SAND2017-13430PE

Exceptional service in the national interest

Sandia National Laboratories

Energy Storage and Modernization of the Electric Grid

Babu Chalamala

City College of New York, Dec 11, 2017

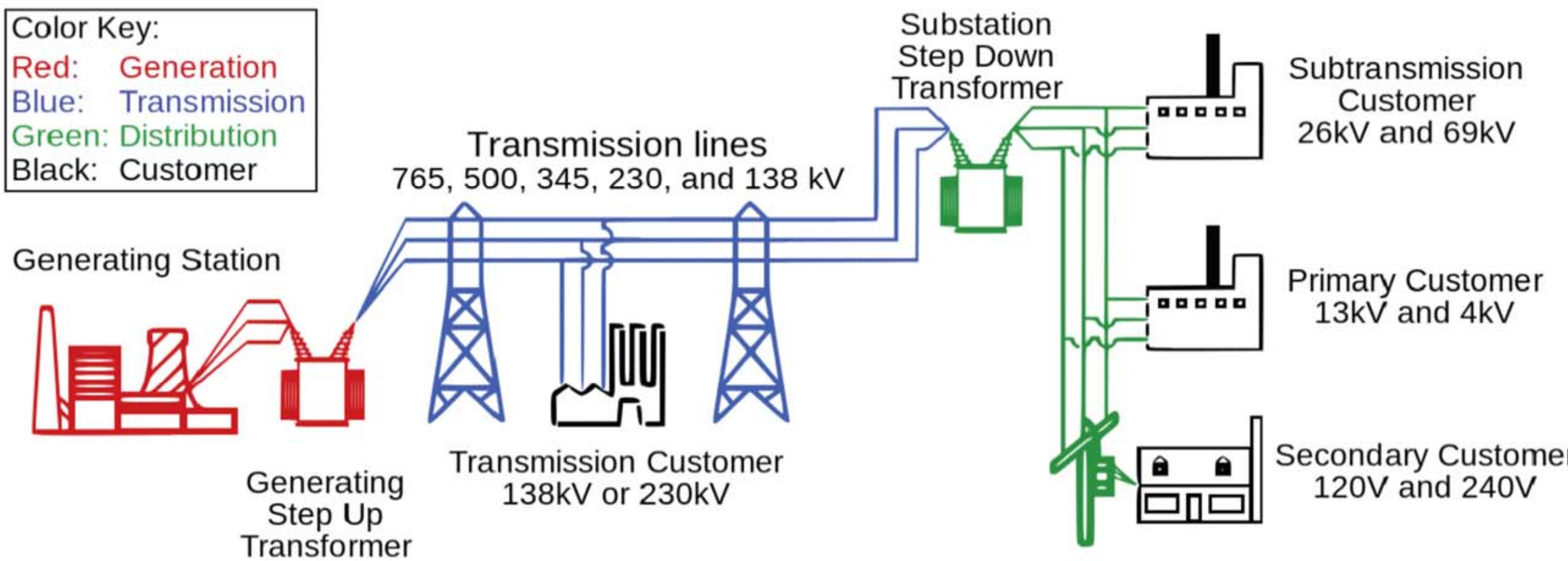
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and 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. SAND No:

Sandia National Laboratories

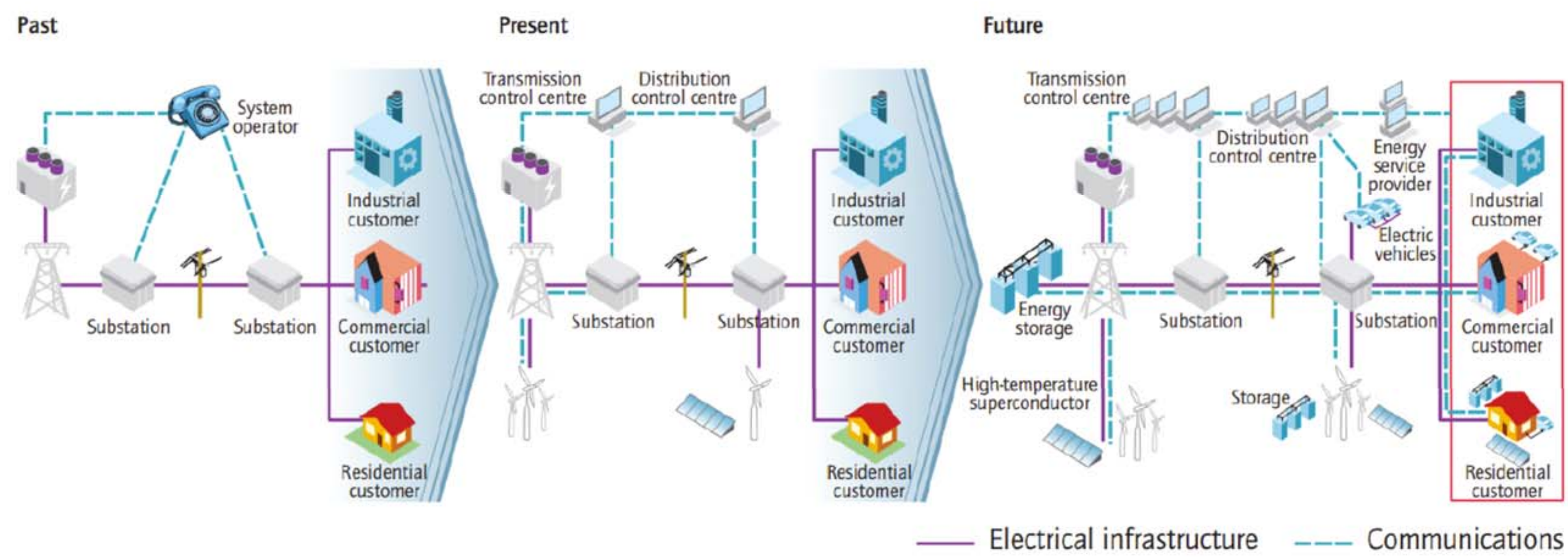
The Electric Grid Today



NERC

- Grid 1.0
  - A one way delivery system with very little flexibility, with generation and load always balanced
  - Utilities deliver reliable power at prices set by regulators in most markers, and variable market driven pricing in a few markets

Grid Evolution and the Future Grid



Source: Quadrennial Technology Review
US DOE, 2015

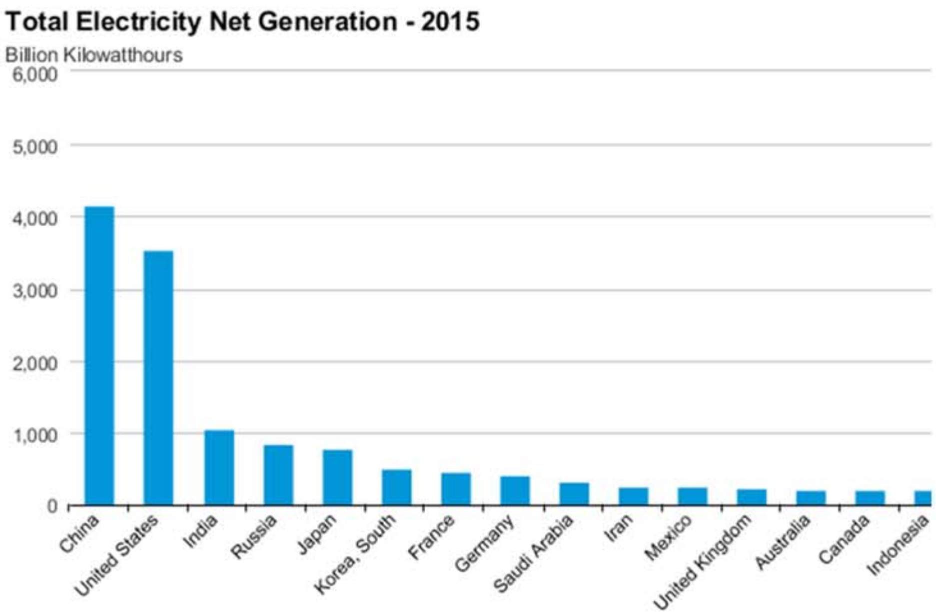
Grid 2.0

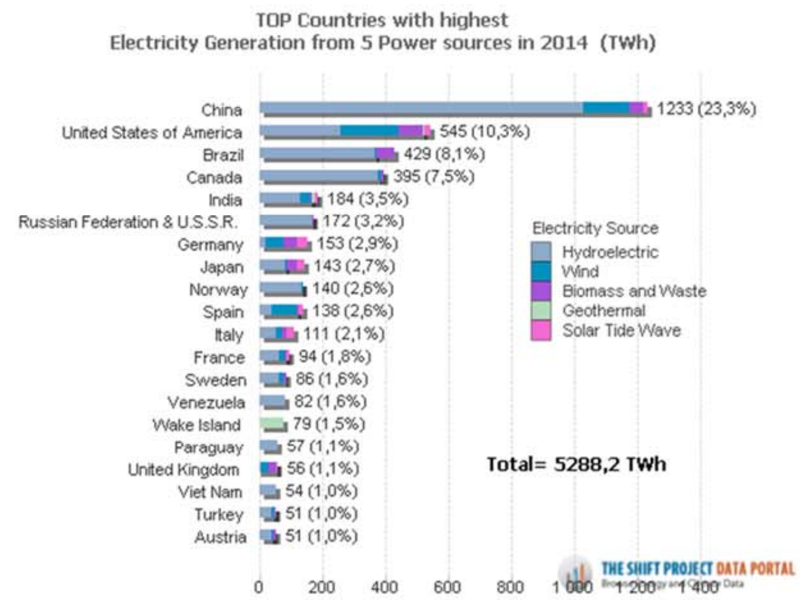
- Integration of renewables and distributed generation beginning to take off
- Minimal tools to manage grid instabilities

Future Grid

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

Grid by the Numbers

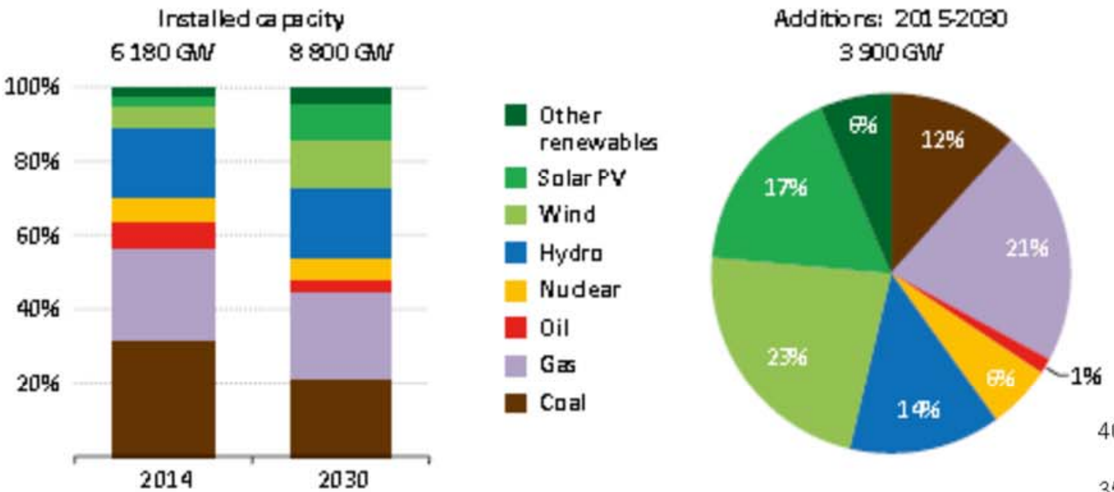


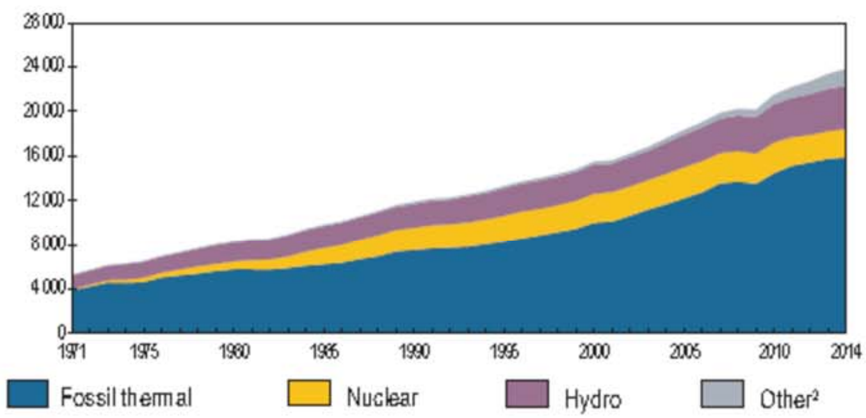


- 24 Trillion kWh of electricity generated annually (2014)

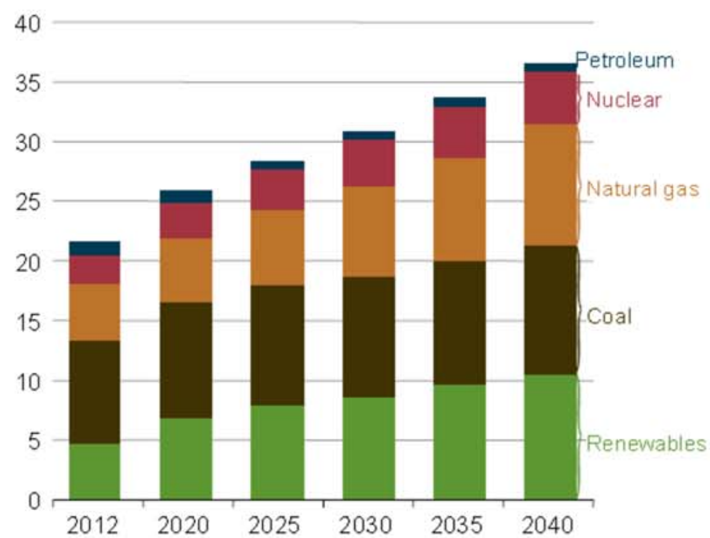
Source: US DOE, EIA (2016)

Worldwide Generation Capacity Mix and Future





World electricity generation by fuel (TWh)



2016 International Energy Outlook, EIA 2016

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

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 includes 6.1% from Hydropower and 7.3% from other renewables including wind and solar.
- Total revenues of $388 billion, average revenue 10.42 cents/kWh

Sources: EIA, EEI

U.S Electricity Generation Mix

- U.S. electricity generation mix at utility-scale facilities in 2016 (EIA)
  - 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%

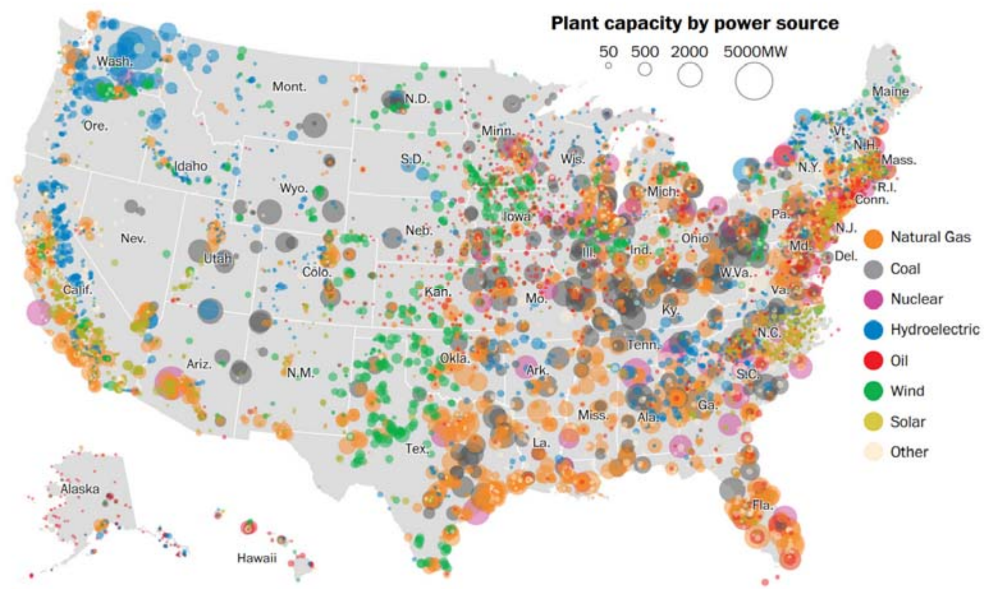


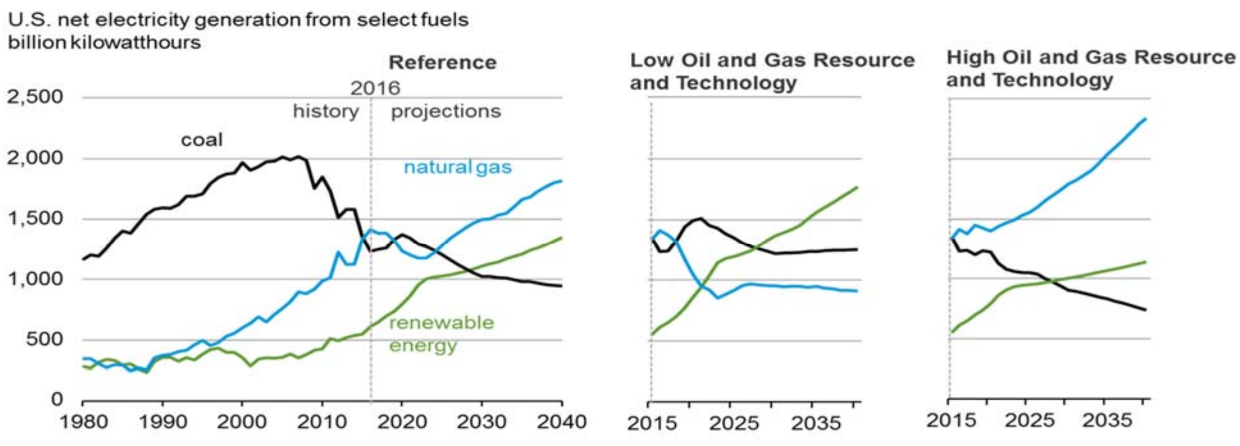
Image credit: Washington Post

Global Trends in Energy

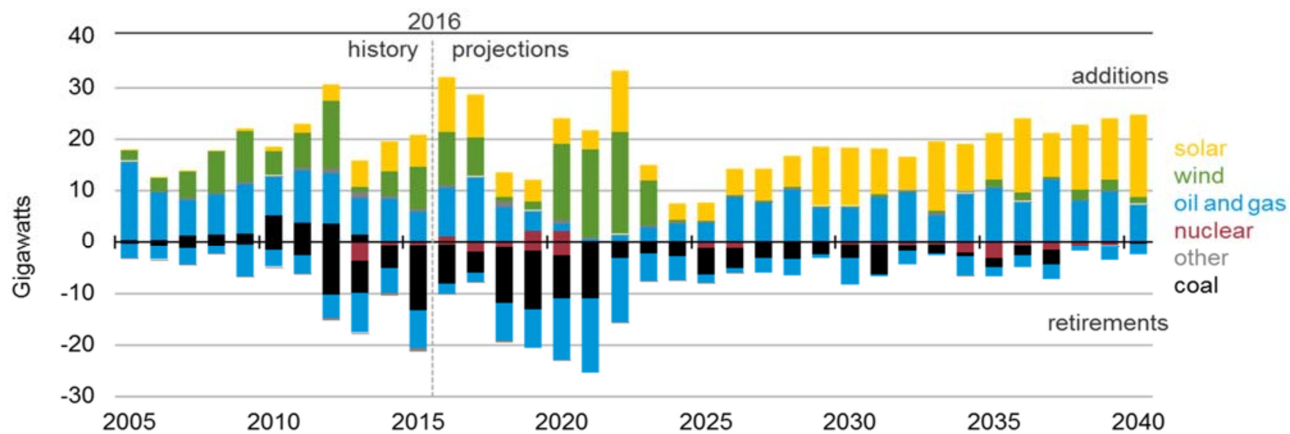
Sandia National Laboratories

- Aging Electricity Infrastructure
  - Grid security and resiliency
  - Need for Grid modernization
  - Transition to a distributed generation model
- Transformation of the Grid Edge
- 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
  - Optimization distributed energy systems across multiple platforms and use regimes (residential, commercial and utility scale)

Capacity Additions and Retirements



Source: EIA, Annual Energy Outlook 2017

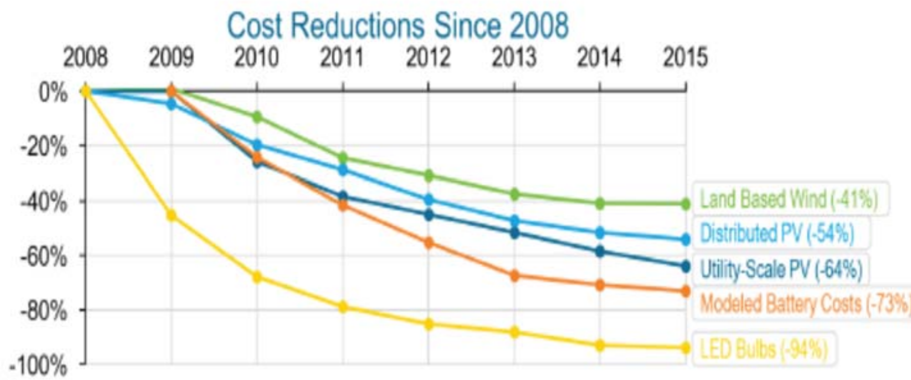


Source: EIA, Annual Energy Outlook 2017

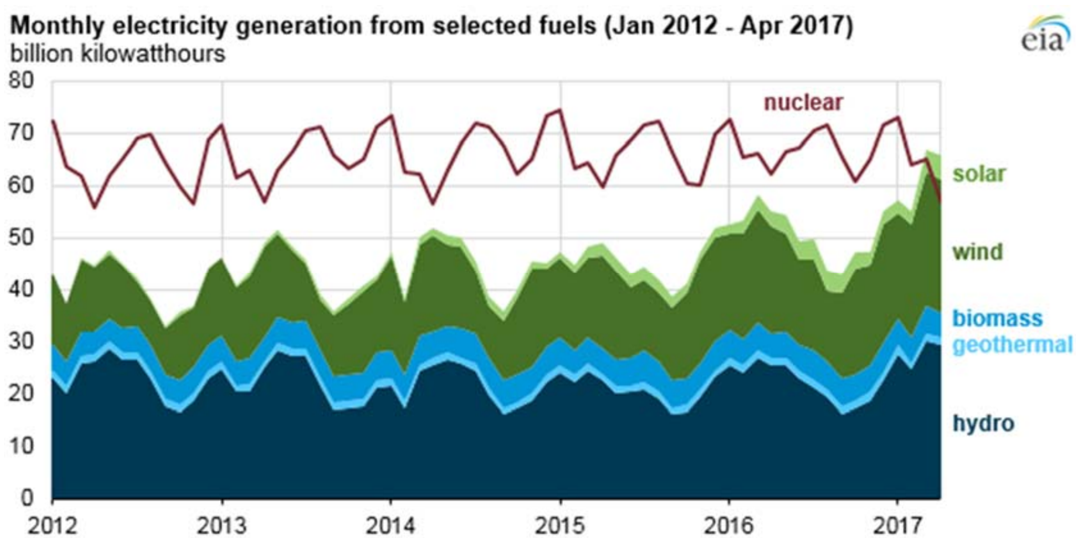
- Natural gas resource availability affects prices and plays a critical role in determining the generation mix.
- Coal-fired unit retirements primarily driven by low natural gas prices

Renewable Energy Growth

- Reductions in solar and wind capital costs and clean energy tax credits sustaining rapid renewable growth:
  - Cost reductions primarily due to high volume manufacturing and large scale deployments

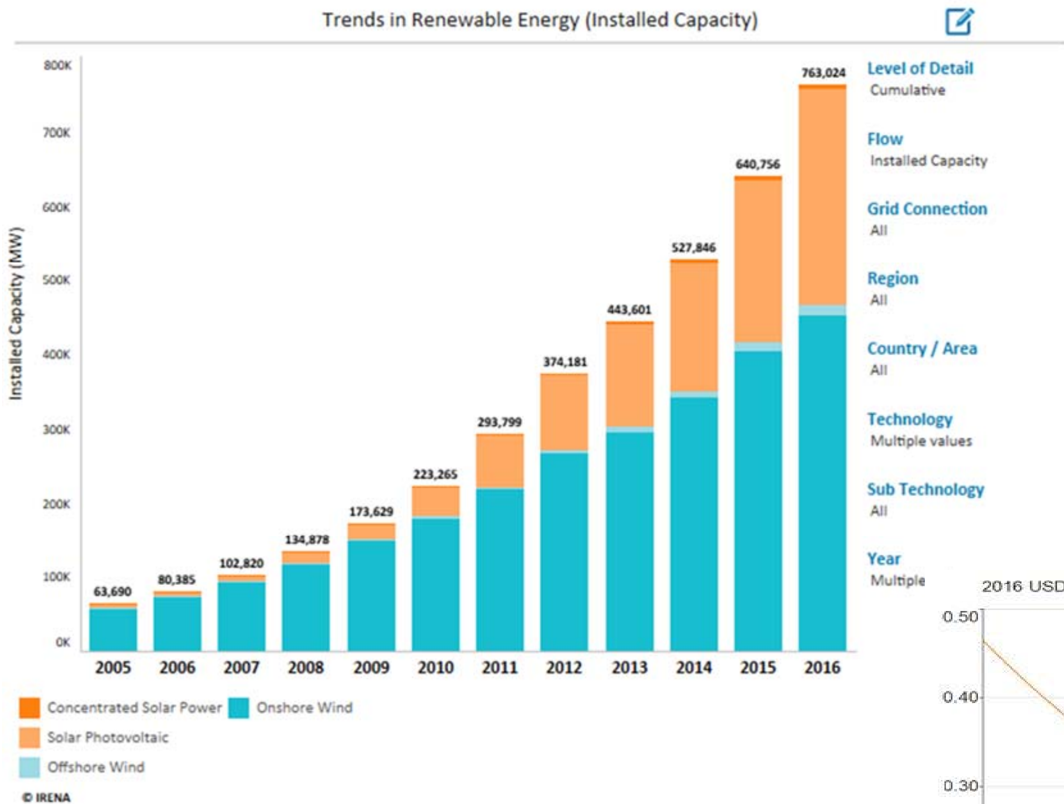


http://energy.gov/eere/downloads/revolutionnow-2016-update



- Utility-scale renewables generation in the US surpassed nuclear generation in April 2017.
- GTM Forecasts by 2021, solar, storage and wind capacity additions will exceed natural gas in California (GTM Research).

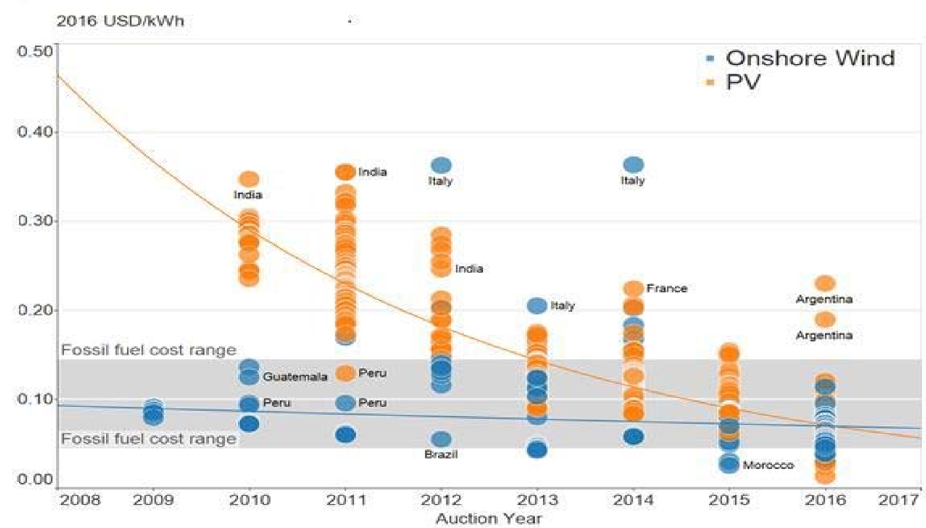
Implications of Renewables on the Power Sector



Rapidly Improving Economics

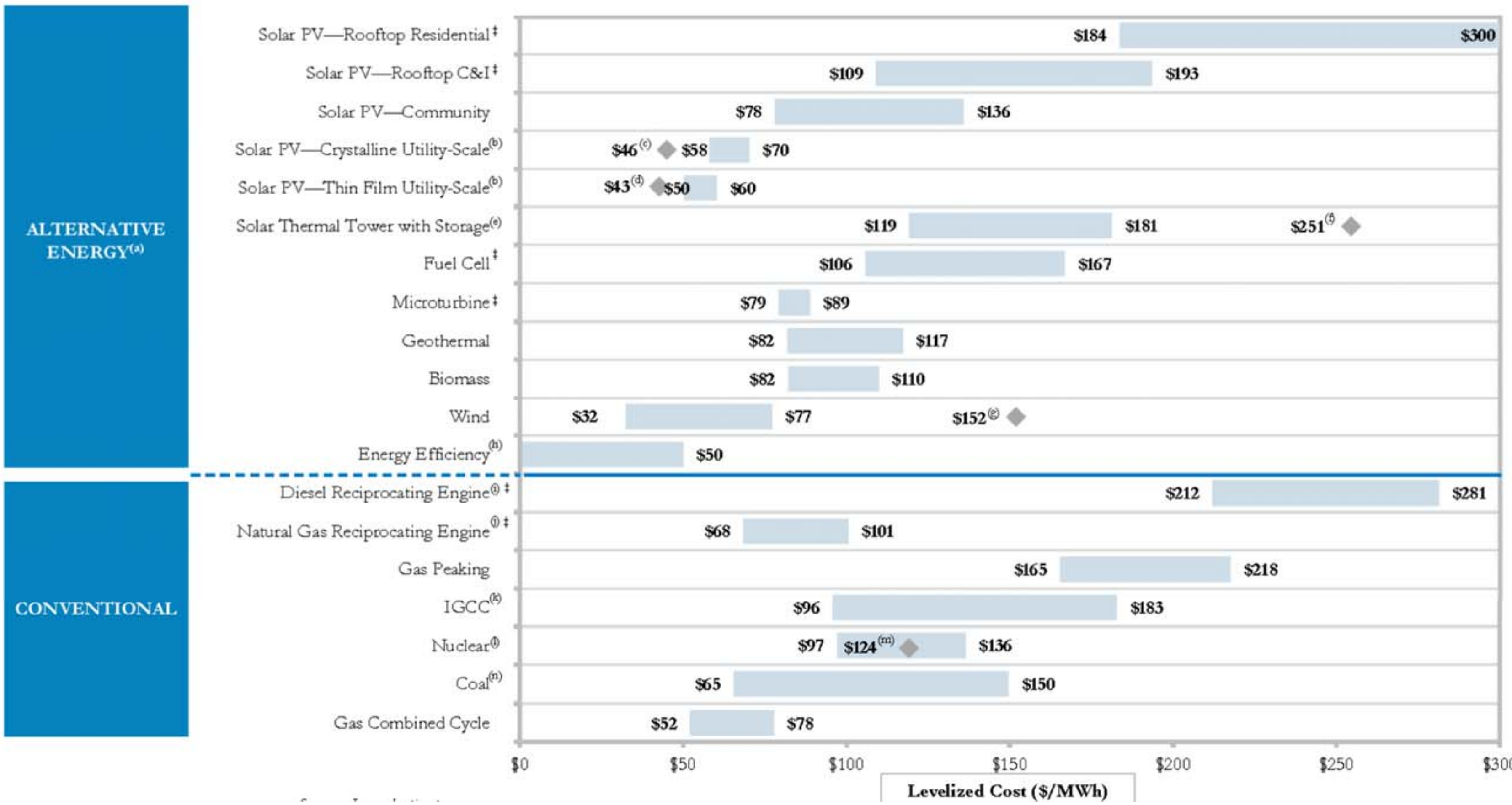
- Convergence of solar PV and onshore wind prices
- Projects for a wide range of technologies and locations are being offered at very low long-term PPAs

- CSP @ 9.5 UScents/kWh (Dubai)
- Solar PV @ 2.4 -3 UScents/kWh (Mexico, Abu Dhabi)
- Onshore Wind @ 3 UScents/kWh (Morocco, Mexico)



IEA, IRENA, 2017

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.

Grid Modernization

- Economic drivers
  - Aging electric power system exacts substantial costs due to outages and inefficient energy technologies.
- Environmental drivers
  - 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 drivers
  - 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 drivers
  - Increasing competition worldwide in energy sector as countries are moving toward clean energy technologies
  - Improving competitiveness domestically and globally requires steep cost reduction by technology/manufacturing advances, and competitive energy market

Image credit: AP

Image credit: T&DWorld

Research & Development 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

Timeline: Sandia Grid Modernization

Sandia National Laboratories

1980s

Distributed Energy Technology Laboratory (DETL) opens

Sandia designs first battery test facility hosted by PSE&G in NJ

Lead Center for the Exploratory Battery Technology Development and Testing Project

1990/2000s

Interconnected PV systems work begins

US Infrastructure Assurance Strategic Roadmaps

DOE designates Sandia as US Rep to IEC TC57, (standards for information exchange for power systems)

2003/04

U.S. Department of Energy – Electricity Delivery & Energy Reliability

DOE/OE Established

National SCADA Test Bed (NSTB) established

IEEE 1547: *Standard for Interconnecting Distributed Resources with Electric Power Systems*

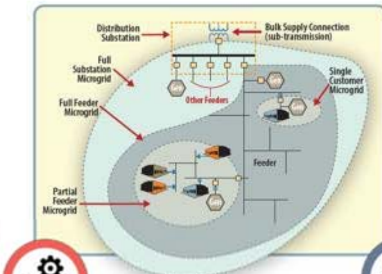
DOE/EPRI Electricity Storage Handbook Published

Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack

Common Vulnerabilities in Critical Infrastructure Control Systems

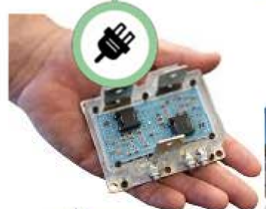
2008

Energy Surety Microgrid (ESM™) Methodology



ESM work begins-LDRD

2009



R&D 100 SiCPower Module

ARRA-funded reconfiguration of DETL to enable high penetration experimentation on distributed generation

2010

Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) established

R&D100: Micro Power Source

Energy Storage Test Pad established as the first facility to test 1MW class storage systems at a national lab

2011

Enabling Secure, Scalable Microgrids with High Penetration Renewables Grand Challenge

SSM SECURE SCALABLE MICROGRIDS It's the end of the grid as we know it

R&D100 Award Winners:
- Ultra-high-voltage Silicon Carbide Thyristor
- The Demand Response Inverter

2013

Sandia develops the DOE/SNL Global Energy Storage Database

2014

Grid Modernization Continuum established & Sandia participates in 29 GMLC projects

GRID MODERNIZATION LABORATORY CONSORTIUM U.S. Department of Energy

2015

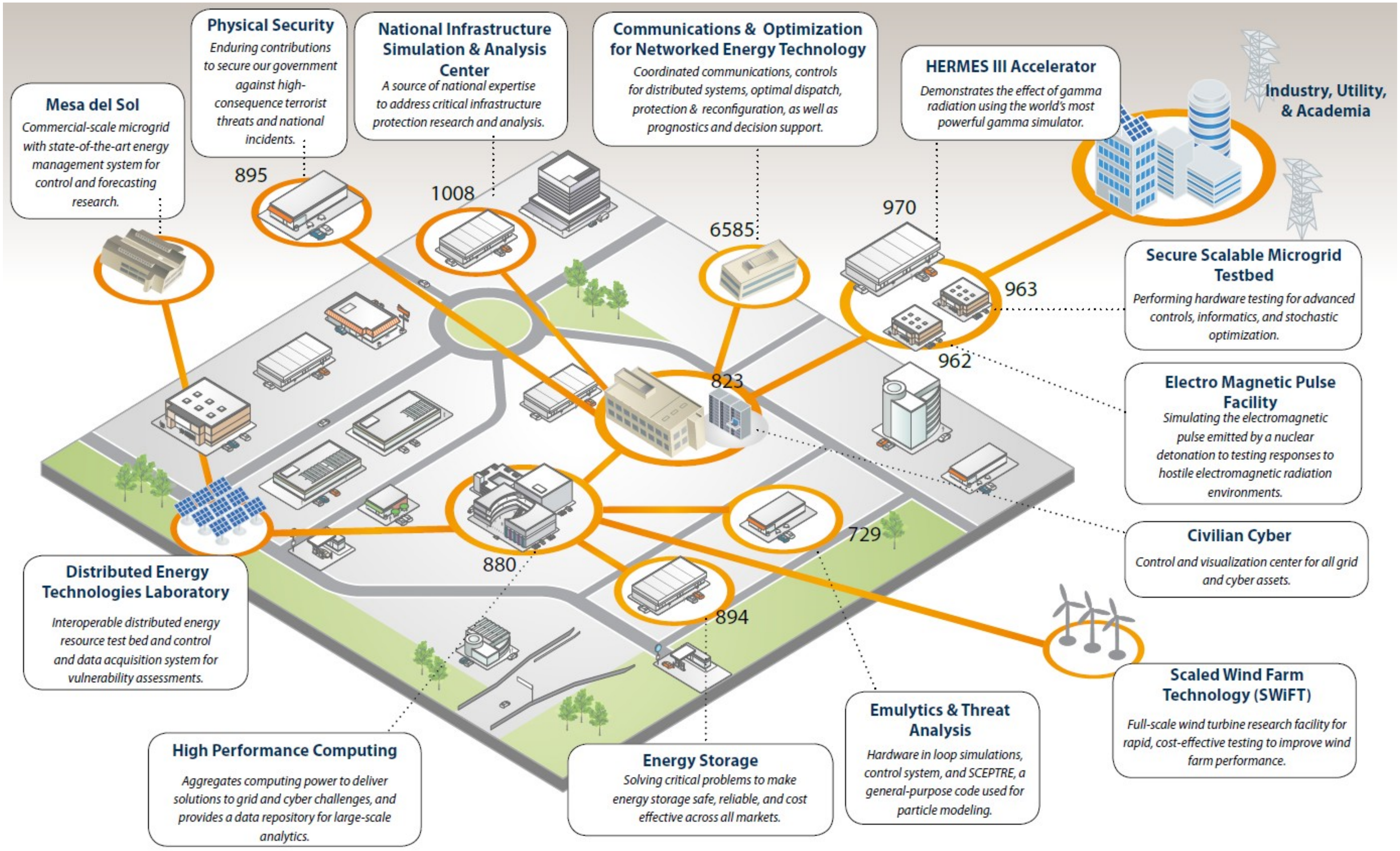
2015 R&D 100 WINNER

Sandia and United Silicon Carbide, Inc., create new high voltage switch

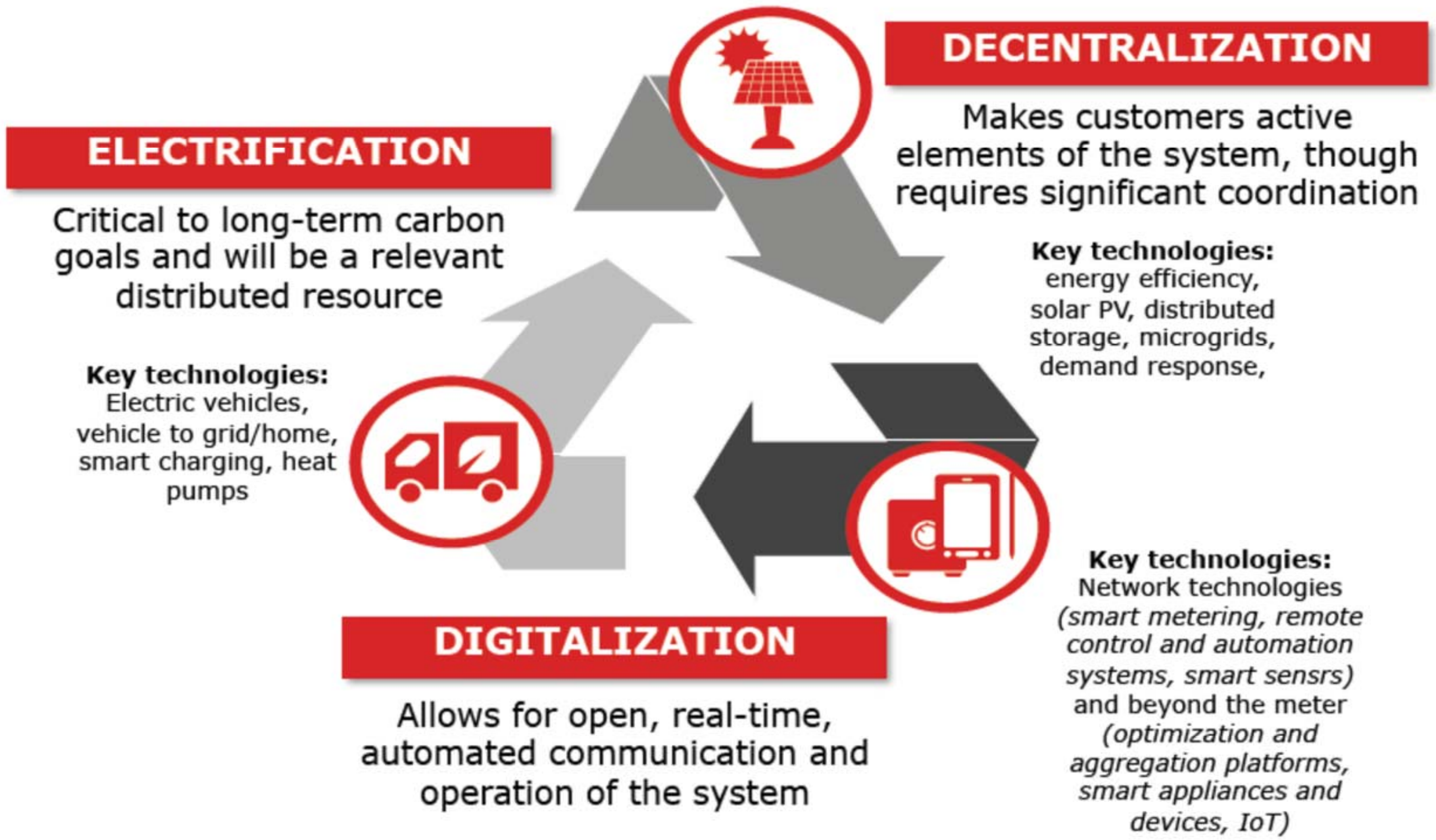
SIRFN established as Annex 5 of ISGAN

Microgrid Design Toolkit available

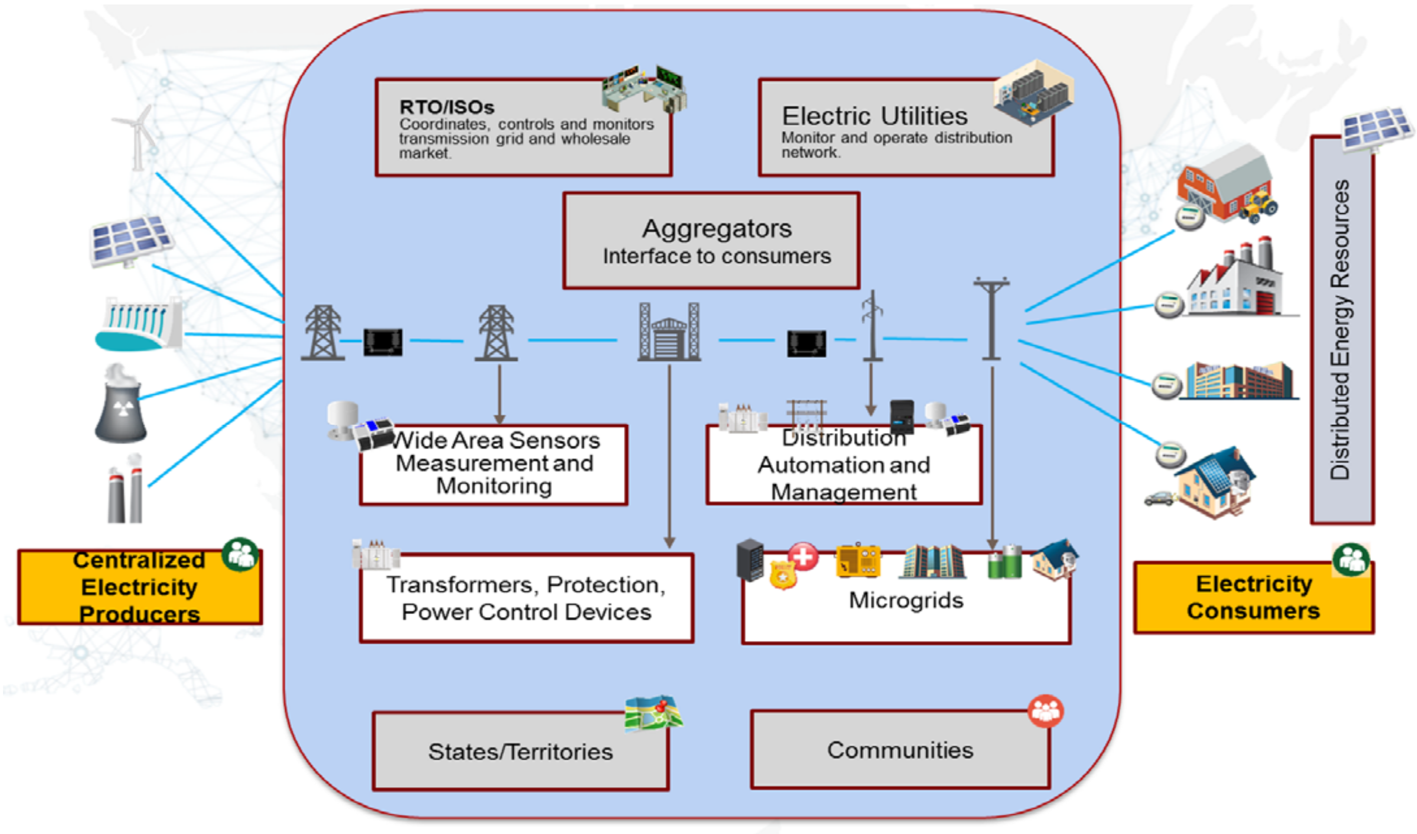
Integrated R&D Capabilities



Grid Edge Transformation



Grid is evolving towards a Hybrid Architecture



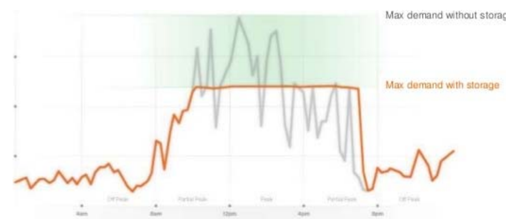
- Throughout these changes in the next 20-30 years, a hybrid grid architecture will emerge: mix of resources, entities, architectures
- Energy Storage is key for the Future Grid. ES needed at every level.

Application Drivers for Grid Energy Storage

Grid-scale energy storage can enable significant cost savings to industry while improving infrastructure reliability and efficiency

- 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.

Example – Peak Shaving in NYISO

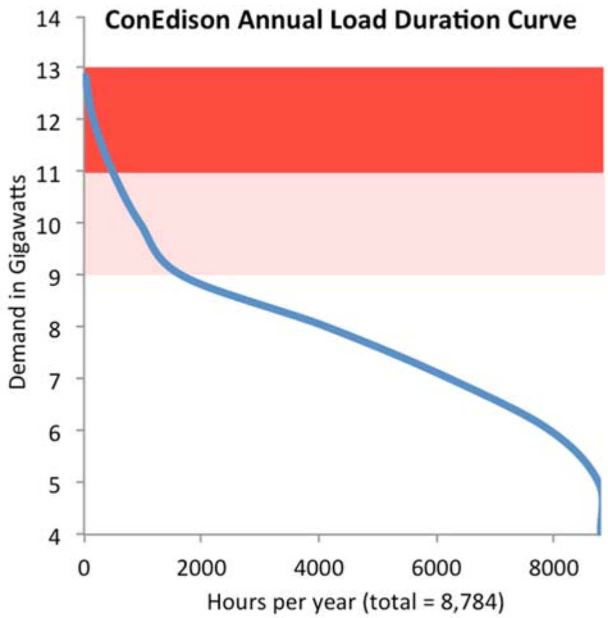


Table I-1: NYCA Energy and Demand Forecasts Net of Energy Saving Impacts

2017 Long Term Forecast[1] - 2017 to 2027

Energy - GWh				Summer Peak Demand - MW				Winter Peak Demand - MW			
Year	Low[3]	Baseline[4]	High[3]	Year	Low[3]	Baseline[4,5]	High[3]	Year	Low[3]	Baseline[4]	High[3]
2016		159,169		2016		33,225		2016-17		24,416	
2017	156,755	158,632	160,504	2017	29,980	33,178	35,487	2017-18	22,693	24,365	25,989
2018	156,128	157,996	159,859	2018	29,891	33,078	35,375	2018-19	22,628	24,294	25,913
2019	155,546	157,405	159,258	2019	29,854	33,035	35,326	2019-20	22,546	24,207	25,821
2020	154,903	156,752	158,598	2020	29,817	32,993	35,279	2020-21	22,439	24,090	25,696
2021	154,017	155,855	157,689	2021	29,832	33,009	35,297	2021-22	22,394	24,043	25,645
2022	153,613	155,444	157,271	2022	29,856	33,034	35,323	2022-23	22,375	24,023	25,624
2023	153,468	155,298	157,124	2023	29,911	33,096	35,388	2023-24	22,361	24,008	25,607
2024	153,306	155,135	156,959	2024	29,962	33,152	35,448	2024-25	22,362	24,007	25,606
2025	153,182	155,009	156,832	2025	30,034	33,232	35,533	2025-26	22,356	24,001	25,600
2026	153,094	154,920	156,743	2026	30,118	33,324	35,629	2026-27	22,356	24,001	25,599
2027	153,143	154,971	156,795	2027	30,185	33,398	35,707	2027-28	22,356	24,000	25,599

Average Annual Growth - Percent

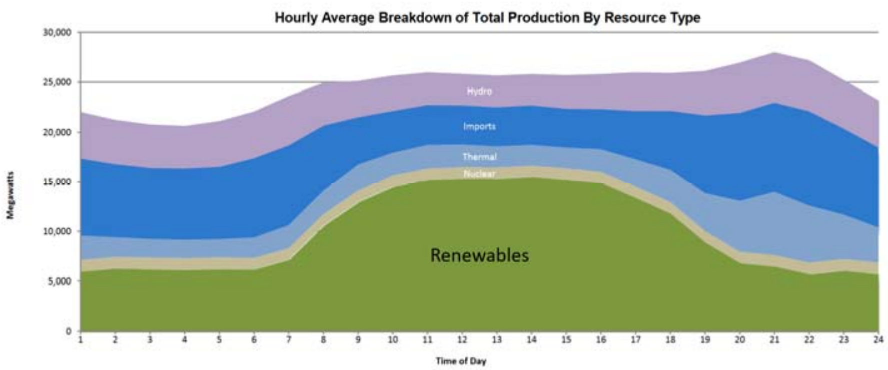
Period	Low	Baseline	High	Period	Low	Baseline	High	Period	Low	Baseline	High
2017-27	-0.23%	-0.23%	-0.23%	2017-27	0.07%	0.07%	0.06%	2017-27	-0.15%	-0.15%	-0.15%
2017-22	-0.40%	-0.41%	-0.41%	2017-22	-0.08%	-0.09%	-0.09%	2017-22	-0.28%	-0.28%	-0.28%
2022-27	-0.06%	-0.06%	-0.06%	2022-27	0.22%	0.22%	0.22%	2022-27	-0.02%	-0.02%	-0.02%

Source: ConEdison, NYISO

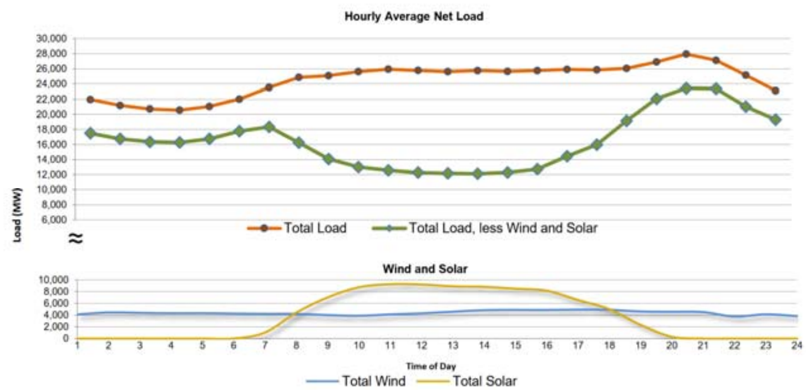
- Top 15% (~5GW) of total demand runs 7 days/yr, <2% of the time
  - Cutting top 100 hours saves $1.7B annually
  - Opportunity for energy storage: at least 500 GWh

Example – High RE Penetration

CAISO – Production in May 16, 2017

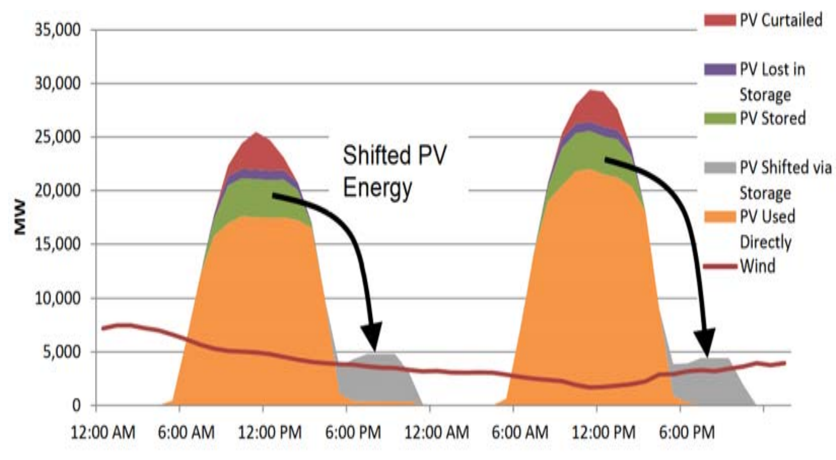


CAISO – Demand in May 16, 2017



Source: CAISO

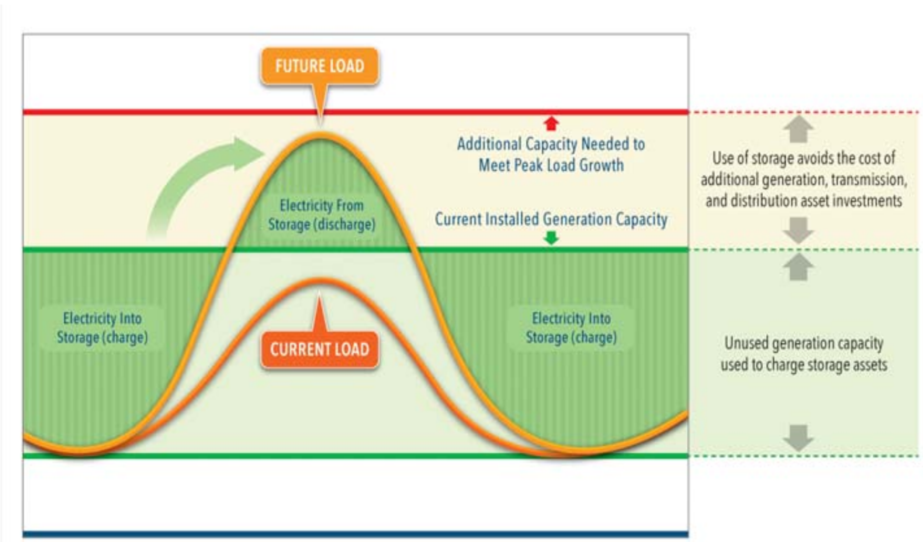
- In May 16, 2017, RE penetration in CAISO reached 42%
  - Ramp rate support needed: 12GW in 4 hours
  - Opportunity for energy storage in ramp support + peak shaving : at least 50 GWh in CA alone



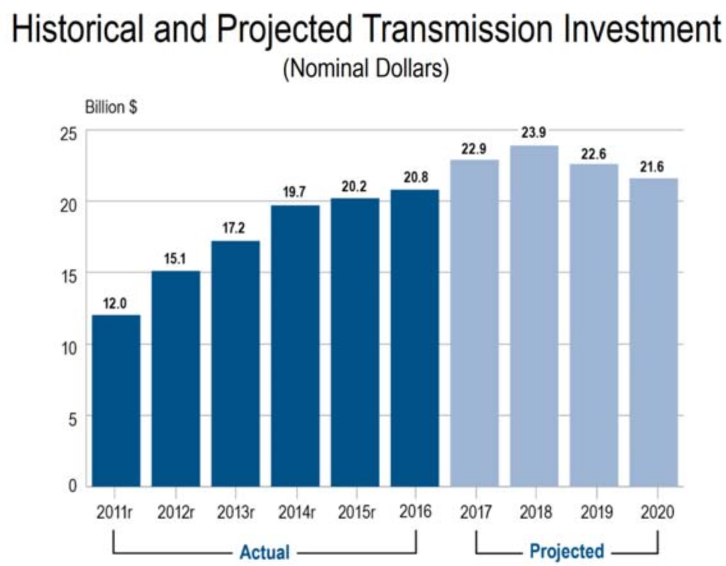
(b) Dispatch of solar energy

Source: NREL

Example – T&D Deferral



Source: NRStor Inc

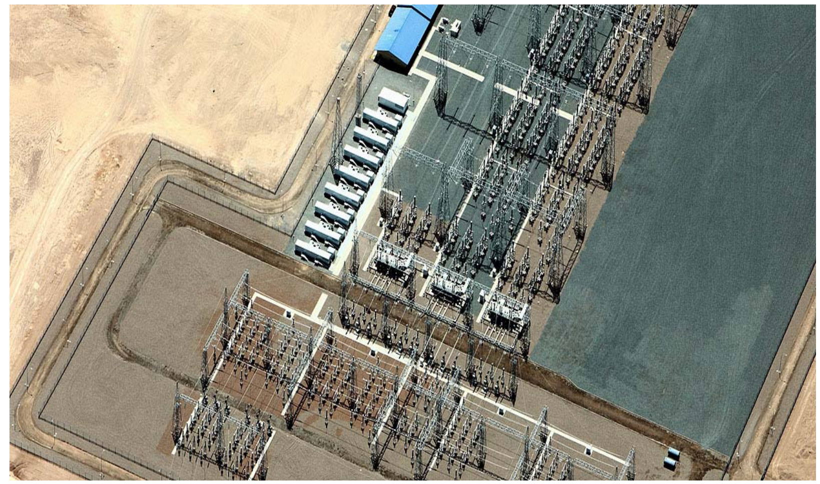


Source: Edison Electric Institute

- According to a new report from Navigant Research, global installed energy storage power capacity for T&D deferral is expected to grow from 331.7 MW in 2017 to 14,324.8 MW in 2026.

Example – Substation Resilience

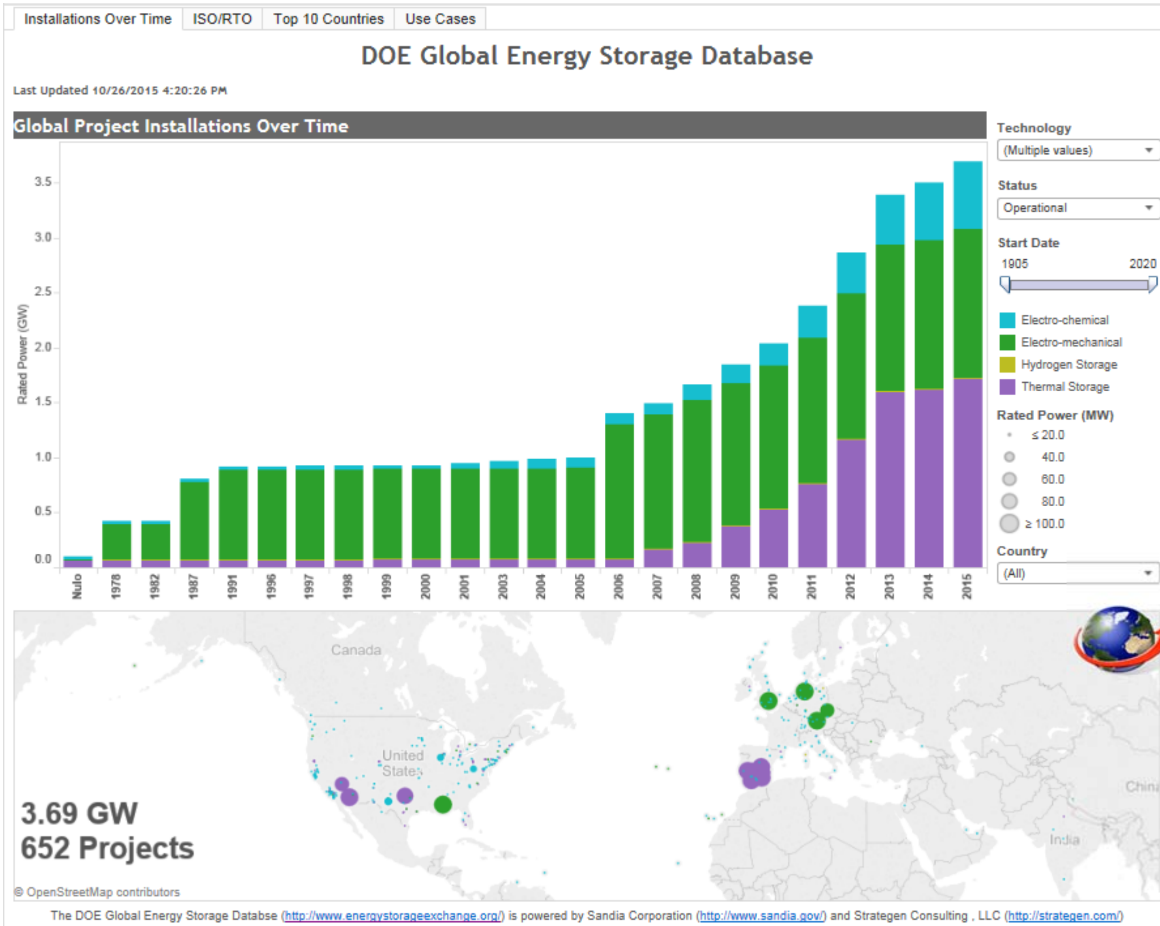
100kW/400kWh Vanadium Redox Flow Battery
EPB, Chattanooga, TN



AES Gener Los Andes Substation, Atacama Desert, Chile
Source: AES Energy Storage

- Big opportunity for ESS in substation resilience
  - Imagine: US mandates 1MW ESS for each of the 66,000 substations

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

Current Battery Energy Storage deployments (Operational as of Nov. 2017)

Energy Storage Comparison

<u>Globally</u>

- *1.7 GW - Battery Energy Storage (BES)*
- *~170 GW - Pumped Hydro Storage (PHS)*

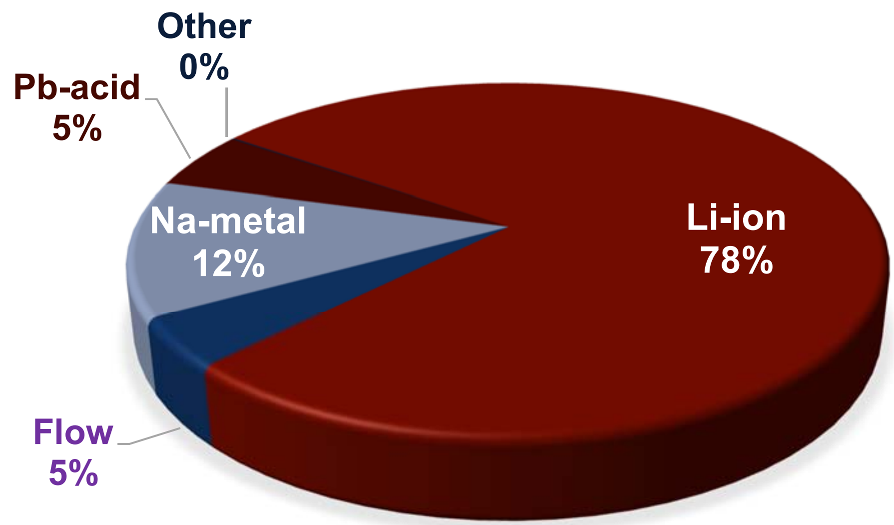
<u>U.S.</u>

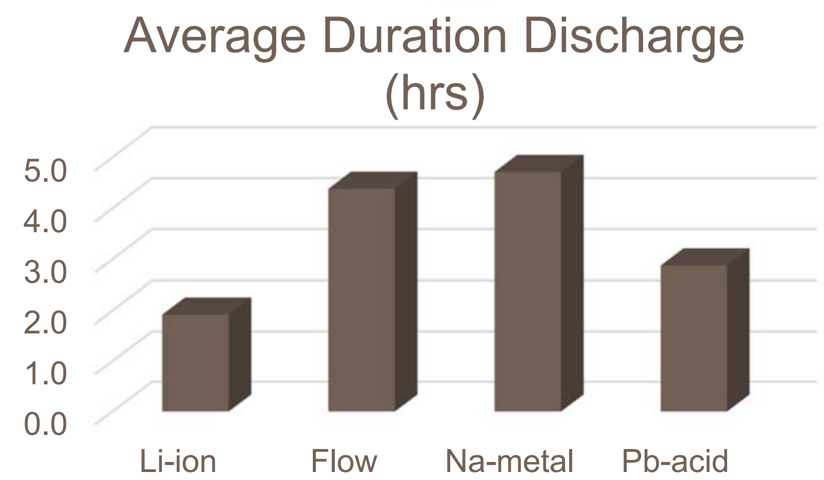
- *0.33 GW BES*
- *22.7 GW PHS*

<u>% of U.S. Generation Capacity</u>

- *0.03% BES*
- *2.2% BES + PHS*

Source: *DOE Global Energy Storage Database http://www.energystorageexchange.org/ Nov. 2017*





Sandia National Laboratories

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

Has Energy Storage Arrived?

Large projects are being built or being proposed.

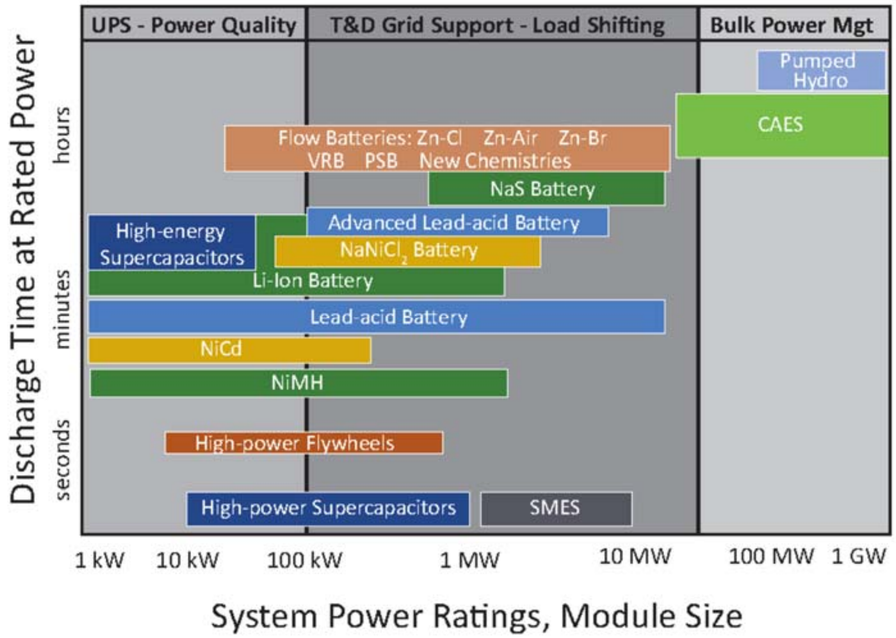
- January 2017 - Kauai Island Utility Cooperative signed a solar-plus-storage PPA at $0.11/kWh. This 28 MW PV and 100 MWh of batteries will displace the utility's current oil-fired baseload generation.
- May 2017 - Tucson Electric Power signed a PPA with NextEra Energy for a solar-plus-storage system at "an all-in cost significantly less than $0.045/kWh over 20 years." 100 MW PV and a 30 MW/120 MWh energy storage system.
- San Diego Gas & Electric commissioned a 30 MW/120 MWh Li-ion battery energy storage system in Escondido, CA (Sept'17)

SDG&E 30 MW/120 MWh Li-ion battery energy storage system in Escondido, Calif.

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

Energy Storage Applications

- 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 (**need for continued R&D**)
  - Electricity markets do not have market mechanisms for services ES can provide (**need to reduce regulatory/policy hurdles**)
- The future ….
  - Higher energy prices – storage starts looking better
  - Lower technology costs – storage starts looking better
  - Efficient market design – helps pay for storage costs



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

Gaps in Technology and Implementation

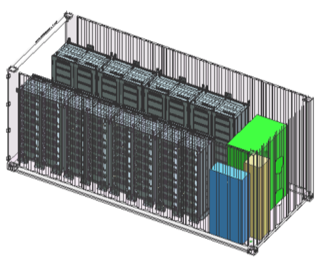
Grid is evolving towards a hybrid architecture. Energy Storage is key for the Future Grid where energy storage is needed throughout the grid infrastructure.

- 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

Elements of an Energy Storage System

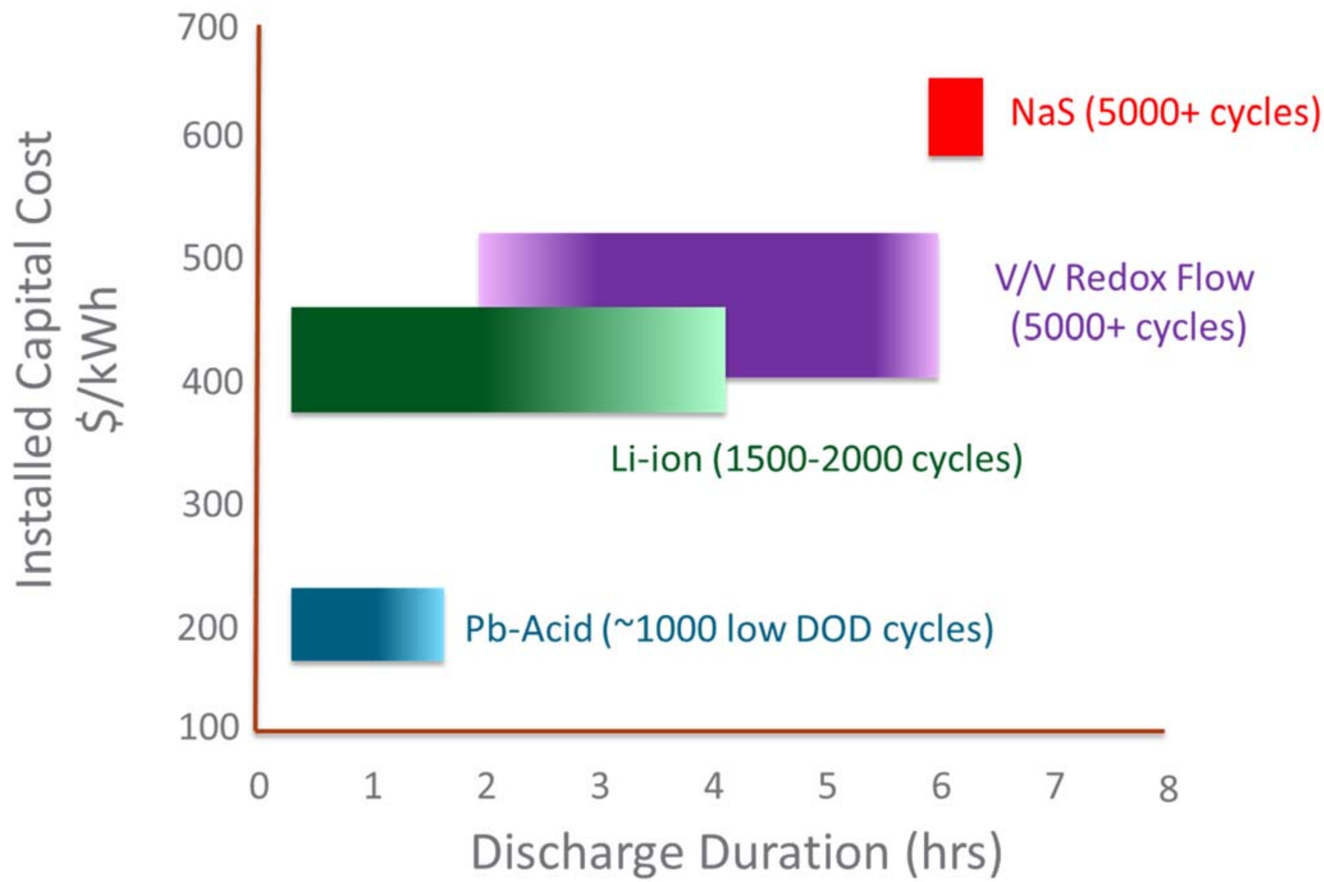
Storage	Integration	PCS	EMS
• Cell • Battery Management & Protection • Racking	• Container / Housing • Wiring • Climate control	• Bi-directional Inverter • Switchgear • Transformer • Skid	• Charge / Discharge • Load Management • Ramp rate control • Grid Stability

\+ Soft Costs



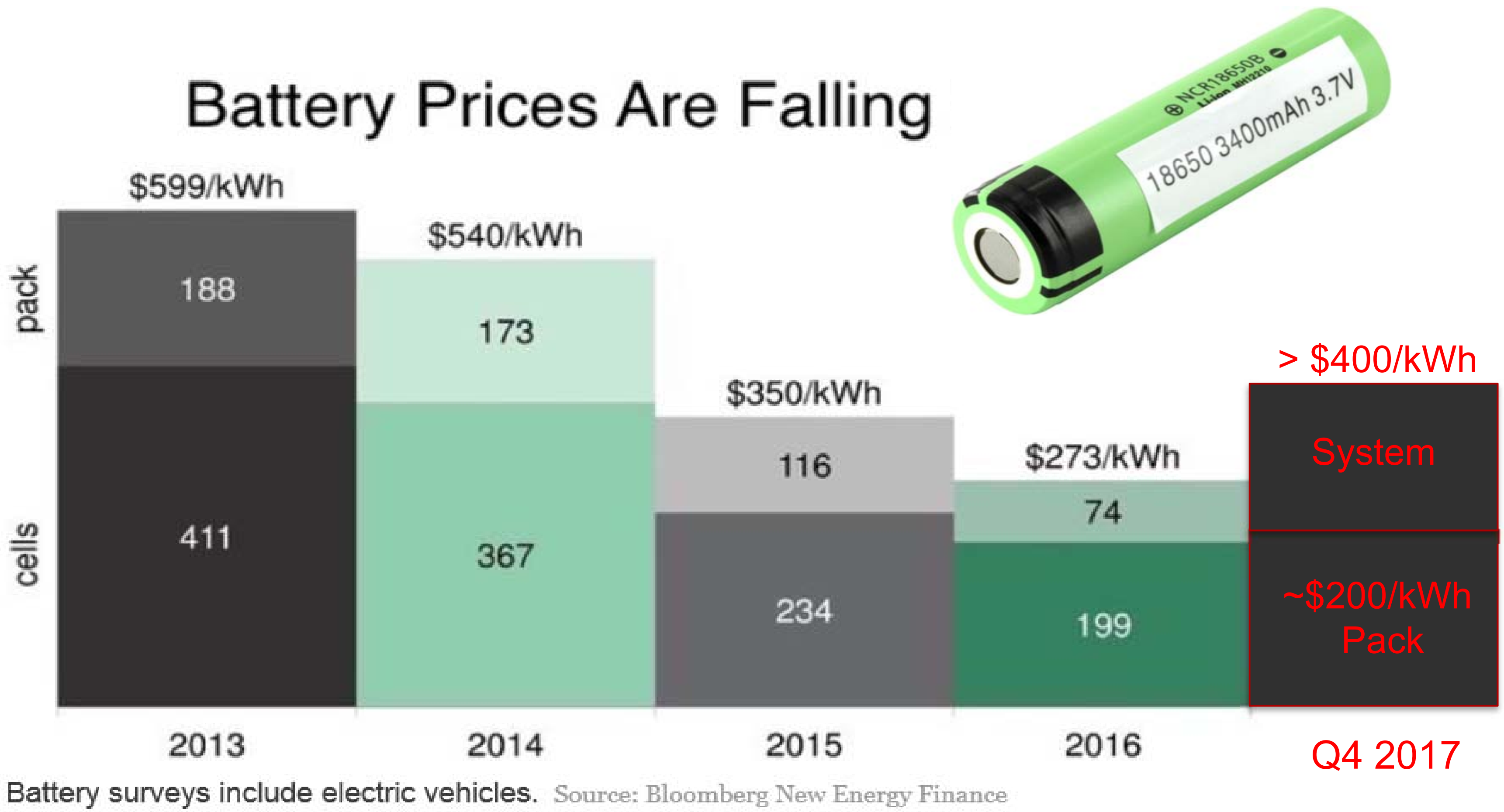
Cell to Battery to a Storage System
Doubling in cost, $250/kWh battery leads to $500-$700/kWh at the System level

Grid Scale Batteries System Capital Costs (Q4'2017)



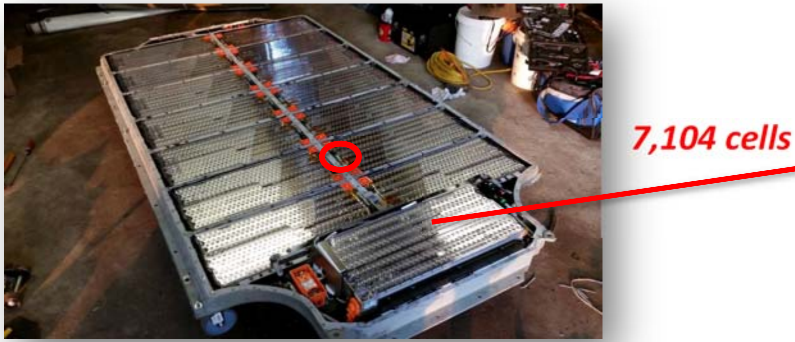
V. Sprenkle, PNNL, 2017

Lithium Ion Battery Prices



V. Sprenkle, PNNL, 2017

Need for Large Format Cells



http://insideevs.com/look-inside-a-tesla-model-s-battery-pac/

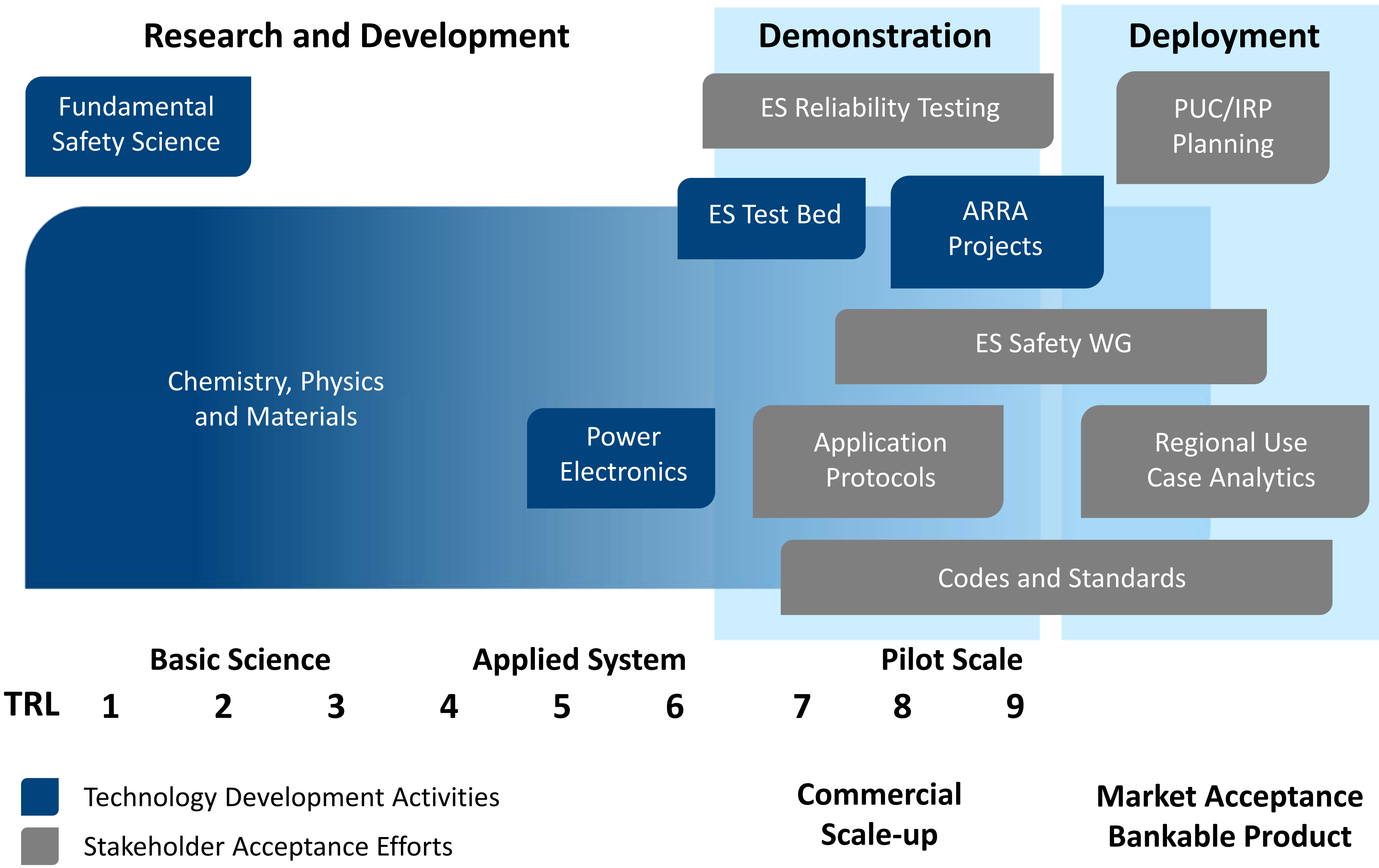
http://club.dx.com/forums/forums.dx/threadid.457734

18650 cell format used in 85 kWh Tesla battery

A system like 20MW -80MWh Mira Loma Battery Storage Facility would require in excess of 6 million of 18650 cells

Large form factor cells are needed to further drive system cost lower

DOE OE Energy Storage Program



Sandia Grid Energy Storage R&D

- Program goal is to solve 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
  - Engineered safety of large systems. Predictive models for storage systems safety
  - Controls and analytics for integration of utility class storage systems
  - Lower BOS and Integration Costs
  - Defining role in the Grid of the Future
- Support demonstration projects and outreach to utilities, regulators, and the industry
- Large multidisciplinary team leveraging resources across the laboratory and outside partners

Sandia ES R&D Program

- 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
  - Excellence in energy storage safety. Predictive models for storage systems safety – safety through large scale systems simulation and optimization
  - Controls and analytics for integration of utility class energy storage systems
  - Defining role in the Grid of the Future

Major Competencies

- Materials R&D including electrochemical materials and new battery chemistries
- Power electronics including high voltage devices (SiC, GaN) and modules
- Energy storage safety – cell and module level safety test and analysis (BATLab, ESTP)
- Energy storage project development
- Developing competencies in analytics and control for energy storage systems

Energy Storage is a Major Crosscut

Wide ranging R&D covering energy storage technologies with applications in the grid, transportation, and stationary storage

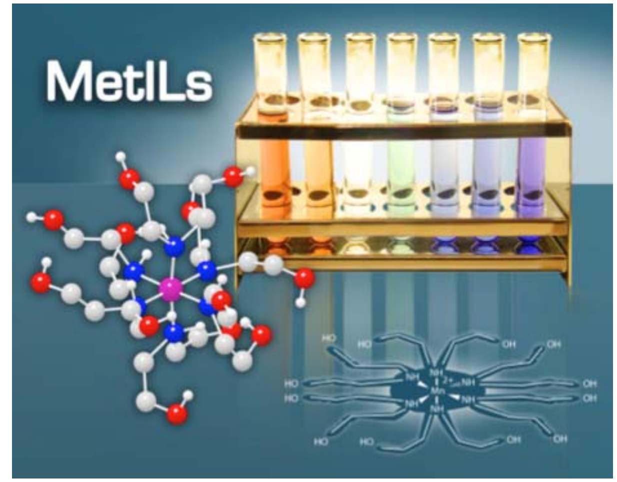
Grid Storage and the Need for Large Format Batteries

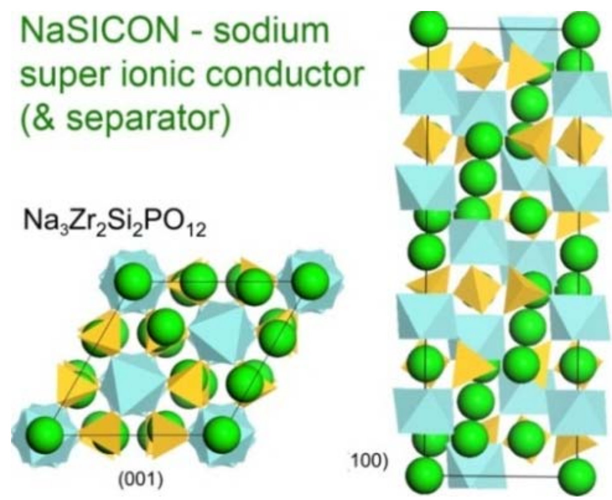
- Engineering costs are significant for small format cells. Large format cells are needed to reduce overall system costs.
- Large format cells also allow for tighter integration of power electronics, sensors, SOH monitoring at the cell level.

Materials & Systems Development

Battery chemistry and component technologies:

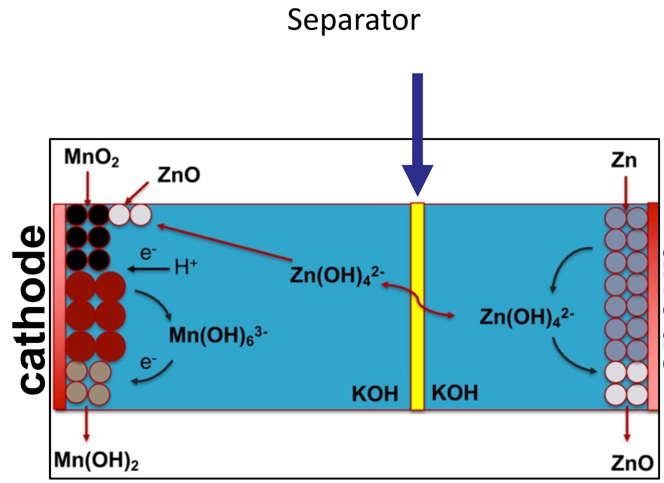
- Low Cost Membranes for Flow Batteries
- Sodium Based Batteries
- Advanced Materials for Ionic Liquid Flow Batteries
- High Voltage Capacitors
- Soft Magnetics
- Lightweight Composites for Flywheels
- Wide Bandgap Materials and Devices for Power Electronics

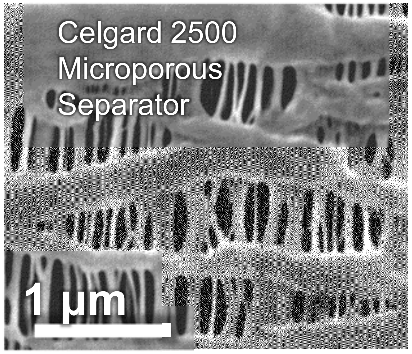


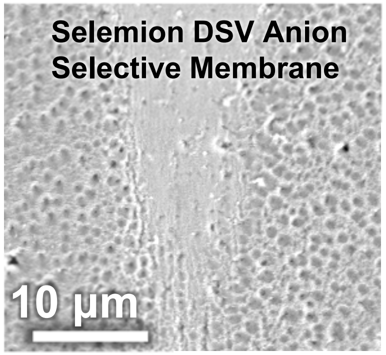


Separators Define the Interface Between Anode and Cathode

- Fundamentally, a separator must
  - Prevent electronic shorting between anode and cathode
  - Enable facile ionic charge balancing (high ionic conductivity)
- Separators may be
  - Microporous - allows anything smaller than pore size through
  - Ion selective – only specific anions or cations transported







NaS and NaNiCl2 Batteries

Sandia National Laboratories

- 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 NaNiCl2 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

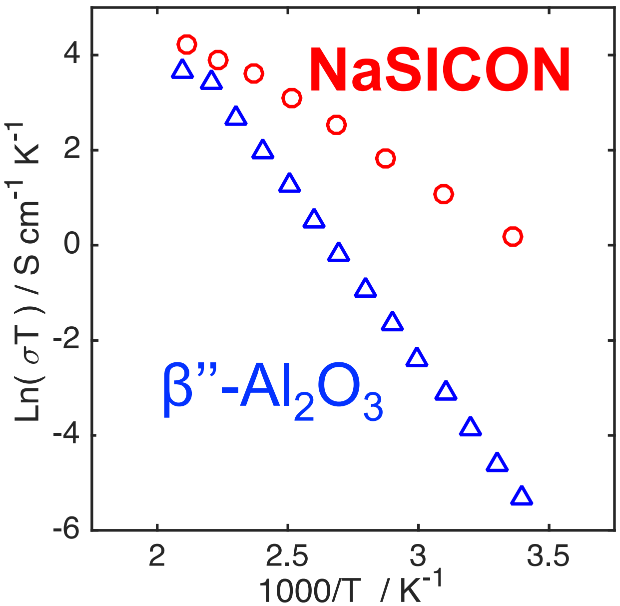
Molten Na Batteries - Engineering Challenges

- 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 °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
- How to engineer cells that operate at lower T (150°C or lower)

Low Temperature NaSICON Electrolyte Enables Multiple Na-Battery Chemistries

Sandia National Laboratories

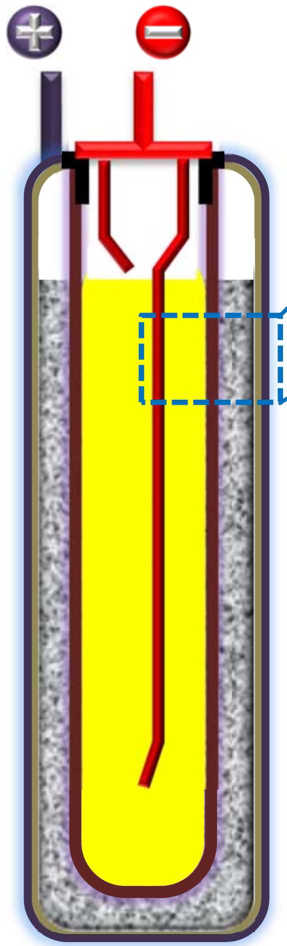
NaSICON (Na Super Ion CONductor): $Na_3Zr_2PSi_2O_{12}$

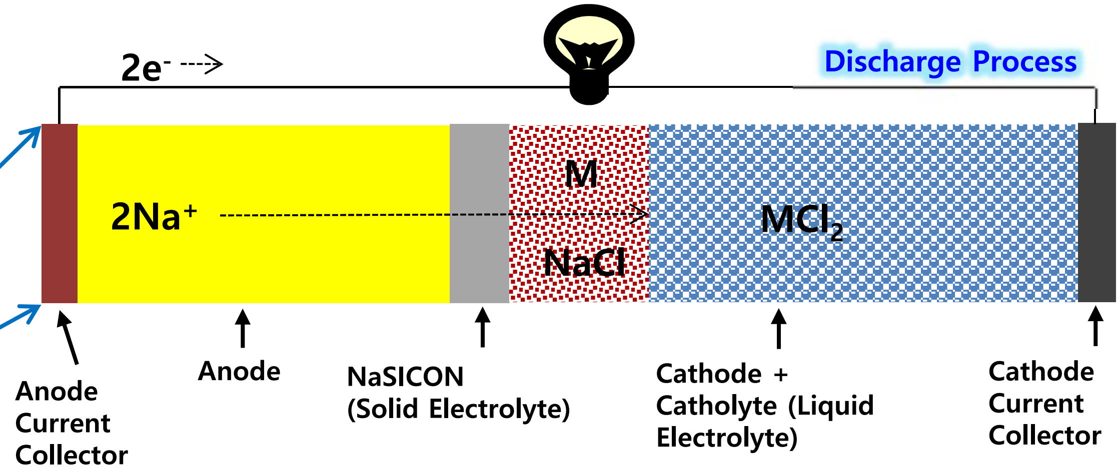


NaSICON a chemically/mechanically stable has high conductivity (>10^{-3} S/cm @RT) at lower temperature. Opens the possibilities for a range of cell chemistries.

CERAMATEC
TOMORROW'S CERAMIC SYSTEMS

Na-$NiCl_2$ Batteries





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

- 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

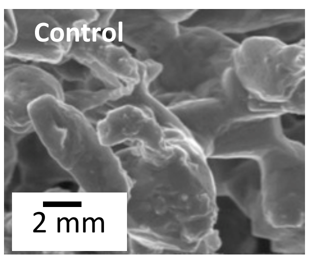
Stable Na-$NiCl_2$ Cell Performance

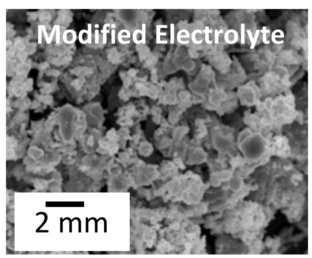
Nickel grain growth at high temperatures during cycling limits cycle life and charge-discharge kinetics for Na-$NiCl_2$ batteries.

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.

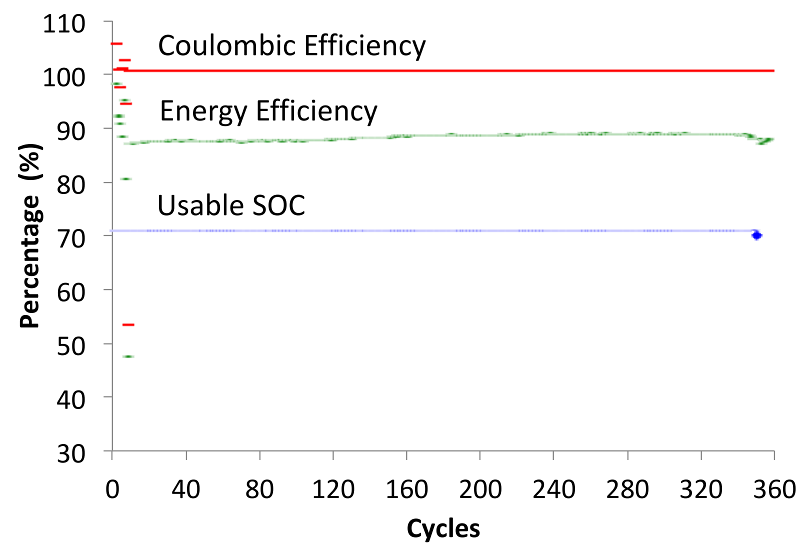
Together, these changes have allowed us to prevent Ni metal particle growth and preserve exceptional, stable battery performance over months (hundreds of cycles).





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

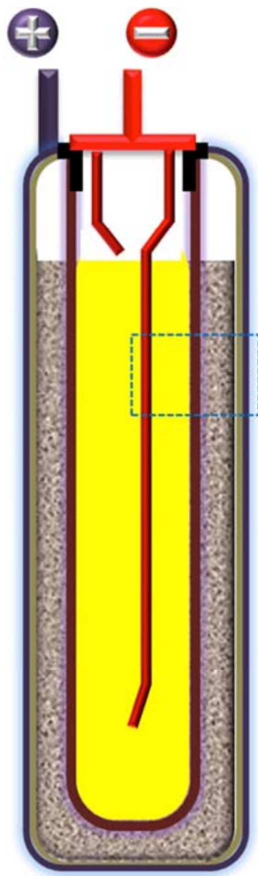
Cycle test (Prototype cell)

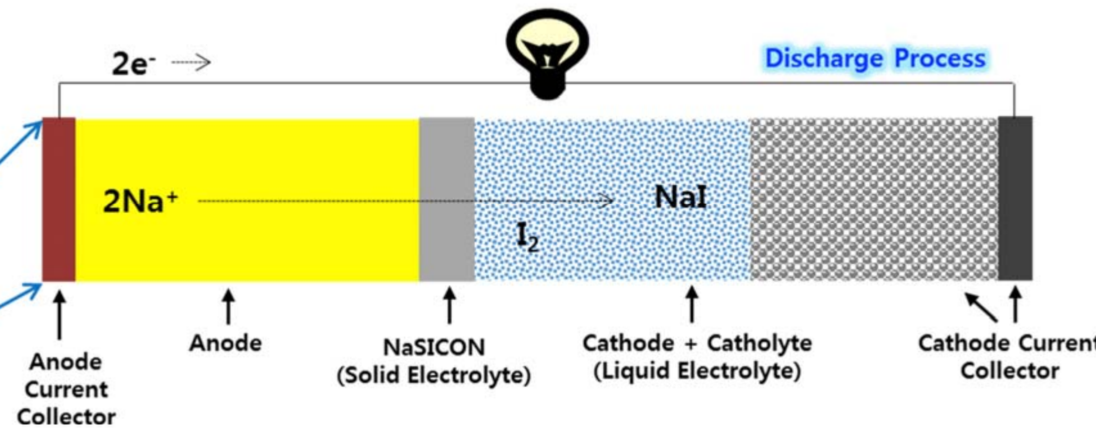


13 Wh Na-$NiCl_2$ (NaX) Cell operation for 9+ months. 70% Depth of Discharge, >85% energy efficiency at 65 mA /cm^2 Charge/Discharge NaSICON current density

CERAMATEC
TOMORROW'S CERAMIC SYSTEMS

Na-I$_2$ Batteries





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

- Increased cell voltage (3.25V)
- Lower temperature (120-180^{o}C)
  - Lower cost materials/seals
  - Lower operational costs
  - New cathode chemistries
- *Liquid cathode increases feasible cycle life*

Early Na-I_2 Prototypes Promising

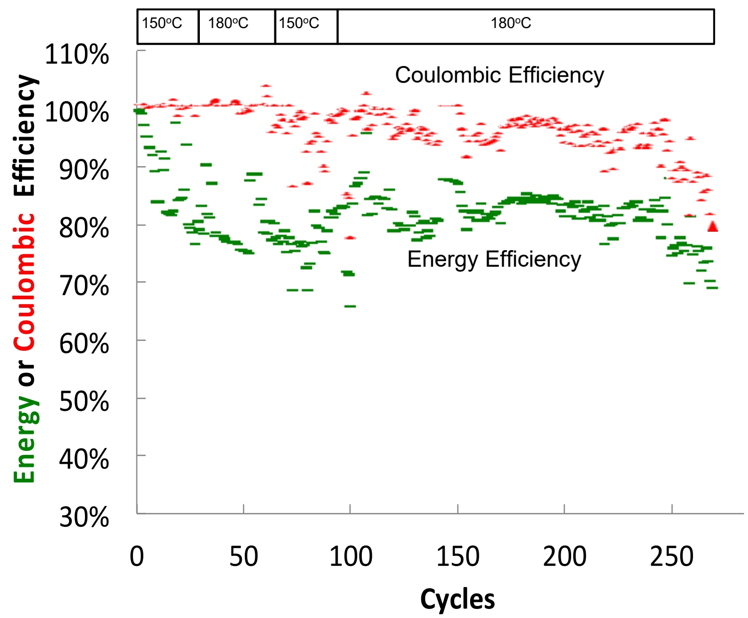
Sandia National Laboratories

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 performa

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

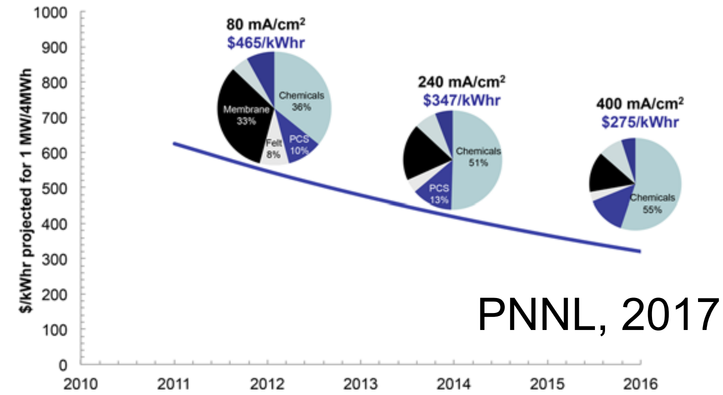


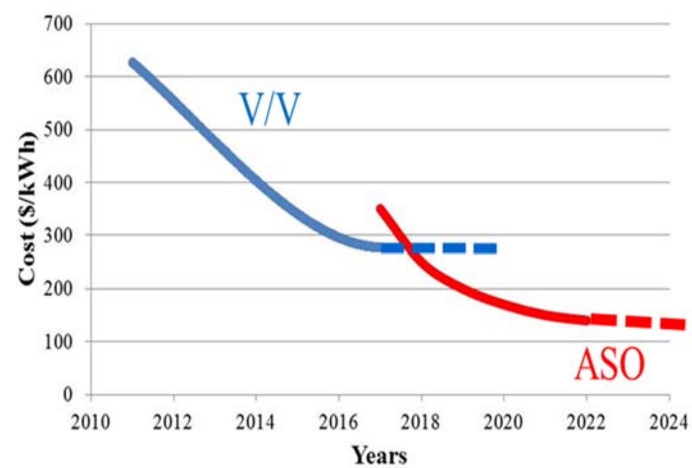
100 Wh Prototype

CERAMATEC

Flow Batteries – Challenges/Opportunities

- 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
  - Membranes are relatively expensive
- 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

Flow battery power plants

Sumitomo Electric, 15MW/60MWh

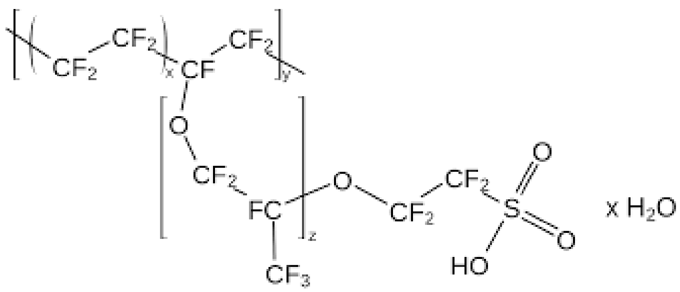
32 KW Stack
Rongke Power/UET
120 mA/cm2
Meter size stack

Stack room

Low cost membranes for flow batteries

- Membranes are approximately 1/3 to 1/10 of the cost of materials in flow batteries
- Need lower cost alternatives to Nafion (Vanadium systems)
- New membranes for next generation non-aqueous systems

Commercial Membranes



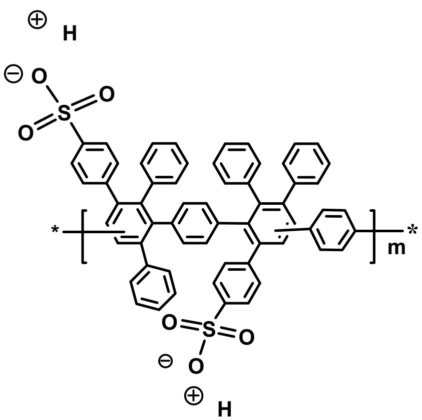
Perfluorosulfonic acid membranes (PFSA)s

Company	Product type	Trade name
DuPont now Chemours	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

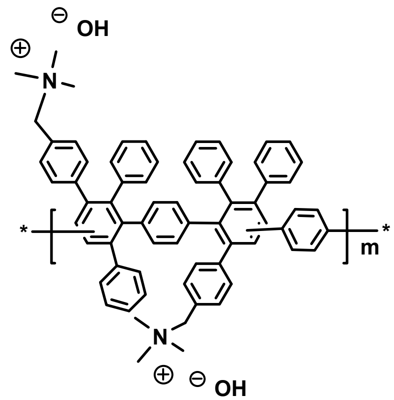
- Various suppliers for perfluorosulfonic acid membranes (PFSA)s
- Primary application chloro-alkali industry
- Low production volumes <65 MT/year
- LPV results in high cost $250-500/m2
- PFSA advocates claim cost of materials “could” reach $20/m^2$ however with no competitor, no real justification to lower costs……

Lower cost polymeric membranes

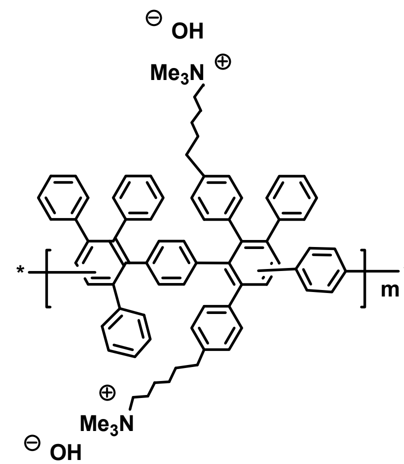
Developing and engineering poly(phenylene) membranes to compete against PFSA.



US Patent 7,301,002

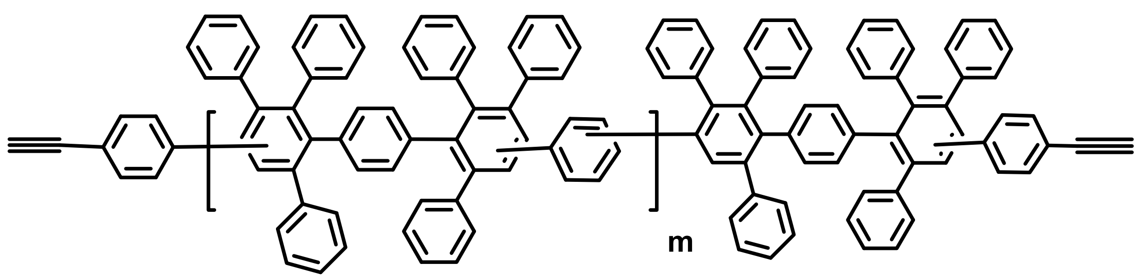


US Patent 7,888,397



US Patent 8,809,483

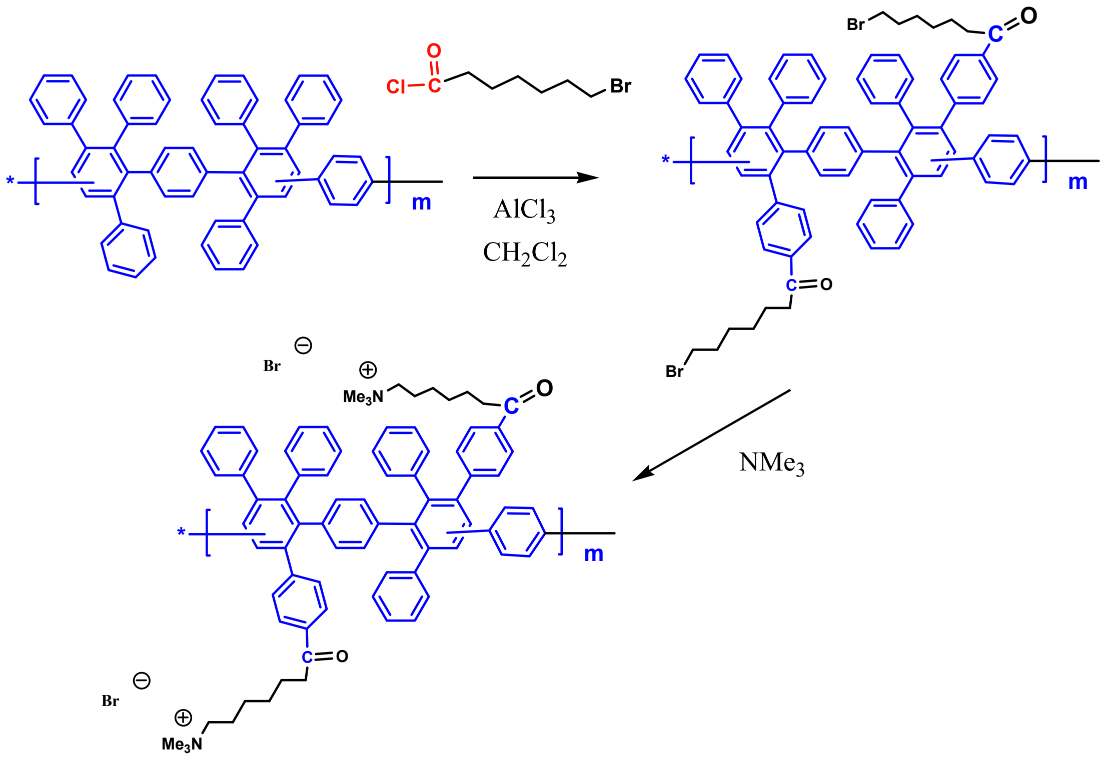
Materials based on chemistry that Dow commercialized as low k dielectric



Low cost at low production volumes

Lower cost polymeric membranes

Membranes contain a polyphenylene backbone with pendant ionic groups; ionic content was varied qualitatively high, medium, and low.



Low Ion Content

Very brittle sample–no data

Medium Ion Content

Best Coulombic efficiency

Best electrochemical yield

Least crossover

High Ion Content

Good Coulombic efficiency

High crossover

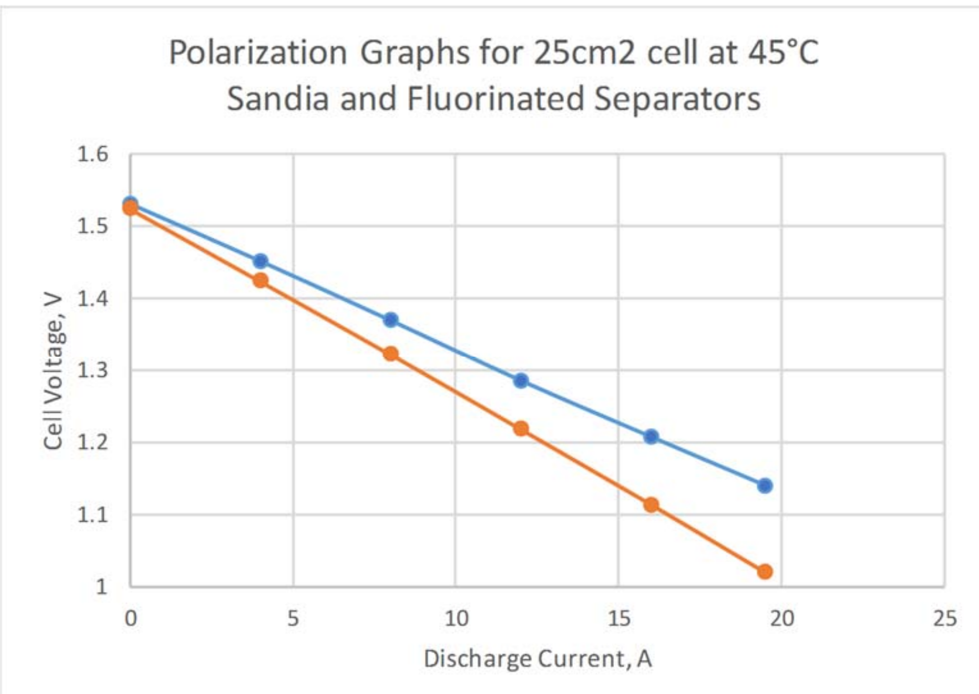
The membranes are prepared by a propriety process using Friedel Crafts acylation with a ketone to add pendant ammonium groups and simultaneously lightly crosslink the polymer backbone.

Small, Pratt, Fujimoto, and Anderson, *J. Electrochem. Soc.*, **2016**, A5106.

VRFB Membrane - Performance

Membrane	Efficiency, Round Trip	Efficiency, Coulombic	Efficiency, Voltaic
Sandia	82.2%	96.2%	85.4%
Fluorinated	72.3%	92.5%	78.2%

	Pmax, mW/cm^2	Specific Resistance, Ωcm^2
Sandia	1159	0.505
Fluorinated	946	0.610



Cycling Performance Comparison in 25-cm^2 cell at 45°C
Sandia and Fluorinated Membranes
WattJoule Electrolyte (2M Vanadium)

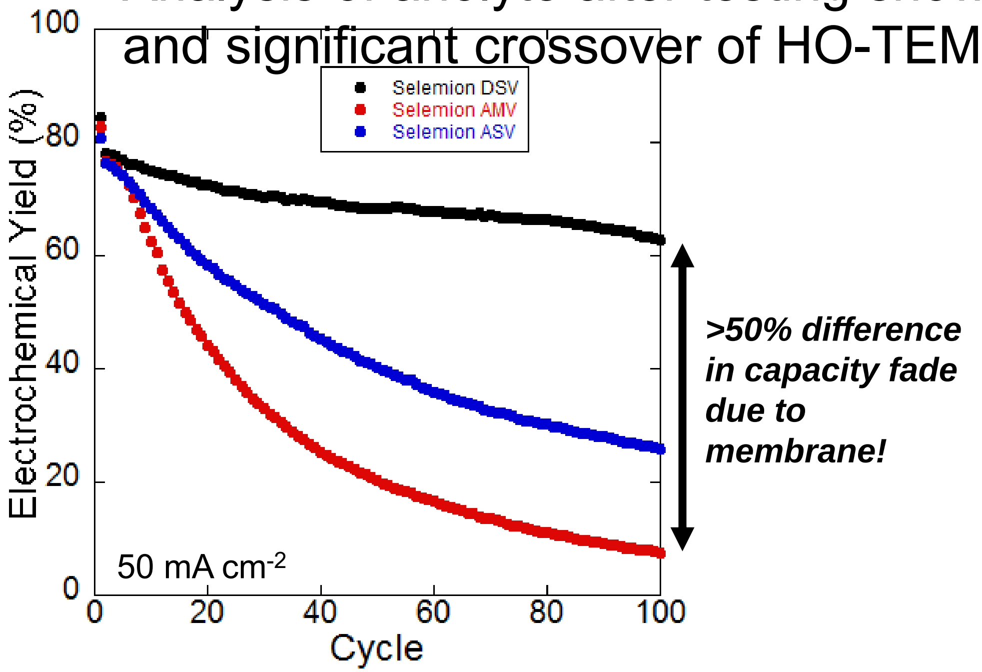
Data from WattJoule shows Gen5 has higher energy efficiency (+10%). High coulombic efficiency.

WattJoule

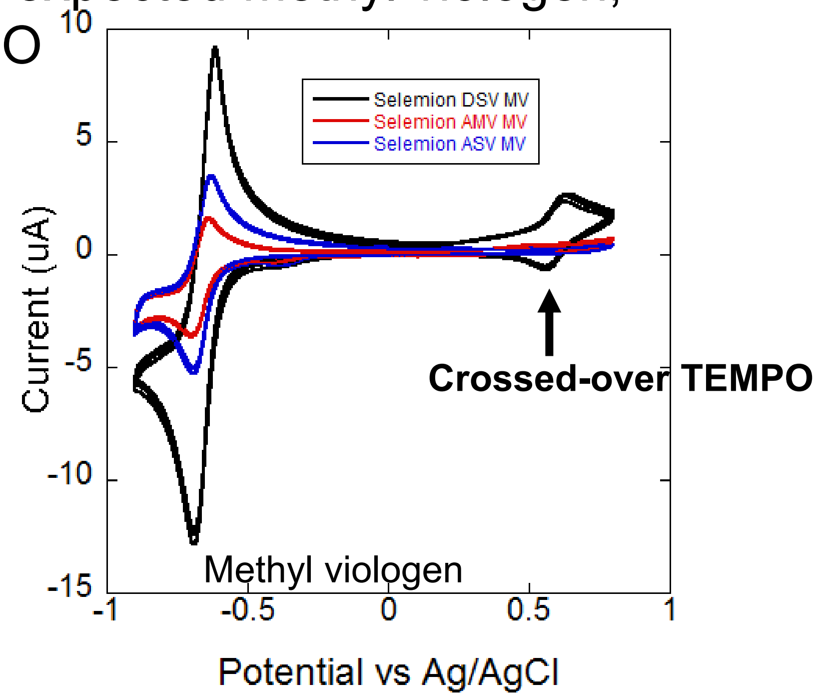
Beyond Vanadium – Aqueous Organic Electrolytes

Membranes significantly influence capacity loss in aqueous organic RFB

- Aqueous-organic RFB, 100 cycles at 50 mA cm^{-2}
  - Anolyte: 0.5 M methyl viologen in 1.5 M NaCl
  - Catholyte: 0.5 M HO-TEMPO in 1.5 M NaCl
- Analysis of anolyte after testing shows expected methyl viologen, and significant crossover of HO-TEMPO



Three anion exchange membranes from same manufacturer show markedly different capacity fade.



Cyclic voltammetry confirms crossover of HO-TEMPO into analyte.

L.J. Small, H.D. Pratt, C.Y. Fujimoto, T.M. Anderson, *in review* (2017).

Beyond Vanadium – Non-Aqueous Electrolytes

- Increasing the energy density of electrolytes needs a radical approach for electrolyte synthesis. Examples include
  - non-aqueous electrolytes with multi-electron redox processes
- Most commercially available, ion Selective membranes are not designed for non-aqueous use.

Alkaline Zn-MnO_2 Batteries

- **Cost**
  - Traditional primary batteries, low cost ($18-20/kWh primaries)
  - Low-cost materials and manufacturing
  - Established supply chain
- **Safety**
  - Aqueous chemistry
  - Non-flammable
  - EPA certified for landfill disposal
- **Reliability**
  - Long shelf-life
  - Limited thermal management required
- **Reversibility and Cycle life are the Challenges**

Zn-MnO_2 Batteries – Critical Issues

Sandia National Laboratories

Cathode

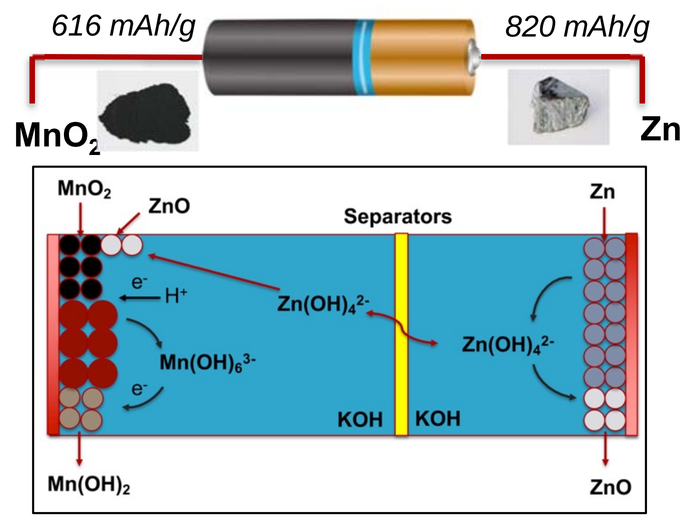
- Irreversibility of Cathode
- Susceptibility to Zinc poisoning

Separator

- Zincate crossover

Anode

- Shape Change
- Dendrite Growth
- Irreversible ZnO Passivation

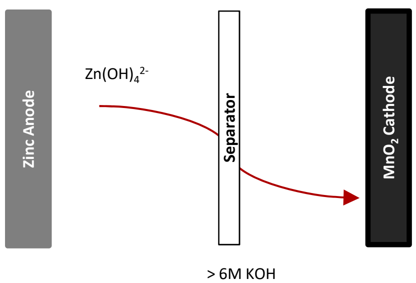


Limiting Depth of Discharge has been shown to be a viable approach
N. D. Ingale, J. W. Gallaway, M. Nyce, A. Couzis and S. Banerjee, J. Power Sources, 276, 7 (2015).

Full 2e- can be stabilized but is still susceptible to zinc poisoning
G. G. Yadav, J. W. Gallaway, D. E. Turney, M. Nyce, J. Huang, X. Wei and S. Banerjee, Nat. Commun., 8, 14424 (2017).

TN Lambert

Need for Selective Separators



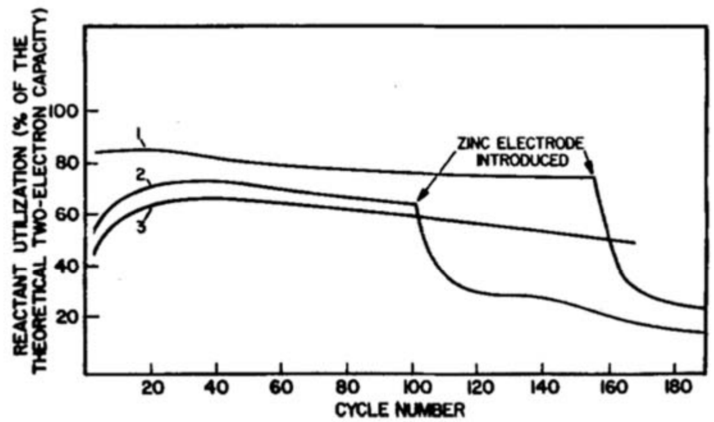
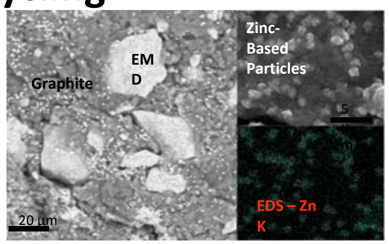


Fig. 5. Effect of the introduction of zinc on capacity retention of modified MnO_2 electrodes: 1) chemically modified electrode; 2) physically modified electrode; 3) physically modified electrode in 9M KOH + 0.1M $Zn(OH)_4^{=}$.

MnO_2 Cathode After Cycling



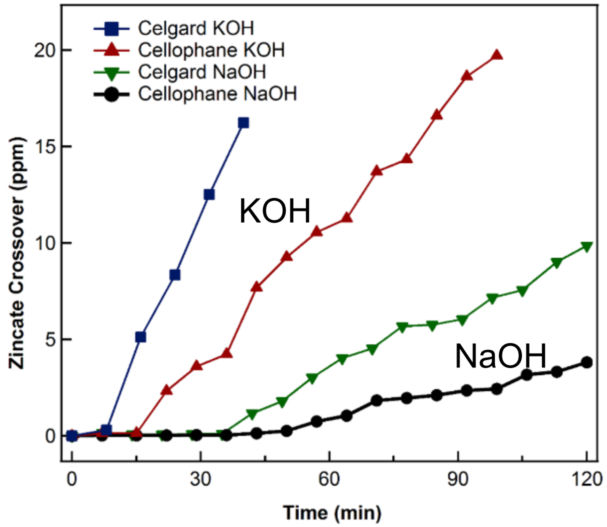
Zinc-Based Particles
-Insulating
-Combine with cathode material to form irreversible compounds

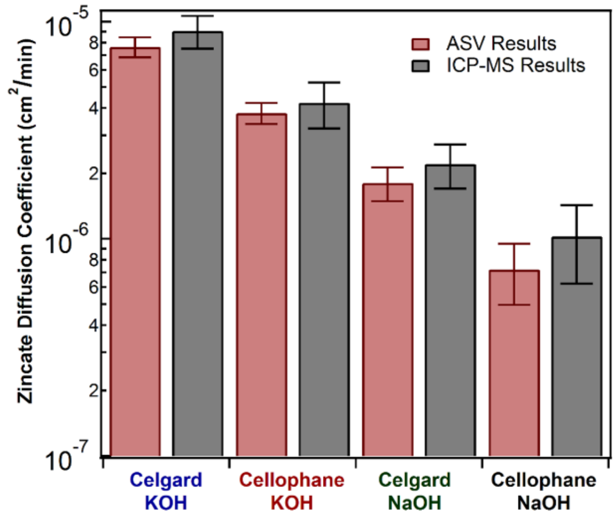
- Research by Ford in the 1980s showed that the MnO_2 cathode could be stabilized at low loadings ***in the absence of Zinc***
- New stabilized 2e- cathodes are 100% reversible ***in the absence of Zinc***

Imperative need for zincate blocking separators

TN Lambert

Rapid screening of separators



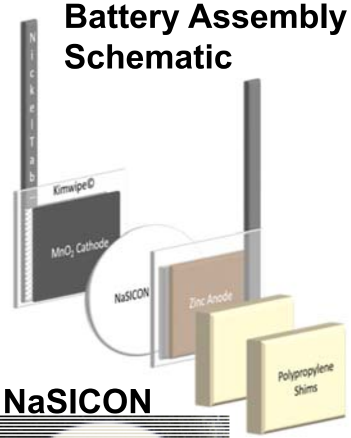


- Compares favorably *vs.* ICP and Complexometric methods
- Faster experiment times, very reproducible, low limit of detection
- First demonstration of ASV measurement of Zinc in alkaline
- Will allow for rapid screening of newly developed membranes

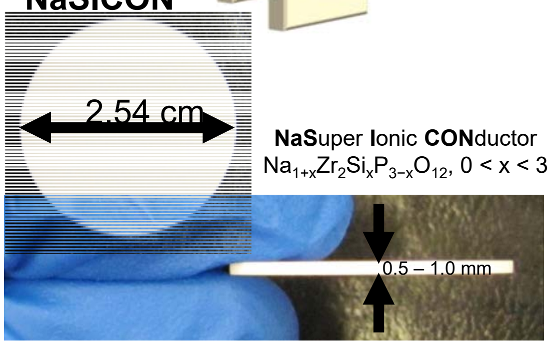
J. Duay *et al. "Stripping Voltammetry for the Real Time Determination of Zinc Membrane Diffusion Coefficients in High pH: Towards Rapid Screening of Alkaline Battery Separators" Electroanalysis 2017, http://dx.doi.org/10.1002/elan.201700337.*

Initial Studies on Stopping Zincates

Battery Assembly Schematic



NaSICON



NaSuper **I**onic **CON**ductor
$Na_{1+x}Zr_2Si_xP_{3-x}O_{12}$, $0 < x < 3$

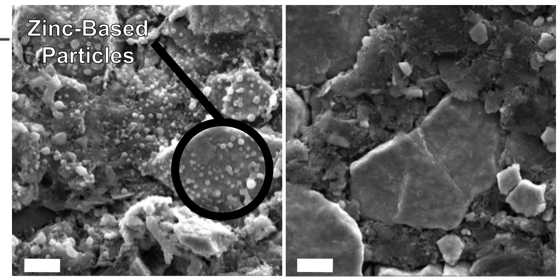
NaSICON purchased from Ceramatec

SEM/EDS analysis after cycling

Celgard + Cellophane Separators

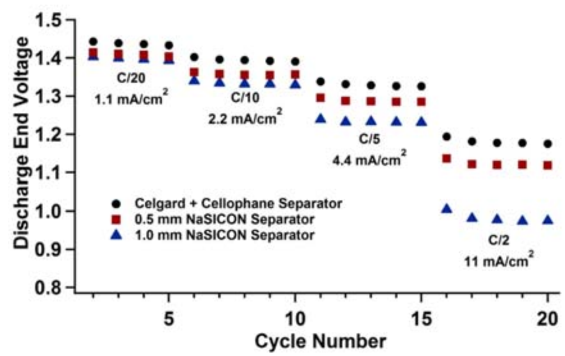
Element	Atomic %
Au K	0.2
C K	43.9
F K	10.7
Mn K	9.8
Na K	1.5
O K	32.3
Zn K	1.6

1.0 mm NaSICON Separator



Element	Atomic %
Au K	0.1
C K	43.6
F K	11.3
Mn K	10.8
Na K	0.9
O K	33.3
Zn K	0.0

Ceramic Separators in NaOH electrolyte are viable at low rates



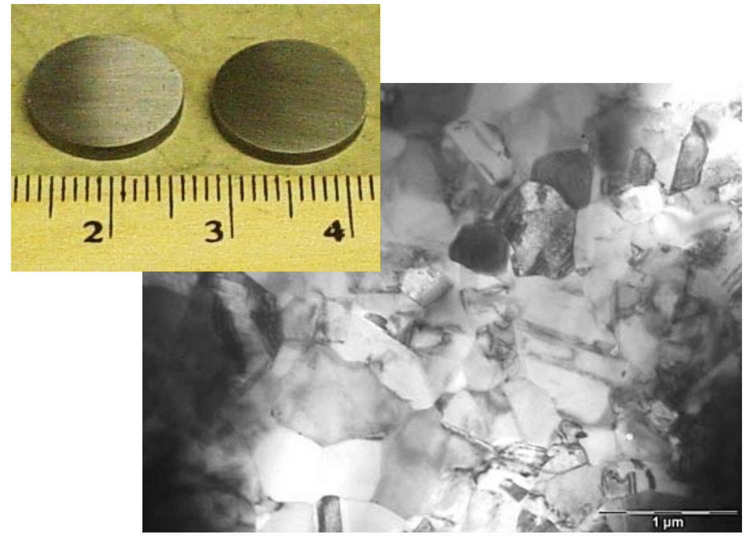
J. Duay *et al. manuscript in preparation.*

TN Lambert

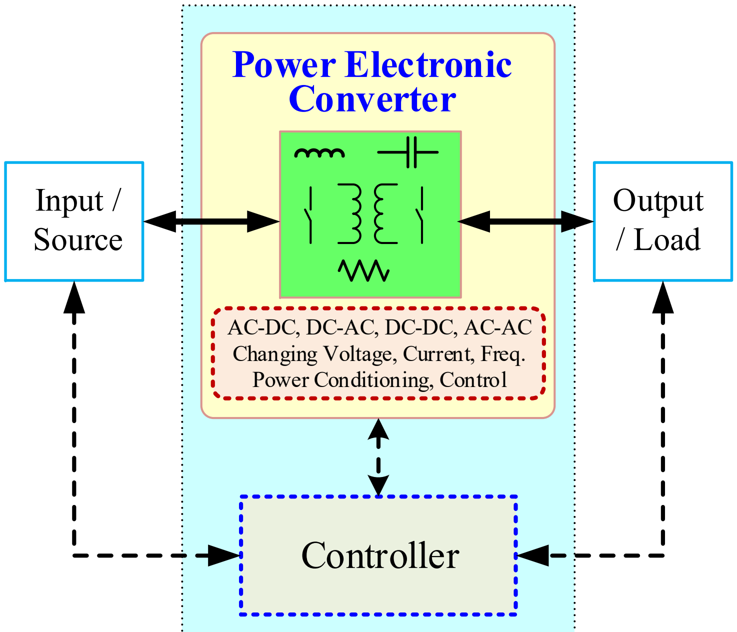
Power Electronics and Power Conversion

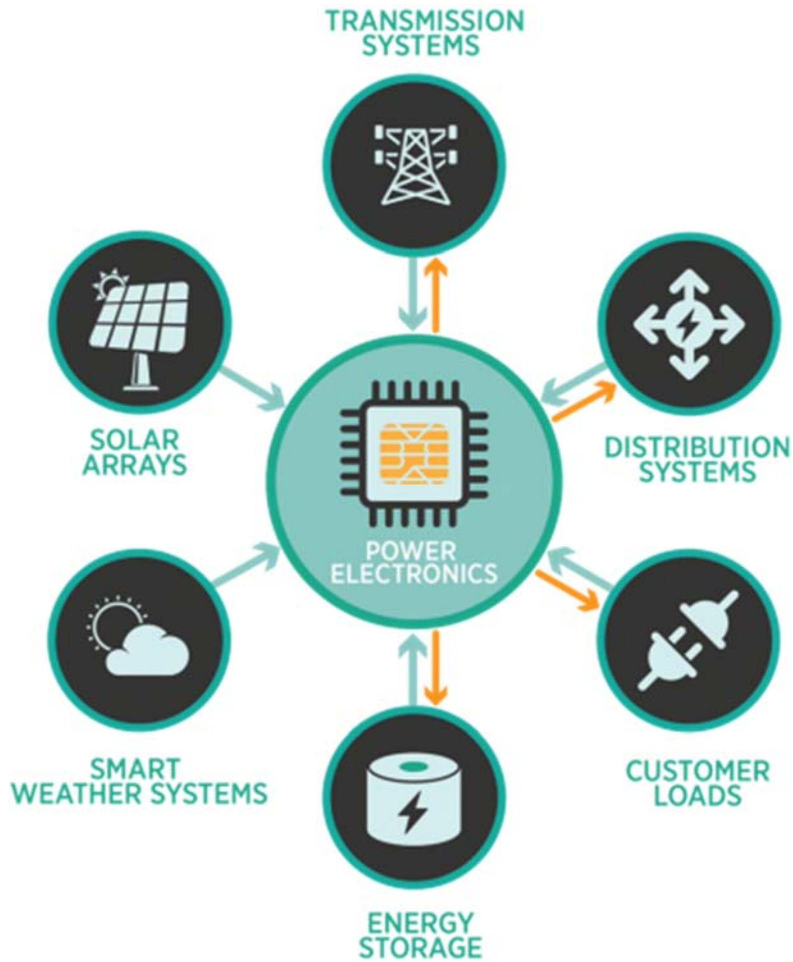
Key Projects

- High-temperature iron-nitride transformer for high frequency converters
- Development of advanced gate oxide for wide band gap devices
- High energy dielectrics for scalable capacitors
- SiC and GaN-based power inverter with GeneSiC Semiconductor, Creare, & Innocit
- Monolithic SiC-based semiconductor switch with GeneSiC Semiconductor



Power Electronics for Energy Storage



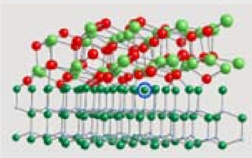


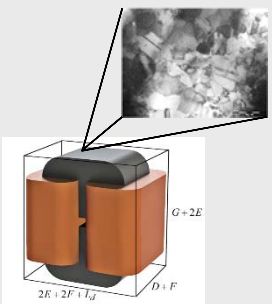
- Power Electronics is an enabling technology;
- It synthesizes, processes, converts, conditions and controls the power flow;

Source: US Department of Energy

Power Electronics

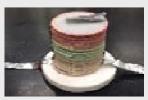
Materials R&D





- Gate Oxide R&D
- Advanced Magnetics

Devices



- ETO
- SiC Thyristors
- Monolithically integrated SiC transistors
- WBG Characterization & Reliability
- High energy dielectric capacitors

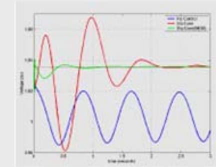
Power Modules

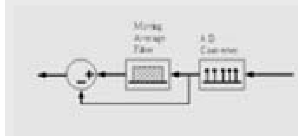
- SiC High Temp/density Power Module
- HV SiC JFET Module
- HV, HT Reworkable SiC half-bridge modules

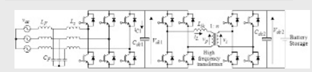
Power Conversion System

- Dstatcom plus energy storage for wind energy
- Optically isolated MW Inverter
- High density inverter with integrated thermal management
- High temp power inverter

Applications



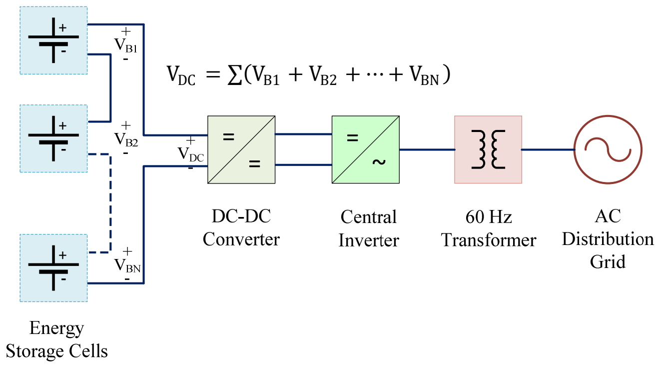




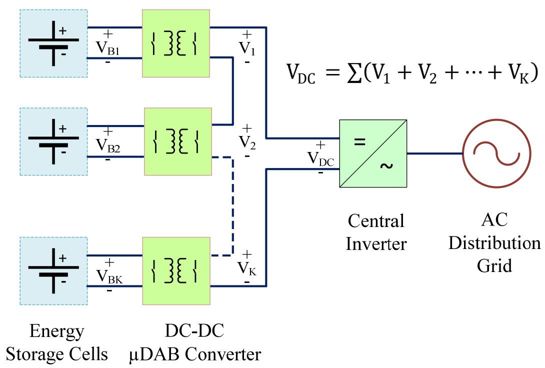
- FACTS and Energy Storage
- Power smoothing and control for renewables
- Dual active bridge for advanced energy storage system designs

μDAB for Cell level Control

- Novel GaN-based micro DAB (μDAB) DC-DC converters for cell-level monitoring and to achieve better efficiency.
  - Eliminates the need of a bulky 60Hz transformer at the inverter-grid interface, thus reduces size and increases overall power density.
- The overall system will enable real-time monitoring and management for safer and more reliable operation by expending and predicting cycle life, as well as understand the earliest indications of failure.



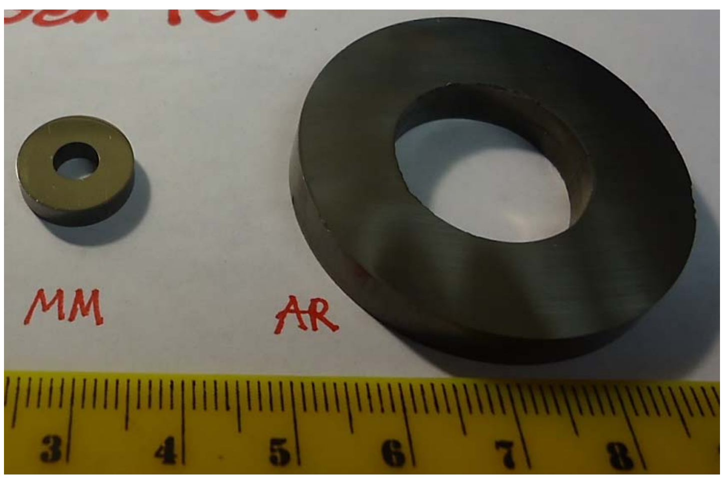
State-of-the-art Power Electronics topology in BSS

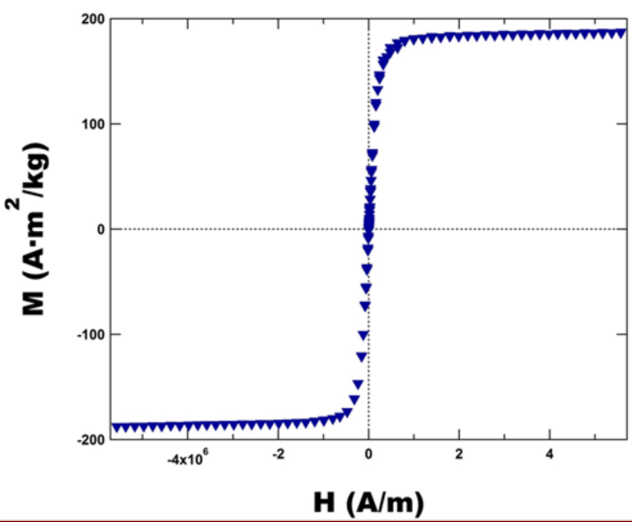


Cell-level Power Electronics topology in BSS

Soft Magnetics

- Current state of the art: soft ferrites (low power density), nanocrystalline and amorphous materials (very costly, power density can still be improved)
- Current TRL: 3 (γ'-Fe_4N prototype inductor/transformer cores fabricated)
- Success enables: high frequency (HF) operation, enhanced power density, and sustained performance at elevated temperatures
- Collaborators: University of California, Irvine
- U.S. Patent applications: 15/002,220, 14/531,075



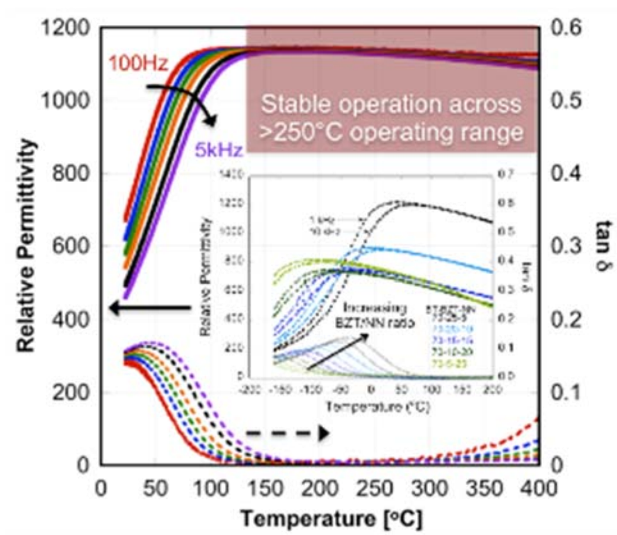


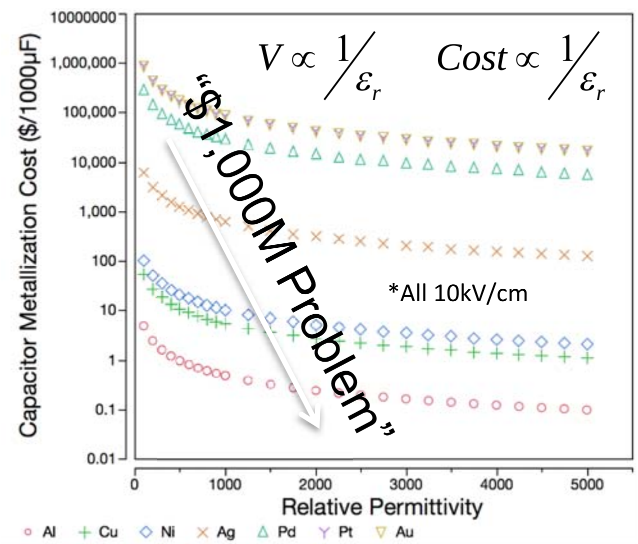
γ'-Fe_4N prototype toroidal inductor cores fabricated using spark plasma sintering (SPS) & magnetic response

High Voltage Capacitors

- **Current state of the art:** High temperature *OR* high energy density capacitors are available for <1000hr lifetimes at *high cost*
- **Current TRL:** 2-3, Relevant compositions were fabricated into multilayer devices that have measurable high temperature stability under relevant DC bias with maintained high permittivity
- **Success enables:** Movement away from high capacity electrolytic DC bus (slow switch speeds at low temperatures) toward base metal integrated high temperature stable capacitors

SNL MLCC





Energy Storage Safety

Key Projects

- Thermal modeling, cell reliability
- Safety and failure propagation
- Suppressants and
- Reliability of commercial cells and packs
- Battery Abuse Testing
- Develop resources for industry
- ESS Safety Strategy Roadmap

February 2017 Safety Forum
Santa Fe, NM

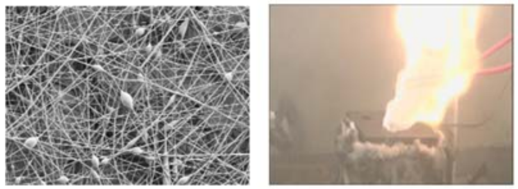
Energy Storage Safety Working Group (ESSWG)

Materials R&D for ES 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

R&D for Making Systems Safe and Reliable

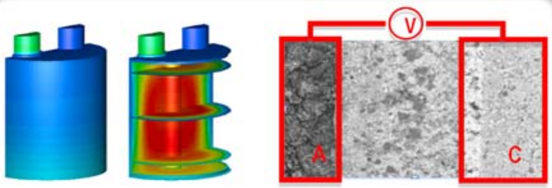
Sandia National Laboratories



Materials R&D to date:
- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials

Materials R&D needs:
- Viable flow batteries
- Aqueous electrolyte batteries
- High specific heat suppressants
- Vent gas composition

Testing
- Electrical, thermal, mechanical abuse testing
- Failure propagation testing on batteries/systems
- Suppressants and delivery with systems and environments
- Large scale thermal and fire testing (TTC)

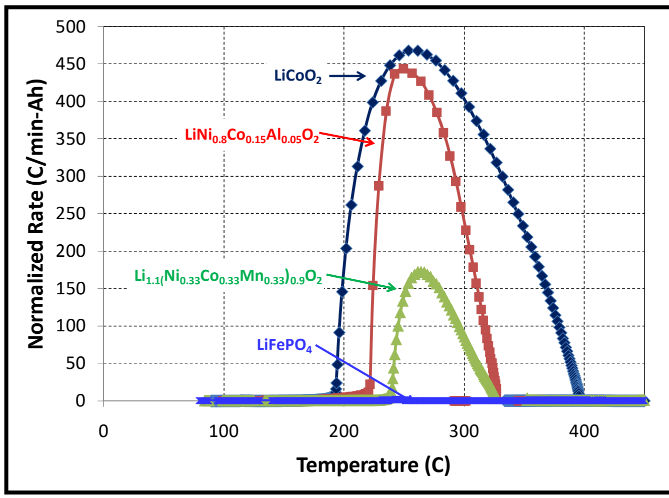


Simulations and Modeling
- Multi-scale models for understanding thermal runaway
- Validating failure propagation models
- Fire Dynamic Simulations (FDS) to predict the size, scope, and consequences of battery fires

Procedures, Policy, and Regulation
- UL 1973-13 Batteries for Use in Stationary Applications
- ANSI/UL 9540-P (ESS Safety)
- UL 1974 (Repurposing)
- IEEE 1635-12 (Ventilation and thermal management)

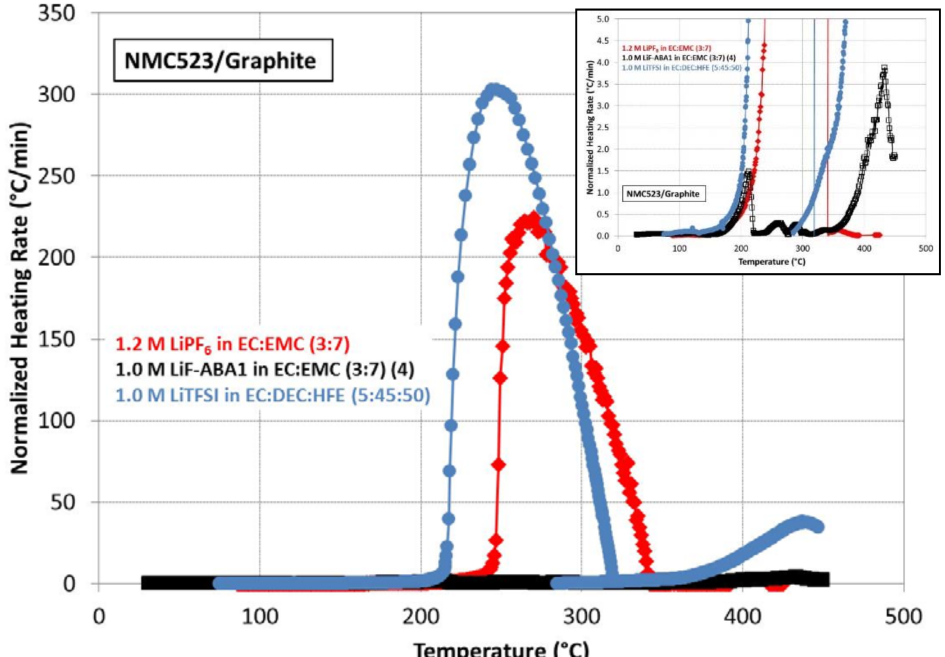
Battery Calorimetry Center

- One of the world's largest dedicated battery calorimetry facilities
- Six accelerating rate calorimeters (ARCs) for materials and cell-level measurements
  - Gas volume measurements for decomposition gas products
  - Quantitative gas analysis capabilities from ARC samples
  - Measurements on 1 to 150 Ah cells
- Two isothermal battery calorimeters
- Microcalorimetry for materials analysis
- Modulated DSC



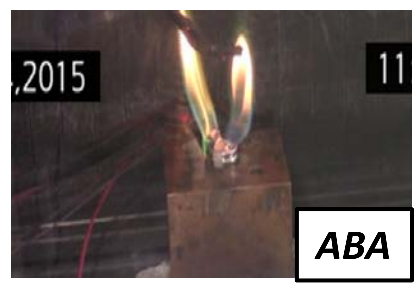
Abuse Tolerance of Li-ion Cells

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

Thermal Runaway and Suppression

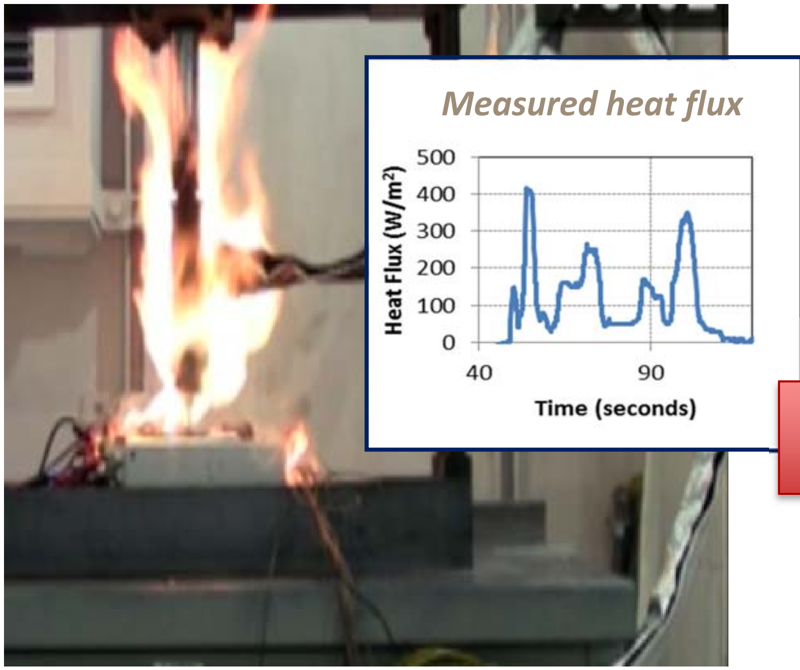
Sandia National Laboratories

- Couple material instability data with cell failure to understand electrode decomposition mechanisms.
- Estimate vent gas composition per decomposition mechanism.
- Understand how cell chemistry affects cell failure.
- Feed this information into models of cell failure and propagation.

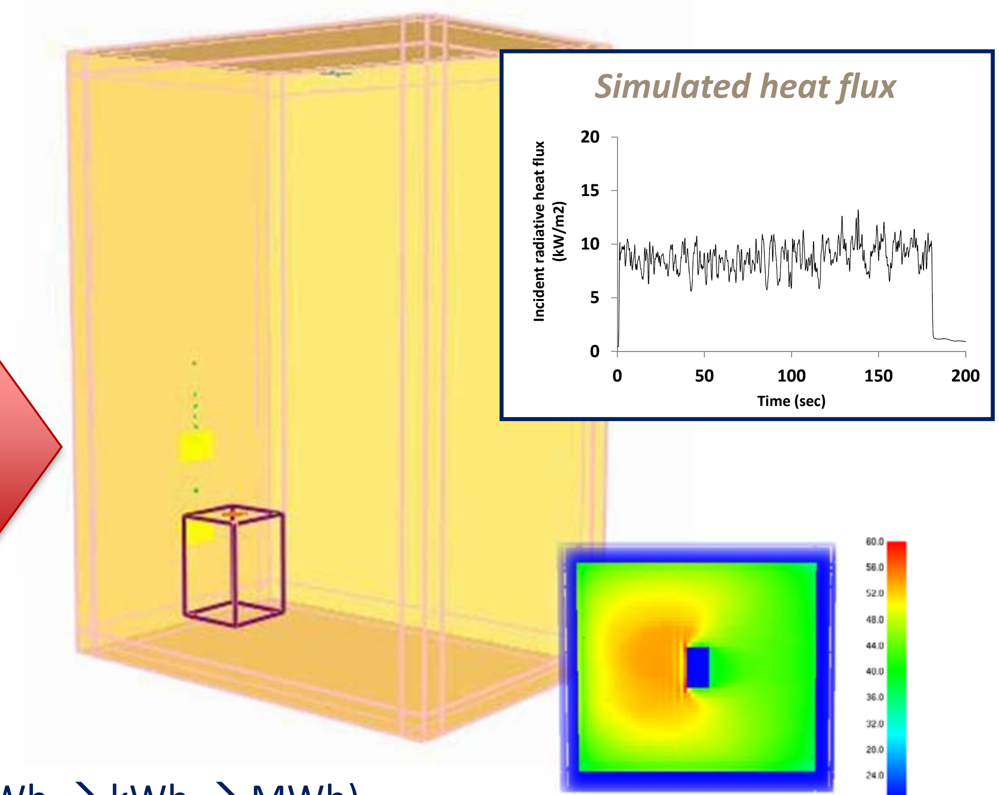
- Use modeling results to plan suppression testing.
- Build a gas/flame model system representing thermal runaway to test suppressants more reliably.

Quantifying Battery Fires

Experimental Data from Battery Fires



Fire Dynamic Simulations (FDS) of Battery Fires



Test bay ceiling temperature

- Scale up experiments to **validate FDS models** (Wh → kWh → MWh)
- Feedback to **design** storage systems
- Inform **fire suppression** system design
- Provide to regulatory agencies (NFPA, IEEE, UL etc.), utility companies, etc.

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

Energy Storage System Analysis Laboratory

Sandia National Laboratories

- Capabilities include cell assembly (multiple chemistries), cell prototyping, 1000 channels of cycle life testing
- Grid connected 1MW test pad for storage system validation

Cell, Battery and Module Testing

- 14 channels from 36 V, 25 A to 72 V, 1000 A for battery to module-scale tests
- Over 125 channels; 0 V to 10 V, 3 A to 100+ A for cell tests

72 V 1000 A Bitrode (2 Channels)

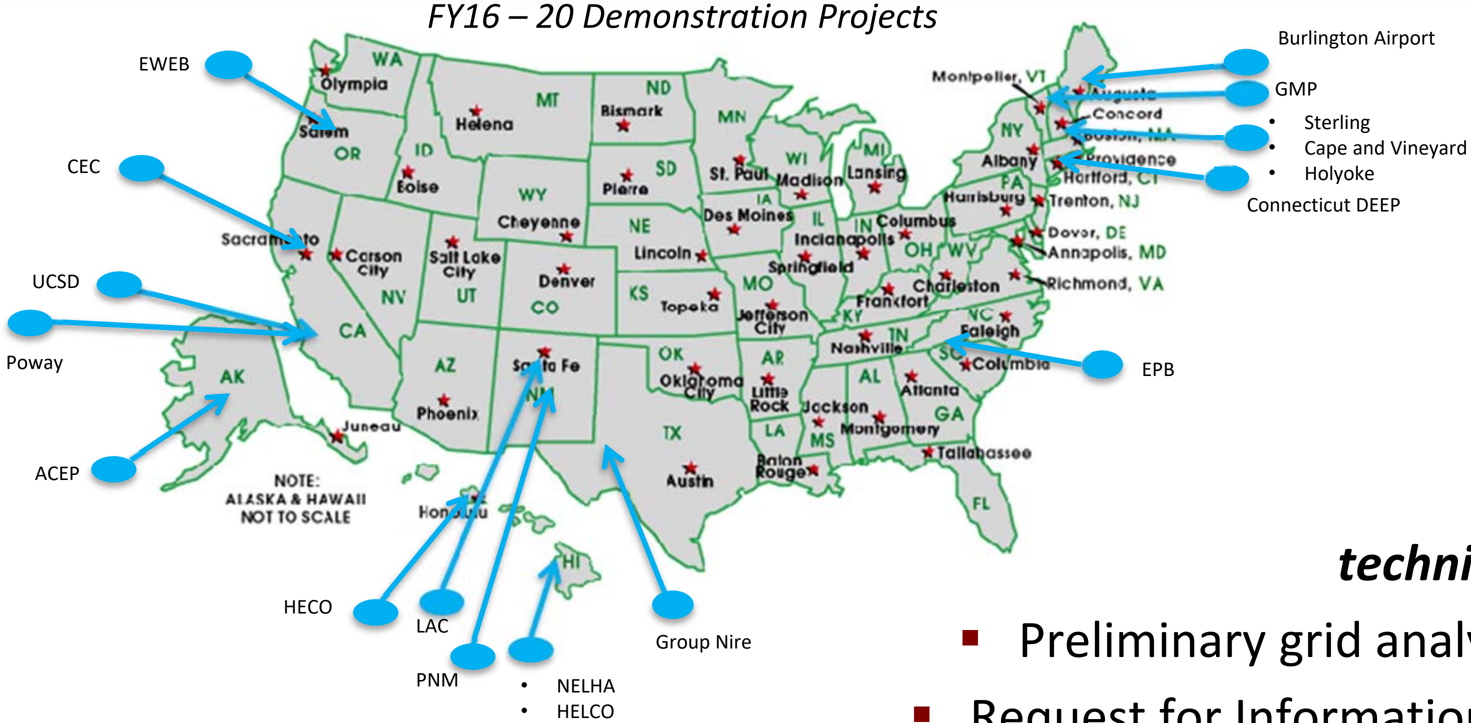
Energy Storage Test Pad (ESTP)

System Testing

- Up to 1 MW, 480 VAC, 3 phase
- 1 MW/1 MVAR load bank

Demonstrations

FY16 – 20 Demonstration Projects



International Projects:
- Canada – WEICAN
- Singapore

Providing technical support for:

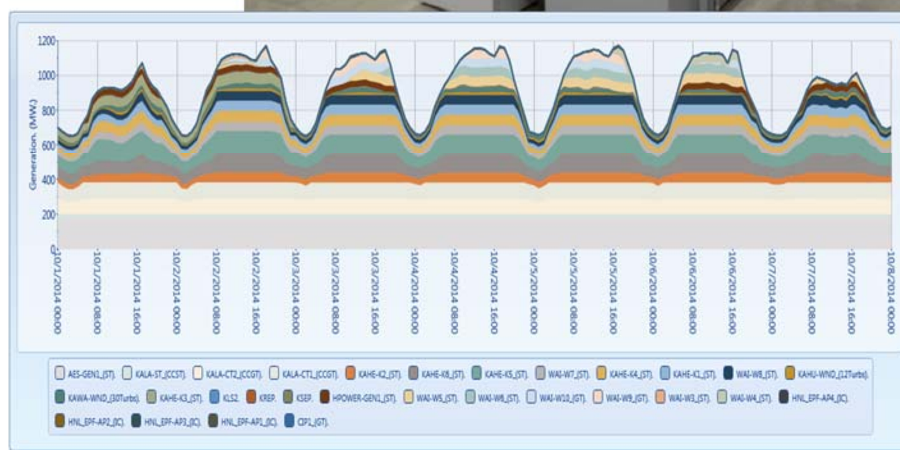
- Preliminary grid analysis & modeling
- Request for Information and Proposals
- Project design, procurement specifications, and construction
- Data Acquisition Systems
- Commissioning plan
- Operational test data and system optimization algorithms

Energy Storage Analytics

- Estimating the value of energy storage
- Control strategies for energy storage
  - Wide area damping control
  - Maximizing revenue
- Public policy: identifying and mitigating barriers
- Standards development
- Project evaluation
  - Technical performance
  - Financial performance
- Model development (e.g. for dynamic simulation)

Analytics and Policy

- Estimating the value of energy storage
- Control strategies for energy storage
  - Wide area damping control
  - Maximizing revenue
- Public policy
  - Identifying and mitigating barriers
- Standards development
- Project evaluation
  - Technical performance
  - Financial performance
- Model development
  - Dynamic Simulation



Key Takeaways

- Engineering energy storage systems that are lighter, with high energy and high power capacities
- 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

Resources

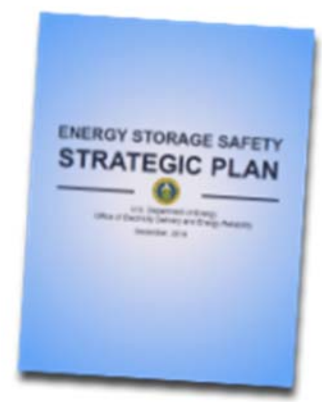
Sandia National Laboratories

- DOE Energy Storage Website (www.sandia.gov/ess/)
- DOE Global Energy Storage Database (www.energystorageexchange.org)
- Energy Storage Association (www.energystorage.org)
- 2015 DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA

U.S. DEPARTMENT OF ENERGY

EPRI ELECTRIC POWER RESEARCH INSTITUTE

NRECA



Acknowledgements

This work was supported by the U.S. Department of Energy Office of Electricity Energy Storage Program.

Dr. Imre Gyuk, Energy Storage Program Director

Batteries and Energy Storage - Drivers

Sandia National Laboratories

- 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