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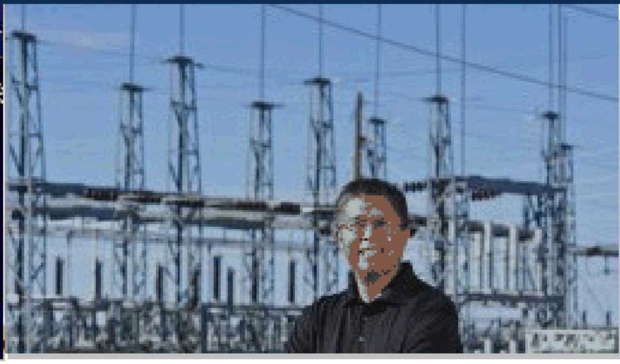

Batteries and Energy Storage: Present and Technology Directions

Babu Chalamala, Ph.D.

Alaska Rural Energy Conference, April 10, 2018

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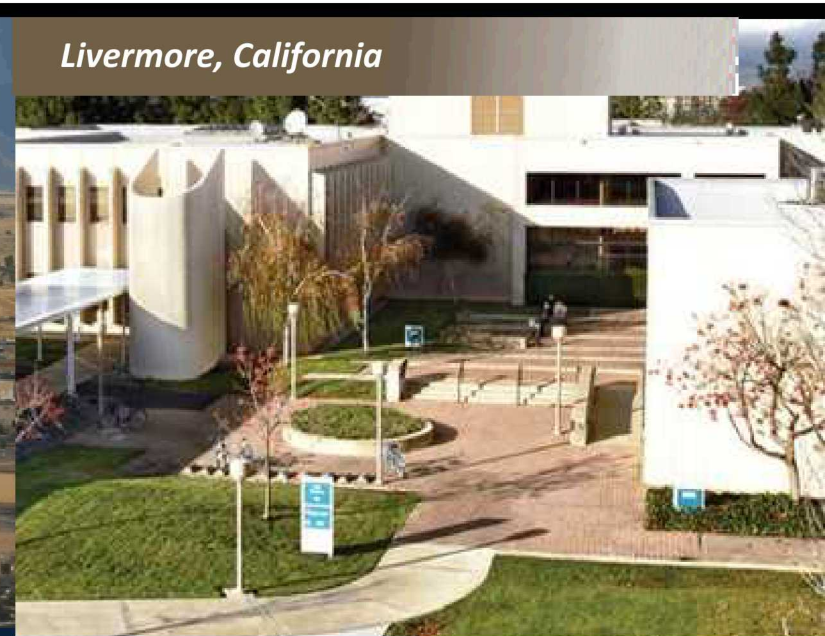
Albuquerque, New Mexico



Livermore, California

Kauai, Hawaii

Waste Isolation Pilot Plant, Carlsbad, New Mexico

Pantex Plant, Amarillo, Texas

Tonopah, Nevada

Batteries and Energy Storage - Drivers

- Enabling electrification of transportation
  - Need energy storage systems with higher energy and power densities
  - Improvements in costs, cycle life, safety and reliability
  - Lighter and faster recharge times

- Transformation of the electricity infrastructure
  - Aging infrastructure, energy storage can improve grid reliability and resiliency
  - Growth of renewables and distributed energy needs energy storage
  - Large T&D infrastructure deferrals
  - Need lower costs, systems scalable from kWh to 100's of MWh
  - Long cycle life and low operating costs

Rechargeable Batteries – Industry Status

Mature Technologies				
	World Wide Capacity (GWh/y)	**Cost and Performance Improvements**	**Key Challenges for Energy Storage**	**Major Suppliers**
Lead Acid Batteries (LAB)	350	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, BAE, Exide, Hagen, Amara Raja
Lithium Ion Batteries (LIB)	100	8%/year (20 year data). Cell level price reaching $200/kWh	Cycle life for deep discharge. Safety. Thermal management	Samsung, LG Chem, Panasonic/Tesla, Saft, BYD, GS Yuesa, Lishen, JCI, Toshiba, CATL
Emerging Technologies				
NaS and NaNiCl	300 MWh	No economies of scale	High temperature chemistry. Safely, Cost	NGK, 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, Gildenmeister
Alkaline chemistries (Zn-MnO2,..)	<100 MWh	Not fully mature. Lowest cost BOM	Has not reached manufacturing scale.	UEP, Fluidic Energy

Examples of recent installations

SD G&E 30 MW/120 MWh Li-ion Battery
Escondido, CA

3 MW/3 MWh Ultrabattery
East Lyons, PA

100kW/400kWh Flow Battery
EPB, Chattanooga, TN

SCE 20MW/80MWh Li-ion Battery
Mira Loma, CA

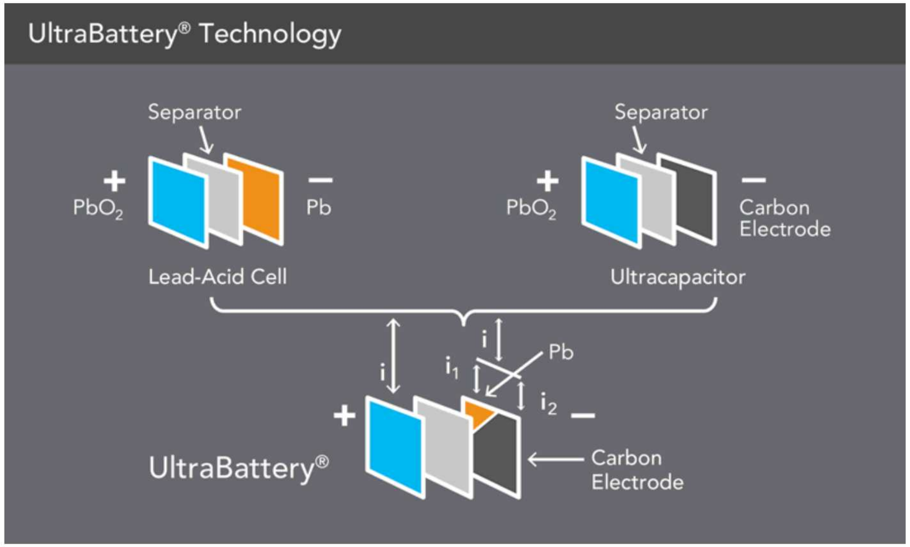
NGK 34MW/245 MWh NaS
Rokkasho, Japan

AVISTA 1 MW/3.2 MWh Flow Battery
Pullman, WA

DOE Global Energy Storage Database, 2017

Lead Acid Batteries

- Advanced Lead Acid Energy Storage
  - A number of companies including Ecoult/East Penn; BAE producing advanced lead acid batteries
  - Carbon plates significantly improve performance
  - Mature technology
  - High recycled content
  - Good battery life
- Applications
  - Load leveling
  - Frequency regulation
  - Grid stabilization
- Challenges
  - Low energy density
  - Limited depth of discharge
  - Large footprint

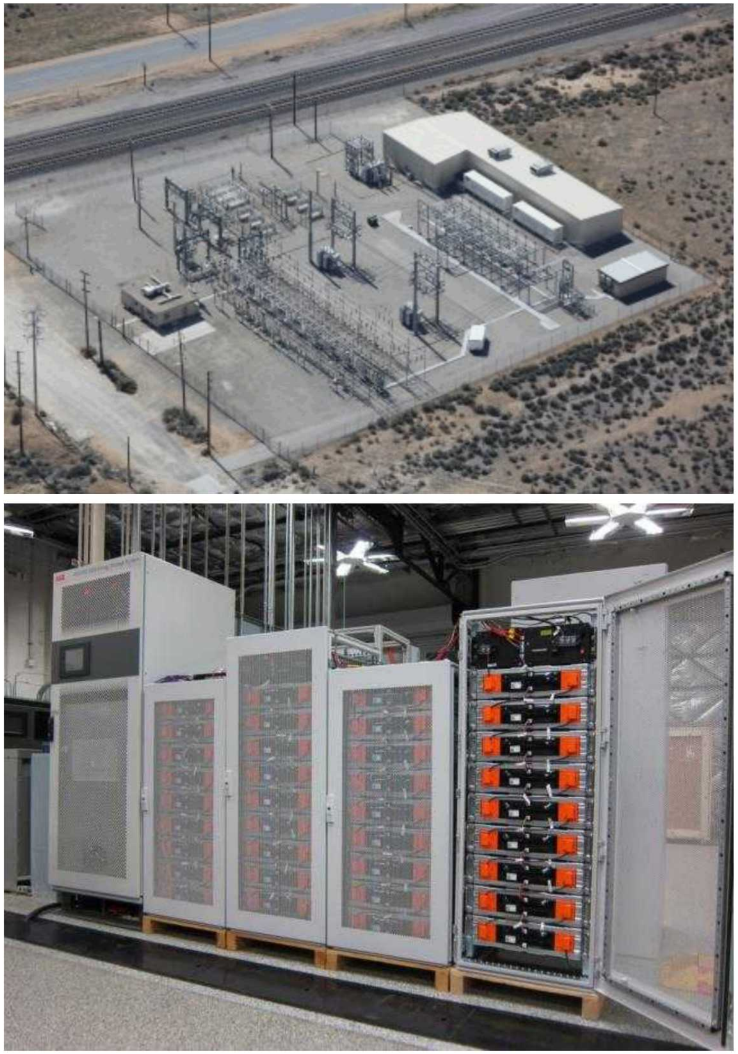


Albuquerque, NM

East Lyons, PA

Li-ion Batteries

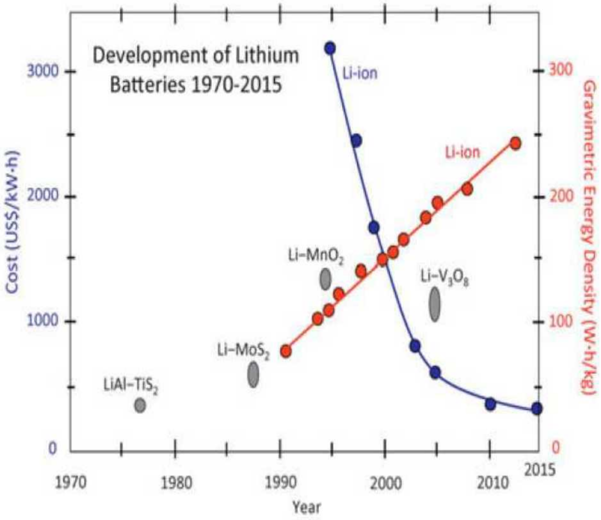
- Li-ion Energy Storage
  - High energy density
  - Good cycle life
  - High charge/discharge efficiency
- Applications
  - Power quality
  - Frequency regulation
  - Now entering energy applications
- Challenges
  - Intolerance to deep discharge
  - Cycle life for energy applications
  - Sensitive to
    - Over temperature
    - Overcharge
    - Internal pressure buildup



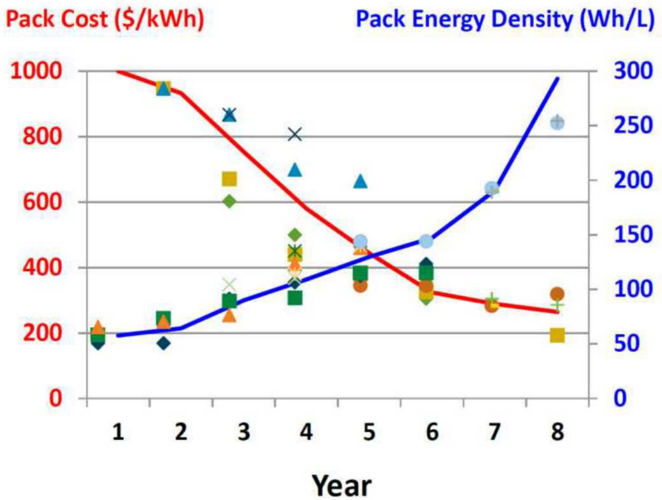
SCE Tehachapi plant, 8MW, 32MWh.

Lithium Ion Batteries - SOA

- First two generations driven by consumer electronics, newer chemistries geared for automotive applications
  - $LiCoO_2$ continues be the dominant technology for consumer electronics
  - 2nd Generation Li-Ion Chemistries offering better performance, wider temp range, improved safety and lower cost
- Rapid growth of application beyond frequency regulation and power quality to energy applications. Large plants in the 100 MW are being built.
- Capacity improvements are incremental
  - 8% for LIB (1992-2007); BOM is 80-85% of cell costs, Scaling down materials cost difficult
  - Engineering larger cells (>100 Ah) is not still economical
- Safety and reliability continue to be significant concerns
- Deep discharge cycle life issues for energy applications (1000 cycles for automotive)



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

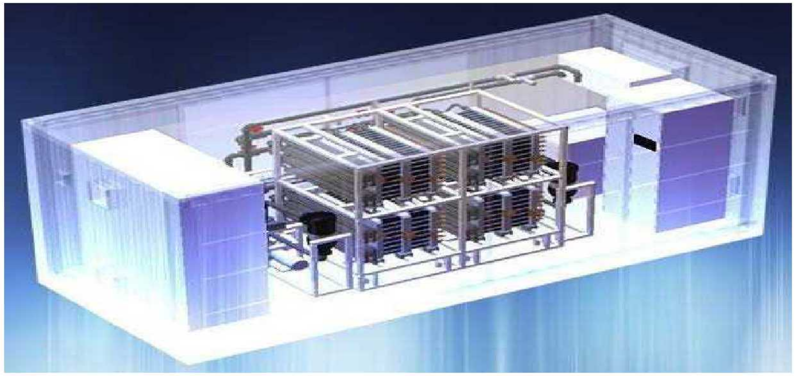


Source: David Howell, DOE VTO, 2017

Redox 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

Sumitomo, 3 MW/ 8 MWh VFB
Miguel, CA, May 2017



Rongke Power, Dalian, China
200 MW/800 MWh (2018 commissioning)

Flow Batteries – SOA

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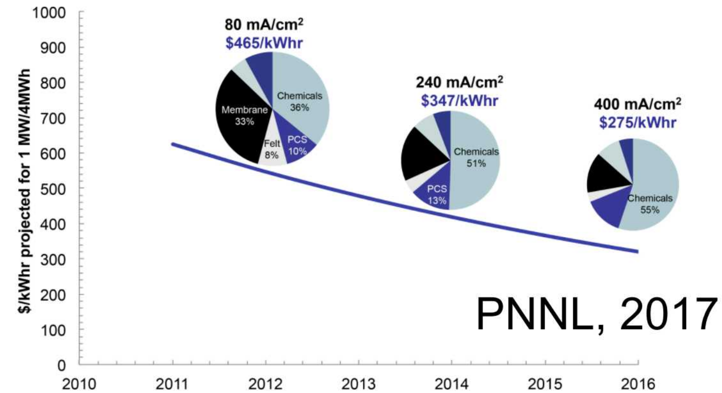
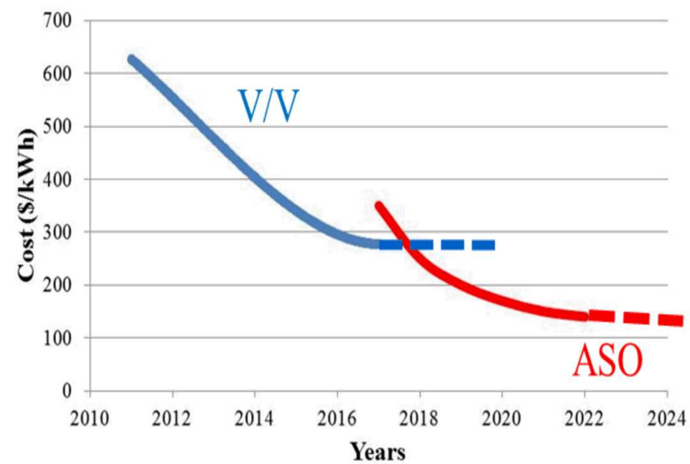
- Significant materials challenges, and opportunities for improvement
  - Electrolytes relatively expensive (esp. Vanadium), need lower cost electrolytes
  - Low energy densities, limited solubility of V in aqueous electrolytes, need new materials
  - Electrolyte is temperature sensitive
  - Not yet in high volume to affect costs
- Potential opportunities to reduce materials cost
  - New redox chemistries, new electrolytes
  - Lower cost of membranes (beyond Nafion)
  - Increased current density and lower cost stack design





Major Opportunities for Improvement
Power Plant (Stack): Membranes
Energy: Electrolytes

RFB stack sizes continue to grow

Containerized Systems

UniEnergy Technologies, 1MW/4MWh

32 KW Stack
Rongke Power/UET
120 mA/cm2
Meter size stack

Flow battery power plants

Sumitomo Electric, 15MW/60MWh

Stack room

Sodium Batteries

- 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, over 1800 MWh of installed capacity
- NaNiCl2 (Zebra) developed in South Africa in 1980's
  - FIAMM in limited production, GE no longer in manufacturing
- Neither NaS nor $NaNiCl_2$ are at high production volumes and the economies of scale needed

NGK 34MW - 245 MWh NaS
Rokkasho, Japan

FIAMM 222-kWh System
Duke Energy Rankin Substation

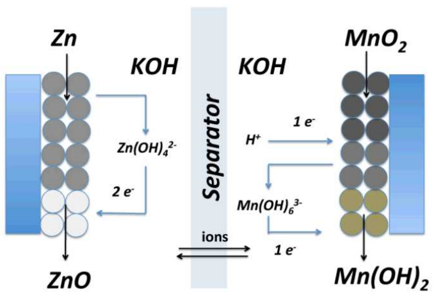
Sodium Batteries – SOA

- Low cost active materials, but challenging systems engineering
- Need for high temperature operation, kinetics driven by the solid ceramic electrolyte
  - Typical operating window 250-350 ^{o}C. Need for continuous thermal management even when not in use. At lower T, Na metal freezes out, degree of distortion to cell dictated by SOC of battery
- Safety concerns related to membrane rupture. In NaS, failure can lead to exothermic reaction.
- Need hermetic seals.
- Charging/discharging limitations
- Engineer cells that operate at lower T (150^{o}C or lower) is still in the laboratory

Alkaline Zn-MnO_2 Batteries

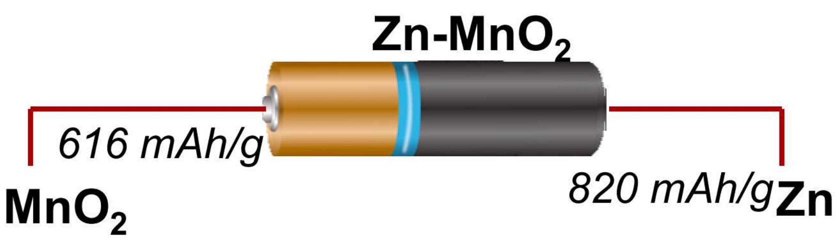
- Traditionally primary batteries at ~$18-25/kWh with long shelf life
- Lowest bill of materials cost, lowest manufacturing capital expenses
- Established supply chain for high volume manufacturing
- Readily be produced in larger form factors for grid applications
- Do not have the temperature limitations of Li-ion/Pb-acid
- Are inherently safer, e.g. are EPA certified for landfill disposal.
- The ultimate challenge in Zn/MnO_2 batteries is reversibility

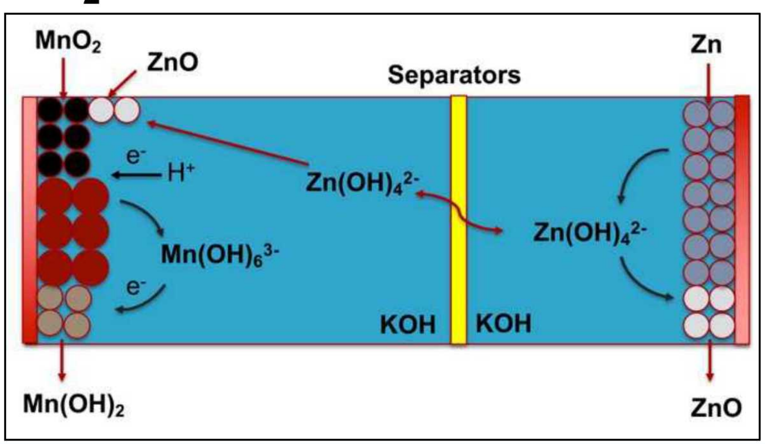
Alkaline Zn-MnO_2 Batteries



Single-use Alkaline Battery $25/kWh

- Alkaline Zn-MnO2 primary cells cost ~$25/kWh
- Zn-MnO_2 - low cost commodity materials, established US based supply chain, developed infrastructure
- **Potential for $50/Wh cells with full-rechargeability of Zn-MnO_2**
  - Recent breakthroughs in making MnO_2 fully rechargeable. Based on the formation of a layered birnessite MnO_2 structure and stabilizing this structure for thousands of cycles
  - Improvement in energy density and cost improved utilization of MnO_2 capacity. Further cost reductions through better materials utilization
  - Cycle-life through improvements through controlling Zn migration and engineering of cells





Further Research Needs

On the MnO_2 (cathode)

- Crystal structure breakdown
- Formation of Inactive phases
- Reducing susceptibility to Zinc poisoning

Separator:

- Reduce Zincate crossover

Anode:

- Control shape change
- Passivation
- Reduce dendrite formation

Improvements in materials utilization, process optimization and engineering larger format cells

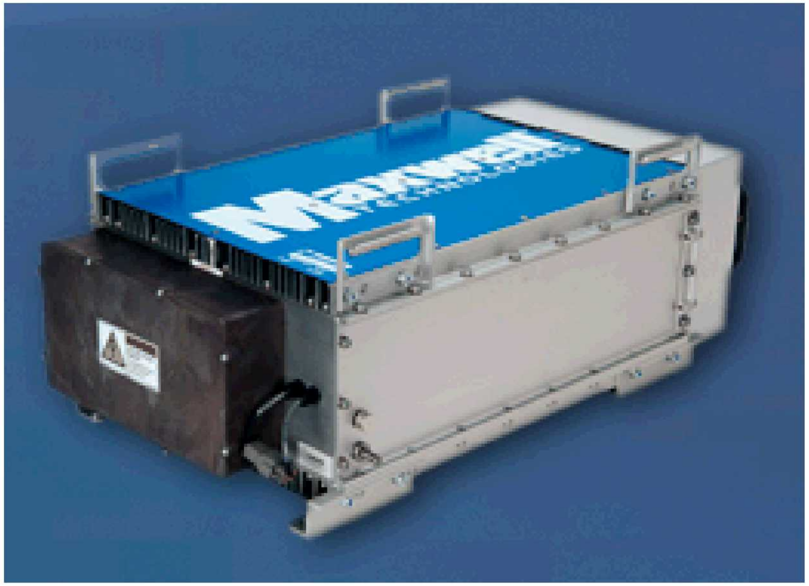
Flywheels

- Flywheel energy storage
  - Modular technology
  - Long cycle life
  - High peak power
  - Rapid response
  - High round trip efficiency (~85%)
- Applications
  - Power quality
  - Frequency regulation
  - Transient stability
- Challenges
  - Limited energy storage time (frictional losses)
  - Improvement in battery technology has made flywheels not competitive in frequency regulation and power quality applications

Beacon Power Hazle Township, PA plant. 20 MW, 5MWh. Operational September 2013. Stephentown, NY plant was built first.

Ultra Capacitors

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



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

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

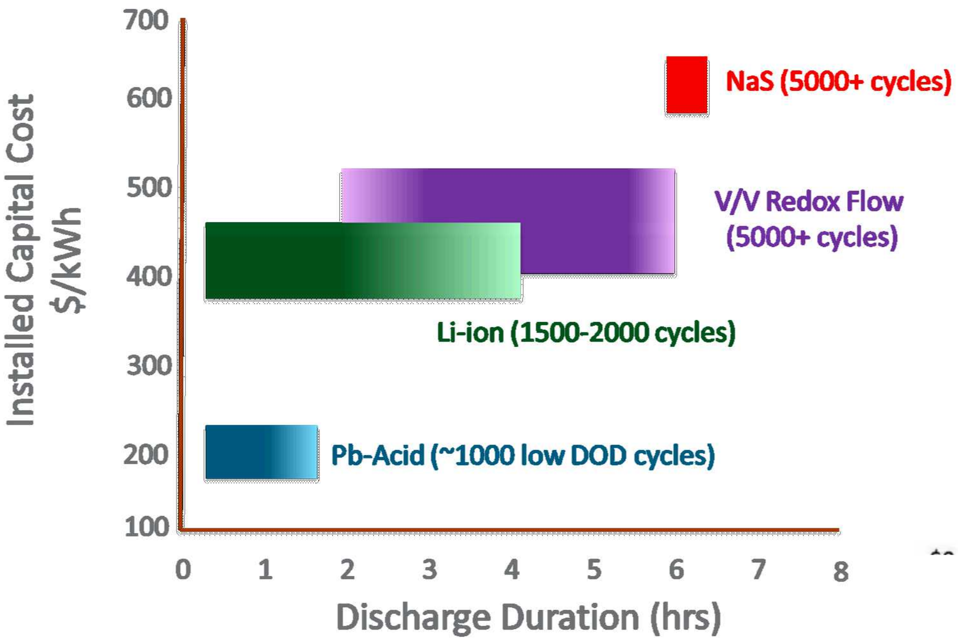
EMS

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

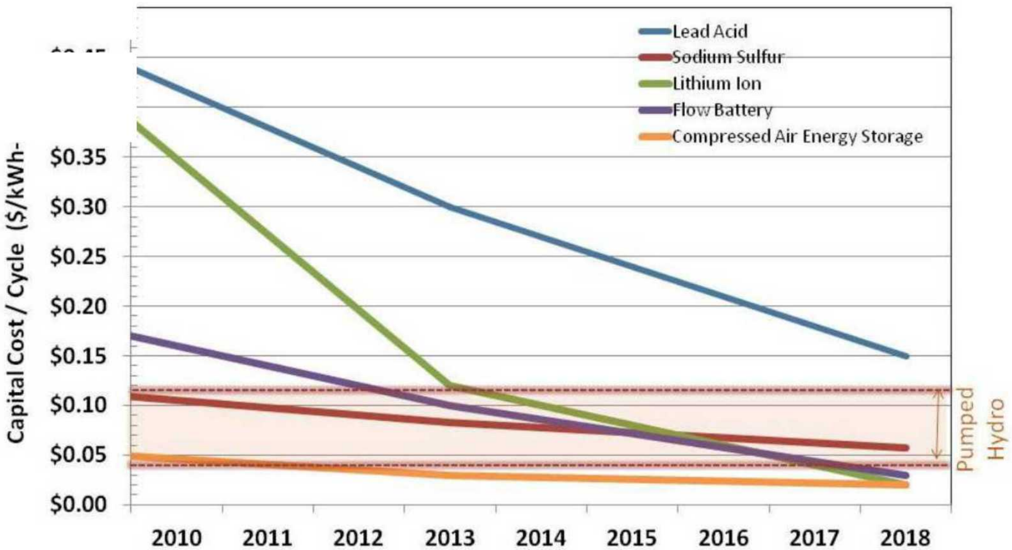
\+ Soft Costs

Cell to Battery to a Storage System
Doubling in cost, $250/kWh battery leads to $500-$700/kWh at the System level

Capital Costs



Source: V. Sprenkle, PNNL, 2017



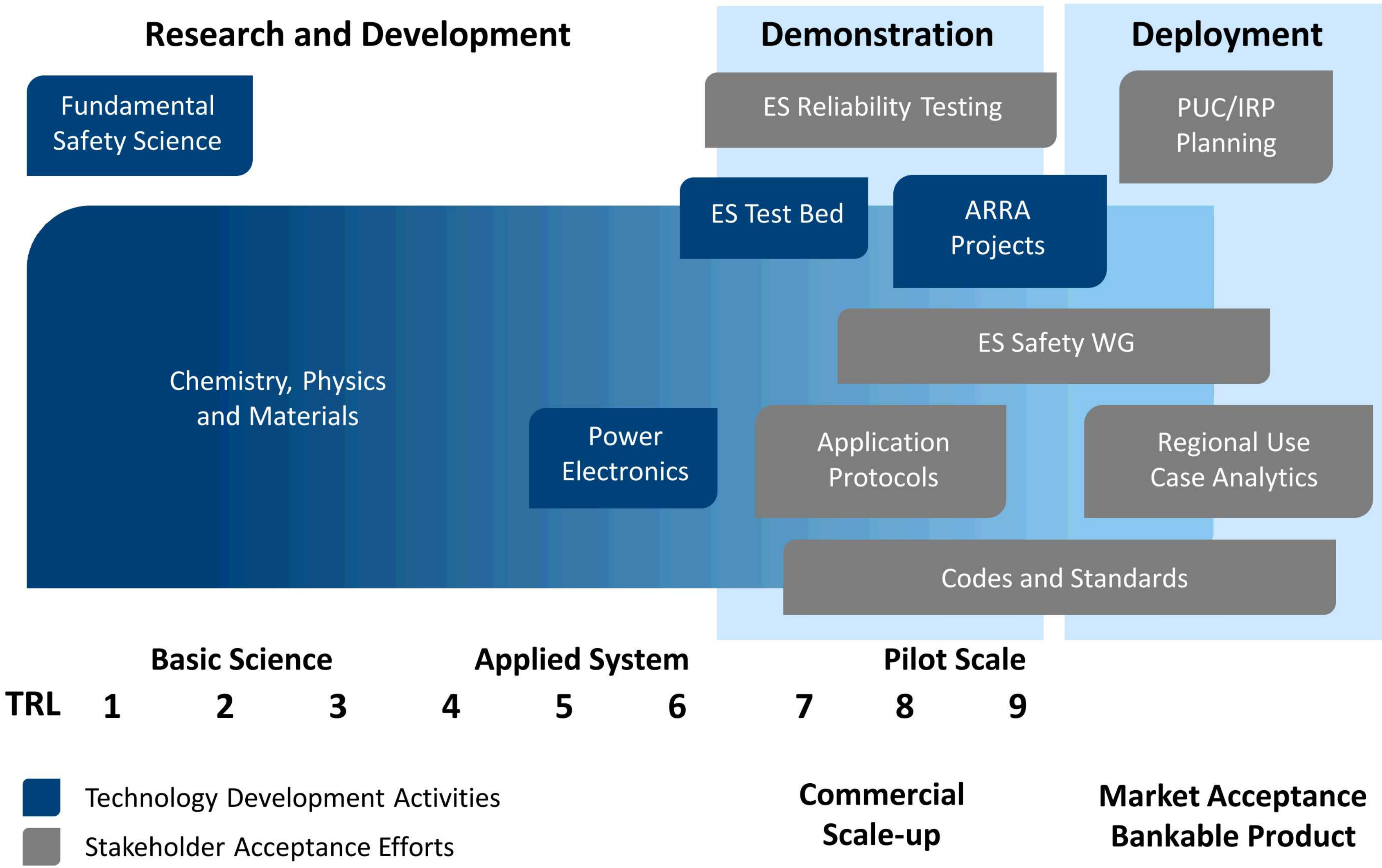
Source: Customized Energy Solutions and IESA (State of Charge Report, MassCEC, 2016)

Gaps in Technology and Implementation

Though energy storage is a key component for the Future Grid, significant gaps exist

- Technology gaps
  - Existing storage solutions are expensive for most applications
  - Deep discharge and longer cycle life
  - Safe and reliable chemistry
  - Scalable technologies to cover all markets/applications
- Implementation
  - Performance data
  - Validation of storage
  - Organizational adaptability of new technologies

How is the DOE OE ES Storage Program Addressing the Gaps?



Key Takeaways

At the systems level:

- How do we engineer energy storage systems that are low cost, safe, reliable, long cycle life and scalable for all application markets ?

In battery materials:

- Engineering energy storage systems with higher energy and high power capacities while keeping safety and reliability as key metrics
- How do we manage the universal tradeoff between energy and power due to a combination of electrical, ionic, structural and chemical effects?
  - How to improve energy capacity without sacrificing safety and life?
  - How do we optimize power and energy at multiple length scales?
  - How do we enable fast ion and electron transport without sacrificing energy density, while maintaining long life and safety?
  - How do we design materials to realize high energy and power simultaneously?
  - How to achieve high reversibility, with low capacity loss, and low over-potentials

Acknowledgements

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