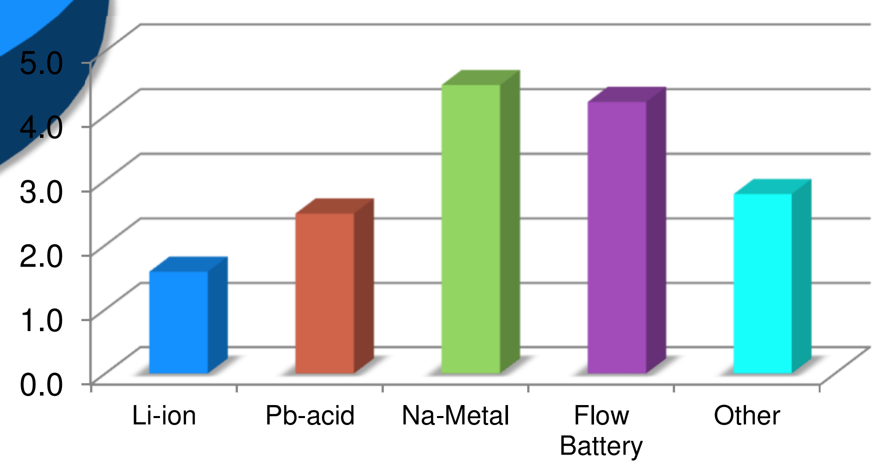
Current Stationary ESS deployments (Battery Only)



~ 1.1 GW of Battery Energy Storage

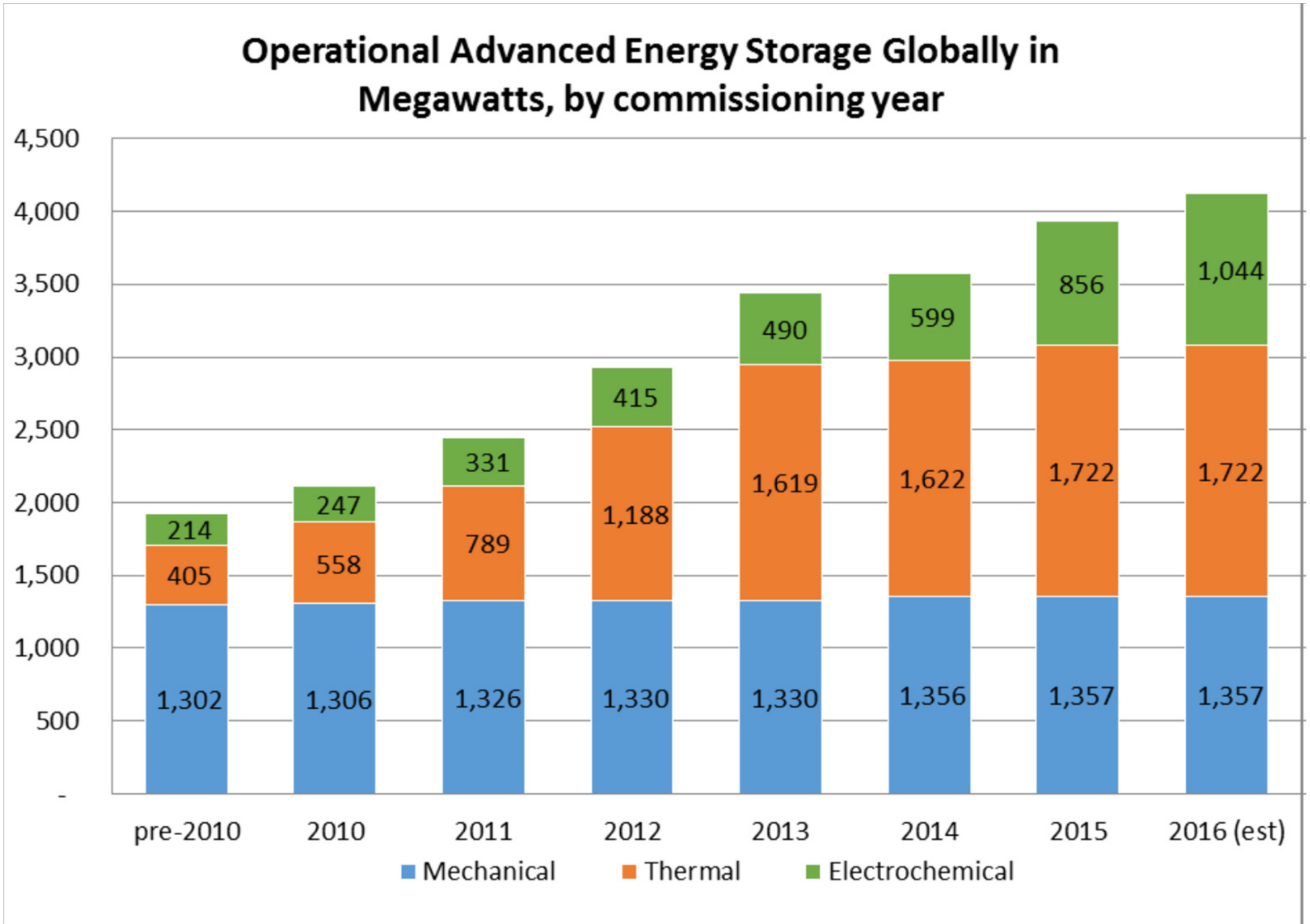
~110 GW of Pumped Hydro

Average Duration (hrs)



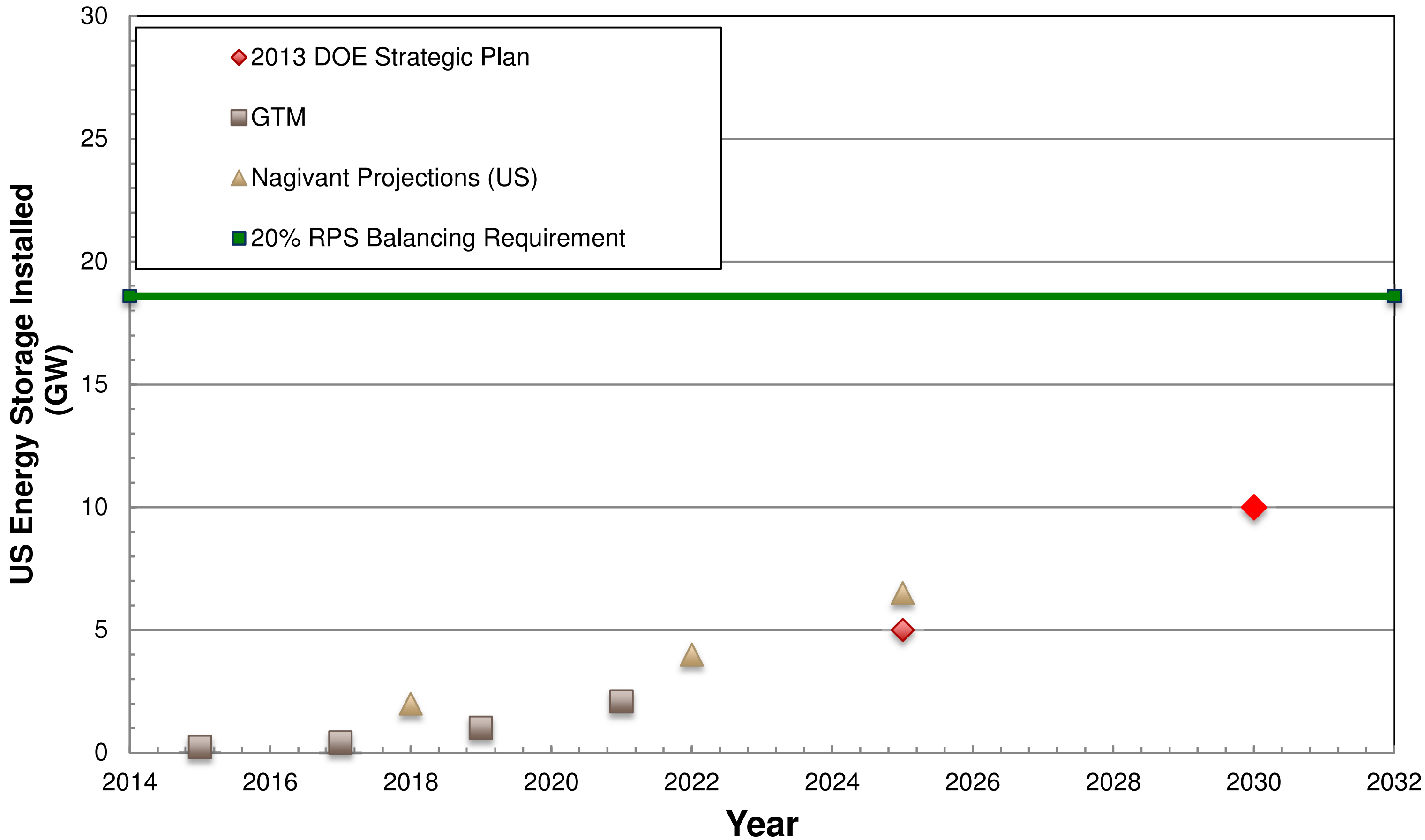
Source: *DOE Global Energy Storage Database*
http://www.energystorageexchange.org/
July 2015

Operational Advanced Energy Storage (MW)



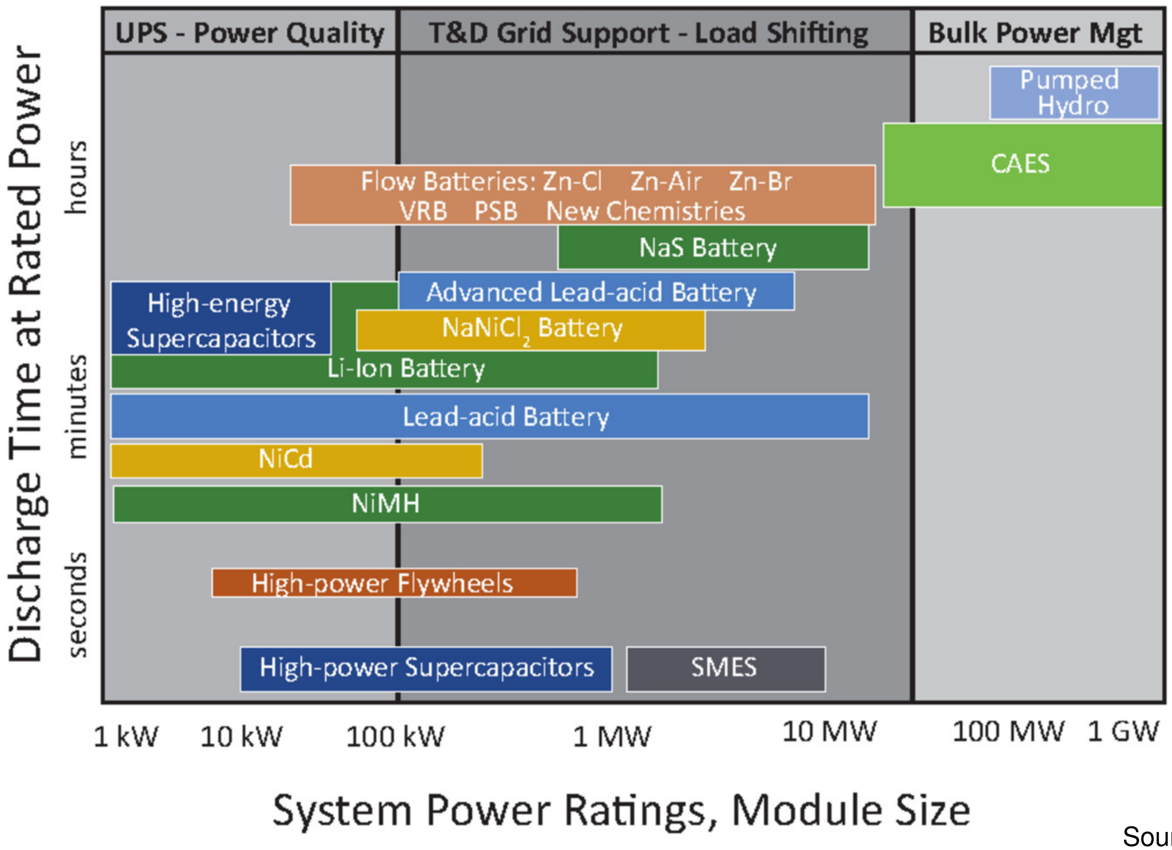
DOE Global Energy Storage Database, March 23, 2016:
www.energystorageexchange.org

How much storage can the grid handle?



US Energy Storage Market Forecasts

Storage Technology and Application Markets

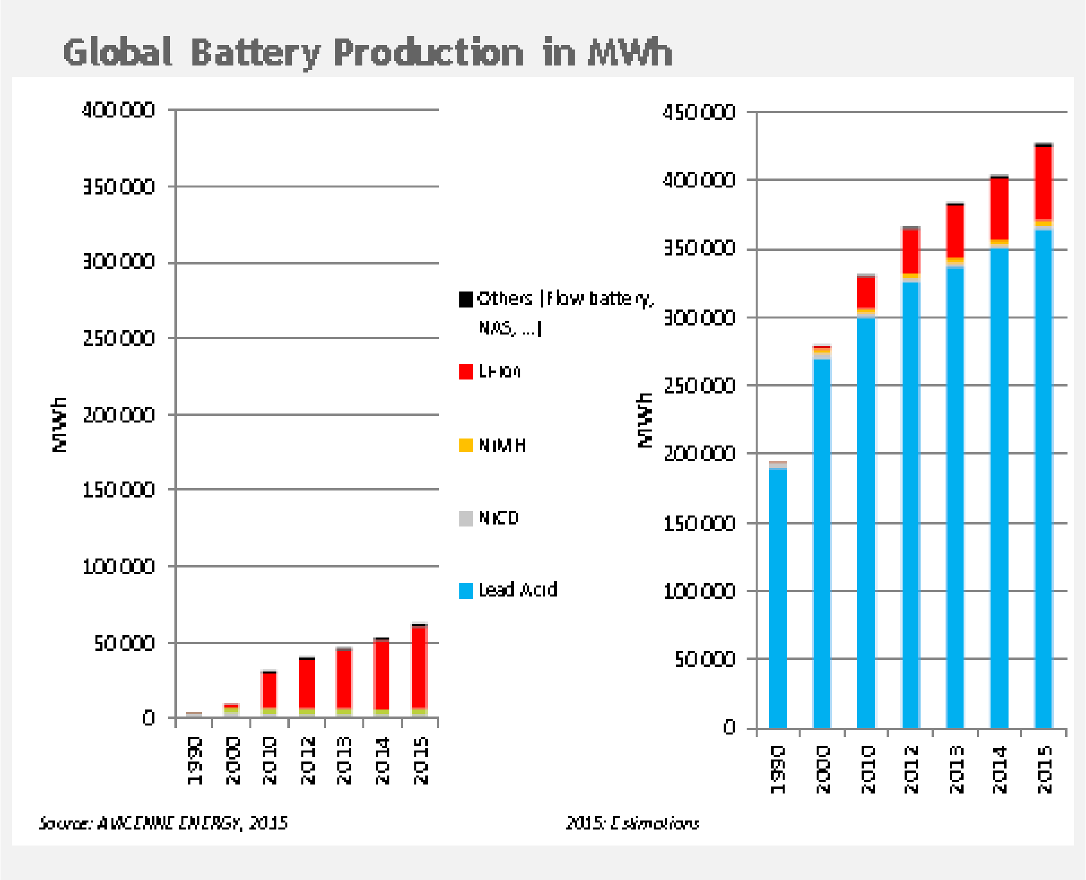


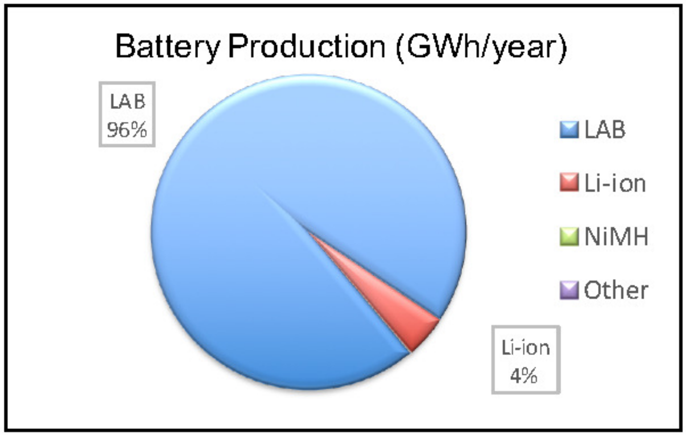
Source: DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, 2013

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

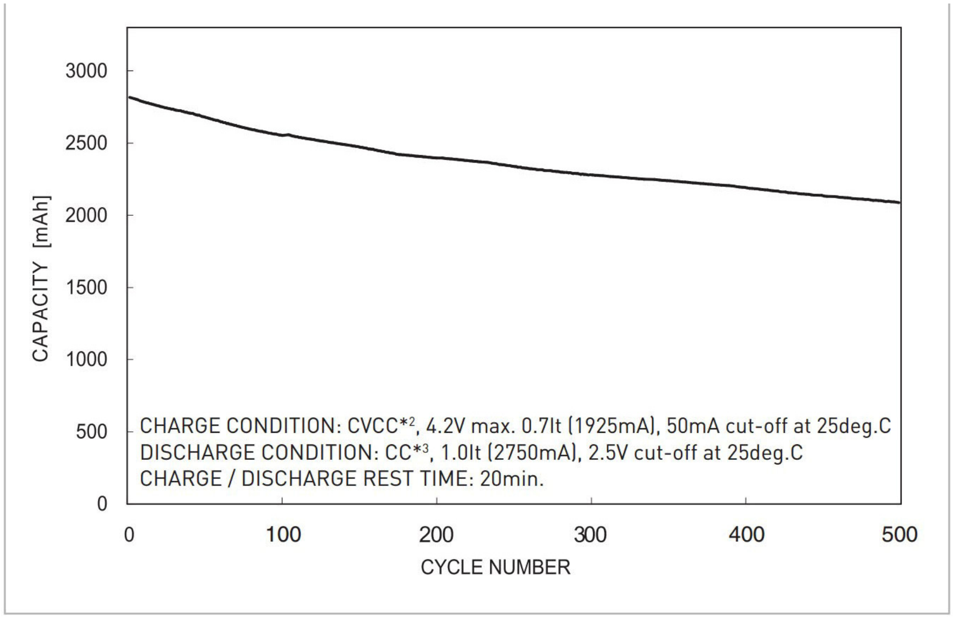




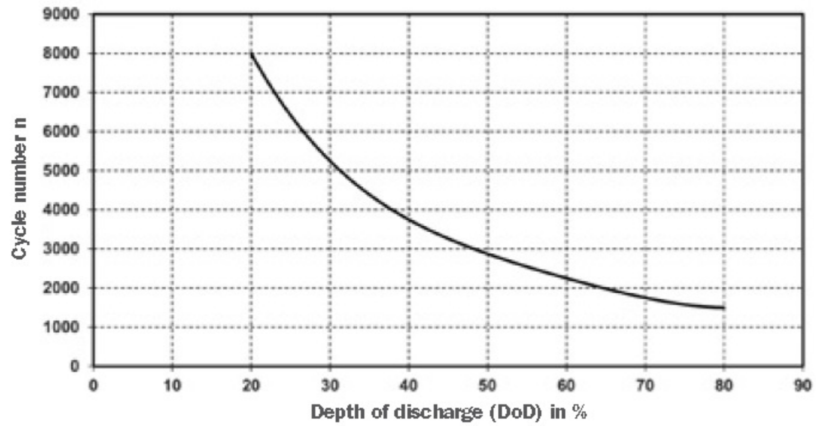
Source: Avicenne (2015), DOE

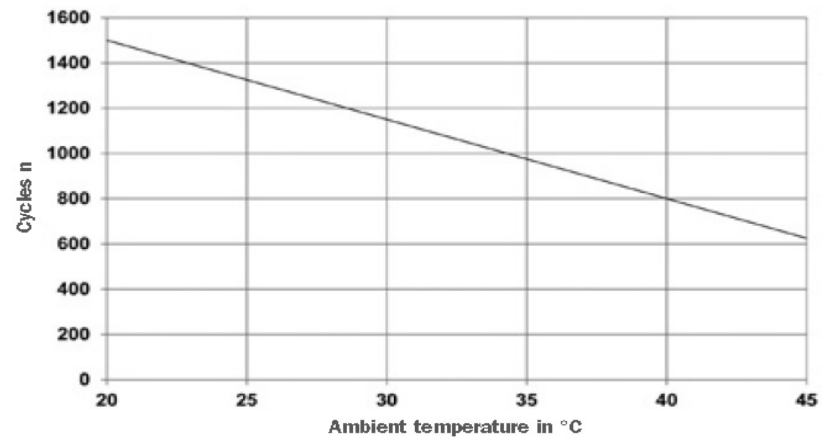
Lead Acid Battery business continues to be highly profitable
Li-ion struggling with low factory utilization rates of ~10-20%

Cycle Life is a Major Challenge



Panasonic NCR18650 cell – cycle life

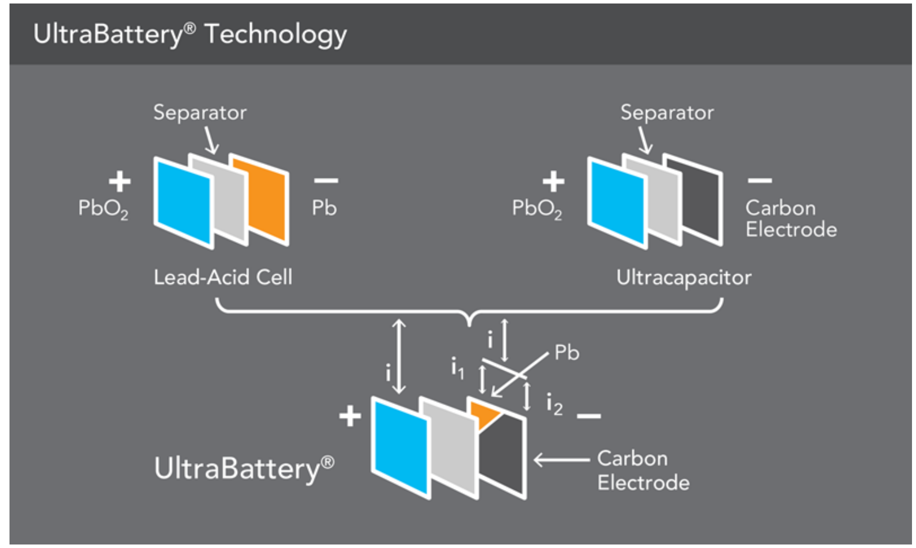




Hoppecke Lead Acid Batteries
Cycle life with DOD and Temperature

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

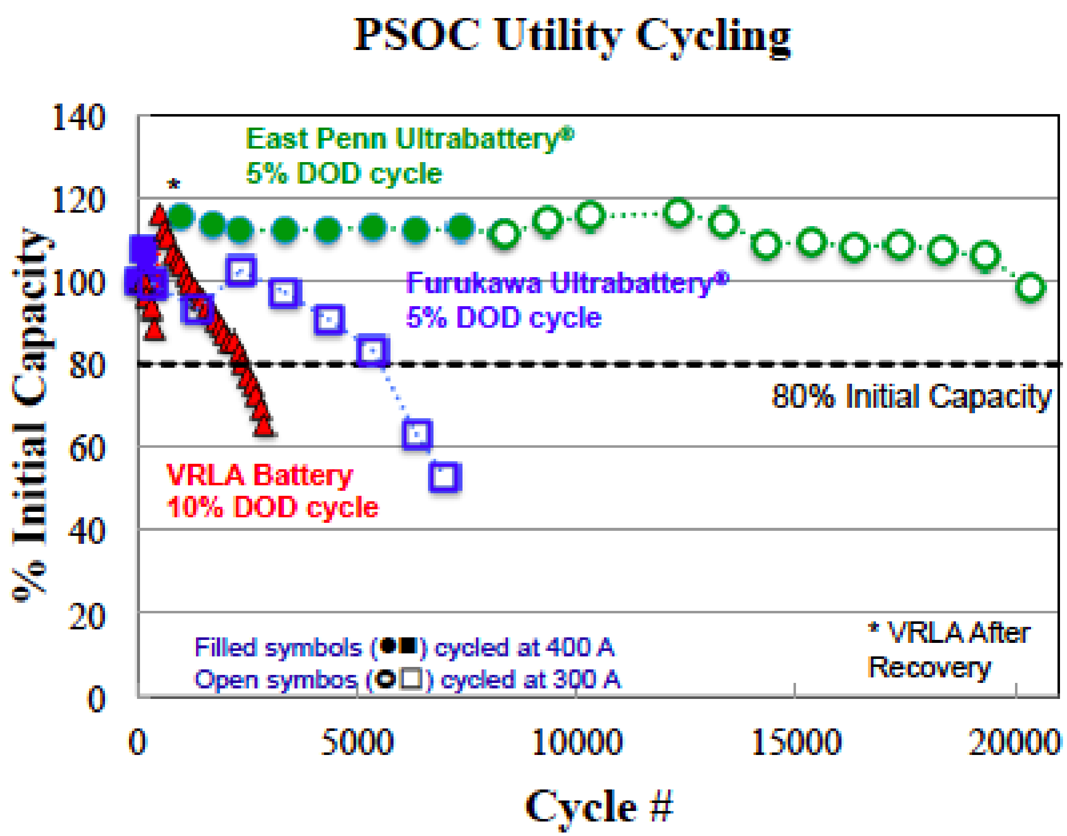


Albuquerque, NM

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, $LiCoO_2$ - 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: Advantages/Issues

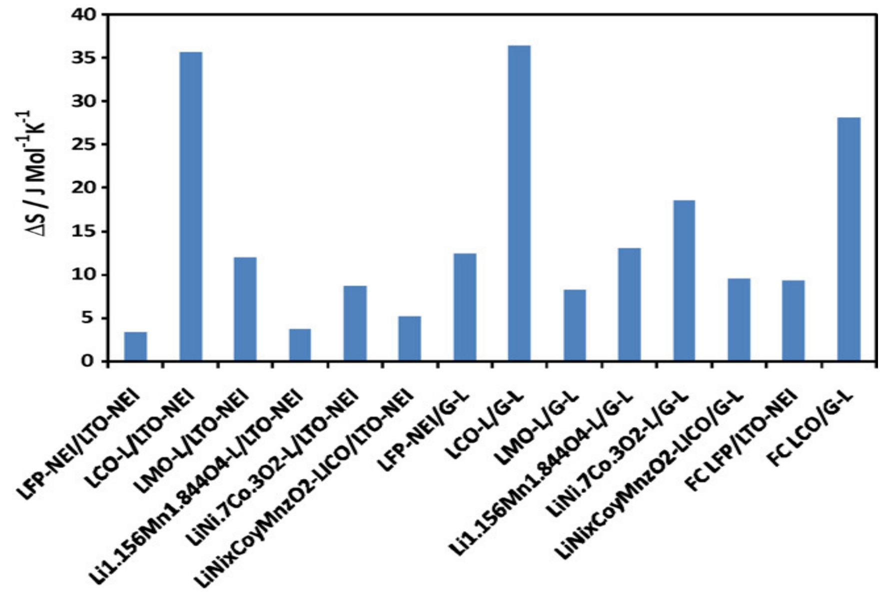
Advantages:

- 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

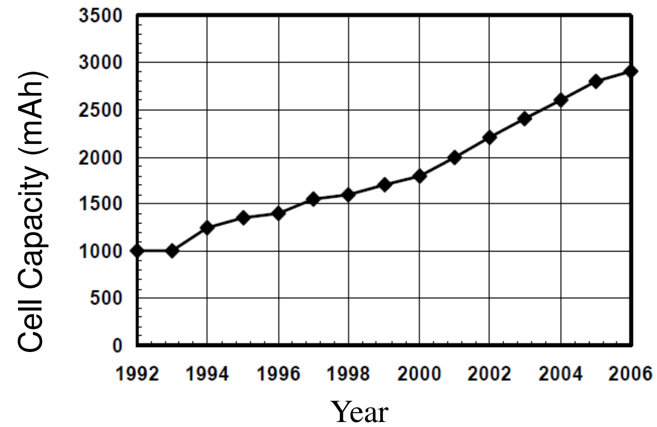


Li-ion Batteries: SOA

- 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

Li-ion – Cycles of Learning

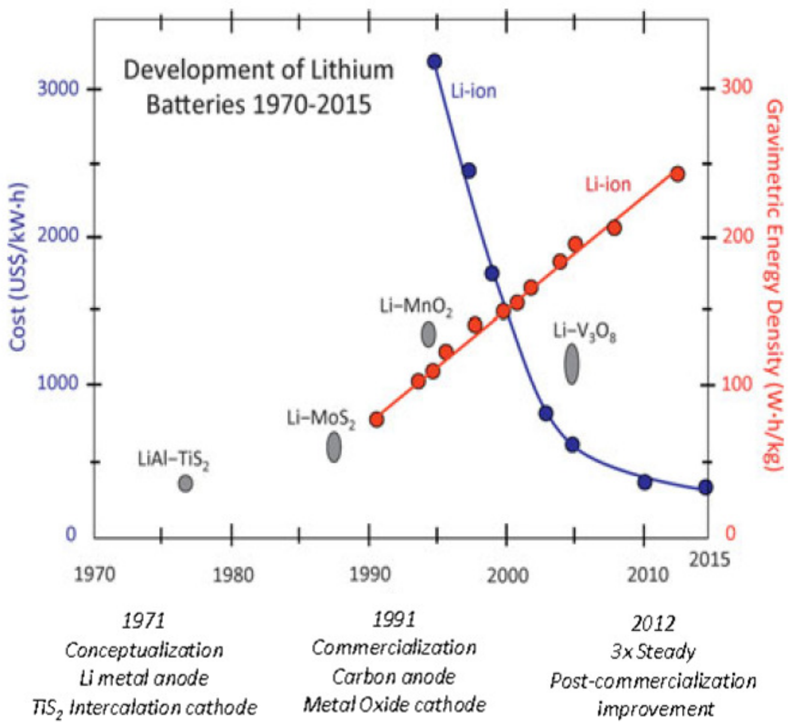
- Capacity improvements are incremental
  - 8% for LIB (1992-2007); 2% for Lead acid
  - Capacity improvements are incremental
- Continued reduction in cost/performance
  - Materials cost can not be scaled down much lower, BOM is 80-85% of cell costs
  - Need significant improvement in electrolytes, 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

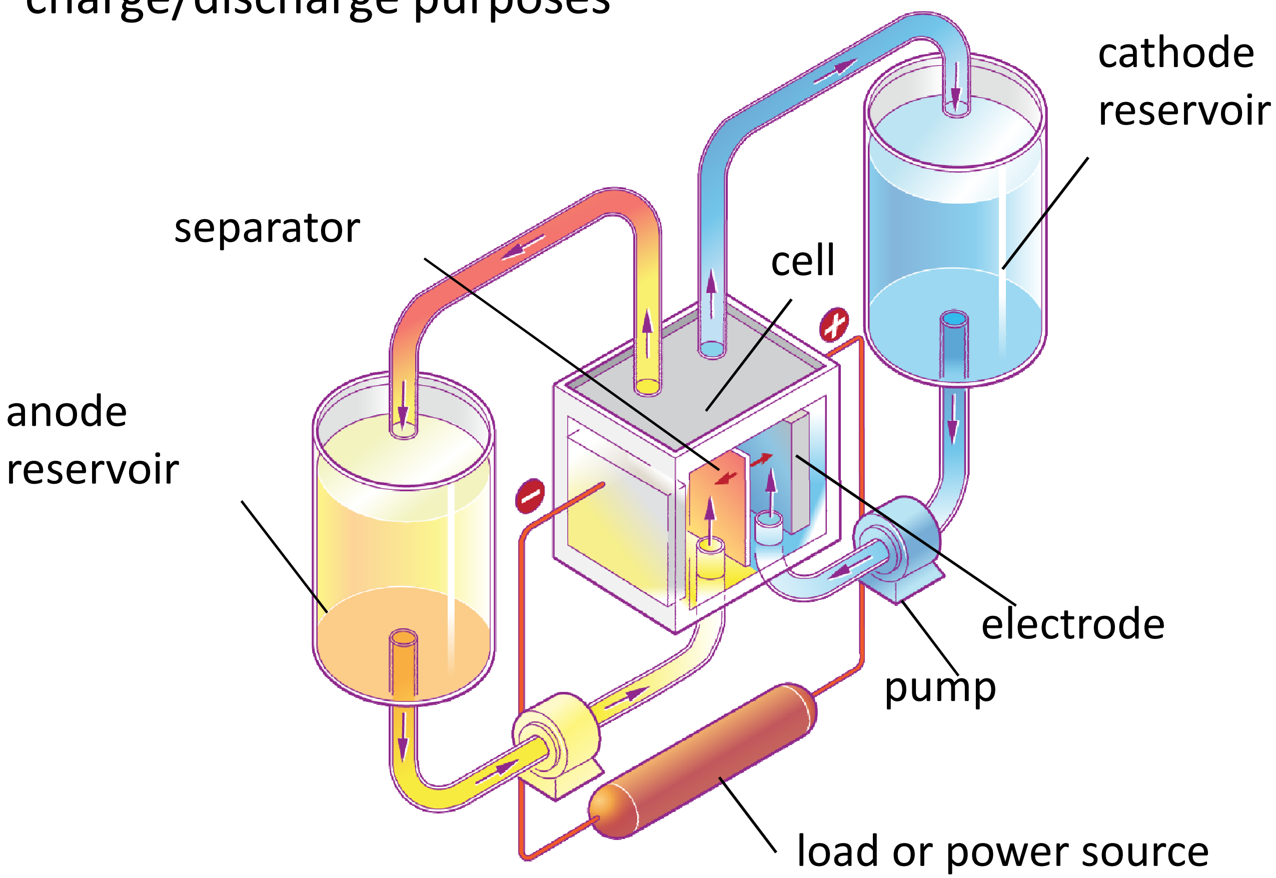
- There is no equivalent of Moore's law in battery technology. Microelectronics scaling laws don't apply. Storage is based on volumetric material properties.
- Major improvements will be based on increased cycle life, reliability, and safety of batteries.

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

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

Flow Batteries

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



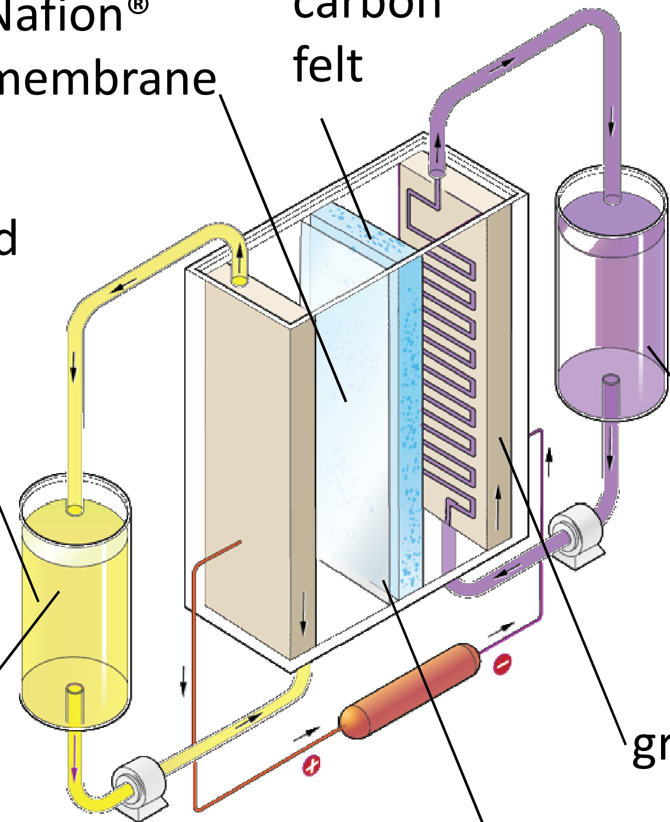
All-Vanadium Battery

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

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

Flow Batteries - SOA

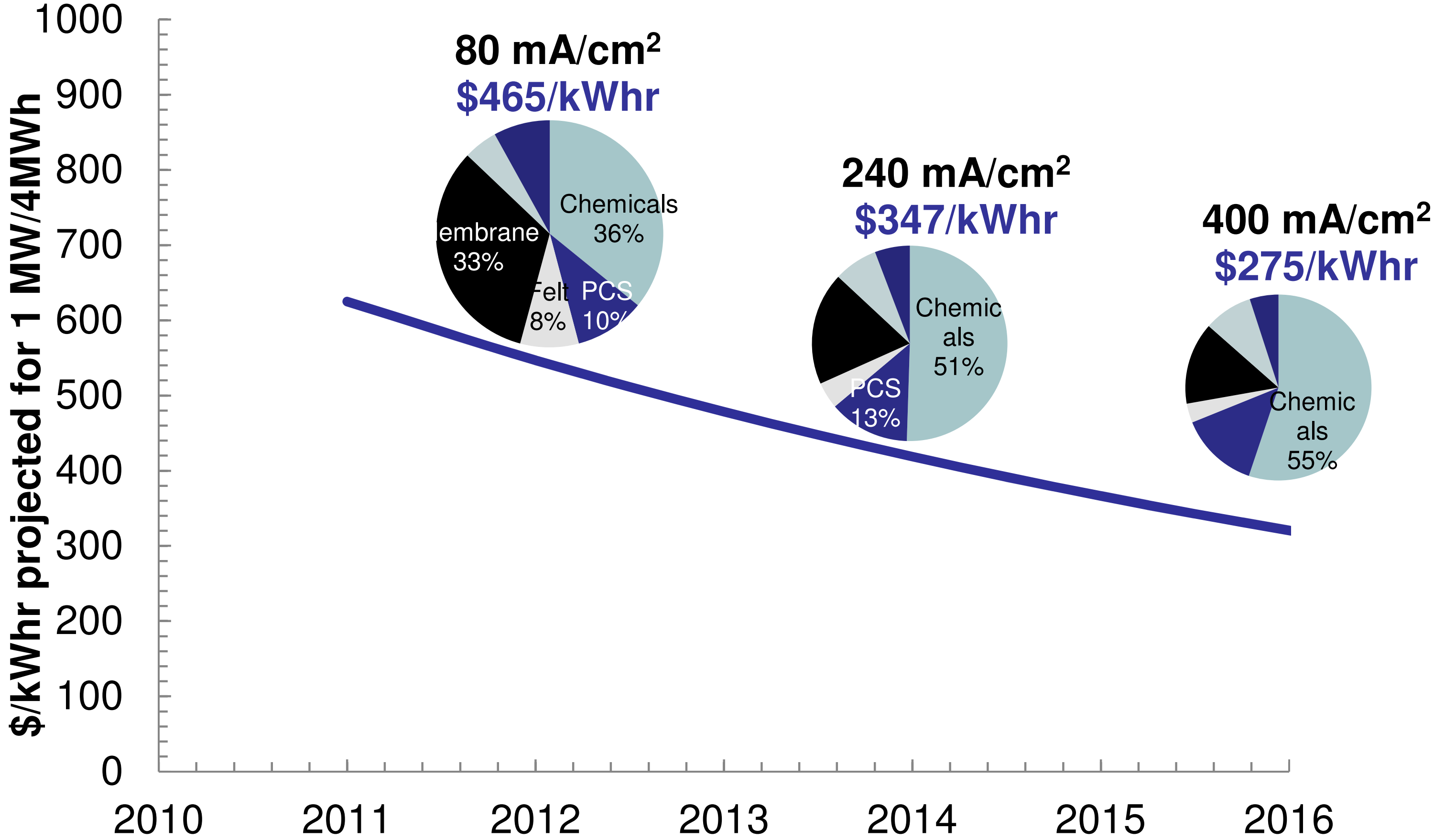
Advantages

- 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

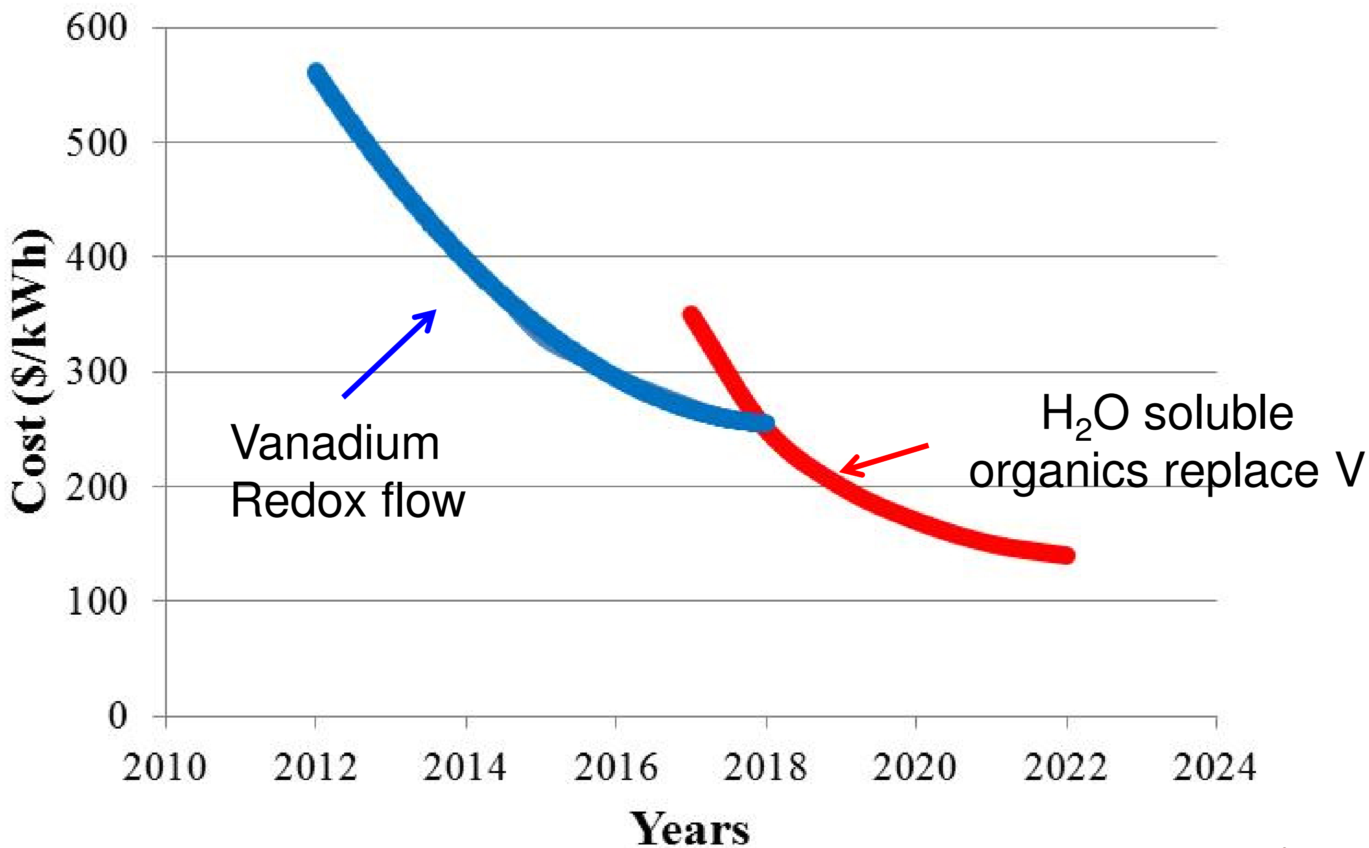
Disadvantages

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

Redox Flow System Component Cost Analysis



Future Redox Battery Development



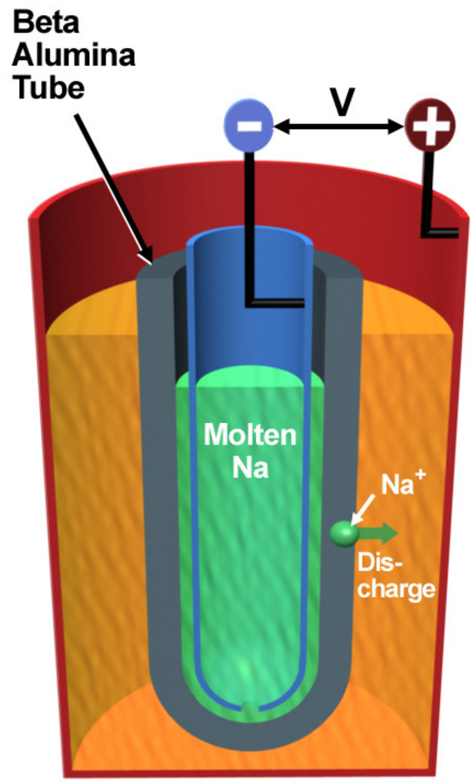
- Utility scale Vanadium flow battery systems approaching $350/kWh. Further reductions in cost requires improved chemistry, lower stack costs.

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

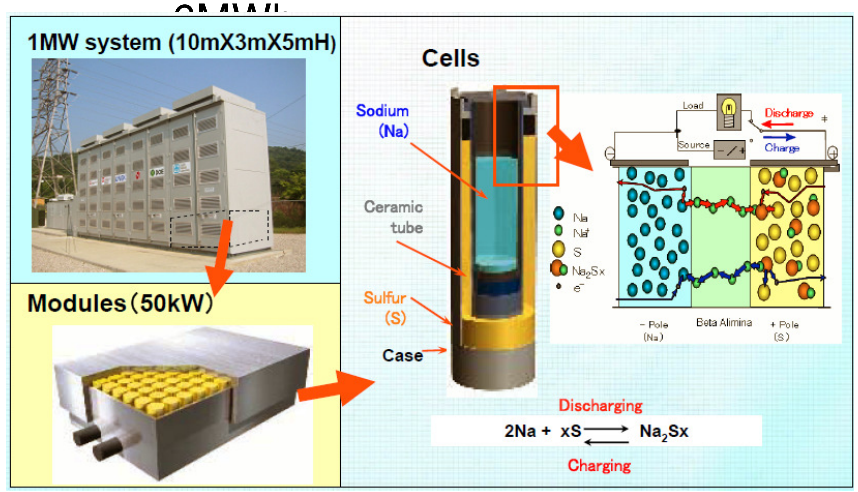
- Batteries consisting of molten sodium anode and β''-Al_2O_3 solid electrolyte (BASE)
  - Low cost starting materials
  - High specific energy density (120~240 Wh/kg)
  - Good specific power (150-230 W/kg)
  - Good candidate for energy applications (4-6 hrs discharge)
  - Operated at relatively high 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

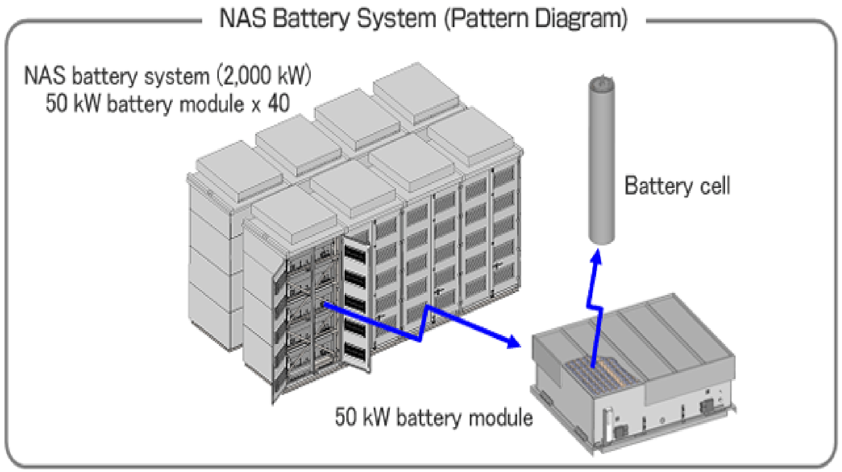
Los Alamos, NM. 1 MW,

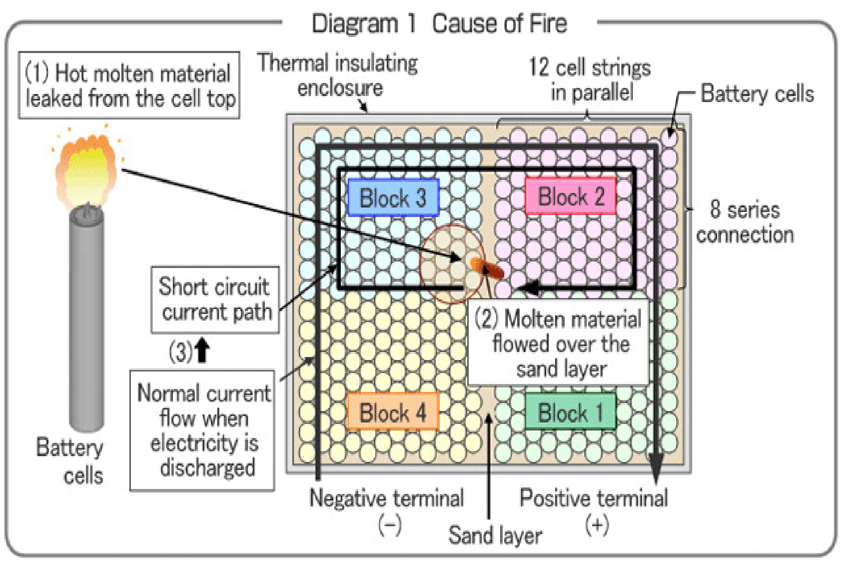


Source: NGK

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



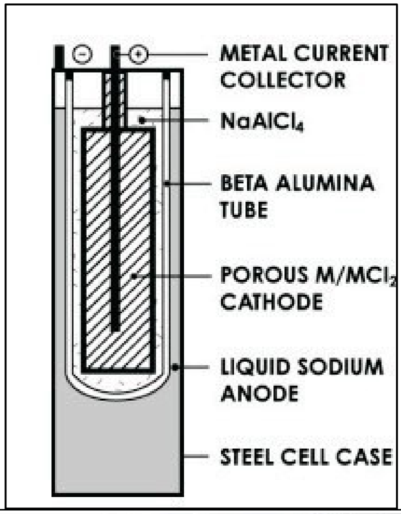


Na-Metal Batteries: Advantages/Issues

- **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

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- Low temperature, safe, nonflammable alternatives to Na-S batteries.
- Enabled by low to intermediate temperature (<200^{o}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: $Na + \frac{1}{2} Br_2 \leftrightarrow Na^+ + Br^-$
- Sodium-iodine: $Na + \frac{1}{2} I_2 \leftrightarrow Na^+ + I^-$
- Sodium-nickel chloride: $Na + \frac{1}{2} NiCl_2 \leftrightarrow Na^+ + Cl^- + Ni(s)$
- Sodium-copper iodide: $Na + CuI_2^- \leftrightarrow Na^+ + 2I^- + Cu(s)$

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

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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

Year	Event
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-MnO2 Rechargeable

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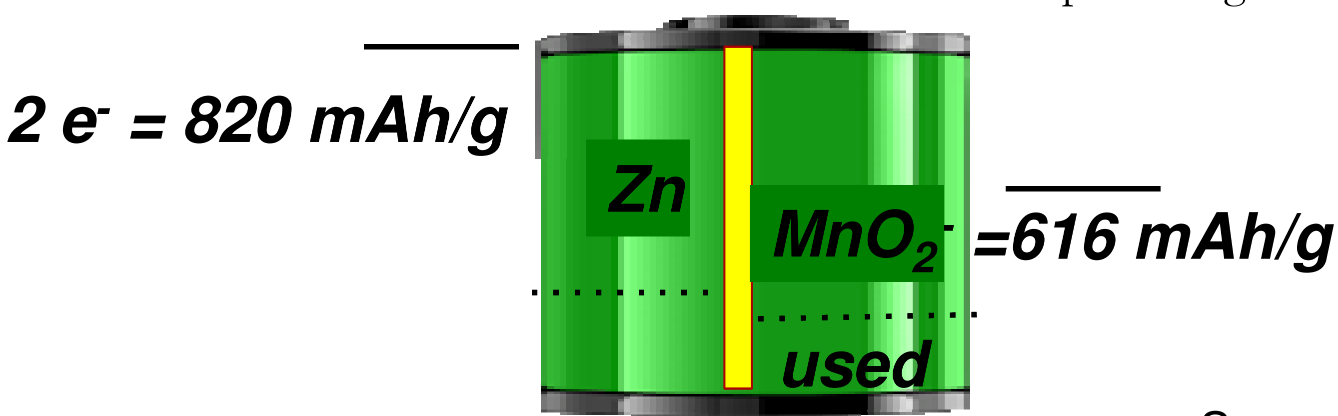
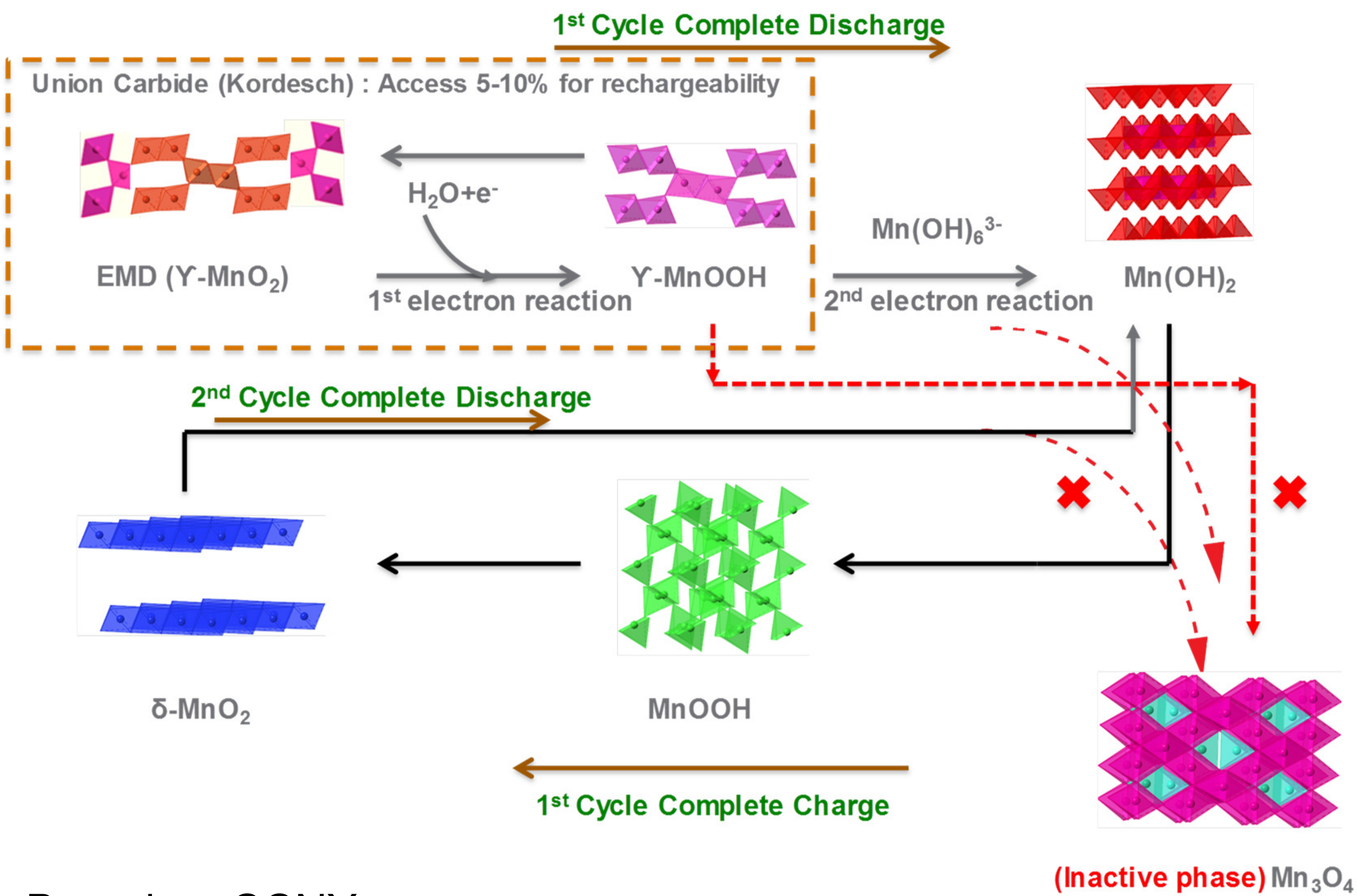
- Anode issues
  - < 10% of total capacity is used
  - Shape Changes
  - Passivation
  - Dendrite Formation
- Cathode issues
  - Only 5-10% of total capacity is used
  - Crystal Structure Breakdown
  - Inactive Phase(s) formed
  - Zinc poisoning



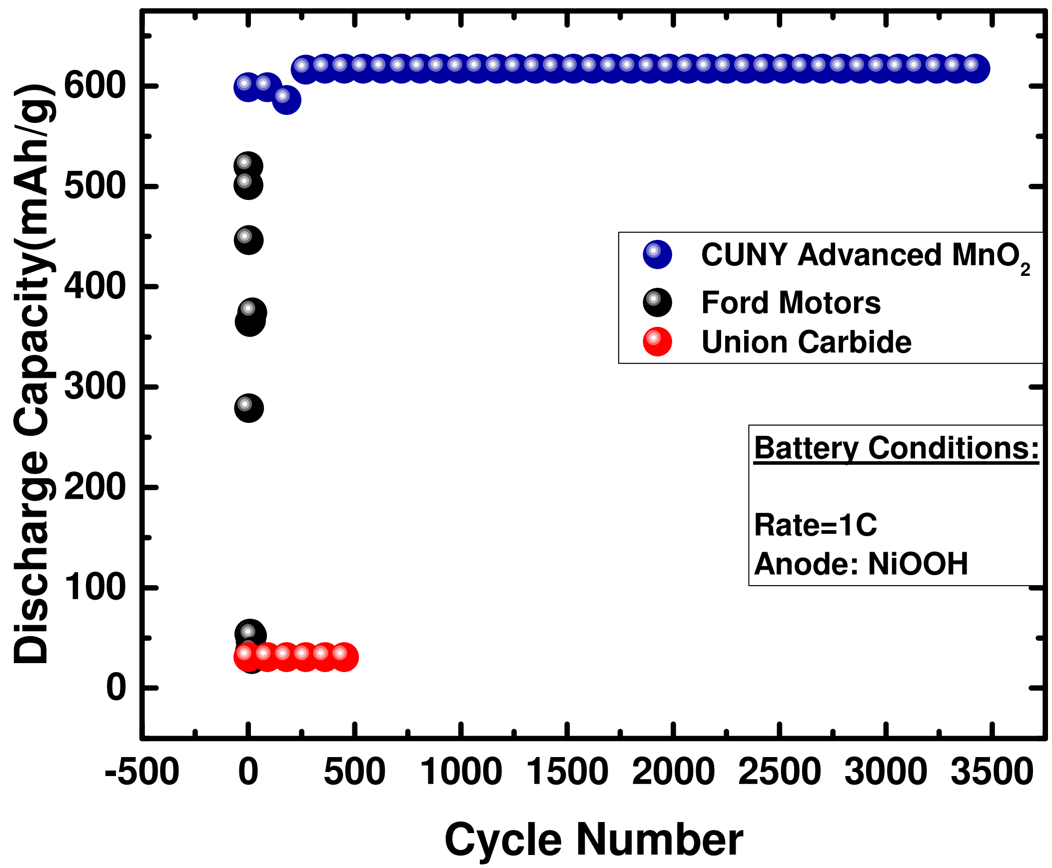
Source: S. Banerjee, CC

MnO_2 Reaction Mechanisms



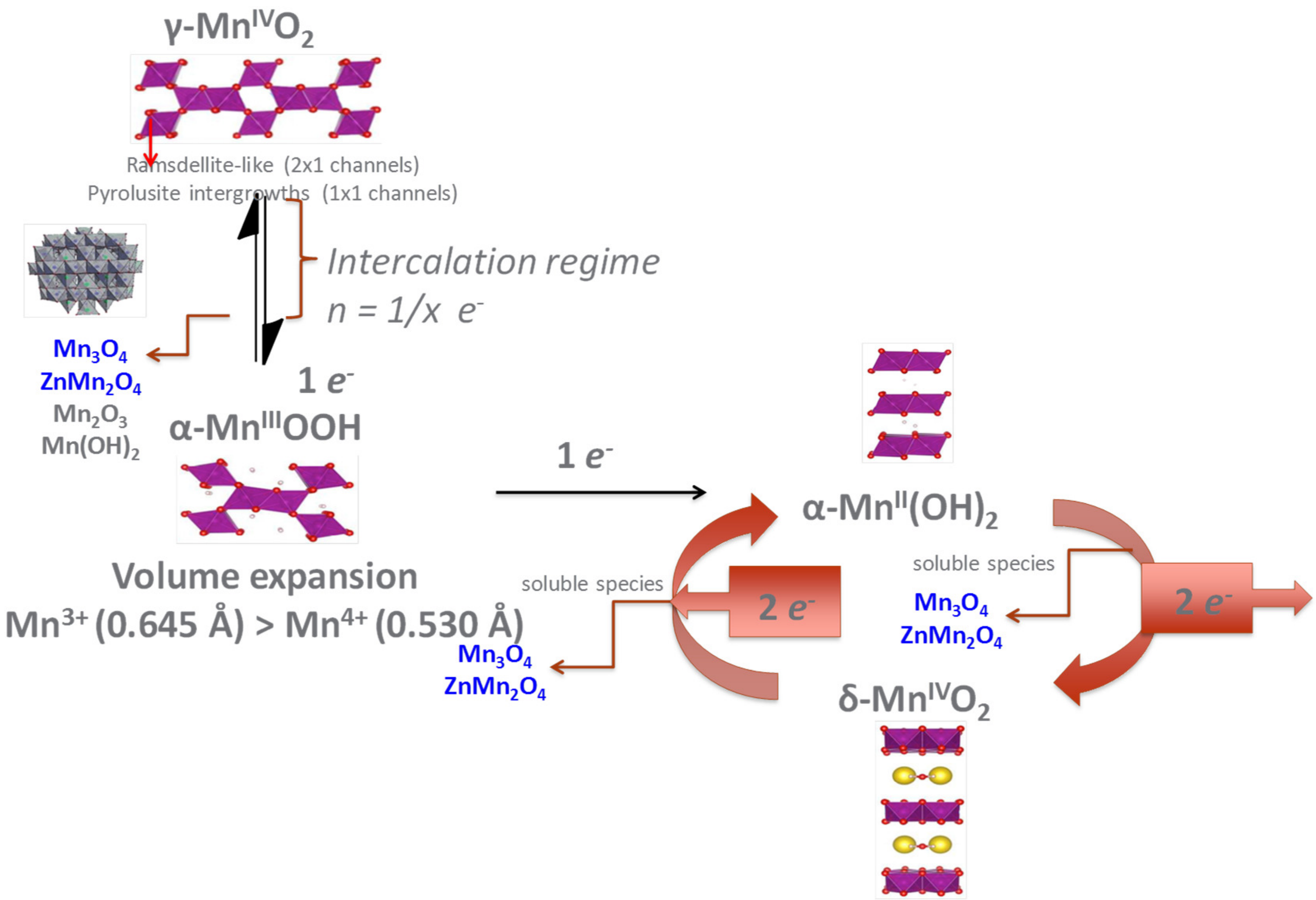
Source: S. Banerjee, CCNY

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 l
- Applications
  - Power quality
  - Frequency regulation
  - Regenerative braking (vehicles)
- Challeng
  - Cost

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

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

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

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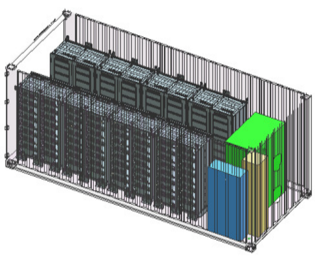
Storage

- Cell
- Battery Management & Protection
- Racking



Integration

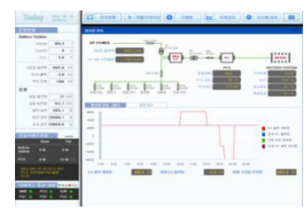
- Container / Housing
- Wiring
- Climate control

PCS

- Bi-directional Inverter
- Switchgear
- Transformer
- Skid

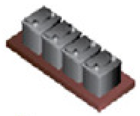
EMS

- Charge / Discharge
- Load Management
- Ramp rate control
- Grid Stability

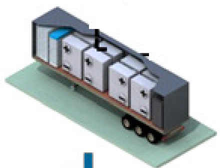


We need cost reductions across all areas, not just batteries

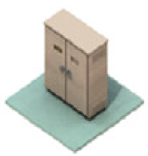
Cost Structure of Storage System in 2016



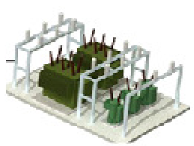
Storage Racks+BMS



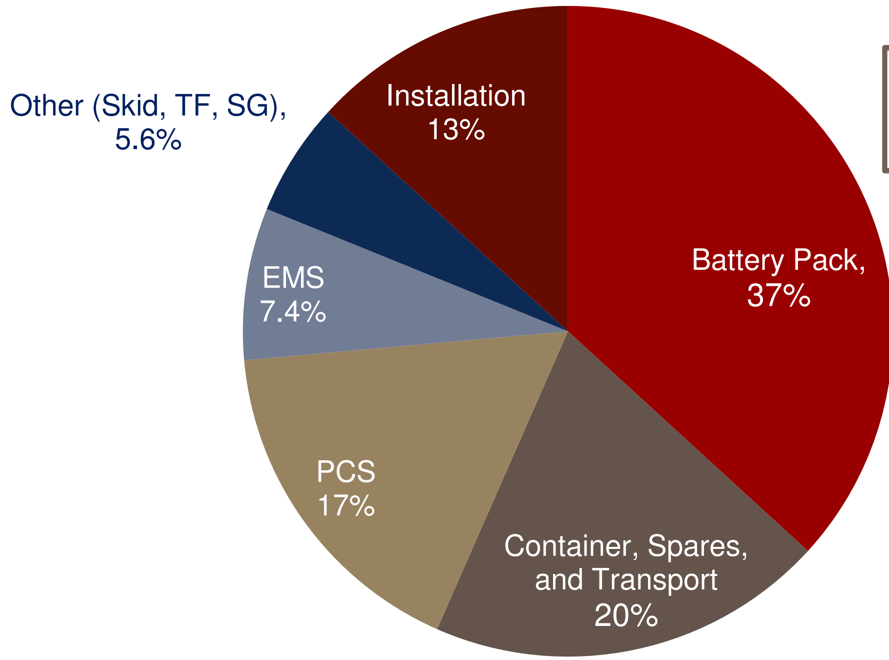
Product Integration



Power Conditioning (PCS)



Field EPC Grid Integration



1MW/1MWh LIB ESS

Data: Multiple industry source

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 (#)

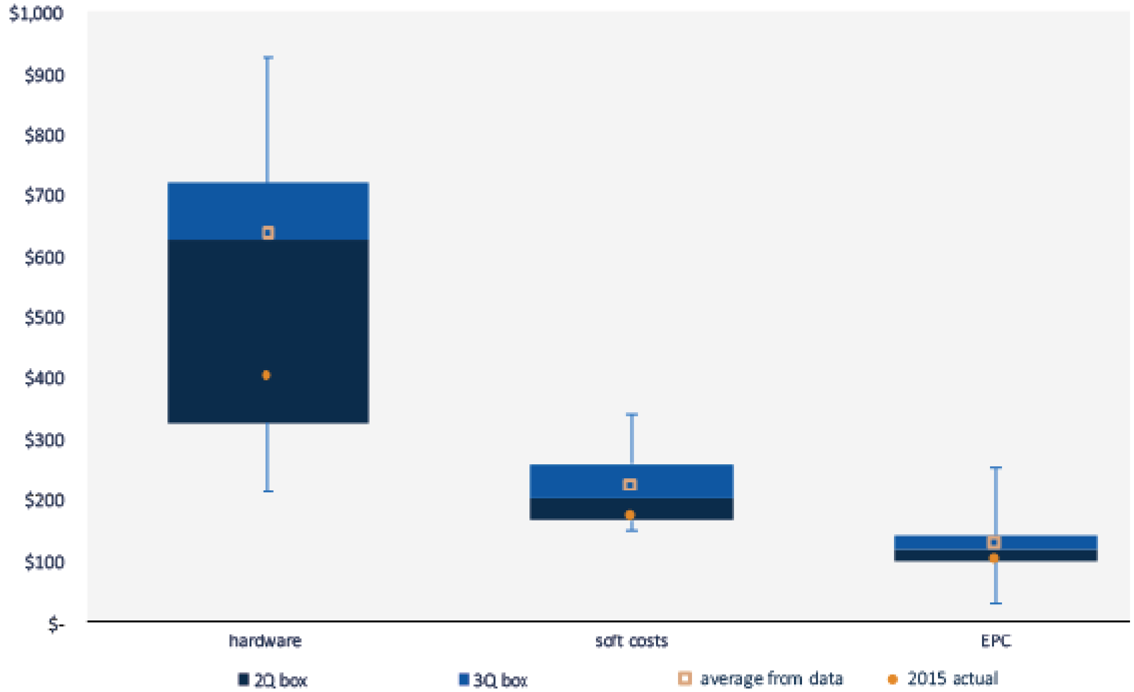
PCS/BOS
- Power Electronics
  $/kW
- BOS (Container, Safety, Thermal Management)

Softcosts
- Interconnection
- Permits
- O&M

Battery to a Storage System: doubling in cost

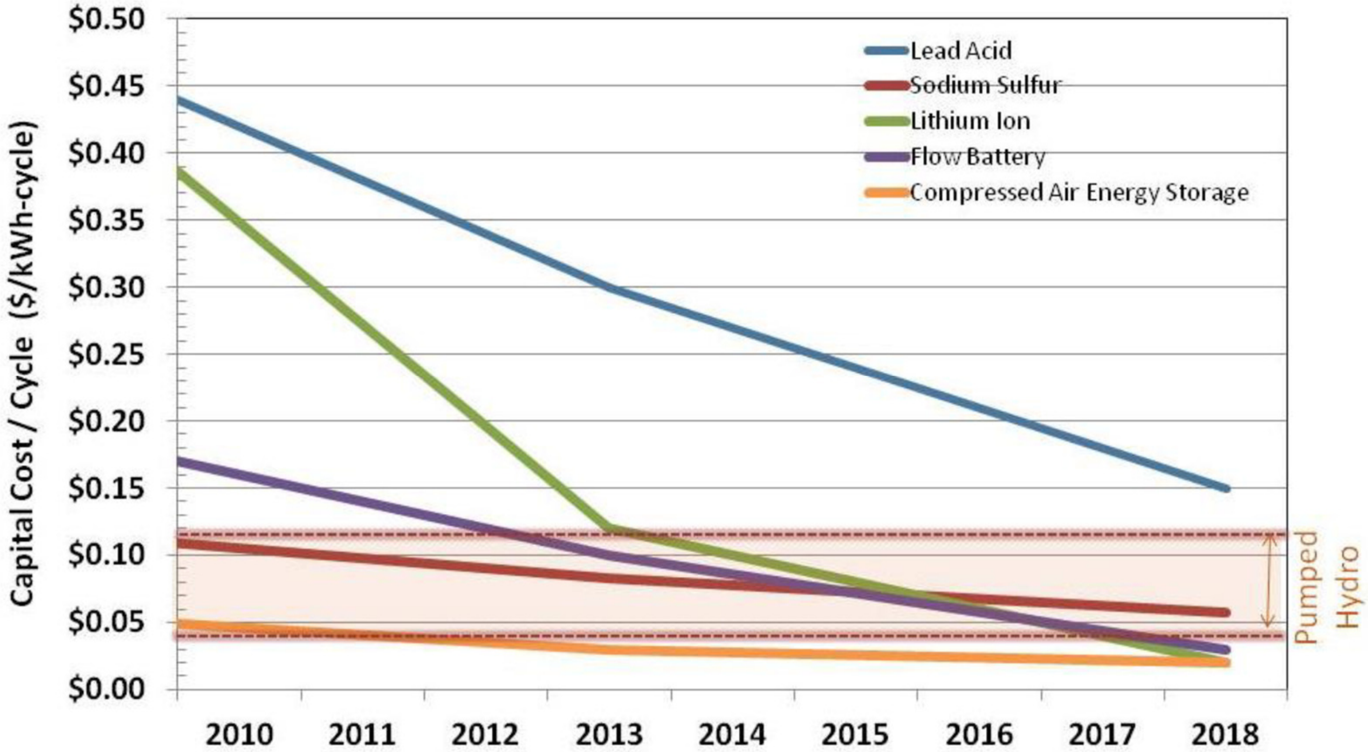
$500/kWh battery ⇨ $1000/kWh Storage System

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 Competitive

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- 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.

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

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

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

Modest improvements

Making storage cost competetive

- 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

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 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

Impact and Consequence of Scale on Safety

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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

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

Materials R&D for Energy Storage System Safety

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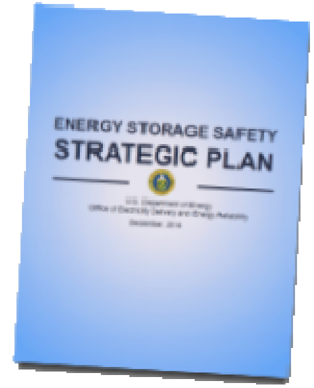
- Major research areas
  - Materials origin of safety and reliability
  - Device level failures
  - Cascading failures
- Advanced simulation and modeling of energy storage systems
  - Further
    - Software's role as a critical safety system
    - Better control of cell behavior through power electronics

Key Takeaways…

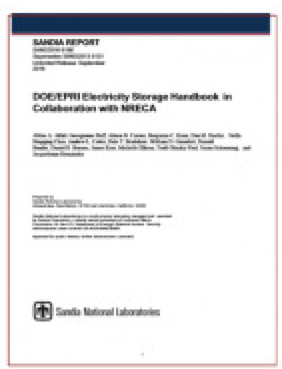
- **We will need much, much more storage on our grid** to increase grid resiliency and accommodate renewables
- Currently, the entire storage system (batteries to interconnection) is too expensive.
- Advances in several areas will make grid-based storage systems safer, more reliable, and cost-effective
  - 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
Unlimited Release
Printed February 2010
Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide
A Study for the DOE Energy Storage Systems Program
Jim Eyer
Garth Corey
Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550



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