SAND2018-14147PE

Grid Modernization, Energy Storage and the Role of Power Electronics

Babu Chalamala

Sandia National Laboratories

bchalam@sandia.gov

University of Central Florida

November 29, 2018

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administratio contract DE-NA0003525. SAND2

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

U.S. Electric Grid

850GW baseload, 1250 GW summer peak, 7,000 operational power plants

3,200 utilities, 60k substations, 642k miles of HV transmission lines, 6.2 million miles of distribution circuit, 159 million customers.

In 2015, total U.S. electricity generation was 4,087,381 GWh

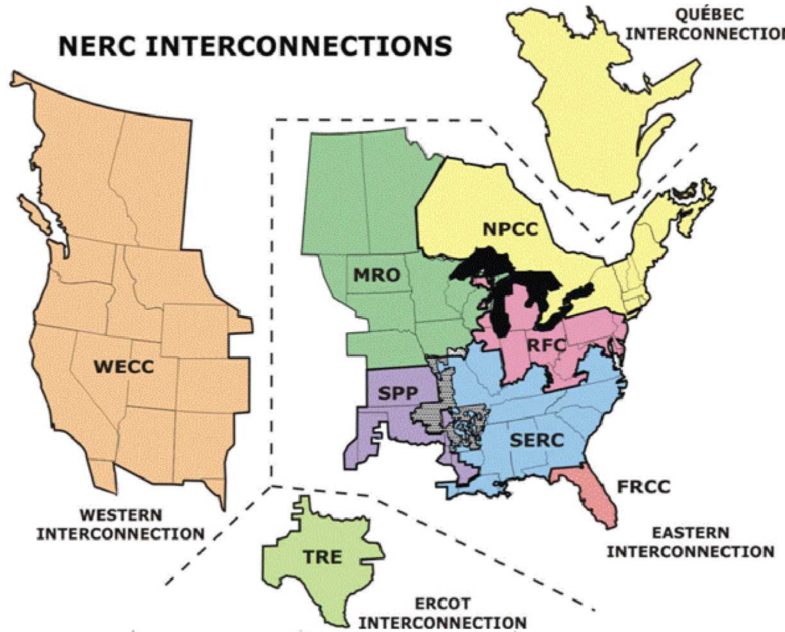
- Increasing NG and renewable generation (6.1% hydropower and 7.3% from wind and solar)

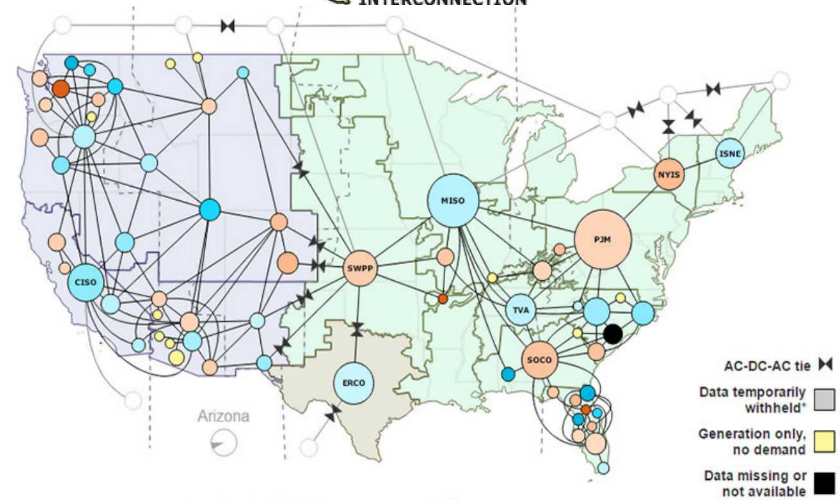
Revenues reaching $400 B, 10.42 c/kWh avg

Four interconnect regions and a number of balancing authorities:

- Eastern Interconnection (31 US, 5 Canada)
- Western Interconnection (34 US, 2 Canada,1 Mexico)
- ERCOT, Hydro-Quebec

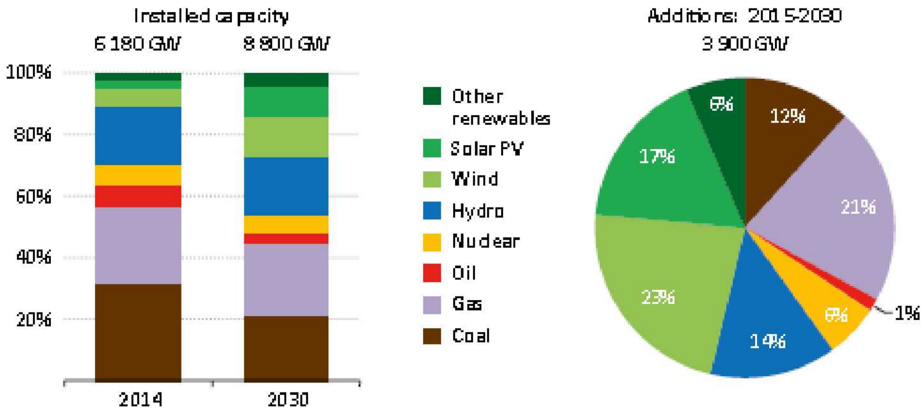
Sources: EIA, EEI

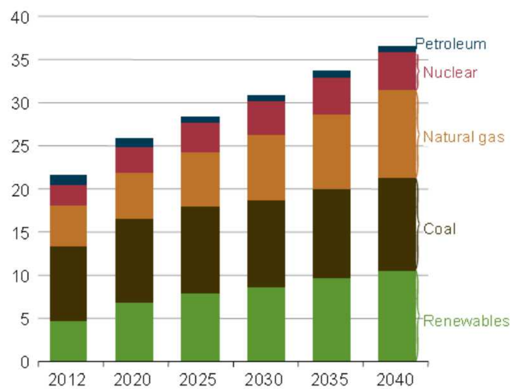




http://www.nerc.com

Electric Grid: Are we at the cusp of a major transformation?





Source: International Energy Outlook, EIA, 2016

Of the 6 TW of worldwide generation capacity, renewables are reaching the 20% range in many markets.

- Installed solar and wind capacity reached 1 TW in 2018, penetration levels approaching 30-40% in some markets.

US Grid: 850 GW baseload, 1250 GW summer capacity.

- Installed solar and wind capacity reached 150GW in 2018

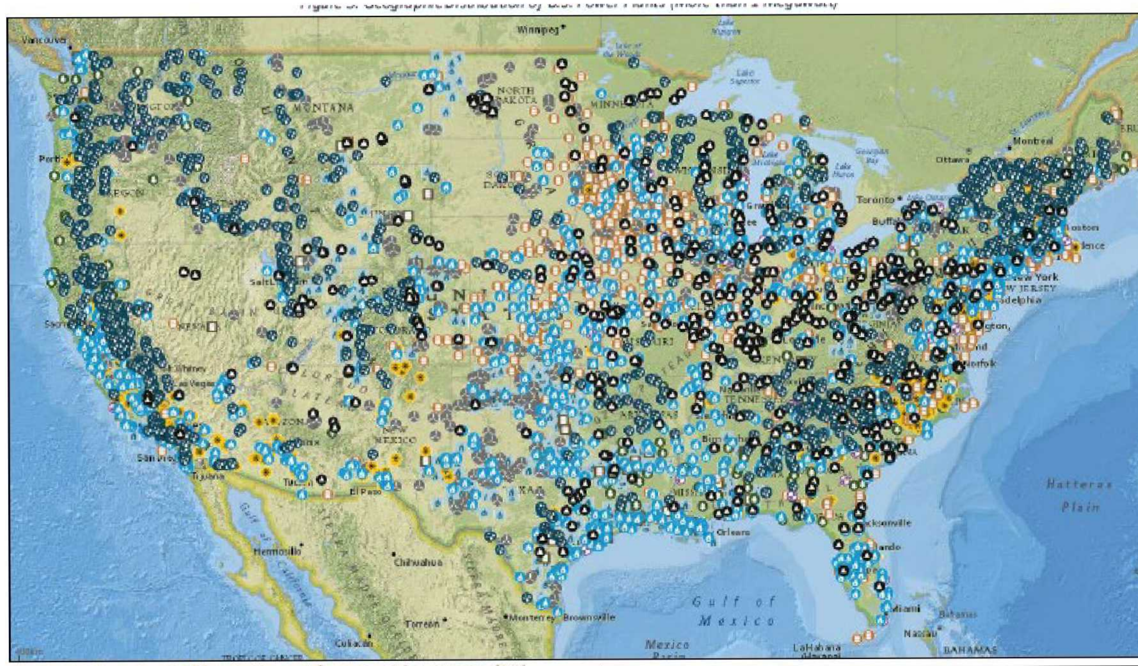
Handling intermittency is becoming a challenge in many markets

- High level integration of energy storage and hybrids, on a grand scale.

In 2000, the IEA forecast that by 2030, renewable energy would be 4.4% of the total mix
In 2018, installed wind and solar capacity reached 1 TW, new generation is more renewable

US Power Plants

- Generation mix at utility-scale facilities in 2016
  - Natural gas = 33.8%
  - Coal = 30.4%
  - Nuclear = 19.7%
  - Renewables (total) = 14.9%
    - Hydropower = 6.5%
    - Wind = 5.6%
    - Biomass = 1.5%
    - Solar = 0.9%
    - Geothermal = 0.4%
  - Petroleum = 0.6%
  - Other gases = 0.3%
  - Other nonrenewable sources = 0.3%
  - Pumped storage hydroelectricity = -0.2%



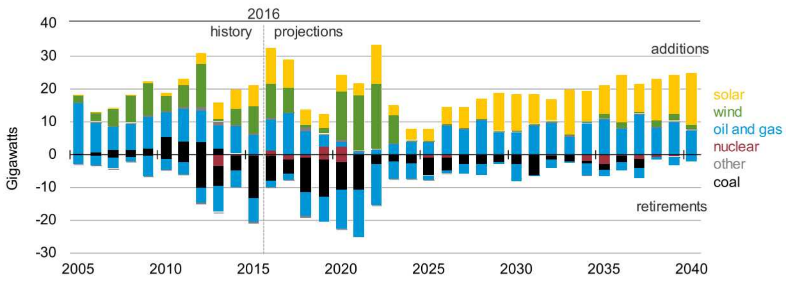
Source: U.S. Department of Energy, Energy Information Administration (EIA) Energy Mapping Tool
Data: http://www.eia.gov/maps/layer_info-m.cfm

Coal Power Plant
Hydroelectric Power Plant
Natural Gas Power Plant
Nuclear Power Plant
Petroleum Power Plant
Solar Power Plant
Wind Power Plant
Wood Power Plant

DOE EIA, 2017

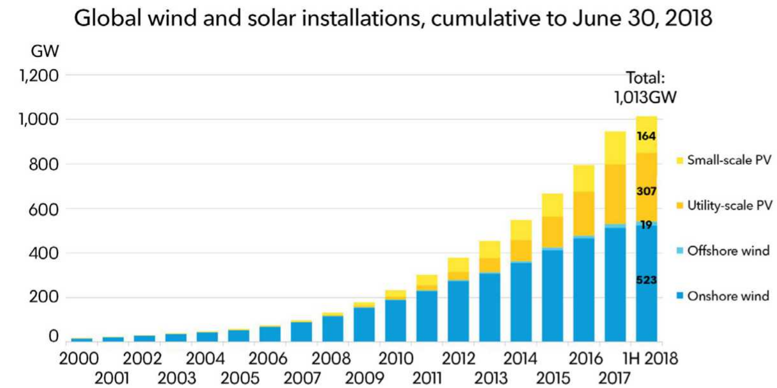
Major Trends in Electricity Markets

Capacity Additions and Retirements



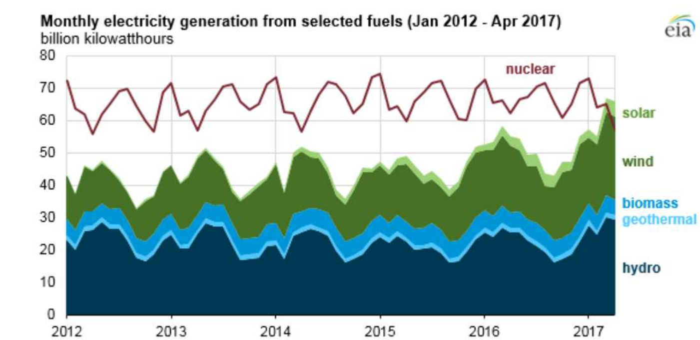
Source: EIA, Annual Energy Outlook 2017

Coal-fired unit retirements driven by low NG prices (EIA, 2017)
In California by 2021, solar, storage and wind capacity additions will exceed natural gas (GTM Research)

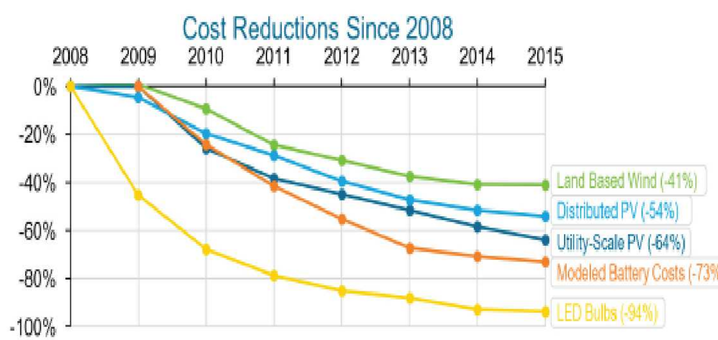


Source: Bloomberg NEF. Note: 1H 2018 figures for onshore wind are based on a conservative estimate; the true figure will be higher. BNEF typically does not publish mid-year installation numbers.

Utility-scale Renewables Generation surpassed Nuclear Generation – April 2017



Cost reductions primarily due to high volume manufacturing and large scale deployments



http://energy.gov/eere/downloads/revolutionnow-2016-update

Transformation of the Grid Edge

Electrification, Decentralization, Digitalization

Electrification of the Transportation Sector

- EV charging infrastructure and fast charging
  - Ensure stability of the power grid
  - Accommodate large loads
  - Provide grid services,. Infrastructure for transactive energy

Advanced Batteries for longer EV range

- Increased energy density and materials use
- Recycling and repurposing
- Improved battery management systems

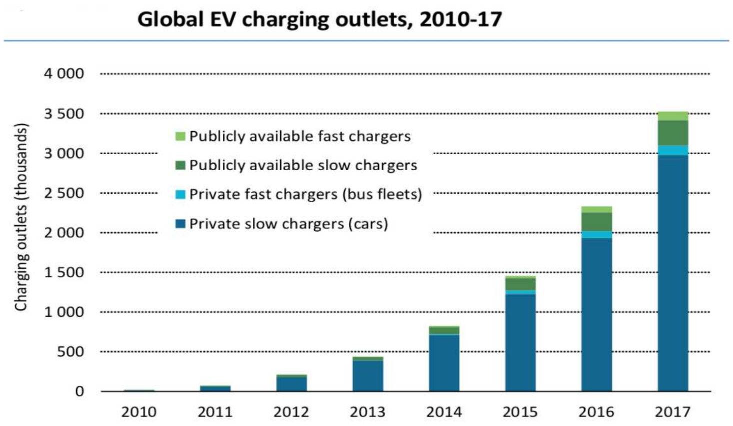
Behind-the-meter technologies with bi-directional communication

- Smart meters, smart loads, rooftop solar, electric vehicles, battery storage

Computation challenges associated with distributed sensing, control, and big data

Increasing Role of Power Electronics

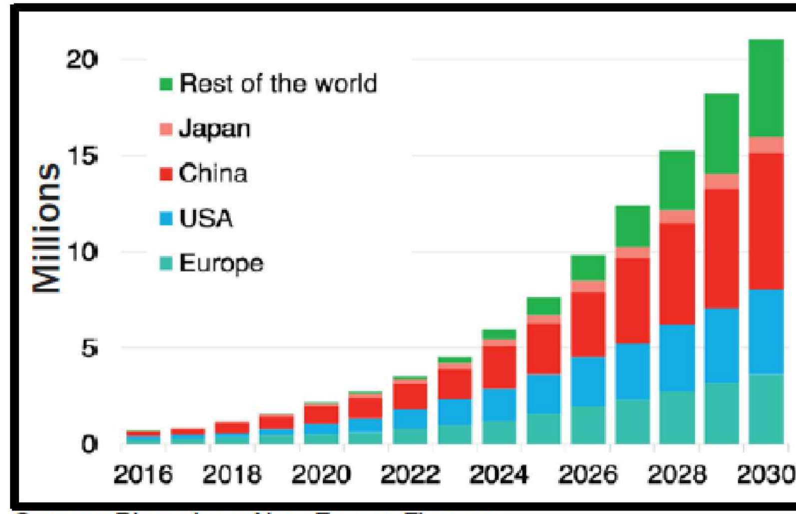
Rapid evolution of off-grid and micro-grids



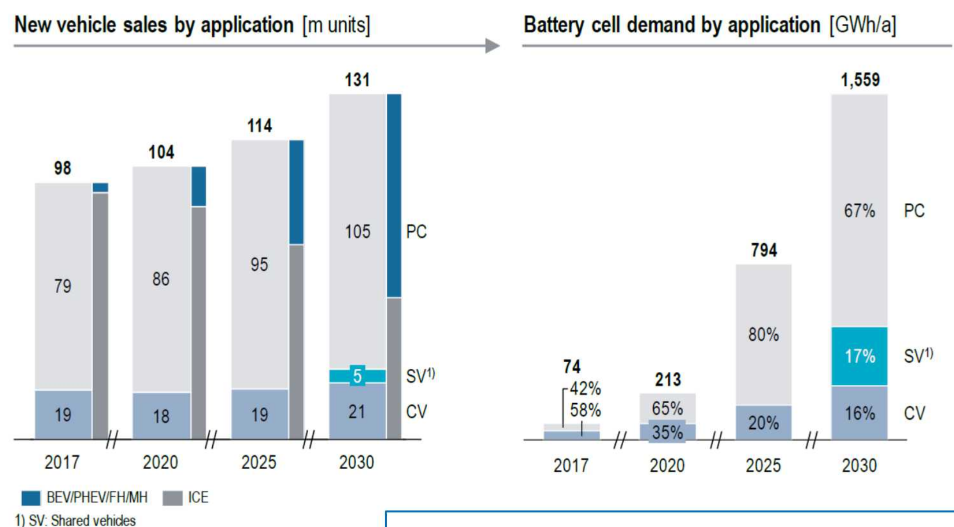
Electrification of Transportation

IEA, IHS, Bloomberg projections for annual production of electric vehicles reaching 20 Million by 2030 and a fleet of 130 Million vehicles (mostly passenger vehicles) on road as base case, 230M vehicles optimistic case'

- Typical battery pack: 100 kWh/80kW, 500 mile



Source: Bloomberg New Energy Finance



Source: IHS; Roland Berger

Projected battery capacity needs for EVs in 2030

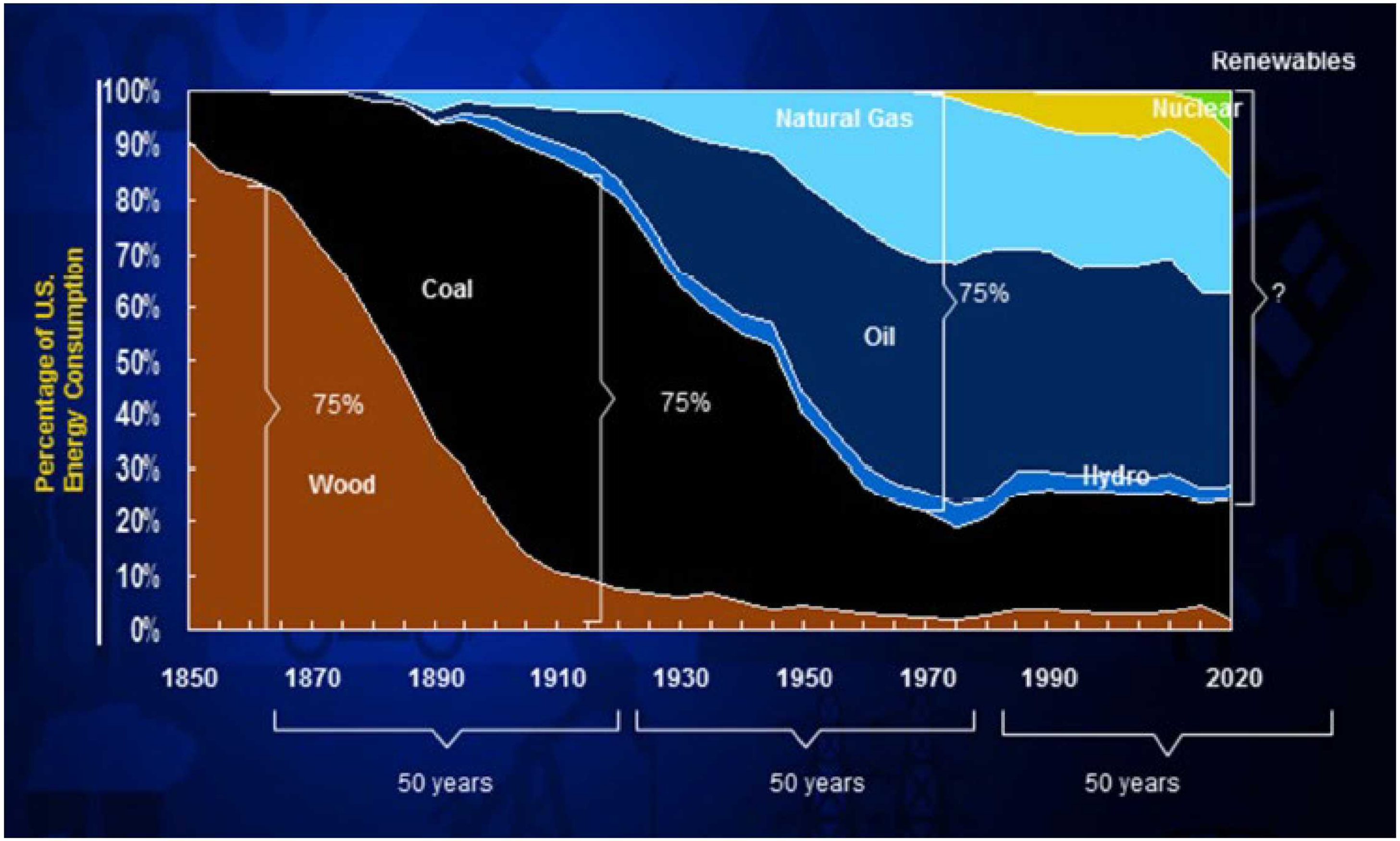
- 1.5 - 2.5 TWh of manufacturing capacity

International Energy Agency projects at least 125 million EVs worldwide by 2030.

Infrastructure updates required:

- prevalent charging stations
- accommodation of increased loads (potentially at ends of distribution feeders)

But, Energy Transition Cycles are Long (50 Year Cycles)



EIA Annual Energy Review 2008

100% fossil free electricity generation is no longer an idea

California and Hawaii are aiming for 100% renewable energy by 2045; many U.S cities and counties have made public commitments to reach 100% clean energy in the next ten to twenty years.

How is the Grid Evolving?

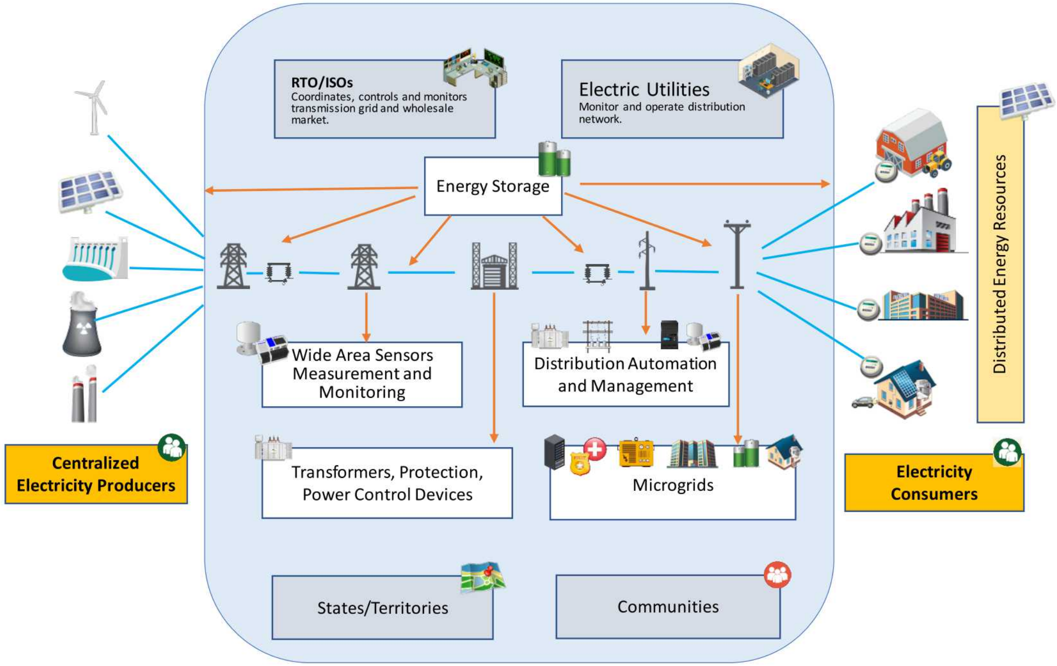
We are beginning to see existing business models breaking down

Flat to declining electricity sales in OECD markets
- Investors struggling with poor returns due to long adoption cycles. $2 Tn Asset Base in the US alone

Conservative regulated utility industry
- Not open or reluctant to change business models
- IOUs and PUCs struggling to adapt to rapid change

Rapid change is bottom-up, with major transformation at the grid edge
- EVs, DER, Smart metering, microgrids, demand response, energy efficiency

Changes cuts across technology, economics, policy, and markets



Source: US DOE Office of Electricity

Centralized to a Decentralized Power Delivery Model?

Will we have a hybrid model?

Energy Storage is needed

Immediate Needs to for Grid Modernization

Economic

- Aging electric power system exacts substantial costs due to outages and inefficient energy technologies.

Environmental and Policy

- Increasing frequency and severity of extreme weather (drought, storms, etc.) affects the ability to generate power and stress the resiliency of electric power grid.

Security

- Physical: damage to infrastructure by malicious actors or natural hazards increasing risk to critical assets
- Cyber: disruption of energy production/energy flow and damage to equipment caused by cyber threats/attacks.

Competitiveness

- Increasing competition worldwide in energy sector as countries are moving toward clean energy technologies
- Competitive energy markets needed for economic competitiveness


Aging Infrastructure


New Generation Sources


Customer Participation


Electric Vehicle Market


Cyber Security Threats


Physical Threats


Extreme Weather Events


Reliability/Resiliency Needs

Grid Modernization R&D Needs

Electric systems	Traditional Grid	Development Trends and Needs	Future Grid
Generation	• Large centralized power plants • Dispatchable generation • Mechanically coupled • Minimal DER	• Growing role of DER • Energy storage • New planning tools to handle RE • Control coordination • NG replacing coal plants	• Hybrid control architectures • Bidirectional power flows and stochastic loads • Power electronic centric infrastructure across the grid
Transmission	• SCADA for status visibility • Operator-based controls • Aging infrastructure. Low peaking capacity utilization. • Threats/vulnerabilities not well defined	• VDC transmission • Growing dc loads • Improving EMS • Integrated planning tools • Growing security awareness • Increasing role of storage	• Wide-spread PMU deployment • Coordinated sensing and control infrastructure • System-wide dynamic power flow management • Resilient and self healing
Distribution	• Minimal to non-existent sensing and automation • Radial design and one-way power flows • Aging distribution infrastructure	• Deployment of ADMS • FACT/inverter enabled voltage regulation • Early adoption of storage in distribution systems	• Truly bi-directional power flows and large scale DG • Pervasive sensing and communications • Local, autonomous coordination • Asynchronous networks
Consumption	• Regional, location and customer specific rate structure • Uniformly high reliability • Predictable behavior based on historical needs and weather • Reliable, yet inflexible	• Customer-determined reliability/power quality • Real time pricing, time of use rates, demand charges • Improved utility communications • Behind-the-meter storage	• Autonomous microgrids • Advanced EMS • Widespread DERs and transactive energy • Pervasive sensor environment
Operation/Market structure	• Vertically integrated utilities, wholesale markets	• Market reform to compensate for services provided	• Diversity of energy products and services

DOE QTR, 2015

DOE Office of Electricity (Grid Operations) Priorities

Puerto Rico and U.S. Virgin Islands

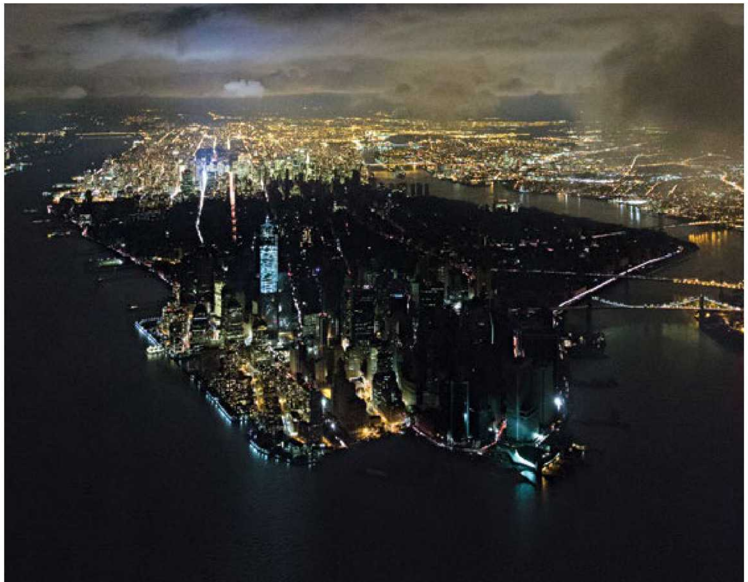
Restoration and Resiliency Efforts

North American Energy Systems Resiliency Model

Mega-Watt Scale Grid Storage

Revolutionize Sensing Technology Utilization

Operational Strategy for Cyber and Physical Threats



Role of Energy Storage in the Grid

Grid resiliency and reliability

Improving power quality

Improving the efficiency of existing generation fleet

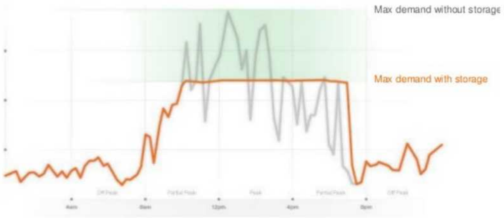
Demand management

Renewable integration

Transmission & Distribution upgrade deferral

Off-grid applications

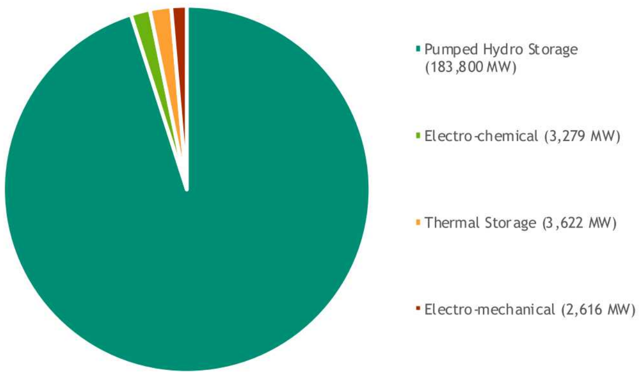
Mitigate $79B/yr in commercial losses from outages



Reduce commercial and industrial electrical bills through demand charge management. 7.5 million U.S. customers are enrolled in dynamic pricing (EIA 2015)

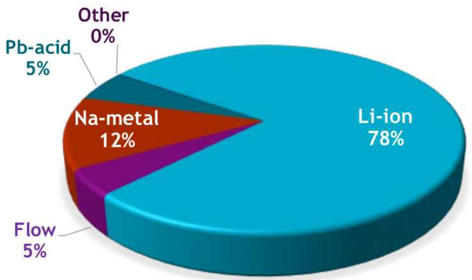
Balance the variability of 825 GW of new renewable generation while improving grid reliability and efficiency.

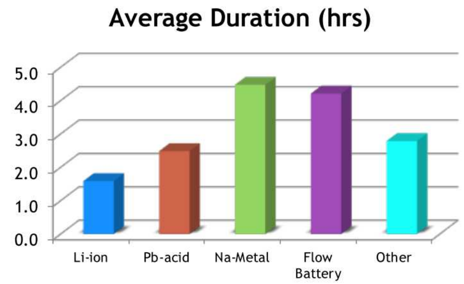
Energy Storage in the Grid Today



Global Installed Storage Capacity

Technology Type	Projects	Rated Power (MW)
Electro-chemical	993	3,279
Pumped Hydro Storage	352	183,800
Thermal Storage	206	3,622
Electro-mechanical	70	2,616





US Battery Energy Storage Deployed Reaching 2 GW in 2018

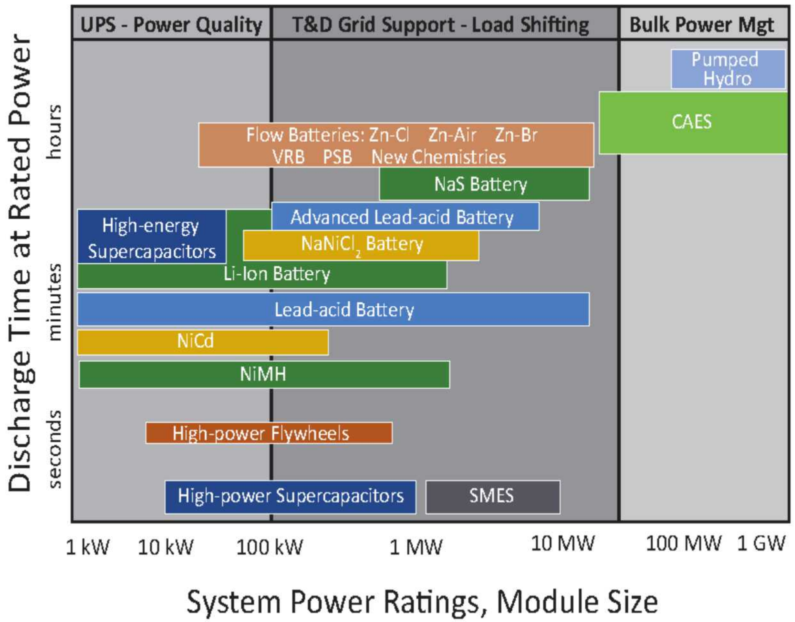
US installed energy storage capacity of 32 GW represents 15 min ride through

Compared to the need, scale of energy storage deployments are insignificant.

Numbers reflect projects reported to the DOE Global Energy Storage Database as of Nov 2017

DOE Global Energy Storage Database
www.energystorageexchange.org

Energy Storage System Needs and Applications



Range of applications and storage system needs [Source: DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, 2013]

Energy Applications	Power Applications
Arbitrage	Frequency regulation
Renewable energy time shift	Voltage support
Demand charge reduction	Small signal stability
Time-of-use charge reduction	Frequency droop
T&D upgrade deferral	Synthetic inertia
Grid resiliency	Renewable capacity firming

Energy storage application time scale

- "Energy" applications – slower times scale, large amounts of energy
- "Power" applications – faster time scale, real-time control of the electric grid

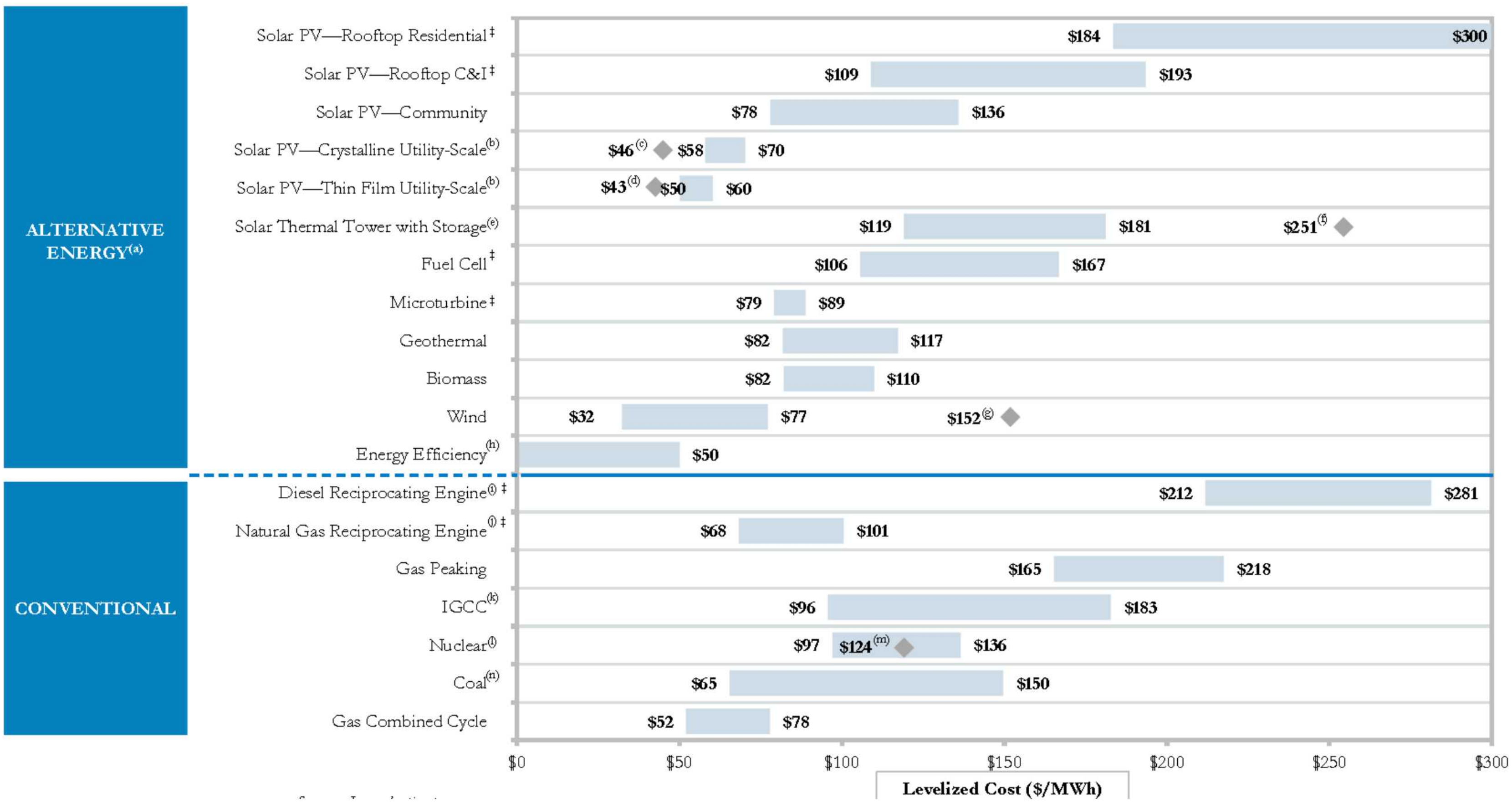
The grid needs energy storage – right now there are several barriers

- Expensive, especially in energy markets
- Electricity markets/utilities do not properly allocate payments/costs for services provided

The future ….

- Higher energy prices – storage starts looking better
- Lower technology costs – storage starts looking better
- Efficient market design – helps pay for storage costs

Unsubsidized Levelized Cost of Energy Comparison



Lazard, 2016

Wind and solar PV have become increasingly cost-competitive with conventional generation technologies on an unsubsidized basis.
Most recent 500 MW solar PPA in CA at 1.9c/kWh

Grid Energy Storage Technoloiges

Range of battery technologies for short duration energy storage, seconds to days

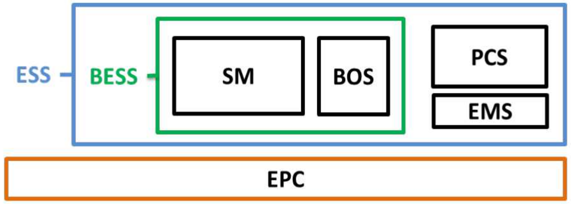
- Li-ion, advanced lead acid, Sodium and Zinc-based battery for power and some energy applications
- Flow batteries – energy applications

Pumped hydro and CAES for hours to day long energy storage

No ready solutions for real long duration and seasonal storage needs

- Range of options including liquid fuels, hydrogen, thermal storage technologies

Energy Storage is Not Just Batteries



SM **Storage Module**
Rack Level System (DC)

BESS **Battery Energy Storage System**
Containerized System (DC)

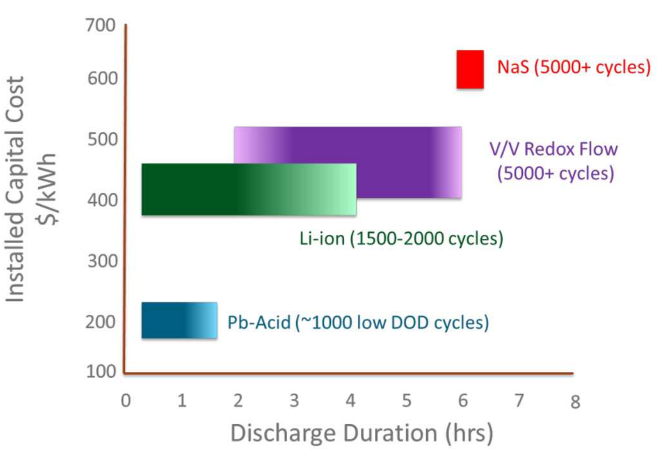
ESS **Energy Storage System**
Complete Storage System (AC)

Storage Module (SM)	Balance of System (BOS)	Power Conversion System (PCS)	Energy Management System (EMS)	Engineering Procurement & Construction (EPC)
Racking Frame / Cabinet	Container	Bi-directional Inverter	Application Library	Project Management
Local Protection (Breakers)	Electrical Distribution & Control	Electrical Protection	Economic Optimization	Engineering Studies / Permitting
Rack Management System	Fire Suppression	Connection to Transformer	Distributed Asset Integration	Site Preparation / Construction
Battery Management System	HVAC / Thermal Management		Data Logging	Foundation / Mounting
Battery Module			Communication	Commissioning

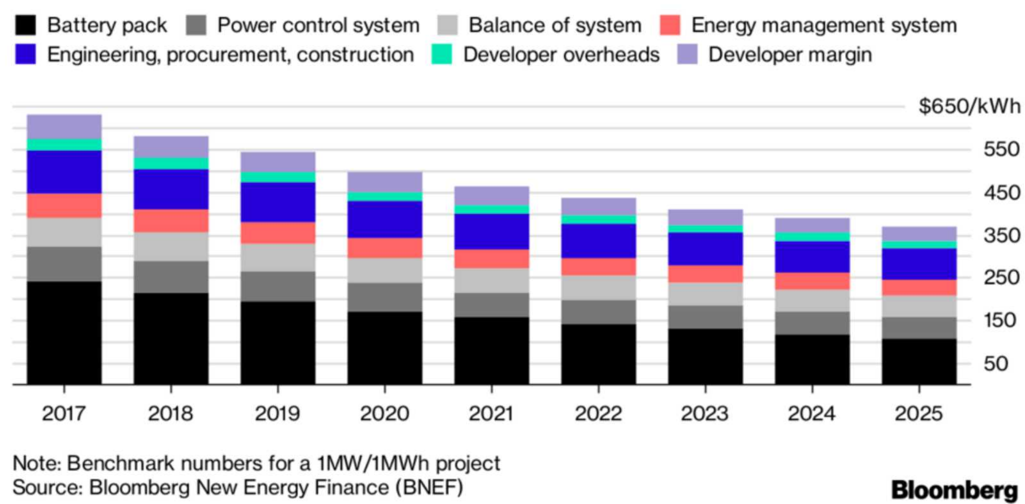
Source: R. Baxter, I. Gyuk, R.H. Byrne, B.R. Chalamala, IEEE Electrification, Aug 2018

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

- Energy Storage is competitive in power markets such as regulation
- Expensive in most energy markets



Source: V. Sprenkle, PNNL, 2017



Energy Storage Installed Costs (BNEF, 2018)

Major Battery Technologies for EVs and Grid Storage

Traditional Batteries
e.g. Lead-acid, Ni-Cd, Ni-MH, Zn-MnO_2

Lithium Batteries
e.g. Li-ion, Li-polymer, Li-metal, Li-S

High-temperature Batteries
e.g. Na-S, Na-$NiCl_2$

Flow Batteries
e.g. Vanadium redox, Zn-Br

	World Wide Production Capacity	Cost and Performance Improvements
Lead Acid Batteries	350 GWh	2%/year (30 year data). $80-150/kWh
Li-ion Batteries	100 GWh	5%/year (20 year data). Cell level price reaching $150/kWh
NaS and NaNiCl	300 MWh	Mature, but no economies of scale
Flow Batteries	<200 MWh	Potential for lower cost. $400/kWh. Reach $270/kWh
Alkaline chemistries (Zn-MnO2, Zn-air)	<100 MWh	Not fully mature. Lowest cost BOM

Data Sources: Avicenne, 2017; Enersys, 2018

Large Commercial Li-ion Deployments

AES 30 MW / 120 MWh ESS, Escondido, CA
Peaker replacement

Tesla 100 MW / 129 MWh ESS
Australia - Grid stability

Saft 6 MW / 4.2 MWh ESS
Kauai - Grid Stability

Lead Acid Batteries – Deployment for Grid Services

3 MW/3 MWh advanced lead acid battery system for utility applications (Source: EastPenn, East Lyons, PA)

1.3MW/1.9 MWh advanced lead acid battery system providing support for a 68MW solar farm in Alt Daber, Germany (Source: BAE Batteries, 2018)

Solar plus Ultrabattery Storage (Source: PNM Albuquerque, NM

RFB Stack Sizes Continue to Grow – Large Plants being built

Containerized Systems

UniEnergyTechnologies, 1MW/4MWh

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

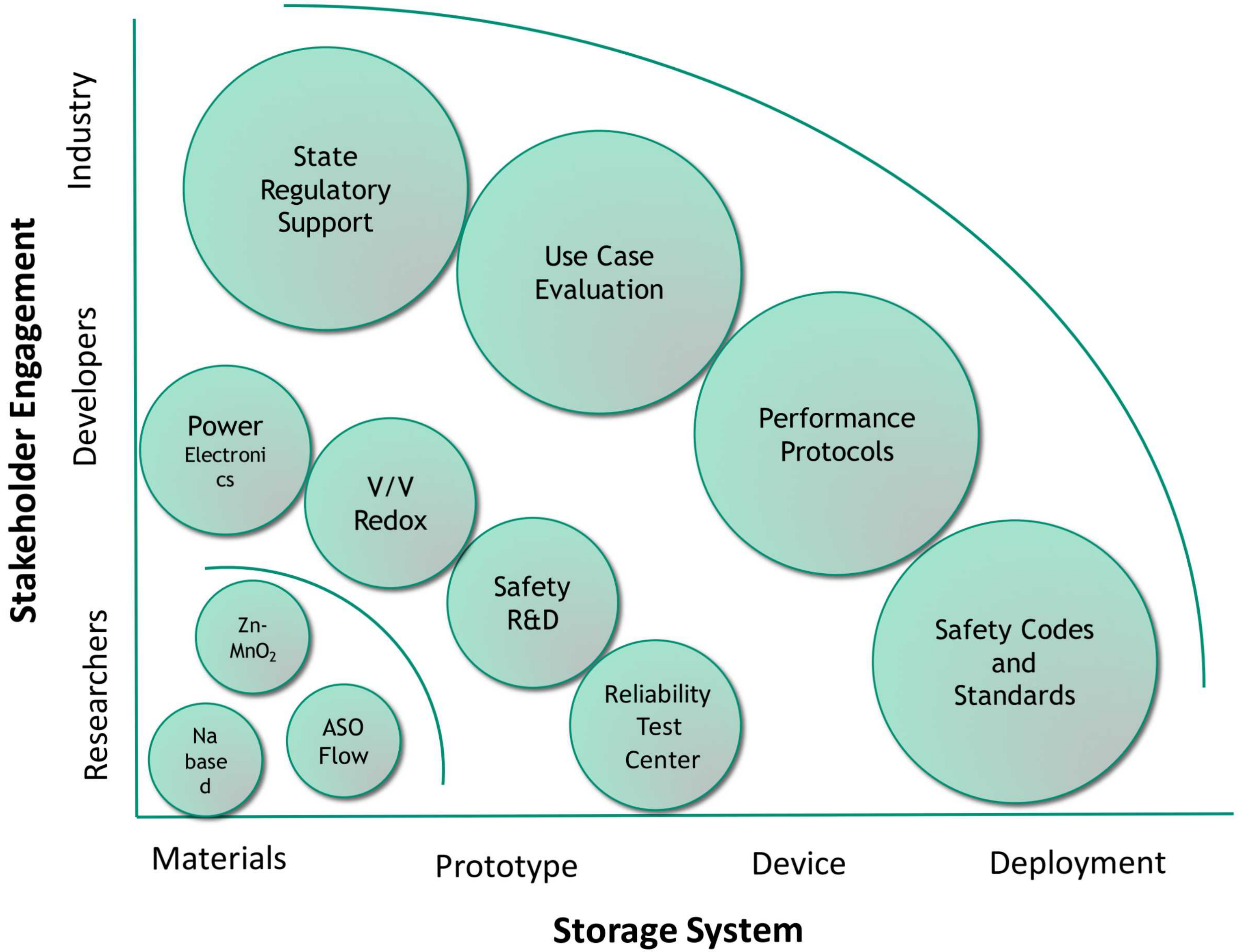
Flow battery power plants

Sumitomo Electric, 15MW/60MWh

Stack room

DOE Grid Energy Storage Program

Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY



Energy Storage - Design and Application Aspects

Cell Architecture
- Cell format
  - Cylindrical, Prismatic
  - Bipolar
  - Flow Cell

Cell Chemistry
- Aqueous
- Non-aqueous

Thermal management
- Heating
- Cooling

Safety
- Abuse resistance
- Flammability
- Toxicity
- Containment

Plant Models
- Modular
- Centralized

Power vs. Energy
- High-power, short-duration discharge
- High-energy, long-duration discharge
- Fast Charging

Modularity and Scalability
- kW to MW (Power Scaling)
- kWh to MWh (Energy Scaling)
- Module stacking and Containerization

Cycle Life
- Electrical
- Thermal

Operational Aspects
- Round-trip efficiency
- Auxiliary power consumption
- O&M Costs

Sandia Grid Energy Storage R&D

Focus on solving critical problems to make energy storage safe, reliable, and cost effective across all markets.

- Advancing new battery chemistries through technology development and commercialization
- Optimization at the interface between power electronics and electrochemistry. Power electronics including high voltage devices (SiC, GaN), high voltage passives and magnetics.
- Energy storage safety – cell and module level safety test and analysis. Engineered safety of large systems. Predictive models for ES safety
- Analytics and controls for integration of utility class storage systems. Improved BMS, EMS systems. Control architectures.
- Standards development
- Grid of the Future
- Energy storage project development

Support DOE's demonstration projects and outreach to the industry

Active University Collaborations

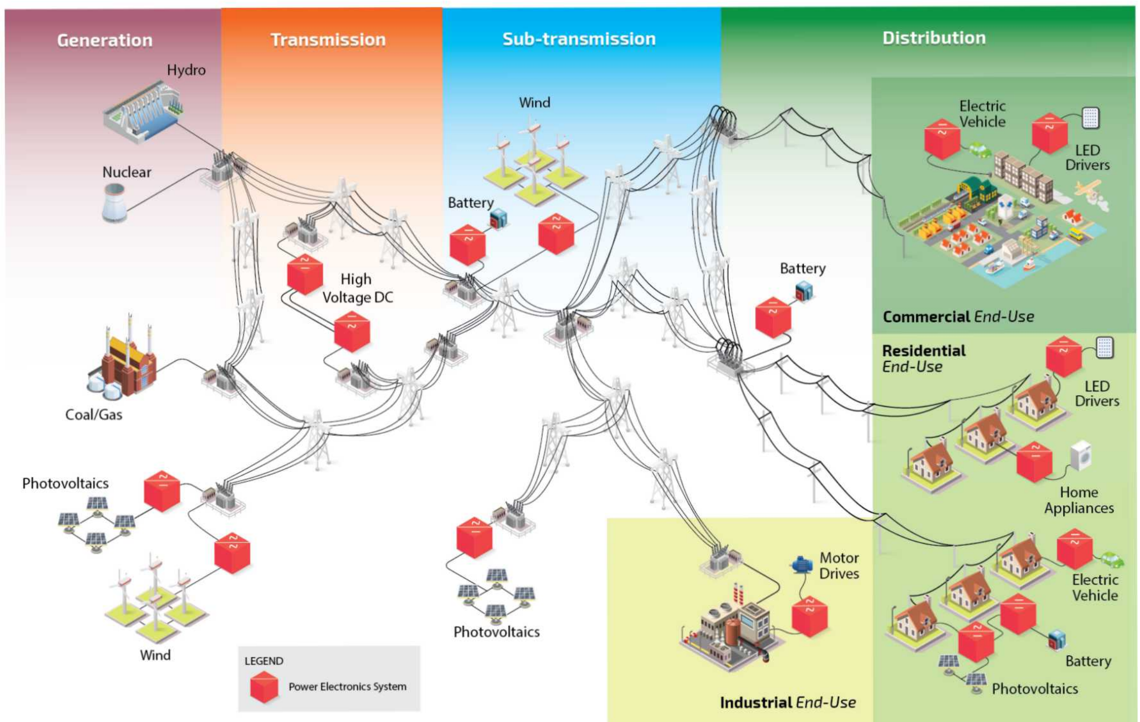
- CUNY Energy Institute
- Davidson College
- Northeastern University
- Stony Brook University
- University of Kentucky
- University of Washington
- UC Irvine
- University of Alaska Fairbanks
- University Texas at Austin
- New Mexico State University
- University of Houston
- Ohio State University
- University Texas Arlington
- New Mexico Tech
- University New Mexico
- Washington University at S. L.
- Michigan State University
- University of Utah
- South Dakota State University
- Clemson University
- Southern Methodist University

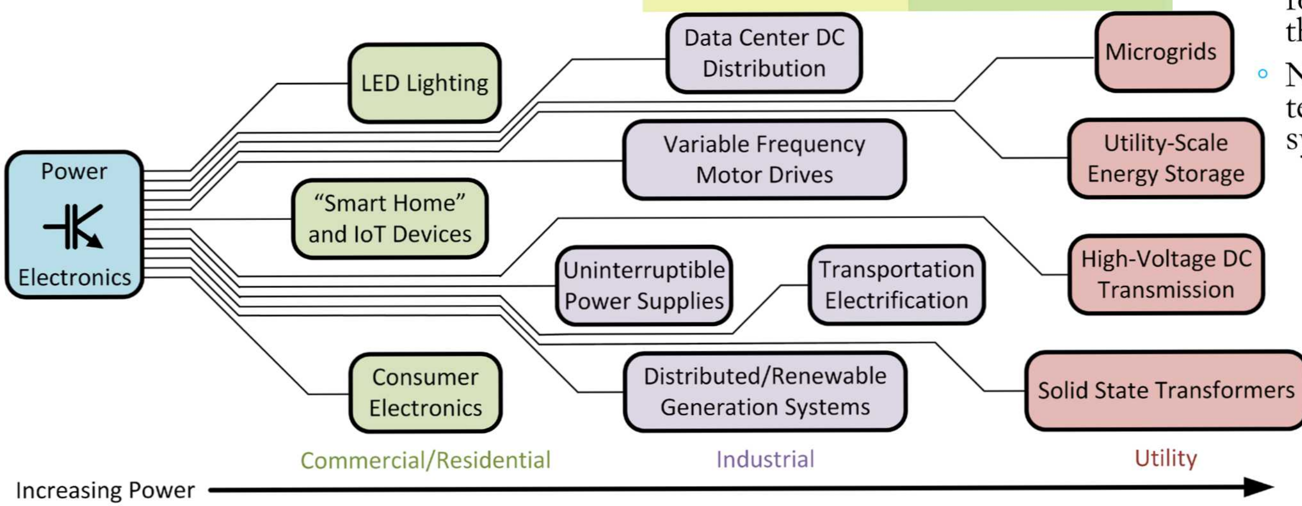
Industry and Utility Collaborators

GeneSic Semiconductor
Creare
InnoCit
Mainstream Engineering
Powdermet
Urban Electric Power
Helix Power Corporation
Eugene Water and Electric Board
Cordova Electric Cooperative
Strategen
Mustang Prairie Energy
ANZA Electric
PNM Resources

WattJoule
UniEnergy Technologies
Sterling Municipal Light Department
Public Service of New Mexico
National Rural Electric Cooperative Association
Hawaii Electric Light
Green Mountain Power
Electric Power Board of Chattanooga
Electric Power Research Institute
Ecoult Battery
Demand Energy
Burlington Electric Department
NELHA

Increasing Role of Power Electronics in Electricity Infrastructure





Continued increase in the role power electronics through out the grid

Approximately 30% of all electric power currently generated uses PE somewhere between the point of generation and distribution.

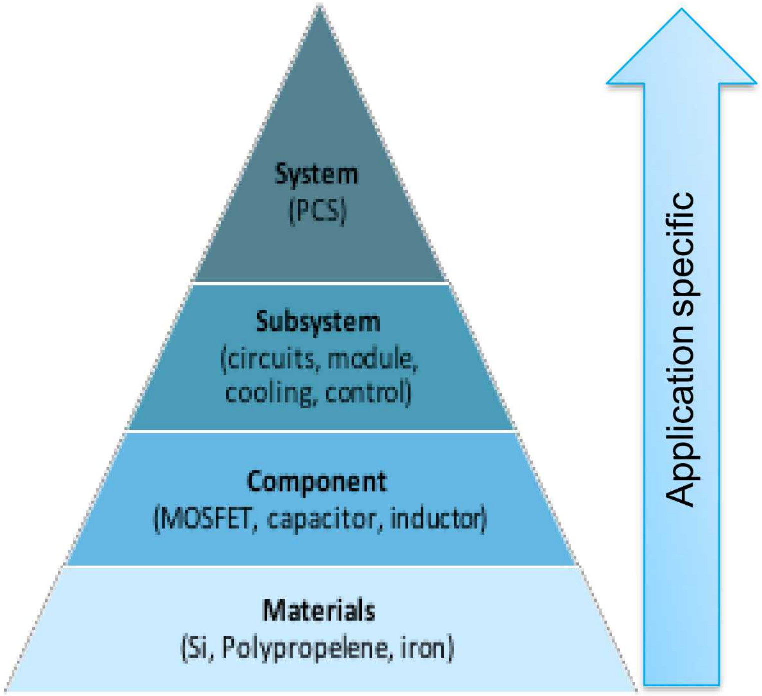
By 2030, it is expected that 80% of all electric power will flow through PE converters.

Cost reductions in power electronics and power conversion systems has been slow to come.

- Bringing in WBG devices can make format factor smaller, reduces thermal management issues
- New magnetics and high temperature capacitors can make the systems more compact and robust

PE R&D is hierarchical – Technology Gaps Exists

- **Systems**
  - Apex block that performs the end-use application
  - Application-specific topologies, novel converter configurations, and optimization of the overall system
- **Subsystems**
  - Multiple components together form subsystem
  - Perform a specific task within the PCS
  - Switching modules and advanced packaging, cooling systems, controls, schemes, etc.
- **Components**
  - Materials are combined together to form components
  - Basic building blocks circuit
  - Includes switches, capacitors, inductors, etc.
- **Materials**
  - Bottom layer in the PE R&D spectrum (non-application specific)
  - Foundation for other technological improvements
  - Advanced semiconductor, magnetic materials, new capacitor dielectrics, etc.



Power Electronics R&D Spectrum

Power Electronics and Power Converters

Optimization at the interface between power electronics and electrochemistry. Development of power converters using SiC and GaN. Reliability of WBG Power Converters. Improved energy storage safety through power electronics.

- New methods for the optimization and efficient coupling between batteries and power electronics for improved power conversion. Topologies and architectures configured for aqueous batteries including flow batteries, alkaline zinc based batteries
- New topologies at the cell and module level power electronics to improve the performance, safety and reliability of cells
- Synthesis, structure property investigations of soft magnetic materials and the development of magnetic cores for high frequency transformers.

External Projects with Universities

- High-temperature iron-nitride transformer for high frequency converters (with UC Irvine)
- Development of advanced gate oxide for wide band gap devices
- SiC and GaN-based power inverters (in collaboration with GeneSiC, Creare, and Innocit)
- High energy dielectrics for scalable capacitors (in collaboration with SMU/UT Dallas)
- Low voltage and high current bidirectional converters for flow battery systems (with UT Austin)
- Medium-voltage power electronics and reliability of MV power converters (with Ohio State and Univ of Houston)
- Power converter integration with large format batteries and PV panels (New Mexico State and Urban Electric Power)

Power Conversion System & Integration

Energy Storage Technologies	PCS interconnect	R&D Opportunity	R&D Opportunity
Flow Batteries	High Current/Low Voltage	Wide band gap electronics - GaN	Energy Density & Controlability
Li-ion	Low Current/High Voltage	High Efficiency - SiC	Safety, Reliability & Controlability
Zinc Manganese Oxide	Low Current/Low Voltage	High Efficiency - SiC	Safety, Reliability & Controlability
Sodium Sulfur	Low Current/High Voltage	High Efficiency - SiC	Safety, Reliability & Controlability

- **Flow batteries require higher current and lower cell voltages for optimal energy conversion. This is a challenge for the PCS and high efficiency semiconductors will be critical such as GaN**
- **Li-ion, Zinc Manganese Oxide and Sodium Sulfur have similar cell voltage and current requirements and the charge and discharge characteristics when interfacing with the PCS are similar.**

Summary

Battery technologies for grid applications are advancing rapidly.

Building energy storage systems with high energy and high power capabilities while keeping safety and reliability remains challenging with a lot of technical questions

Scaling the size and cost of power conversion system is needed to further reduce the overall cost of energy storage

Improving the safety of MWh to GWh storage poses challenging problems for safety. What can be done with power electronics to mitigate system level failures

Market Gaps

- Existing battery technology solutions remain expensive for many applications
- Technologies not scalable to cover all markets and applications

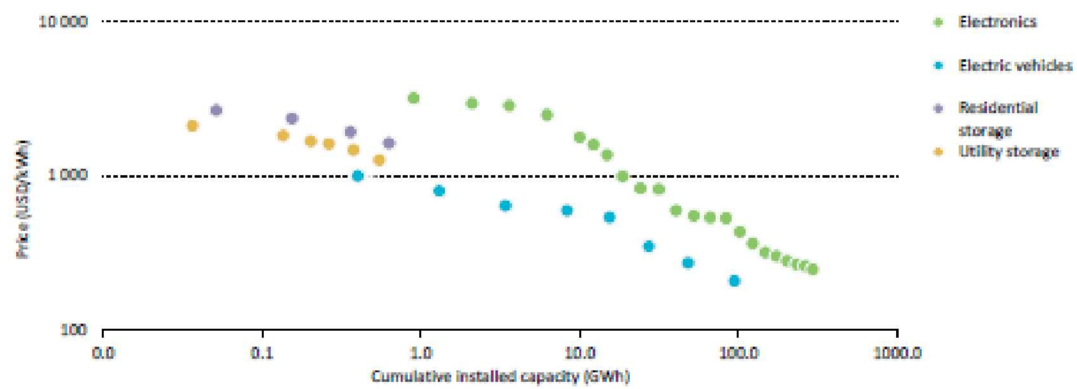
This work was supported by

US DOE Office of Electricity Delivery

Energy Storage Systems Program

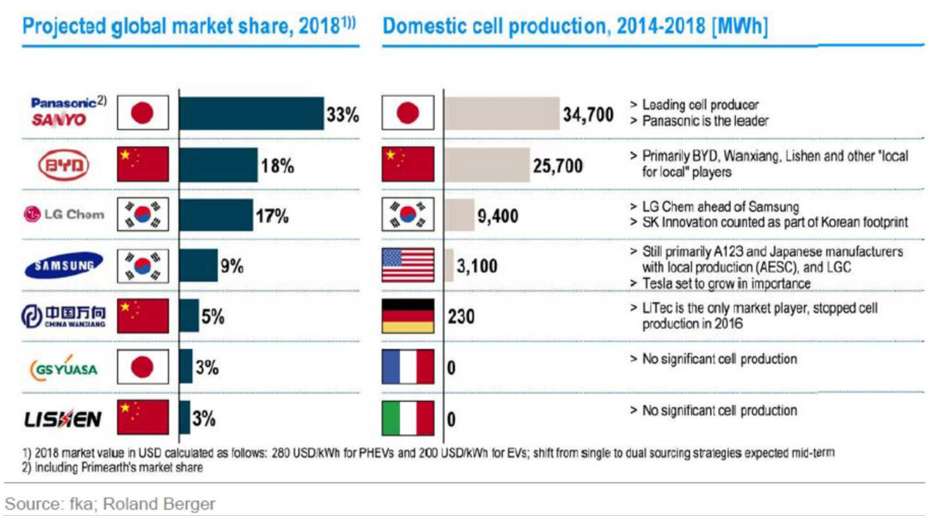
U.S. DEPARTMENT OF ENERGY

Manufacturing Scale and Cell/System Costs

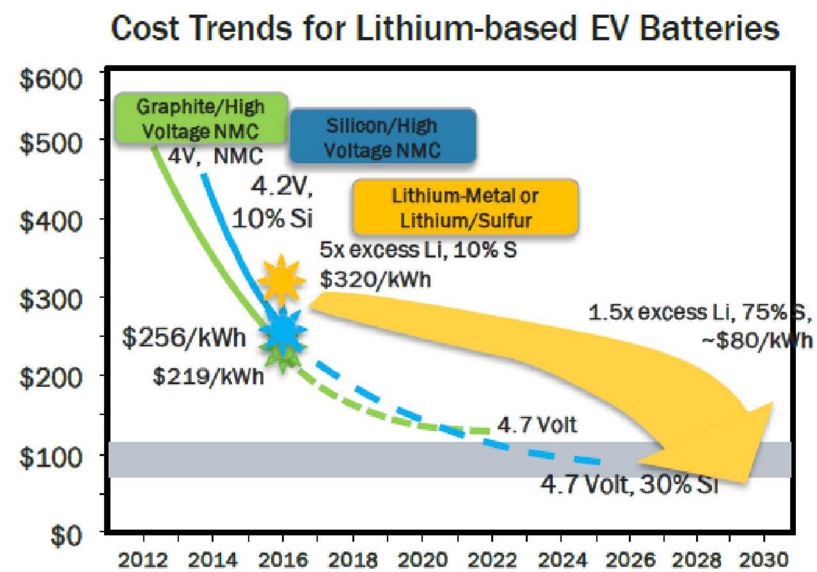


Li-ion storage technology price with manufacturing volume
Source: IEA, 2018

Future cost projections predicated on stable commodity prices, significant improvements in energy density, and cell performance



Most new capacity coming online is primarily for EVs



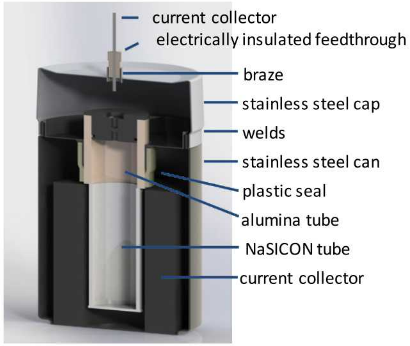
Cost trends for Li-based EV Batteries (pack level)
Source: David Howell, DOE VTO, 2018

Grid Storage needs Large Format Cells

Engineering costs are significant for small format cells. Large format cells are needed to reduce overall system costs.

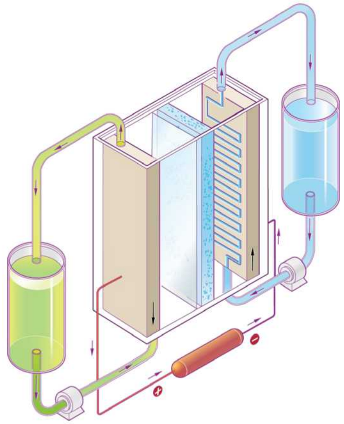
Large format cells also allow for tighter integration of power electronics, sensors, SOH monitoring at the cell level.

High Conductivity Separators for Low Temperature Molten Sodium Batteries



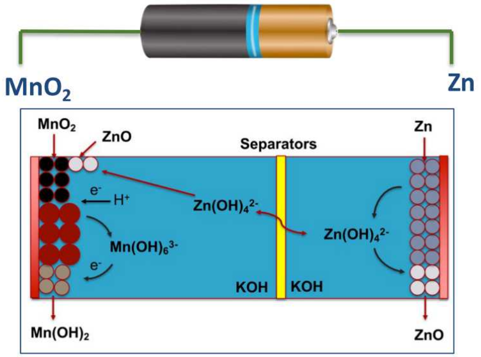
Robust ceramic separators exhibit low Na^+ conductivity at lower, more cost effective temperatures (120-180 °C).

Crossover in Redox Flow Batteries



Cross over of the electroactive species through the separator leads to severe capacity decay in flow battery systems.

Zincate poisoning of MnO_2 in Zn/MnO_2 Batteries



Zincate diffusion and subsequent poisoning of MnO_2 impairs reversibility and significantly decreases lifetimes.

Safety of Battery Storage Systems

Ensuring safety of battery storage systems remains a major concern

Need significant advances at materials, engineering and systems level

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

Figure courtesy of Summer Ferreira, Sandia, 2017