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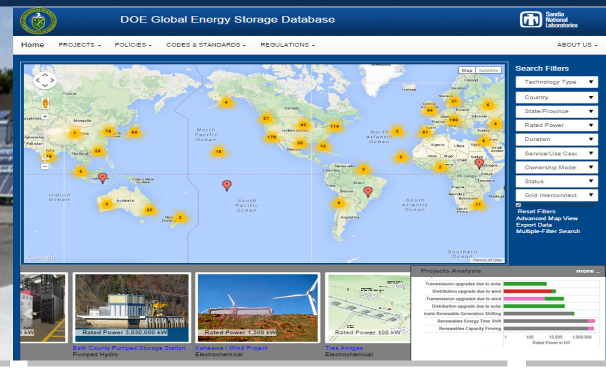

Energy Storage – The Future

Babu Chalamala, Ray Byrne and Dan Borneo

IEEE ESSB Winter 2017 Meeting

New Orleans, Jan 8, 2017

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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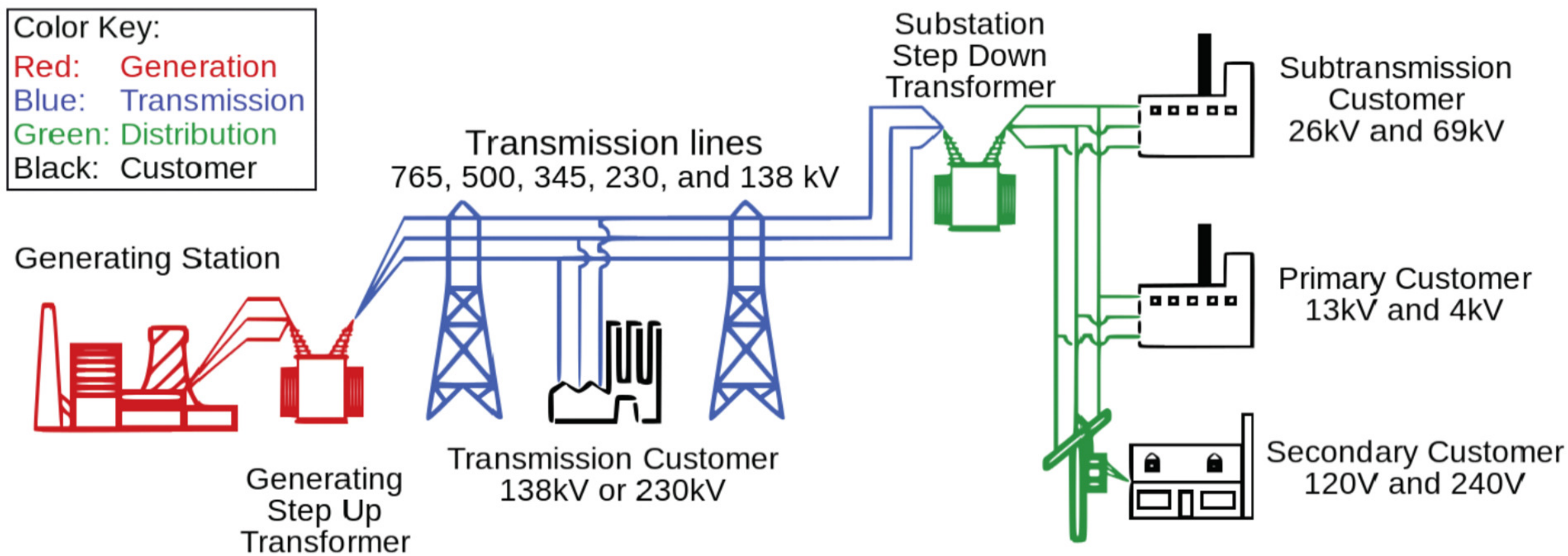
Agenda

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

The Grid Today



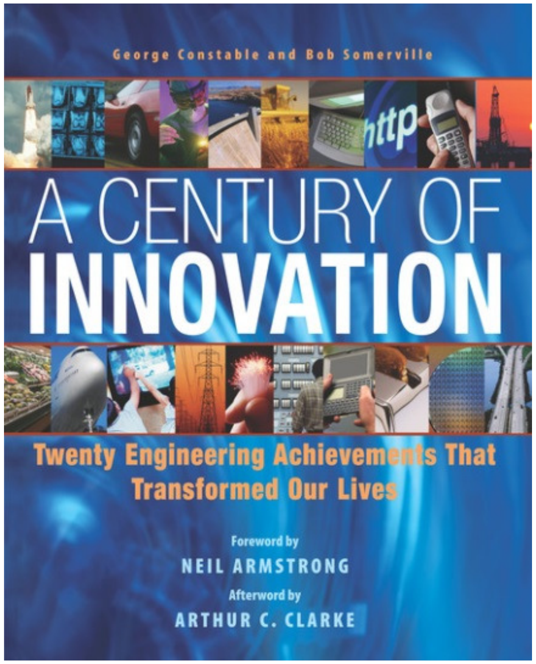
- Grid 1.0
  - One way energy flow
  - Generation and load must always be balanced

NERC

The Success of the Grid

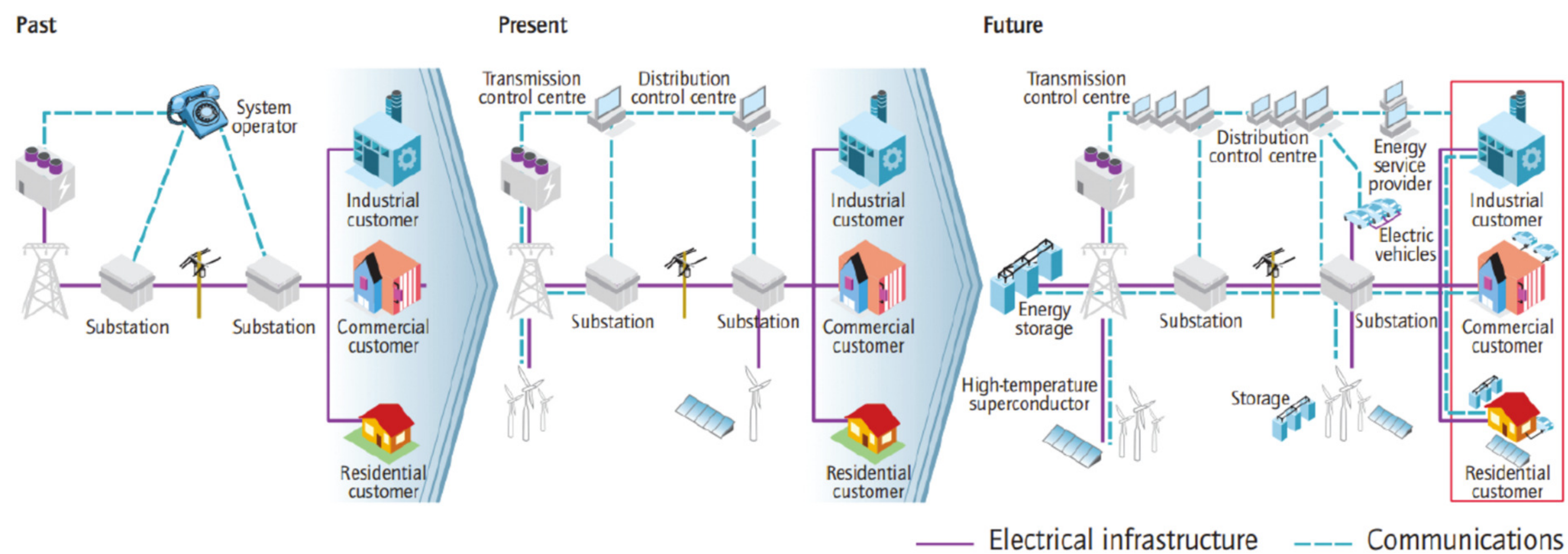
- Remarkably reliable and efficient
  - Large interconnected network
  - Just-in-time production and consumption
  - Highly reliable 99.999%

- Success rests on two important principles
  - Diversity of aggregated loads
    - Aggregated loads change is predictable
    - Control over generation, throttled to provide power as needed



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

Grid Evolution and the Future Grid



Source: Quadrennial Technology Review
US DOE, 2015

Grid 2.0

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

Future Grid

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

U.S. Electricity Facts

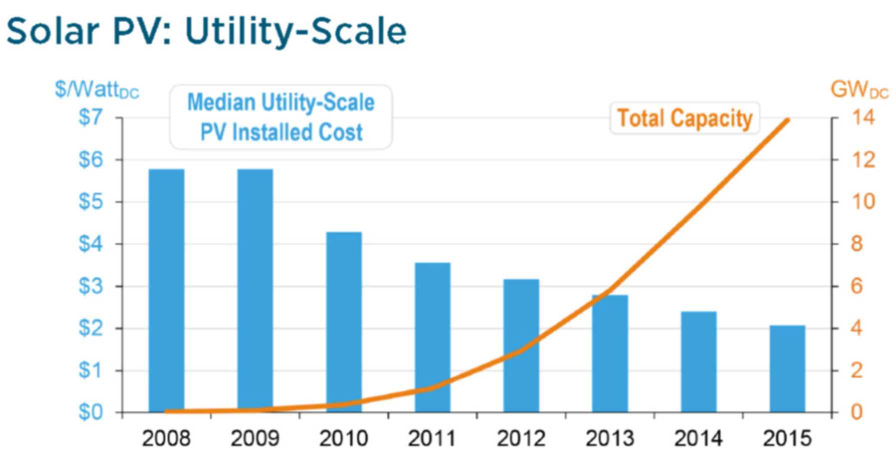
- Over 3,200 utilities, 60,000 substations, 160,000 miles of high-voltage transmission lines, 7 million miles of distribution circuit
- As of Dec 31, 2015, generation capacity of 1,176,185 MW
- In 2015, total U.S. electricity generation was 4,087,381 GWh
  - U.S. investor-owned electric companies accounted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

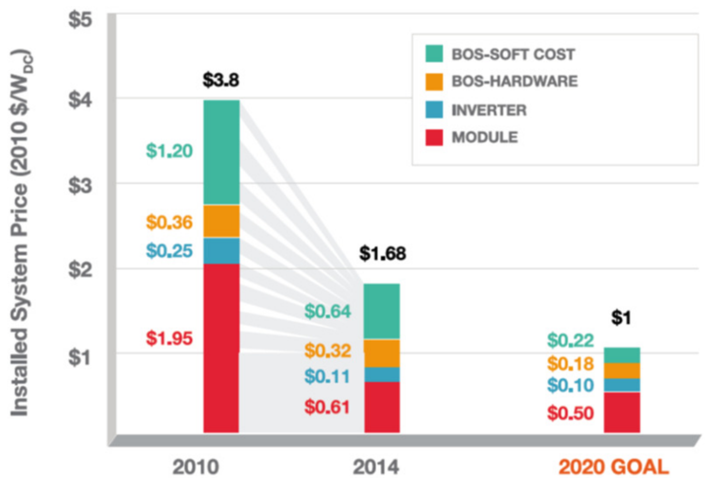
Sources: EIA, EEI

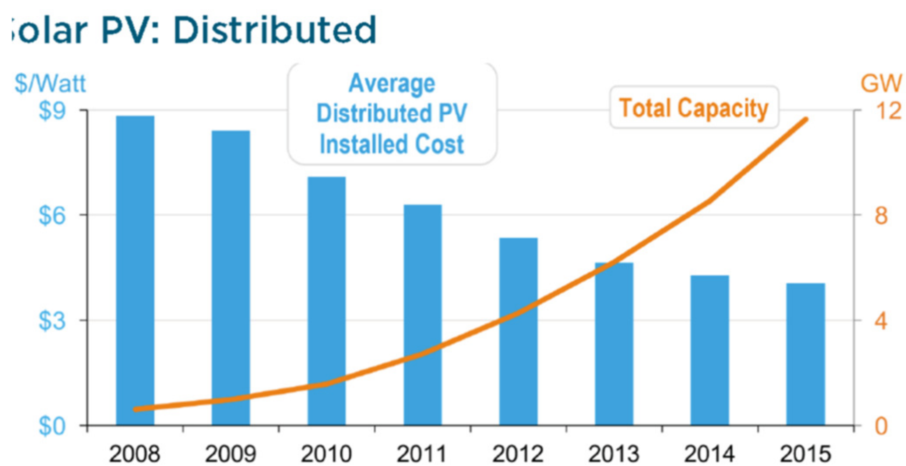
Global Trends in Energy

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

PV Deployments

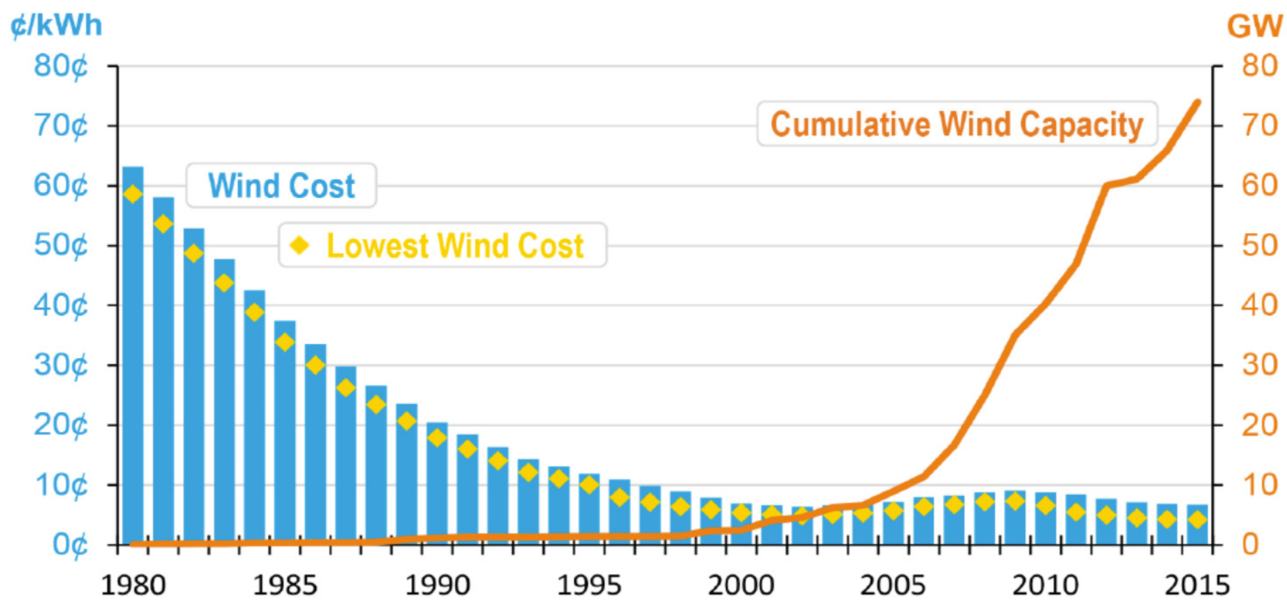






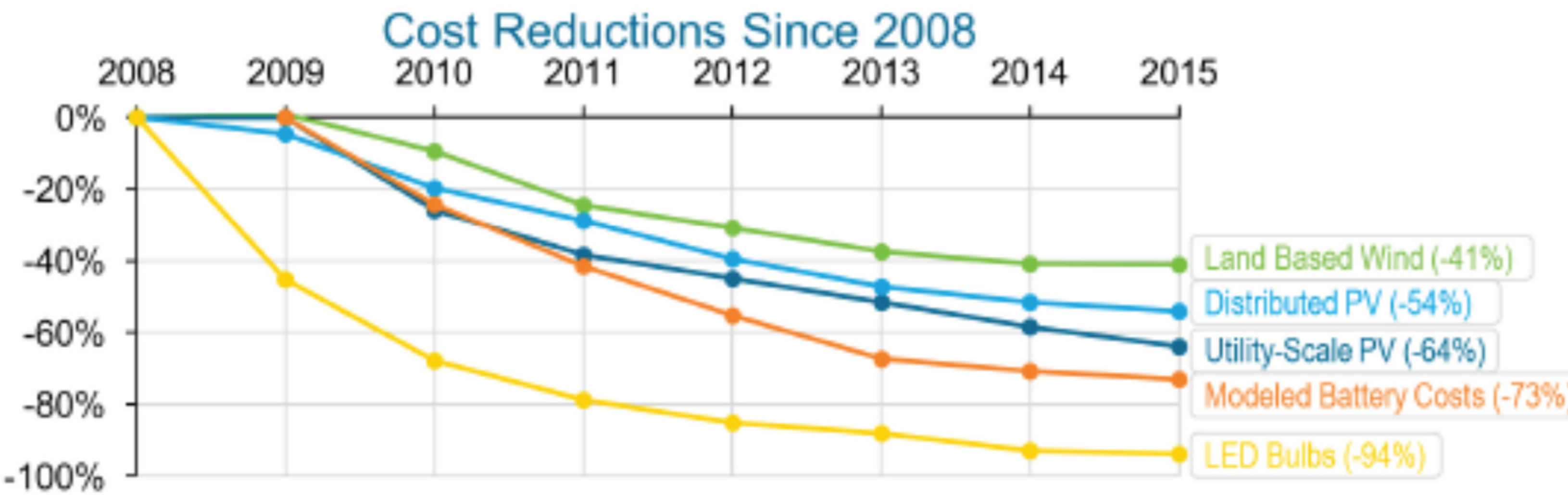
The Future Arrives for Five Clean Energy Technologies – 2016 Update, US DOE
http://energy.gov/eere/downloads/revolutionnow-2016-update

Growth of Wind Generation



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

Cost Reduction through Manufacturing



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

Major driver for rapid reductions in costs is manufacturing at scale and large scale deployments

Technology Cycles – Energy, 50-Year Cycles

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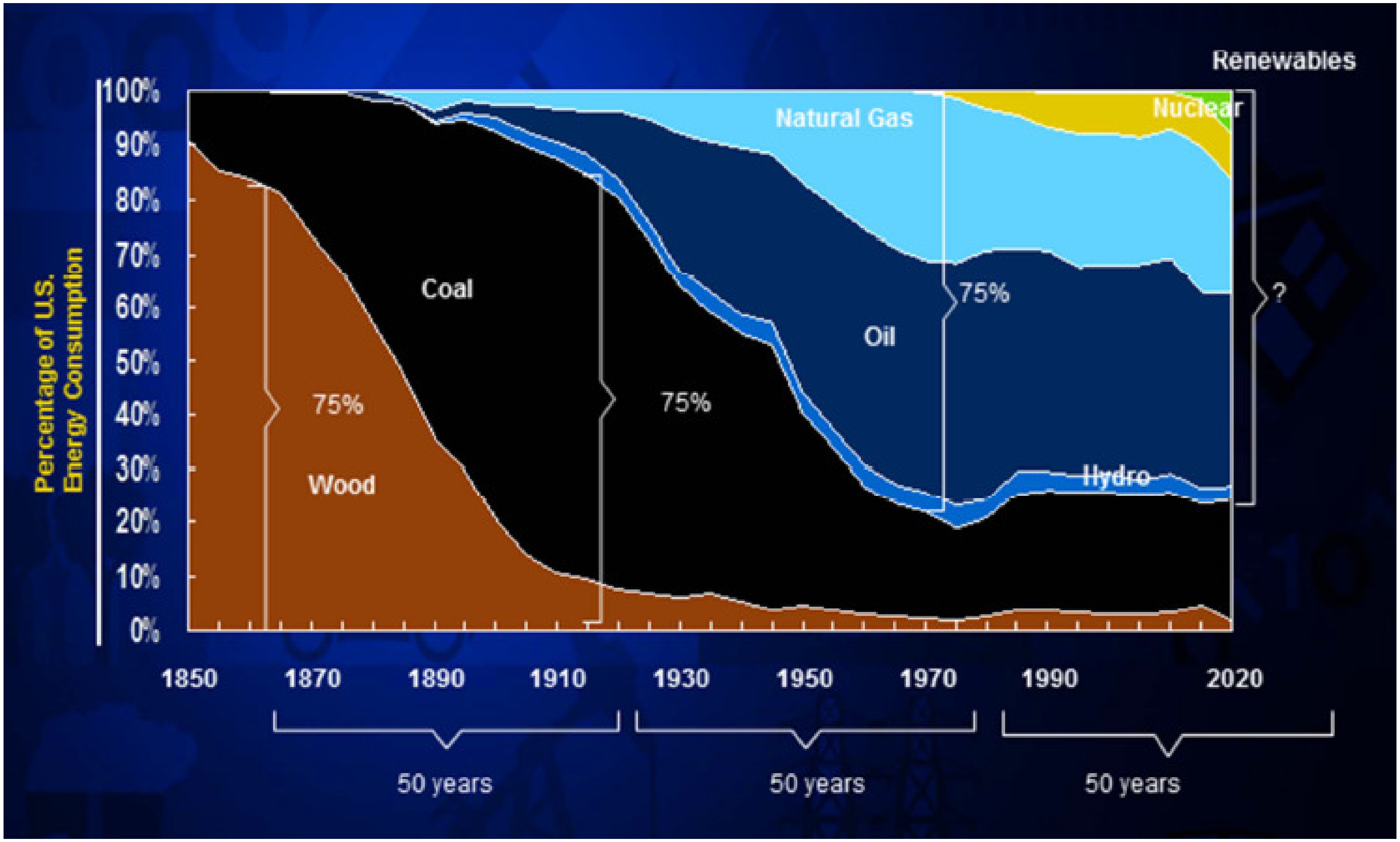
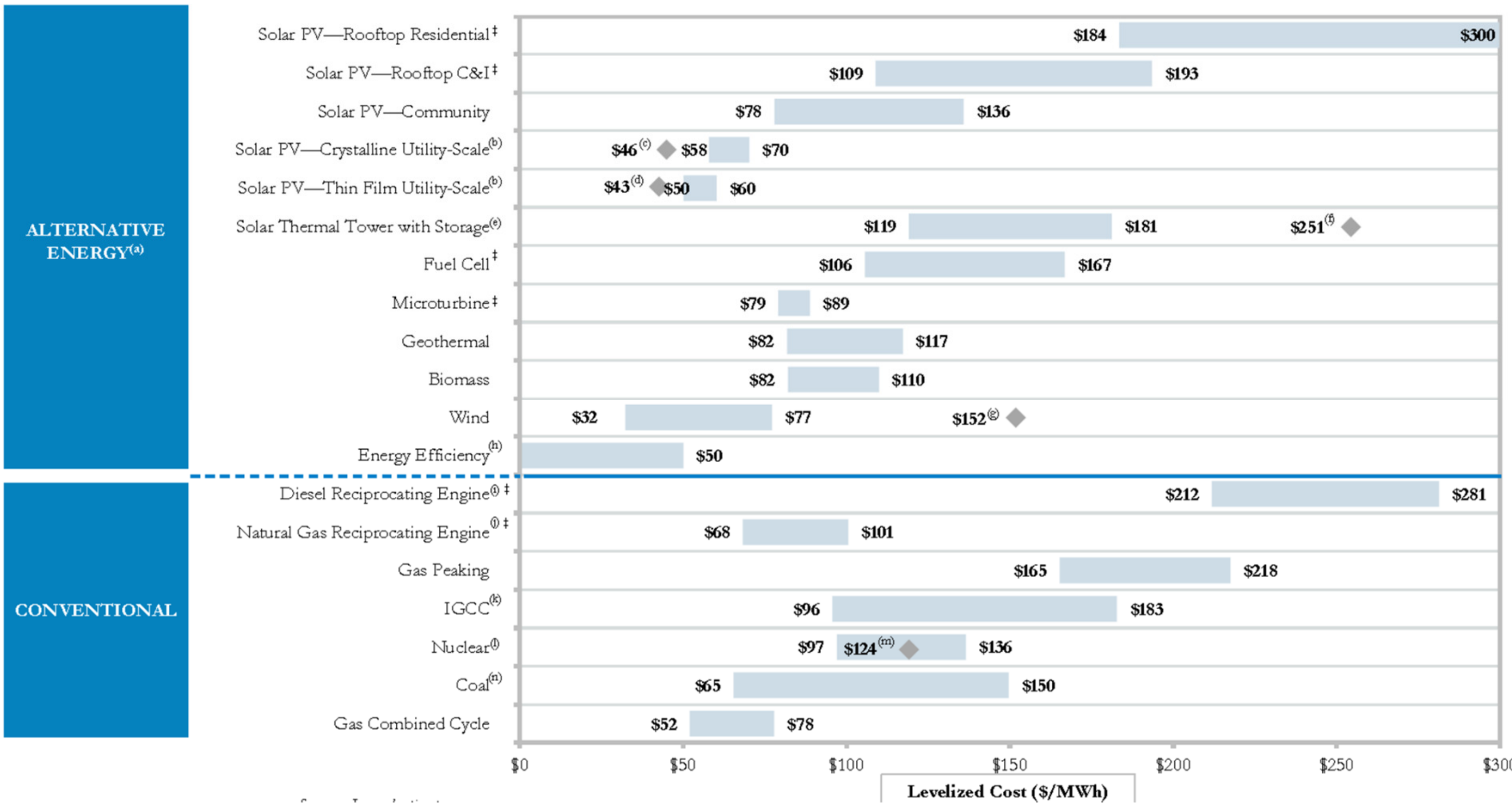


EIA Annual Energy Review 2008

Electricity Infrastructure

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

Unsubsidized Levelized Cost of Energy Comparison



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

Why Do We Need Energy Storage?

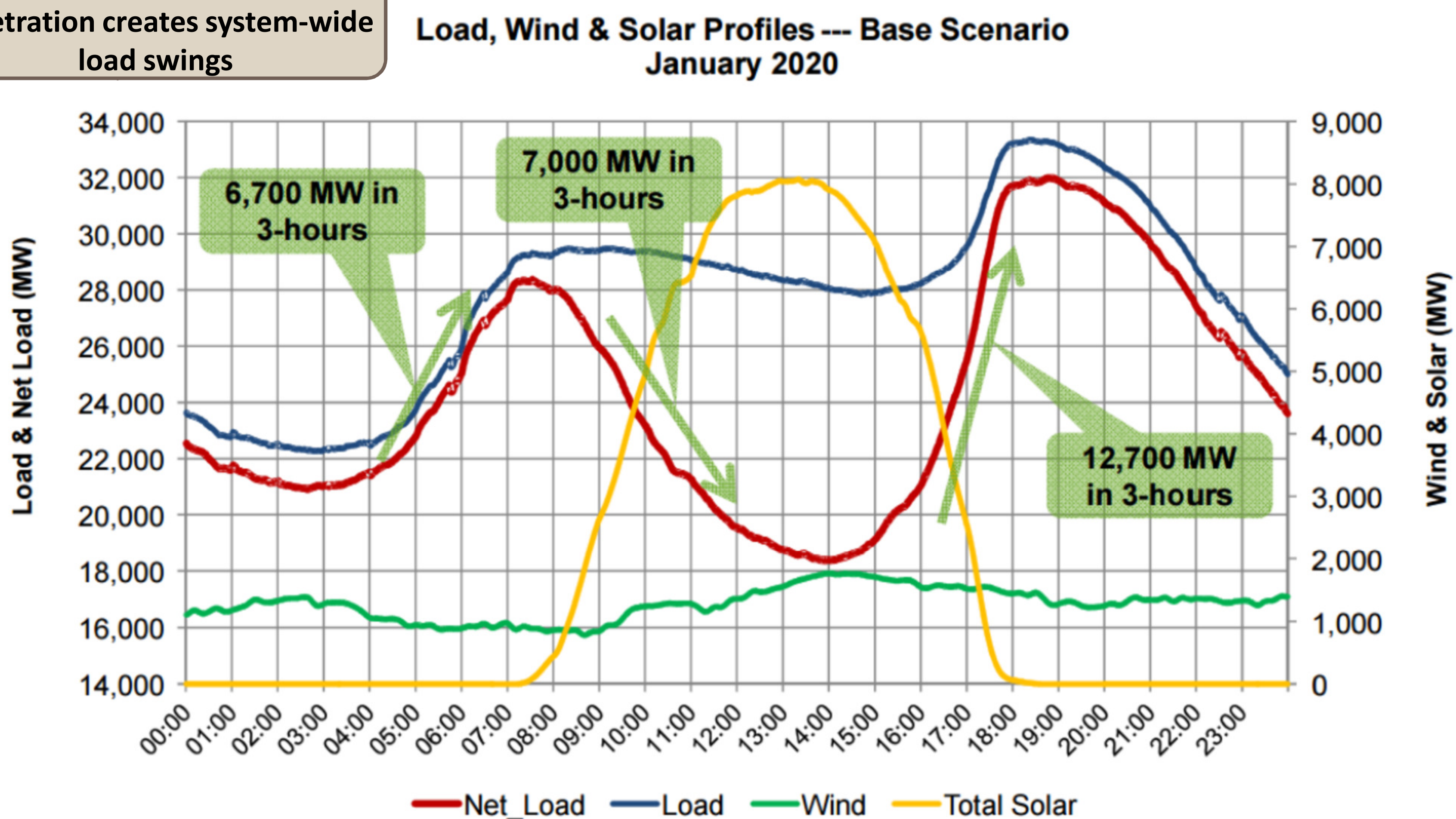
- Application drivers for large scale energy storage
  - Renewable integration
  - Transmission and Distribution upgrade deferral
  - Power quality, e.g., UPS application, microgrids, etc.
  - Improved efficiency of nonrenewable sources (e.g., coal, nuclear)
  - Off-grid applications

Energy storage mediates between variable sources and variable loads

Without storage, energy generation must equal energy consumption

Wind and Solar Load Balancing (CAISO)

Increased renewable penetration creates system-wide load swings



Source: Rob Cummings, NERC, 2016

Improved Efficiency of Existing Generation Assets

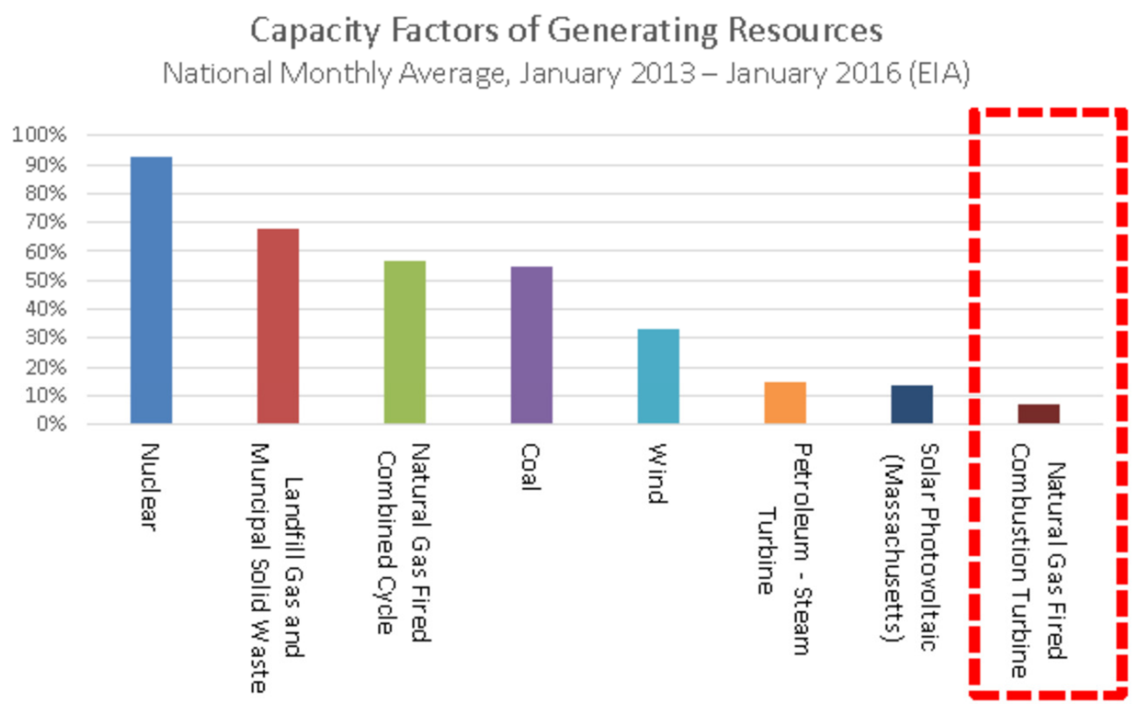
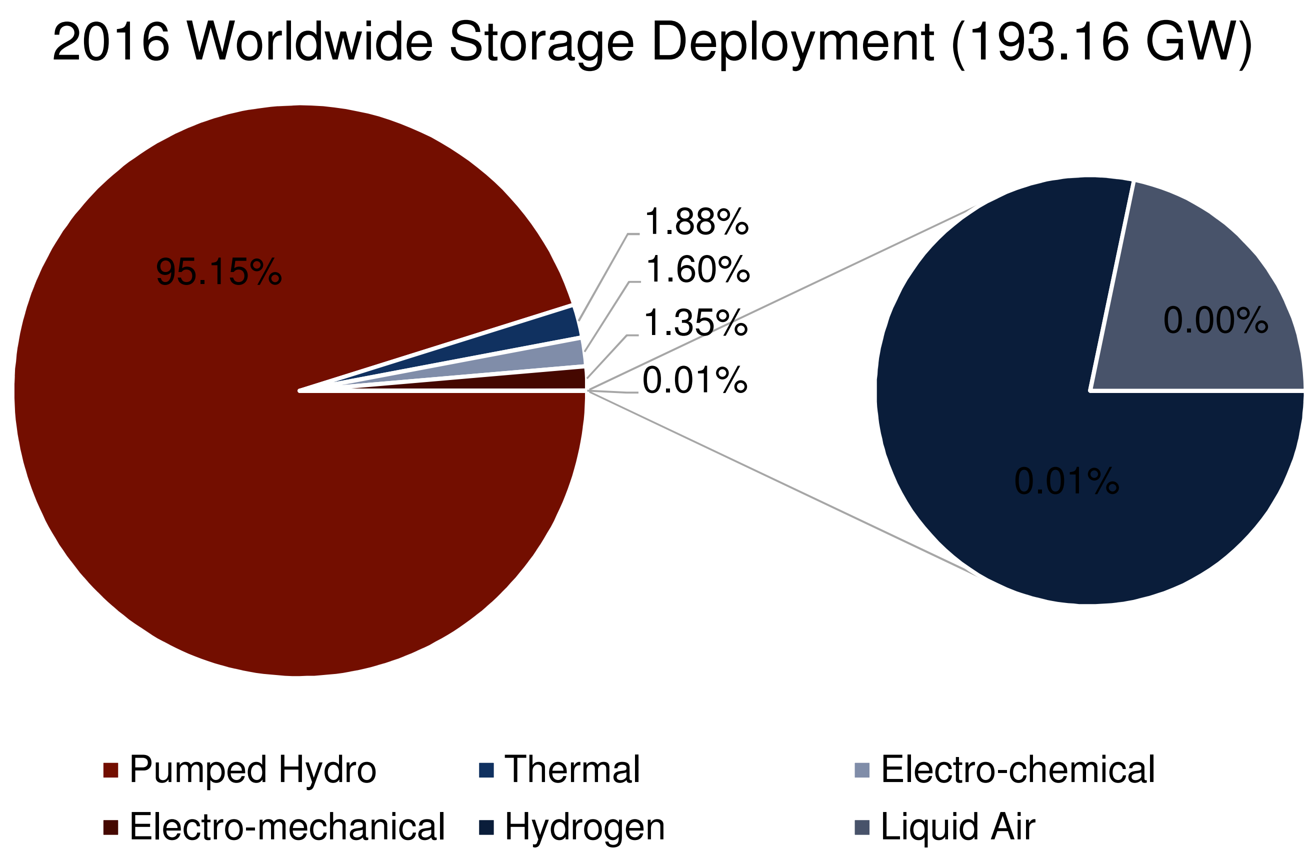


Figure 2-8: Average Monthly Capacity Factors[44]

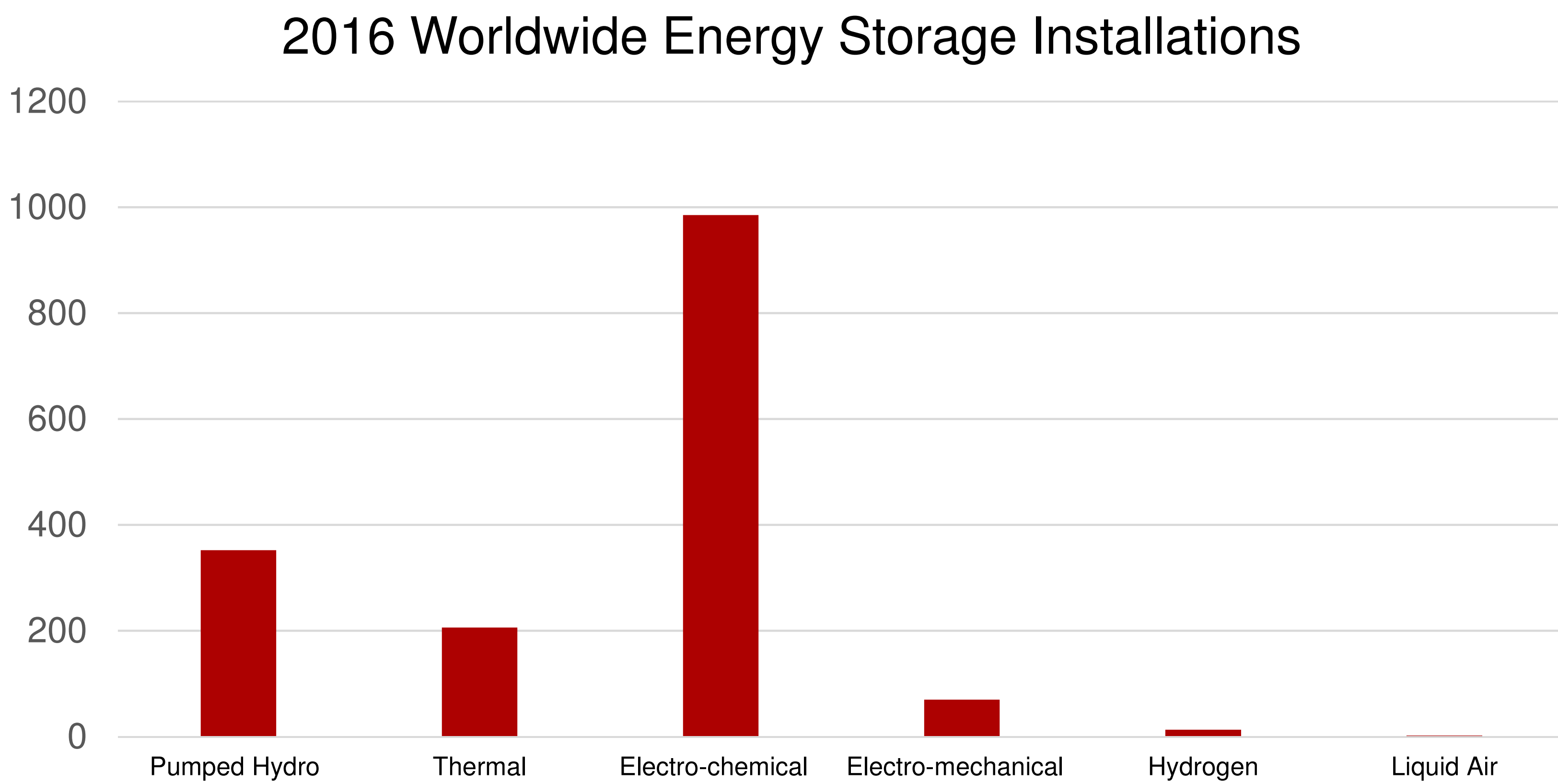
EIA Electric Power Monthly, Table 6.7.A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels, January 2013-January 2016; https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_6_07_a

Energy Storage on the Grid Today



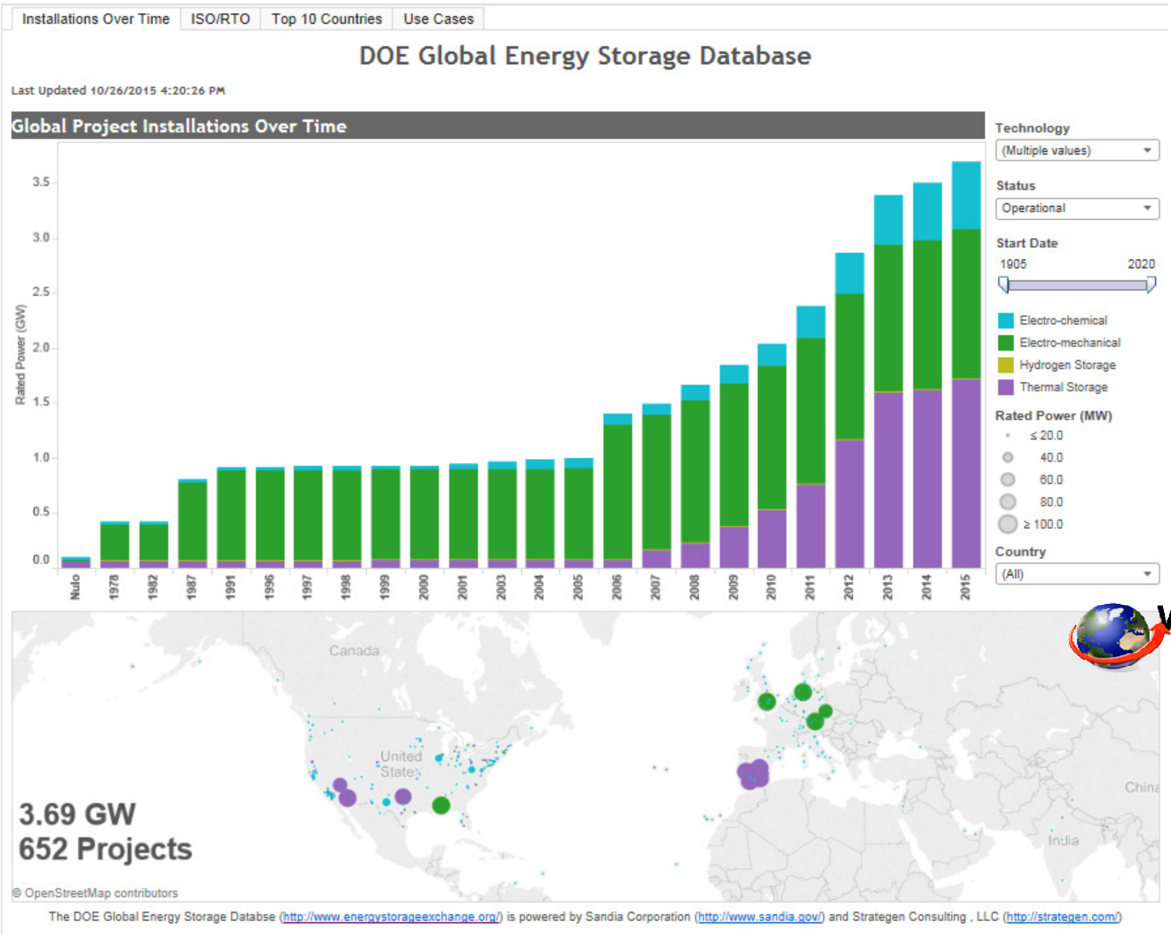
Source: U.S. Department of Energy Storage Database, December 2016.

Energy Storage on the Grid Today



Source: U.S. Department of Energy Storage Database, December 2016.

Energy Storage on the Grid Today

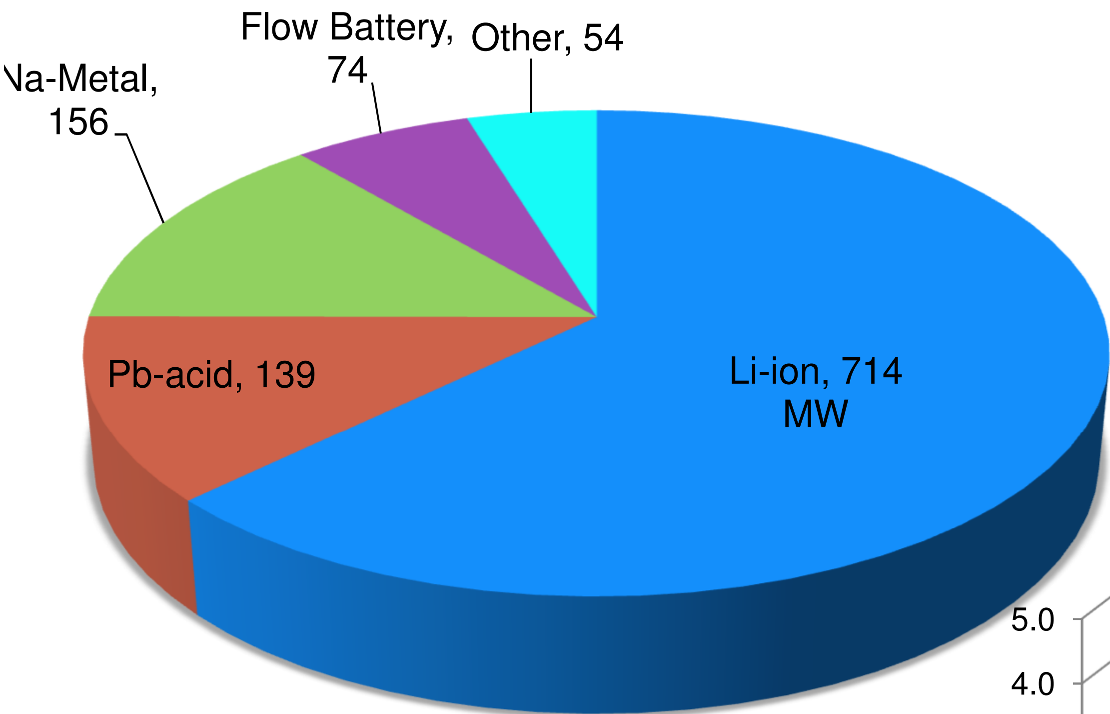


World-wide 2.2%

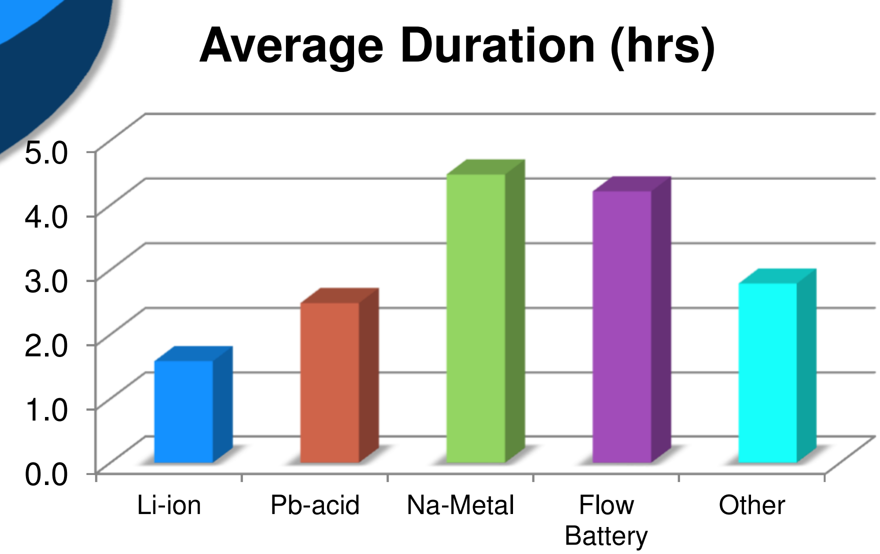
- **Japan 8.9%**
- **Europe 4.7%**
- **USA 2.2%**

Source: DOE Global Energy Storage Database, 2016

Current Stationary ESS deployments (Battery Only)

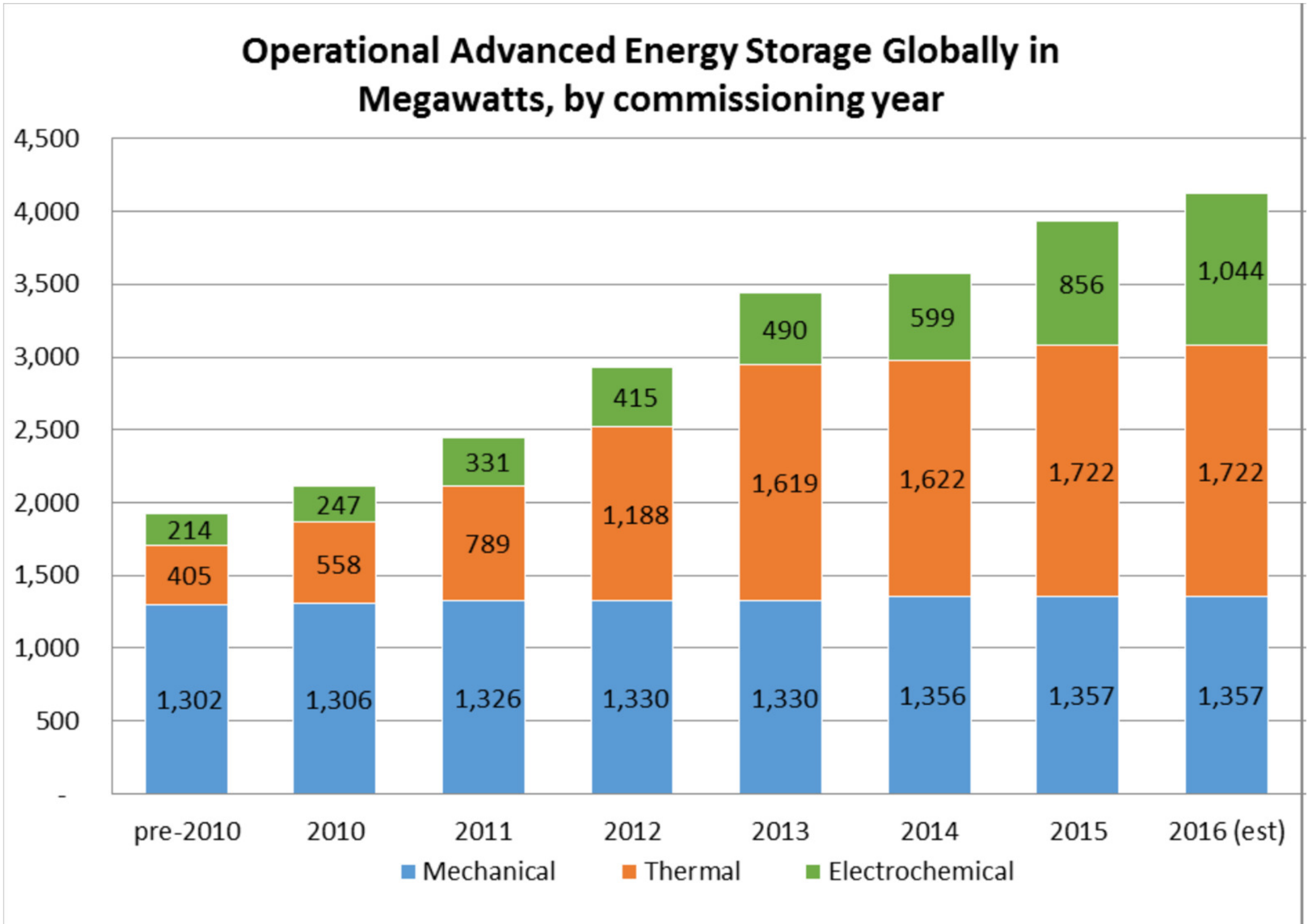


~ 1.1 GW of Battery Energy Storage (US)



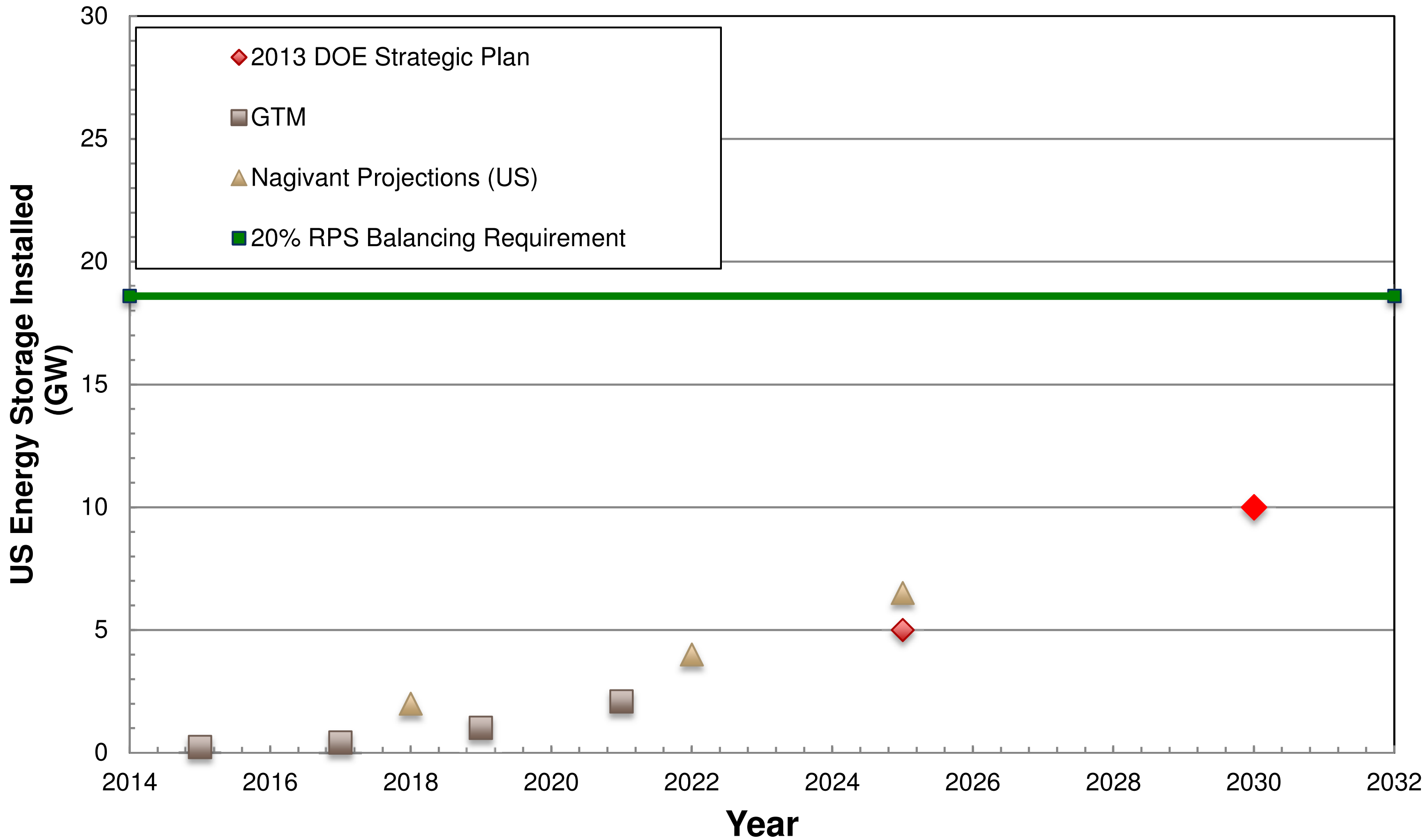
Source: *DOE Global Energy Storage Database*
http://www.energystorageexchange.org/

Operational Advanced Energy Storage (MW)



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

How much storage can the grid handle?



US Energy Storage Market Forecasts

Large Potential Market

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

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

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

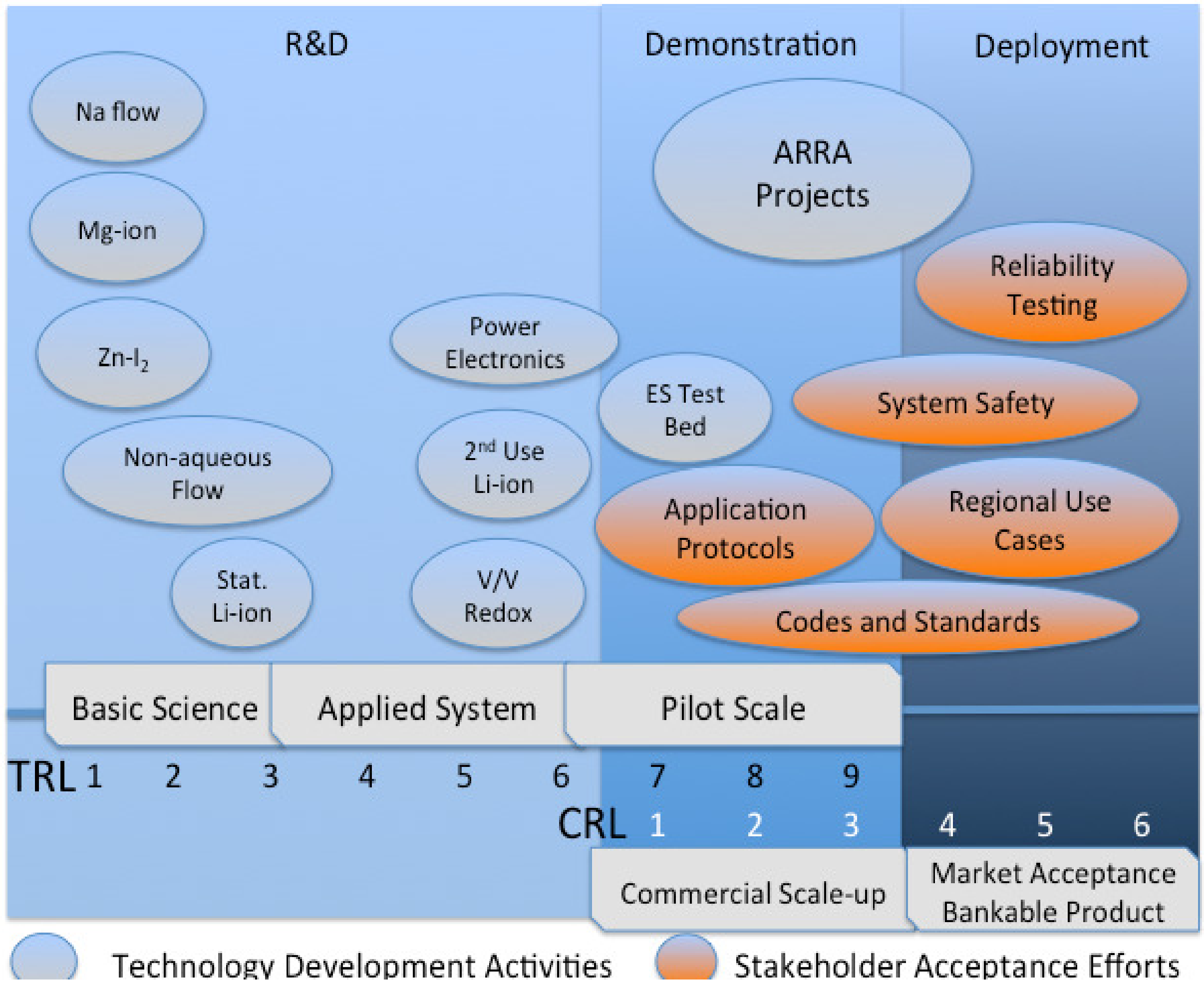
Current Status and Future

- We will need much, much more storage on our grid to increase grid resiliency, T&D deferral, accommodate renewables, etc …
- Currently, the entire storage system (batteries to interconnection) is too expensive.
- Advances in several areas will make grid-based storage systems safer, more reliable, and cost-effective
  - Technology advances
  - Manufacturing and scale-up
  - Codes and standards
- Current demonstration projects are leading the way

Making storage cost competitive

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

DOE Grid Energy Storage Program



Program focuses on the entire technology development cycle, in partnership with the industry, universities, and other labs

Exceptional service in the national interest

Sandia National Laboratories

Storage Technologies, Analytics and Valuation

Ray Byrne, Ph.D.

U.S. DEPARTMENT OF ENERGY

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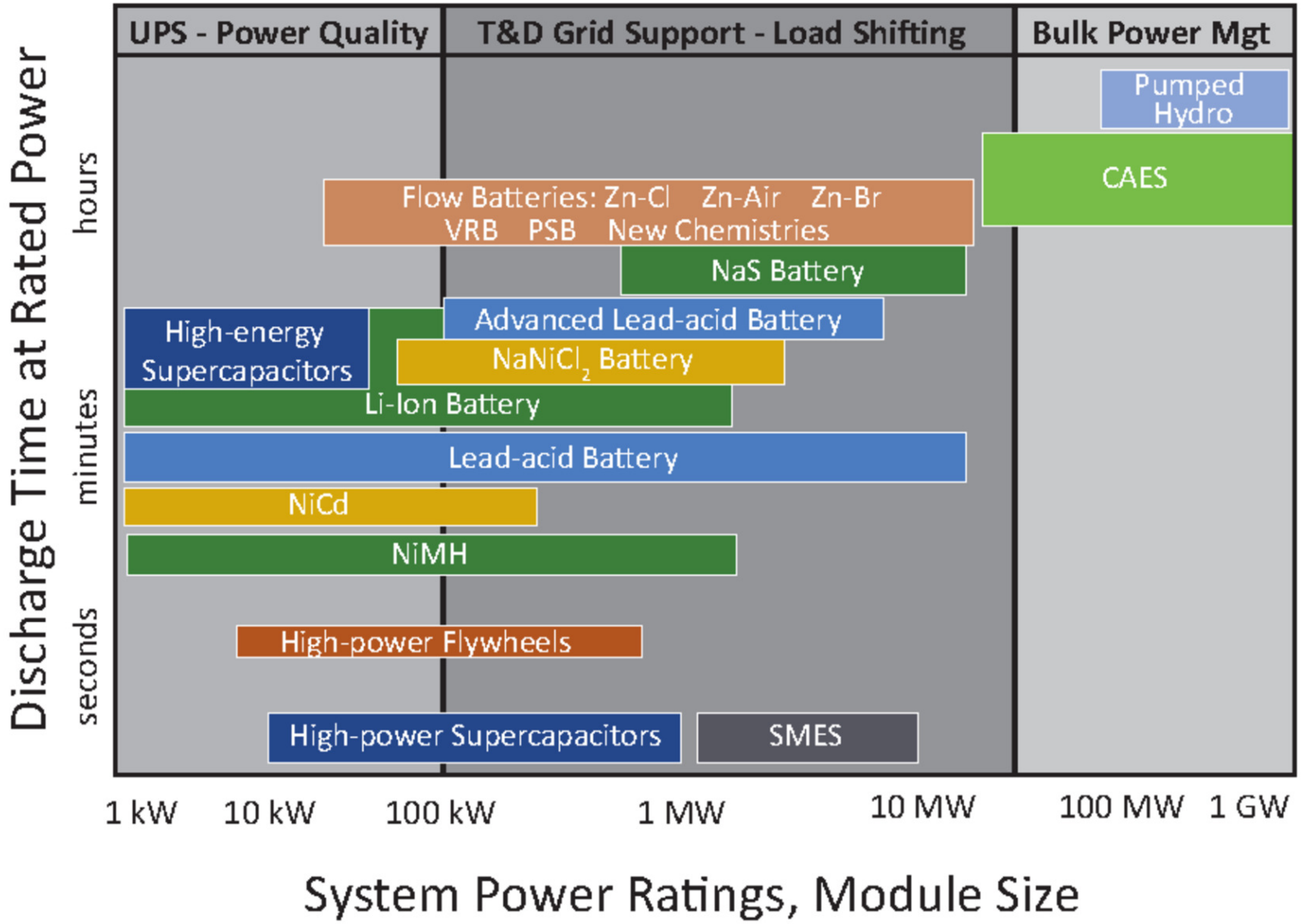
Grid Scale Energy Storage

- Primary methods for energy storage
  - Electrochemical
    - Lithium batteries
    - Lead acid batteries
    - Flow batteries
  - Mechanical
    - Compressed air
    - Pumped hydro
    - Flywheels
  - Thermal
    - Molten salt
    - Ice
  - Electrical
    - Ultra Capacitors

Storage Technology and Application Markets



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

Technology Maturities

Deployed
- Pumped hydro
- Compressed Air Energy Storage (CAES)
- Batteries (NaS, Li-ion, Pb-Acid)
- Flywheels

Demonstration
- Advanced Pb-acid and Flow batteries
- Superconducting Magnetic Energy Storage (SMES)
- Electrochemical Capacitors

Some early stage technologies
- Adiabatic CAES
- Hydrogen
- Synthetic Natural Gas

Source: U.S. Department of Energy, "Grid Energy Storage", December 2013.

Technology Overview – Pumped Hydro

- Pumped hydro energy storage
  - Developed and mature technology
  - Very high ramp rates
  - Most cost effective form of storage
- Applications
  - Energy management
  - Backup and seasonal reserves
  - Regulation service (variable speed pumps)
- Challenges
  - Geographic limitations
  - Plant site
  - Lower efficiency
  - High overall cost
  - Environmental impact

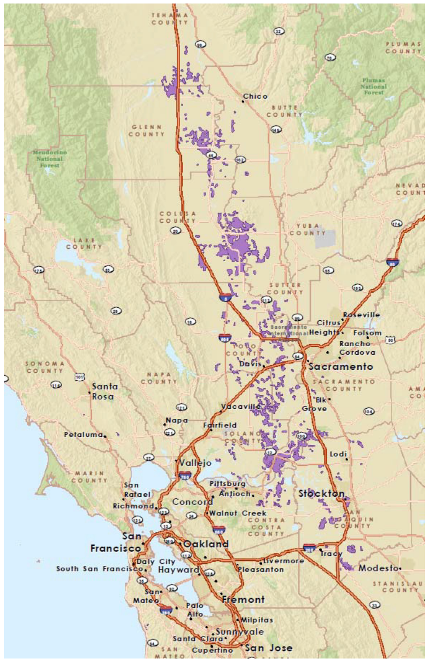
Mt. Elbert Pumped Hydro, 0.2MW, peaking plant, operational 1981.

Bath County Pumped Storage (Dominion Resources), 3 GW, operational December 1985

Technology Overview - CAES

- Compressed air energy storage (CAES)
  - Established technology in operation since the 1970's
  - 110 MW (26+ hours) plant in McIntosh, Alabama – operational since 1991
  - Better ramp rates than gas turbines
- Applications
  - Energy management
  - Backup and seasonal reserves
  - Renewable integration
- Challenges
  - Geographic limitations
  - Lower efficiency
  - Slower than flywheels or batteries
  - Environmental impact

Solution-mined salt dome in McIntosh, AL



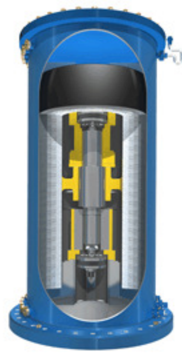
PG&E CAES feasibility study (porous rock)

SustainX isothermal CAES

Technology Overview - Flywheels

Sandia National Laboratories

- Flywheel energy storage
  - Modular technology
  - Long cycle life
  - High peak power
  - Rapid response
  - High round trip efficiency (~85%)
- Applications
  - Load leveling
  - Frequency regulation
  - Peak shaving
  - Transient stability
- Challenges
  - High cost per unit energy stored
  - Lack of codes and standards for safe design and operation



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

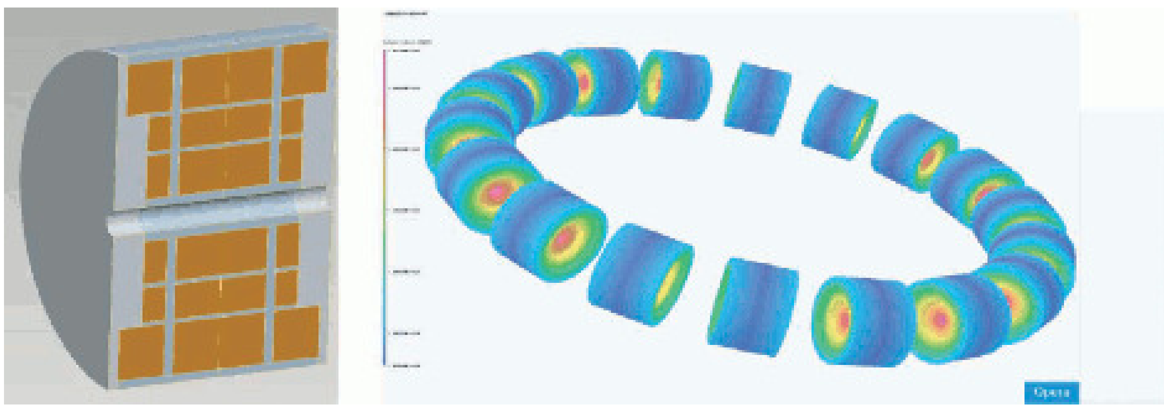
Technology Overview - Capacitors

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

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

Technology Overview - SMES

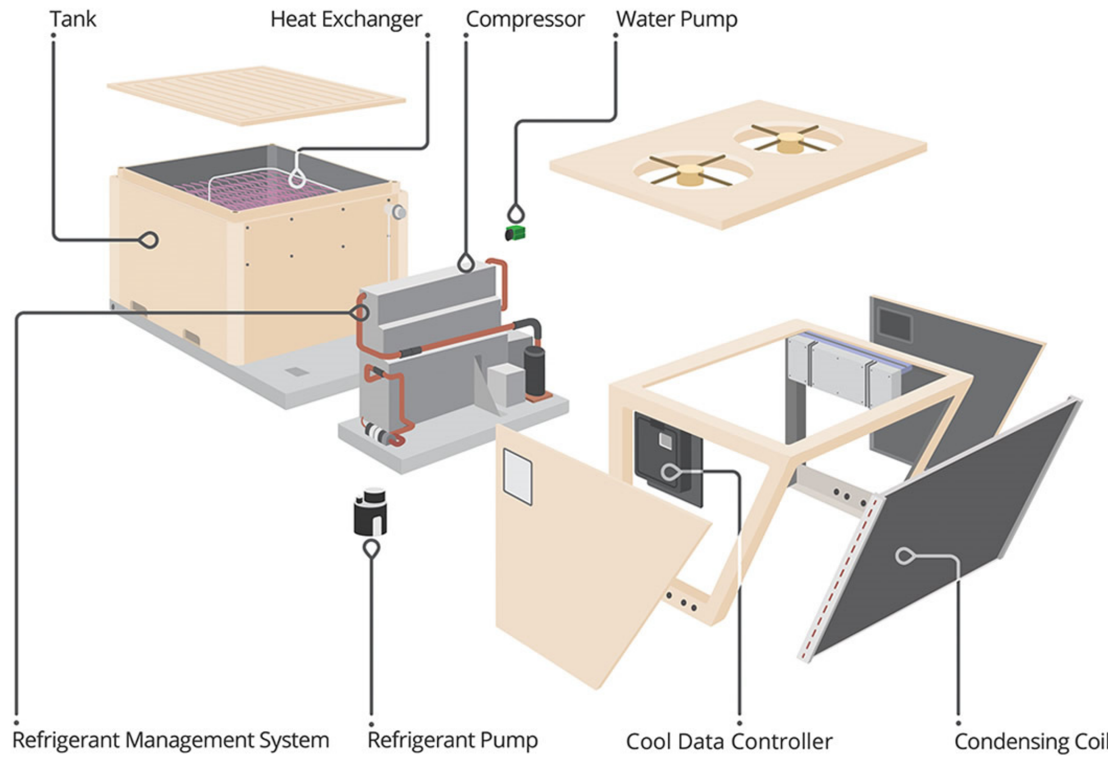
- Super Conductive Magnetic Energy Storage
  - Highest round trip efficiency (~95%)
- Applications
  - Power quality
  - Frequency regulation
- Challenges
  - Low energy density
  - Component and manufacturing cost



2010 SMES Project (ARPA-E)

Technology Overview – Thermal

- Thermal Energy Storage
  - Ice-based technology
  - Molten salt
- Applications
  - Energy time shift
  - Renewable firming
- Challenges
  - Lower efficiency (~70%) for electricity-electricity
  - Solar thermal plants more expensive than PV



Ice Energy's proven Ice Bear® system, www.ice-energy.com

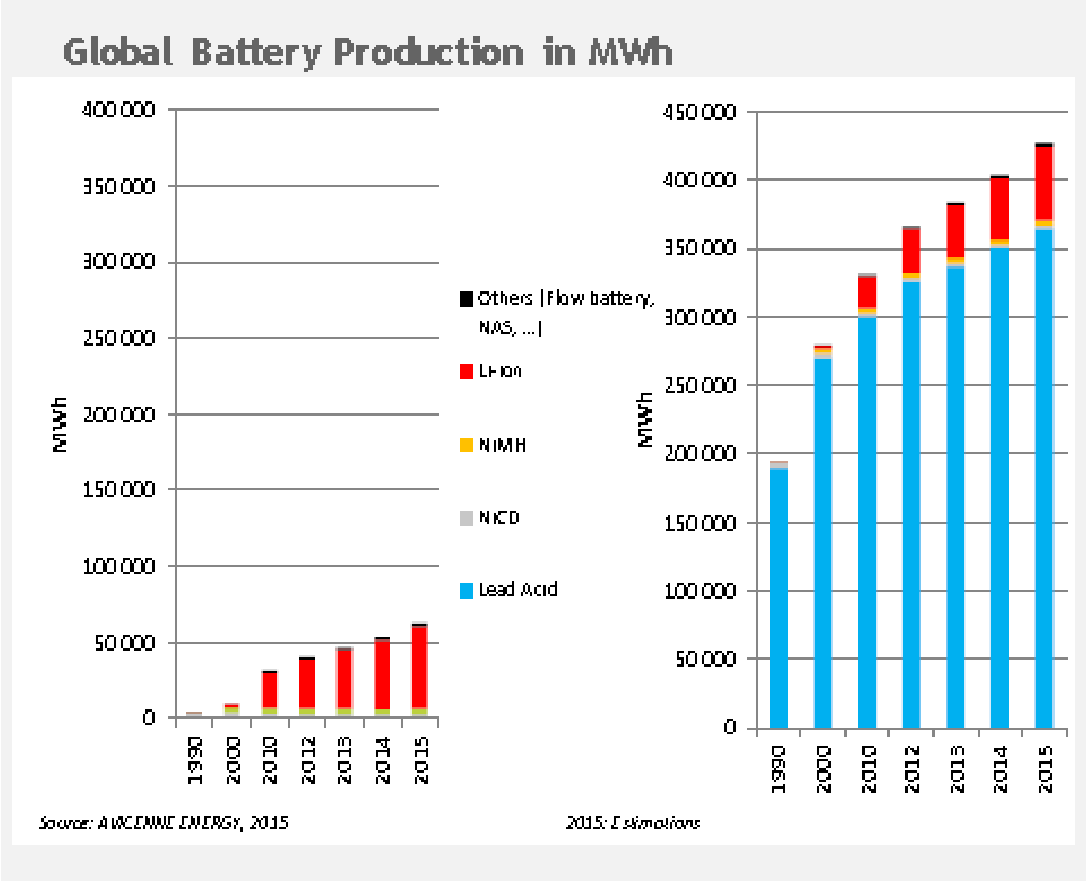
Battery Technologies

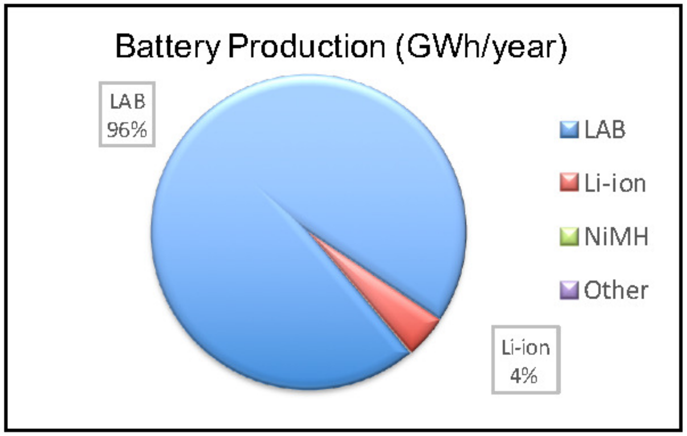
Mature Technologies				
	World Wide Capacity (GWh/y)	**Cost and Performance Improvements**	**Key Challenges for Energy Storage**	**Major Suppliers**
Lead Acid Batteries (LAB)	300	2%/year ((30 year data). $150/kWh	Cycle life. Advanced lead acid cycle life on par with EV grade LIB	JCI, GS Yuesa, EastPenn,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

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

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

Global Production Volumes



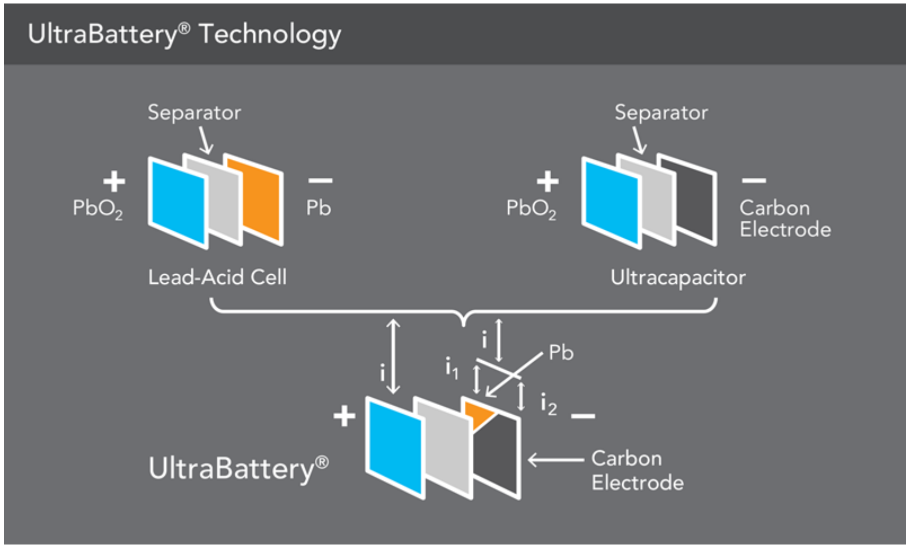


Source: Avicenne (2015), DOE

Only lead acid and Li ion are at capacities to support large scale grid applications. While Lead Acid Battery business continues to be profitable, large format Li-ion struggling with low factory utilization rates.

Technology Overview - Lead Acid

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

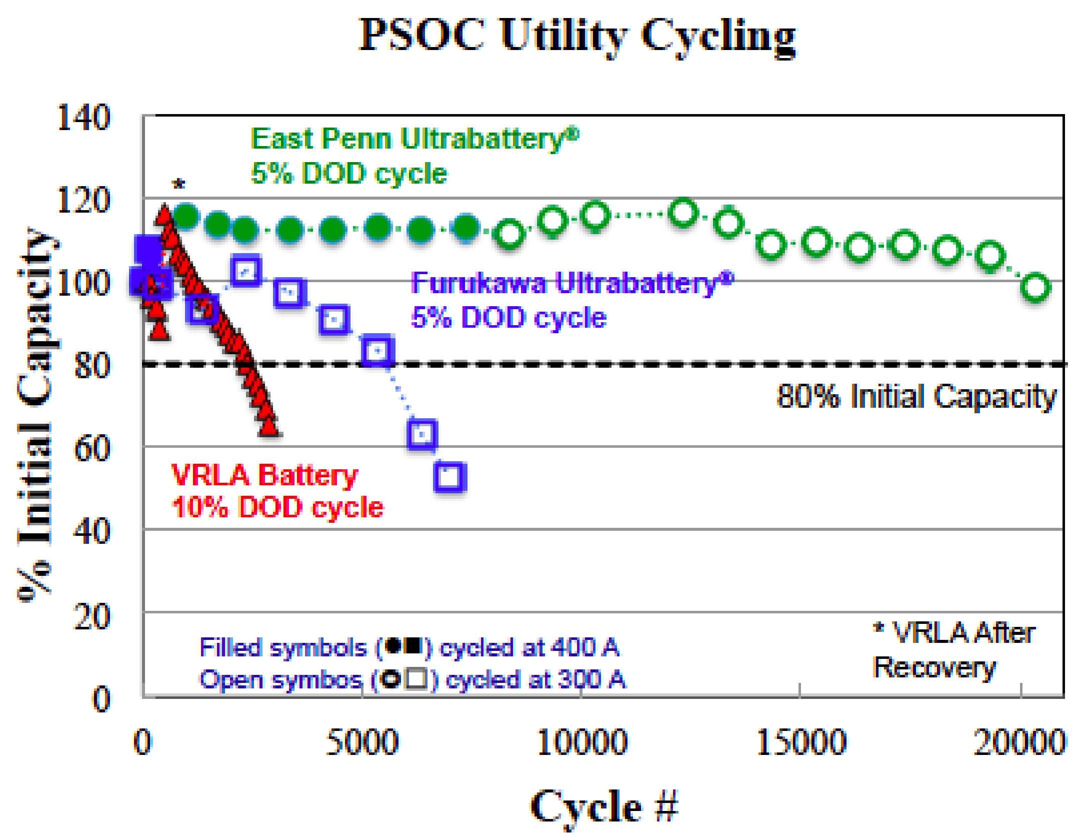


Albuquerque, NM

East Lyons, PA

Advanced Lead Acid: Cycle Life

East Penn



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

Technology Overview - Li-ion Batteries

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

SCE Tehachapi plant, 8MW, 32MWh.

Lithium Ion Batteries

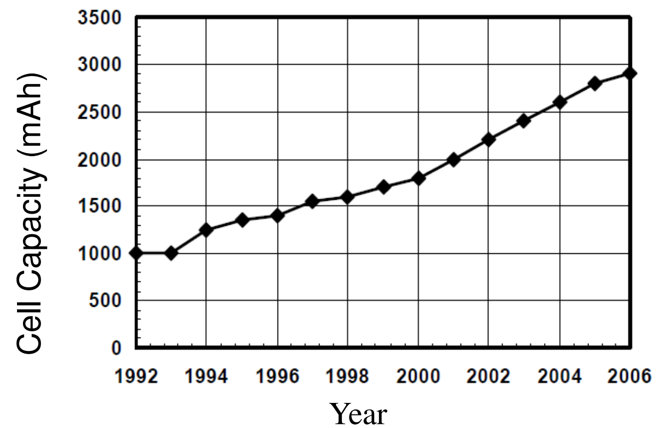
- First two generations driven by consumer electronics, newer chemistries geared for automotive applications
  - Li-Ion Chemistries, $LiCoO_2$ - dominant technology for consumer electronics
  - 2nd Generation Li-Ion Chemistries
    - Better performance, up to 300 Wh/kg with fast recharge
    - Wider temp range, Improved safety and potentially lower cost
  - Spill off into Power applications, competitive for power applications in the grid. Several installations for power regulation (2-20 MW)
- Li ion chemistry
  - Safety and reliability continues to be significant concerns
  - Power control and safety adds significant cost to Li ion storage
  - Packaging and thermal management add significant costs
  - Deep discharge cycle life issues for energy applications (1000 cycles for automotive)

Li-ion Batteries: SOA

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

Li-ion – Cycles of Learning

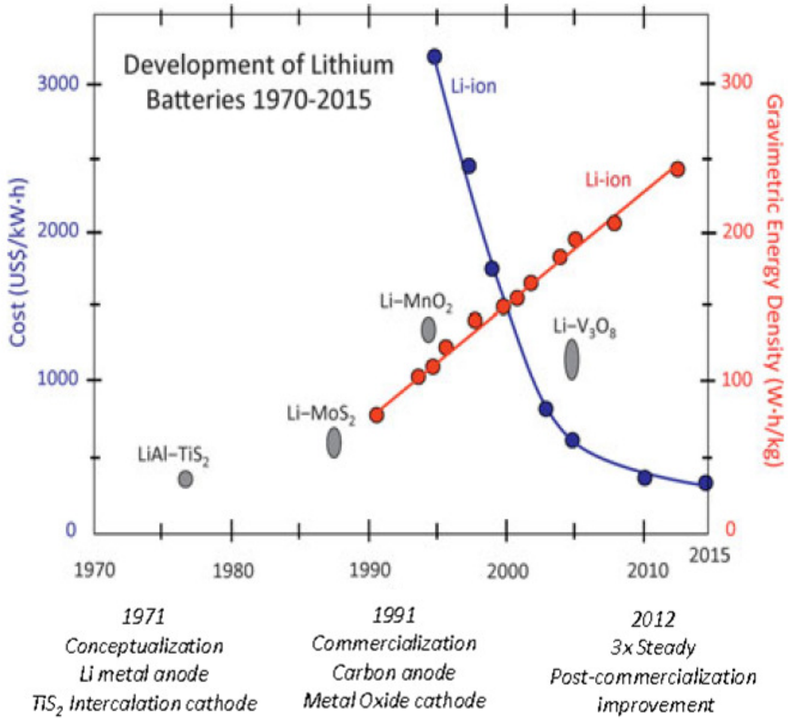
- Capacity improvements are incremental
  - 8% for LIB (1992-2007); 2% for LAB
  - Capacity improvements are incremental
- Continued reduction in cost/performance
  - Materials cost can not be scaled down much lower, BOM is 80-85% of cell costs
  - Need significant improvement in electrolytes, membranes,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



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

- 2015 LIB manufacturing capacity: 50 GWh
- 2015 LAB manufacturing capacity: 300 GWh

Capacity Scaling is Volumetric



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

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

Technology Overview - Flow Batteries

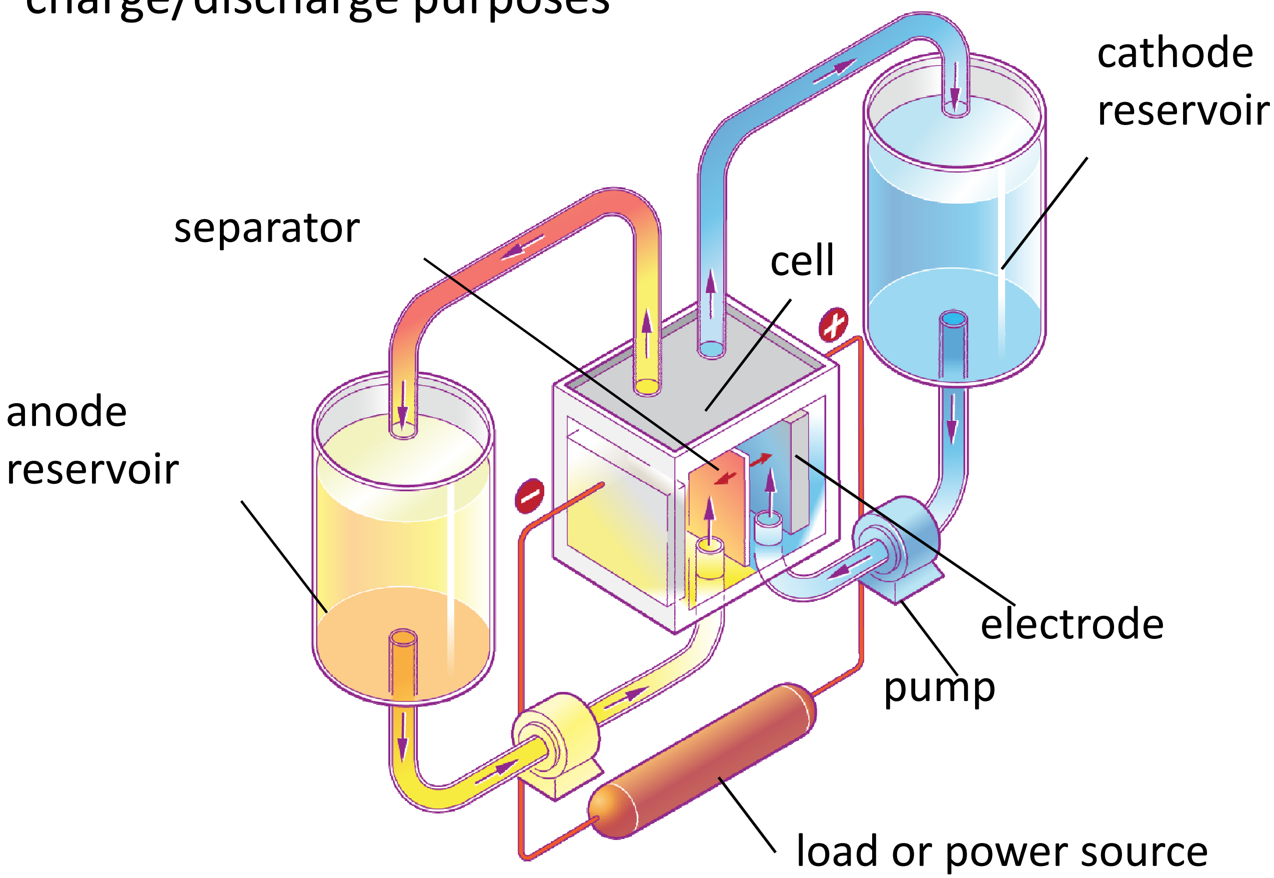
- Flow Battery Energy Storage
  - Long cycle life
  - Power/Energy decomposition
  - Lower efficiency
- Applications
  - Ramping
  - Peak Shaving
  - Time Shifting
  - Power quality
  - Frequency regulation
- Challenges
  - Developing technology
  - Complicated design
  - Lower energy density

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

Vionx Vanadium Redox Flow battery, 65kW, 390kWh

Flow Batteries

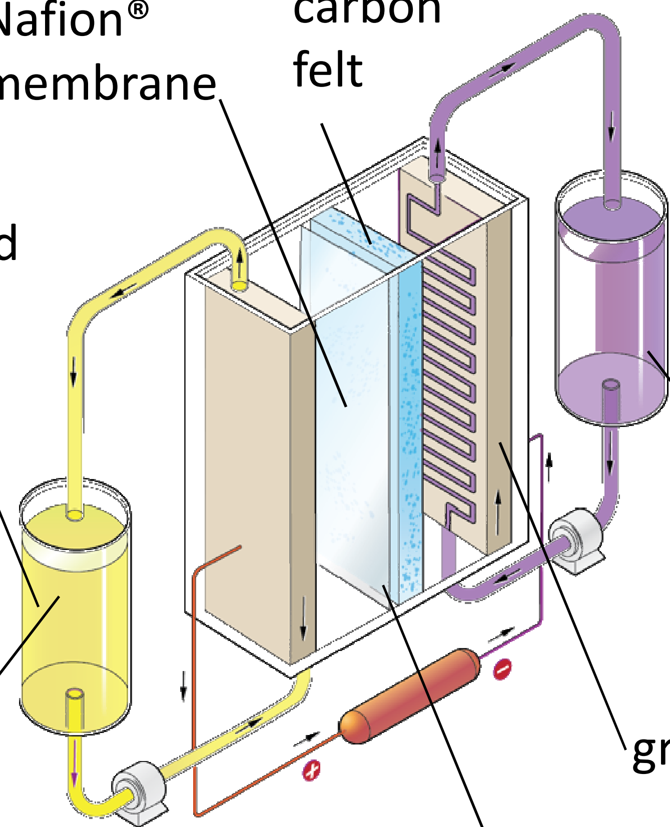
- Energy storage technology utilizing redox states of various species for charge/discharge purposes



All-Vanadium Battery

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

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



Redox Flow Batteries - Advantages/Issues

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

Flow Batteries - SOA

Advantages

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

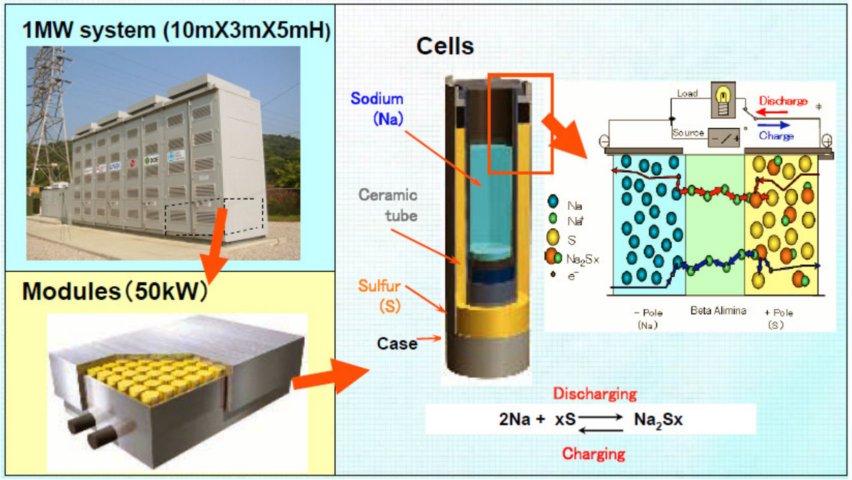
Disadvantages

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

Technology Overview - NaS Batteries

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

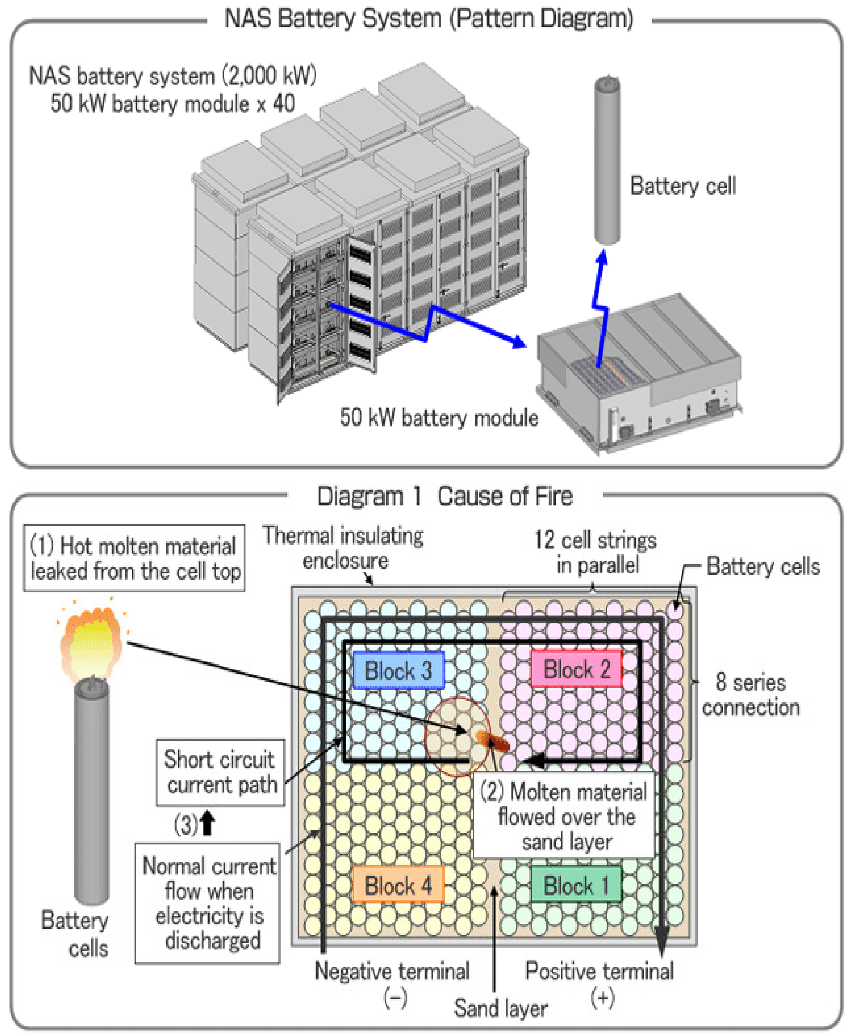
Los Alamos, NM. 1 MW, 6MWh



Source: NGK

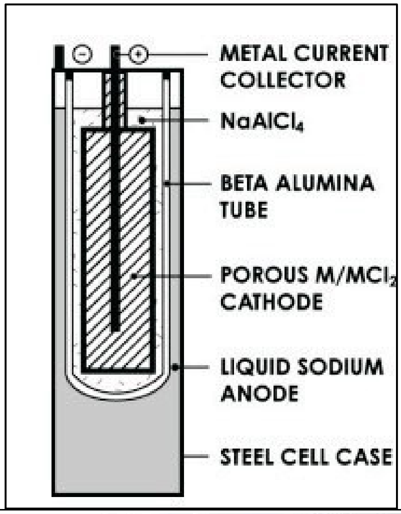
NaS - Challenges

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



Technology Overview - NaNiCl2 (Zebra) Batteries

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



FIAMM 222-kWh System Duke Energy Rankin Substation

High Energy Density Li and Metal Air Batteries

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

Further Away: Other Li-like Chemistries

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

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

Technology Overview - Super Capacitors

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

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

Energy Storage Systems

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

Elements of an Energy Storage System

Storage

- Cell
- Battery Management & Protection
- Racking

Integration

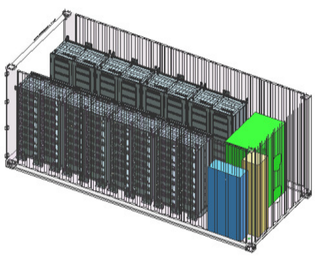
- Container / Housing
- Wiring
- Climate control

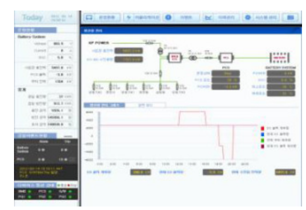
PCS

- Bi-directional Inverter
- Switchgear
- Transformer
- Skid

EMS

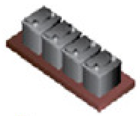
- Charge / Discharge
- Load Management
- Ramp rate control
- Grid Stability





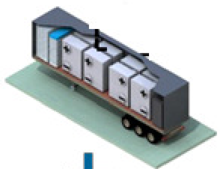
We need cost reductions across all areas, not just batteries

Cost Structure of Storage System in 2016



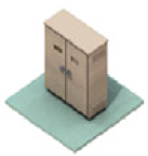
Storage
Racks+BMS

+



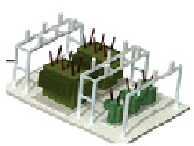
Product
Integration

+

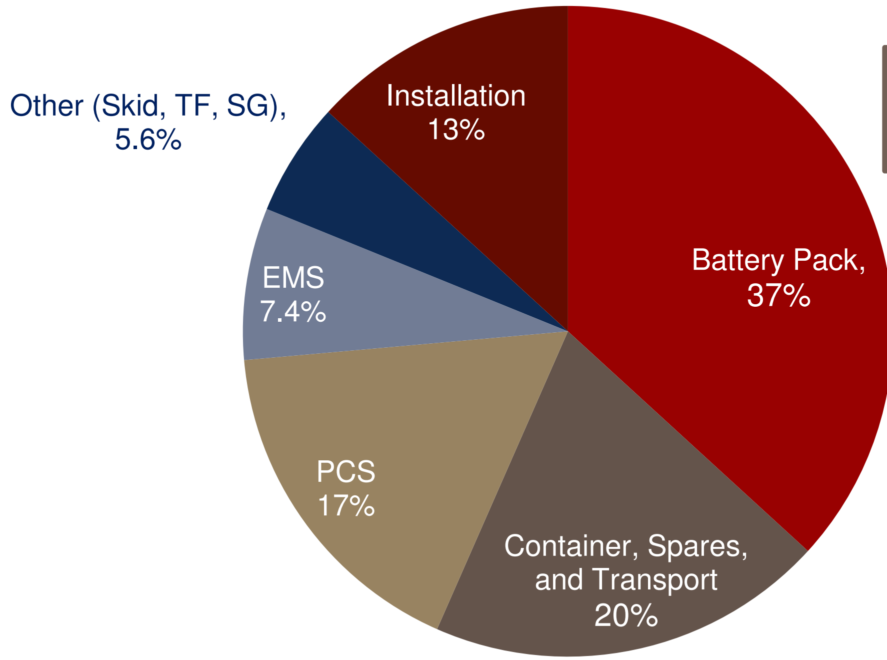


Power
Conditioning
(PCS)

+



Field EPC
Grid Integration



1MW/1MWh
LIB ESS

Data: Multiple industry source

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

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

Battery to ES System

Sandia National Laboratories

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

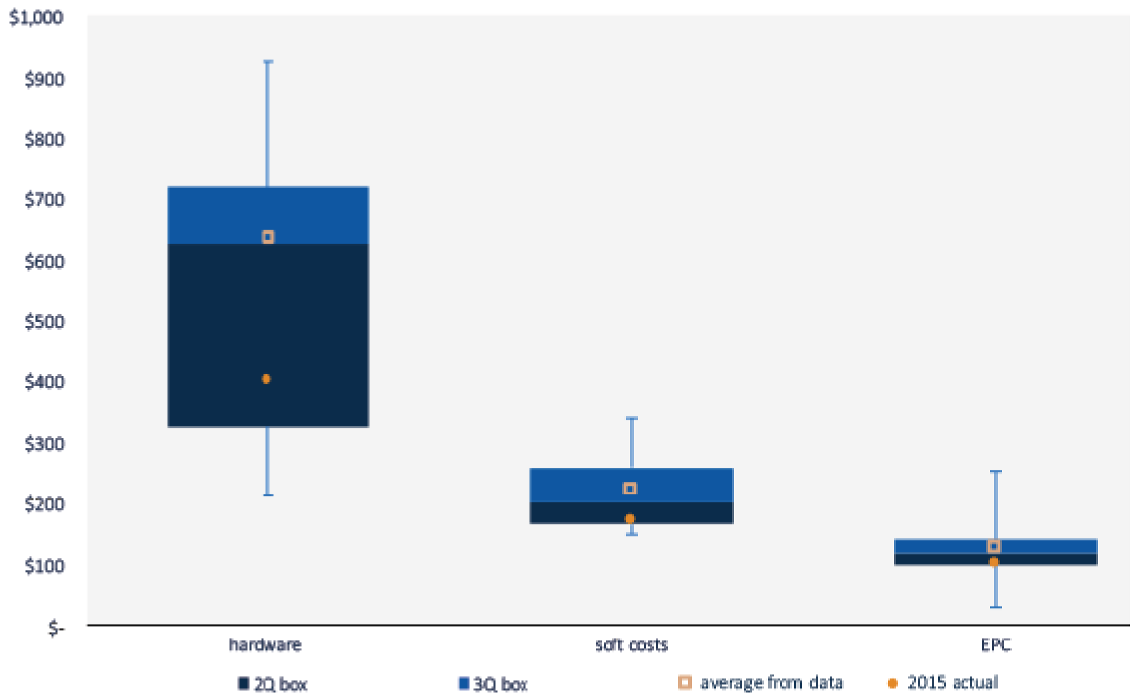
PCS/BOS
- Power Electronics $/kW
- BOS (Container, Safety, Thermal Management)

Softcosts
- Interconnection
- Permits
- O&M

Battery to a Storage System: doubling in cost

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

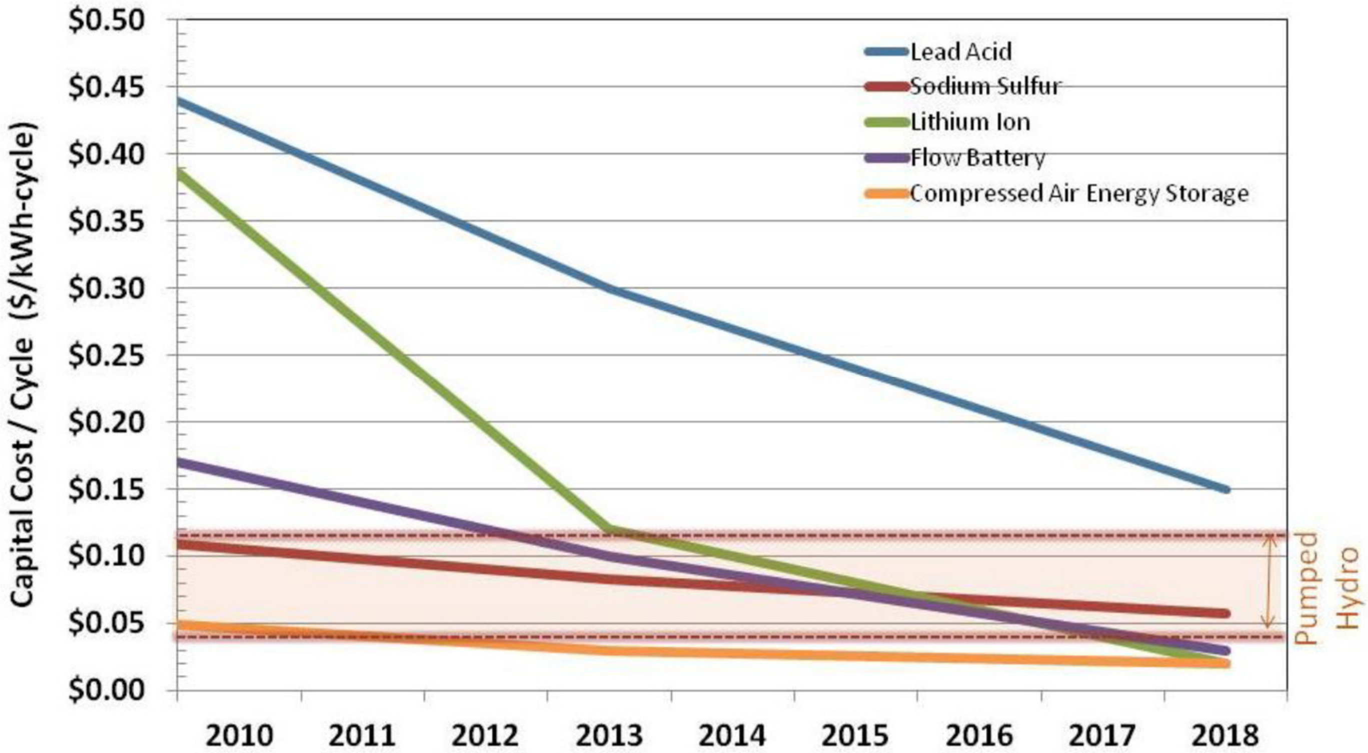
Balance of System Costs



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

Estimated Capital Costs by Technology and Type

Sandia National Laboratories



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

Making LCOE of Energy Storage Competitive

Sandia National Laboratories

- For large scale deployment, levelized cost of energy stored (LCOES) need to be competitive with combined cycle NG plants
- Storage LCOES needs to reflect cycle life, efficiency, depth of depth, and other long term performance metrics.

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

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

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

Modest improvements

Safety and Reliability

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

Energy Storage Safety


2011 Beacon Power Flywheel Failure


2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

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


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

2012 GM Test Facility Explosion, Warren, MI

Improving Storage Safety

Sandia National Laboratories

Development of Inherently Safe Cells

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

Safety Devices and Systems

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

Effective Response to Off-Normal Events

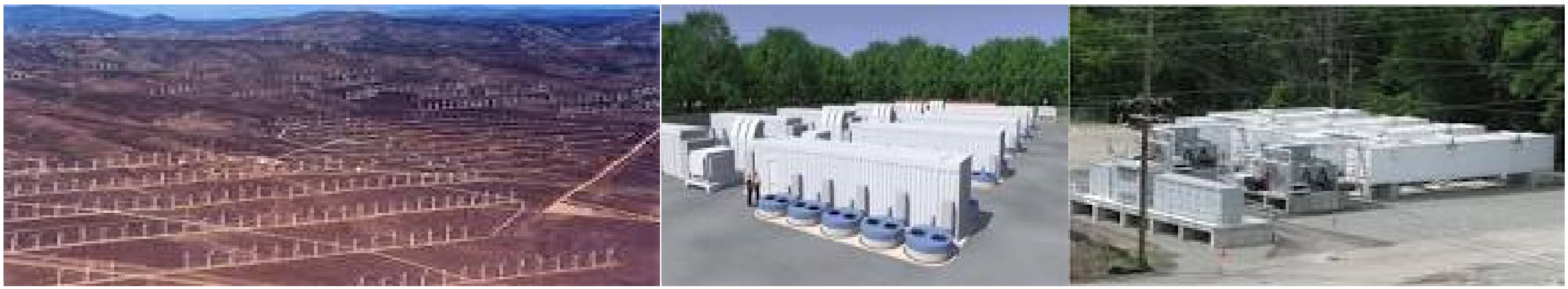
- Suppressants
- Containment
- Advanced monitoring and controls

Safety through Codes and Standards

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

Exceptional service in the national interest

Sandia National Laboratories



Analytics and Energy Storage Economics

Ray Byrne, Ph.D.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Recent Storage Policy Breakthroughs

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

California Energy Storage Mandate

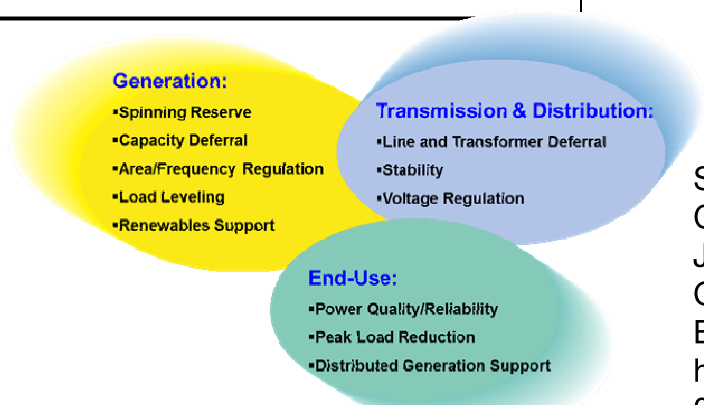
Sandia National Laboratories

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

Energy Storage Services

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

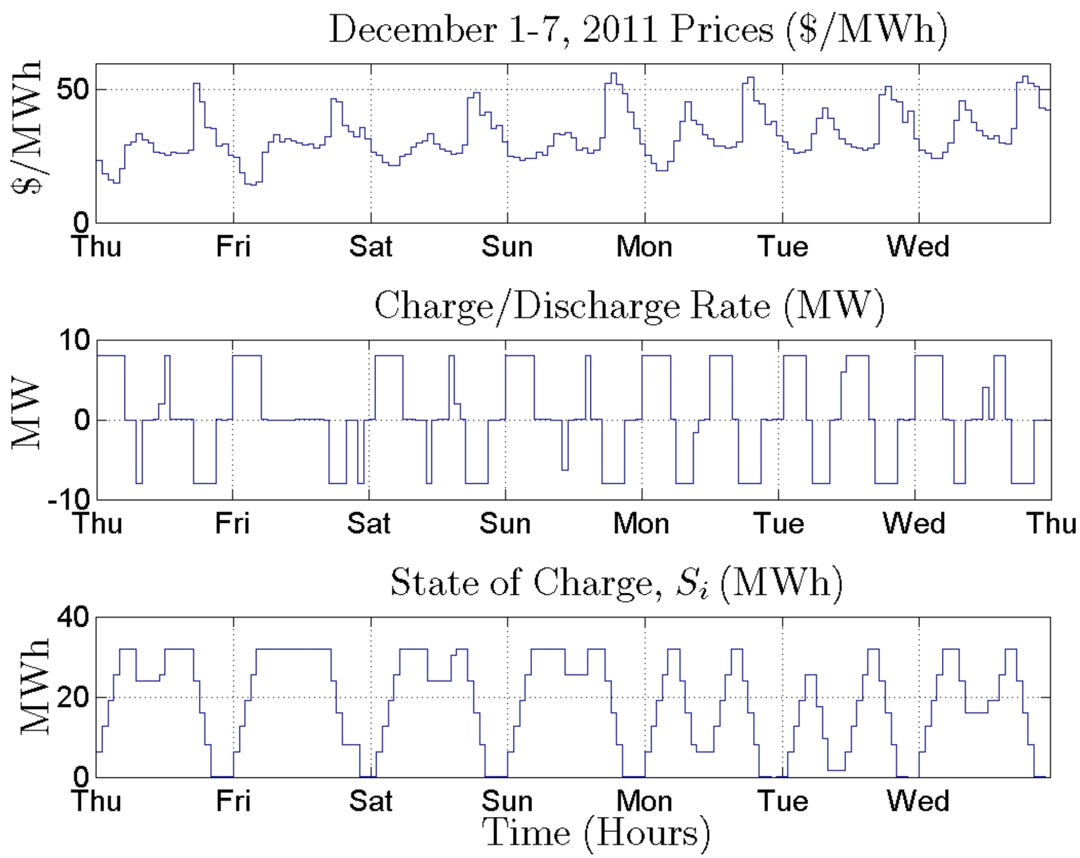
Transmission Infrastructure Services
Transmission Upgrade Deferral
Transmission Congestion Relief
Distribution Infrastructure Services
Distribution Upgrade Deferral
Voltage Support
Customer Energy Management Services
Power Quality
Power Reliability
Retail Electric Energy Time-Shift
Demand Charge Management



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

Energy Storage Value Streams

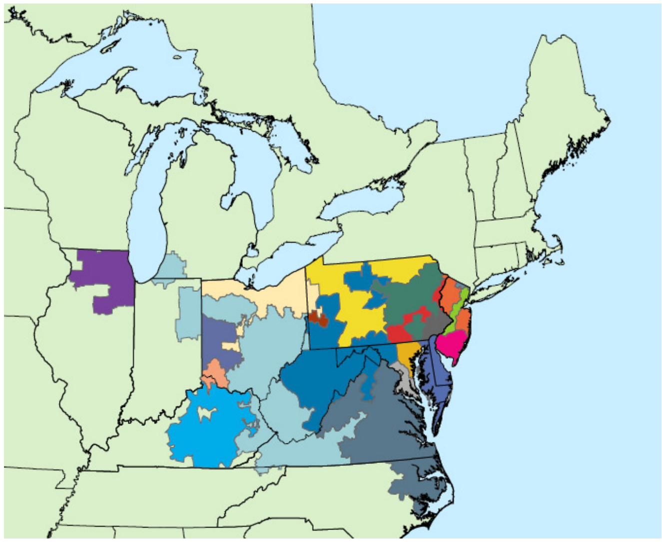
- Energy arbitrage – buy low, sell high
- Energy price swings must be larger than efficiency losses
- Rarely captures the largest value



Energy Storage Value Streams

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

Month	Year	% q^R	% q^D	% q^{REG}	Revenue
Jun	2014	0.65	0.41	98.67	$487,185.94
Jul	2014	1.22	0.38	98.06	$484,494.90
Aug	2014	1.20	0.38	98.06	$354,411.61
Sep	2014	1.23	0.52	97.73	$401,076.97
Oct	2014	1.30	0.38	97.85	$535,293.84
Nov	2014	1.71	0.58	96.43	$431,106.41
Dec	2014	1.07	0.50	96.92	$341,281.46
Jan	2015	0.80	1.10	97.34	$443,436.10
Feb	2015	1.03	1.37	96.59	$998,392.65
Mar	2015	0.87	0.71	98.41	$723,692.29
Apr	2015	0.90	0.20	98.76	$527,436.11
May	2015	1.02	0.37	98.62	$666,290.70
				Total	$6,394,098.97

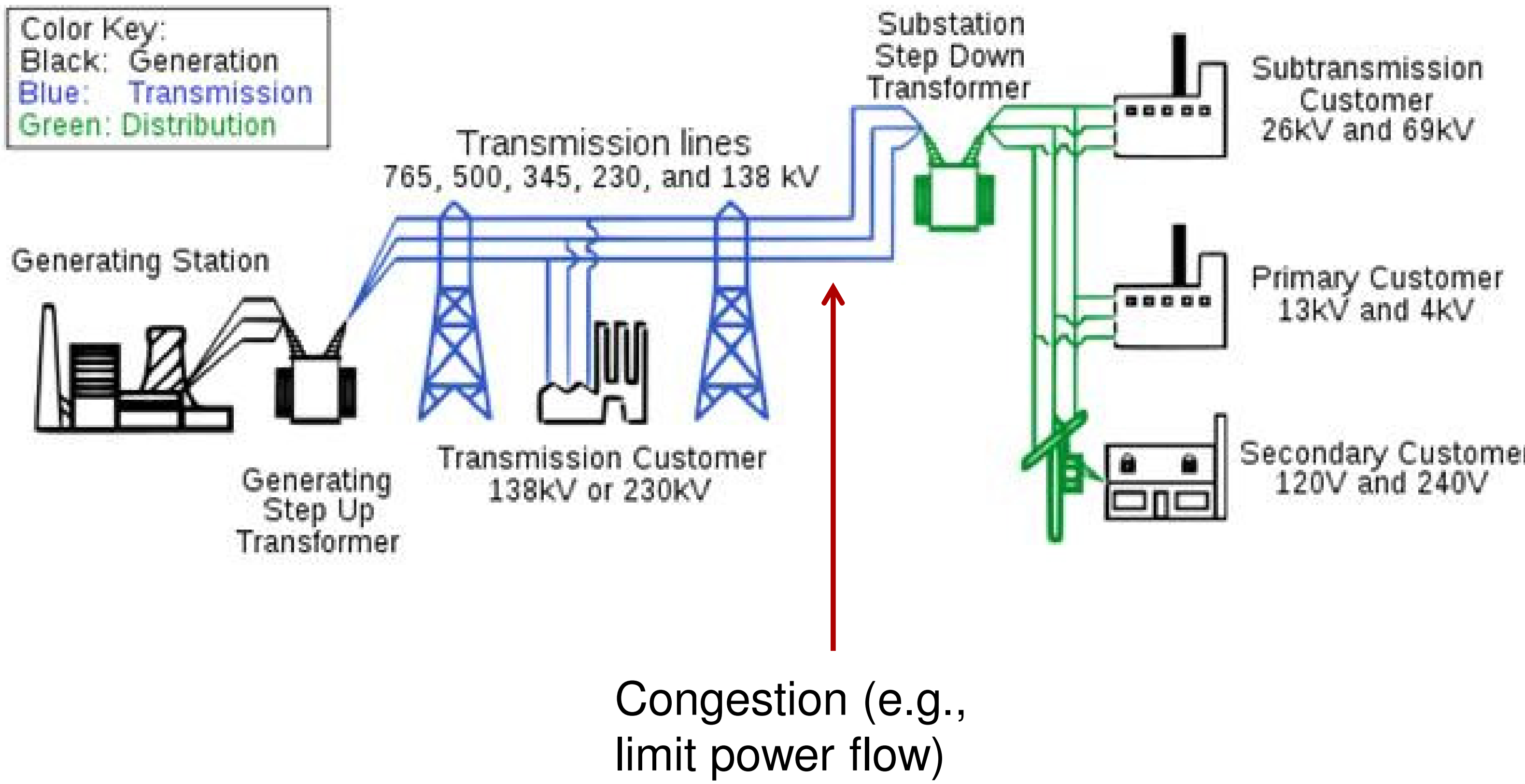


PJM results, 20MW, 5MWh 200-flywheel system

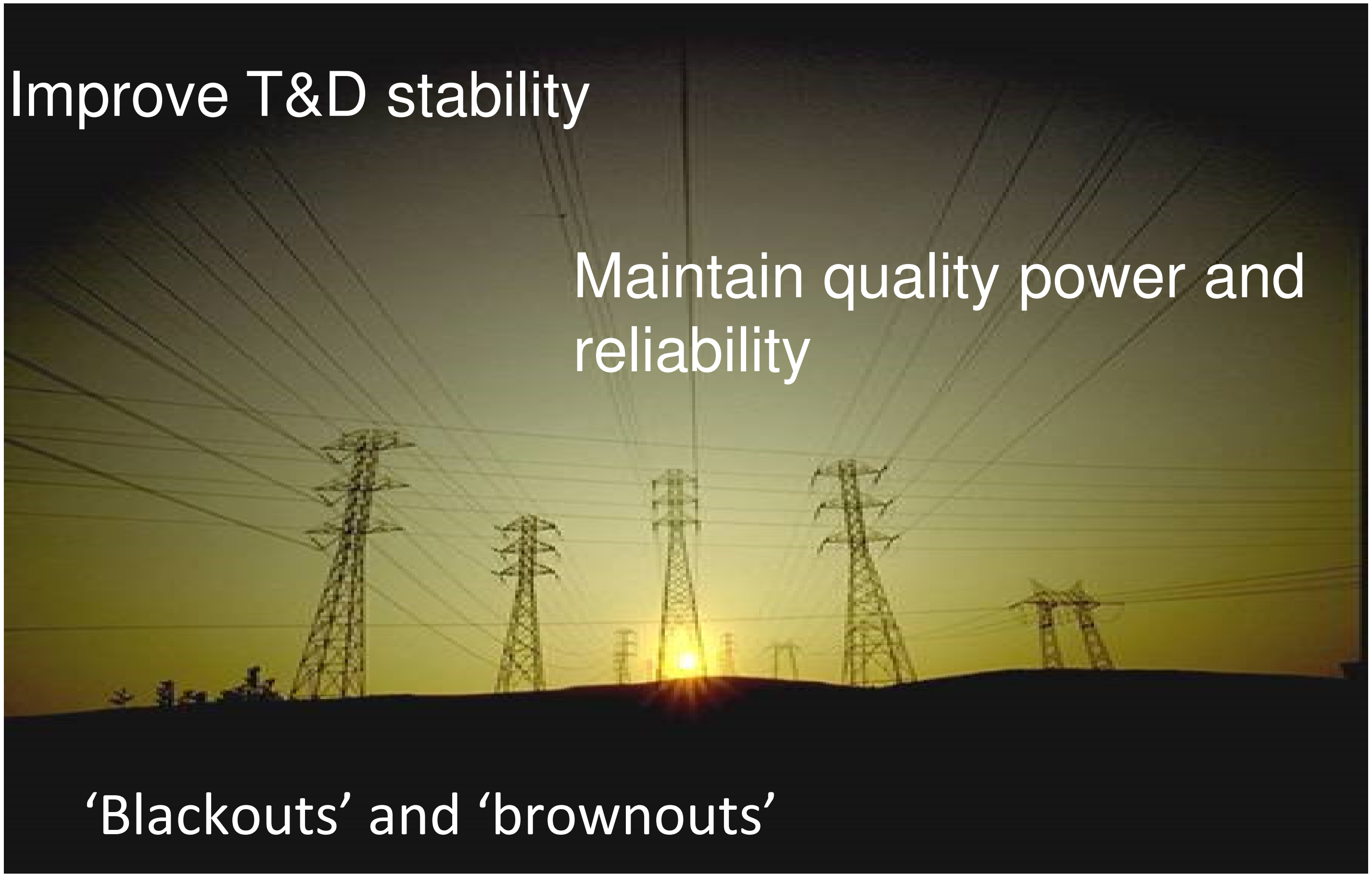
Beacon Power Flywheel

Energy Storage Value Streams

- Transmission and Distribution deferral
  - Can be a very large $$$$
  - Very location specific

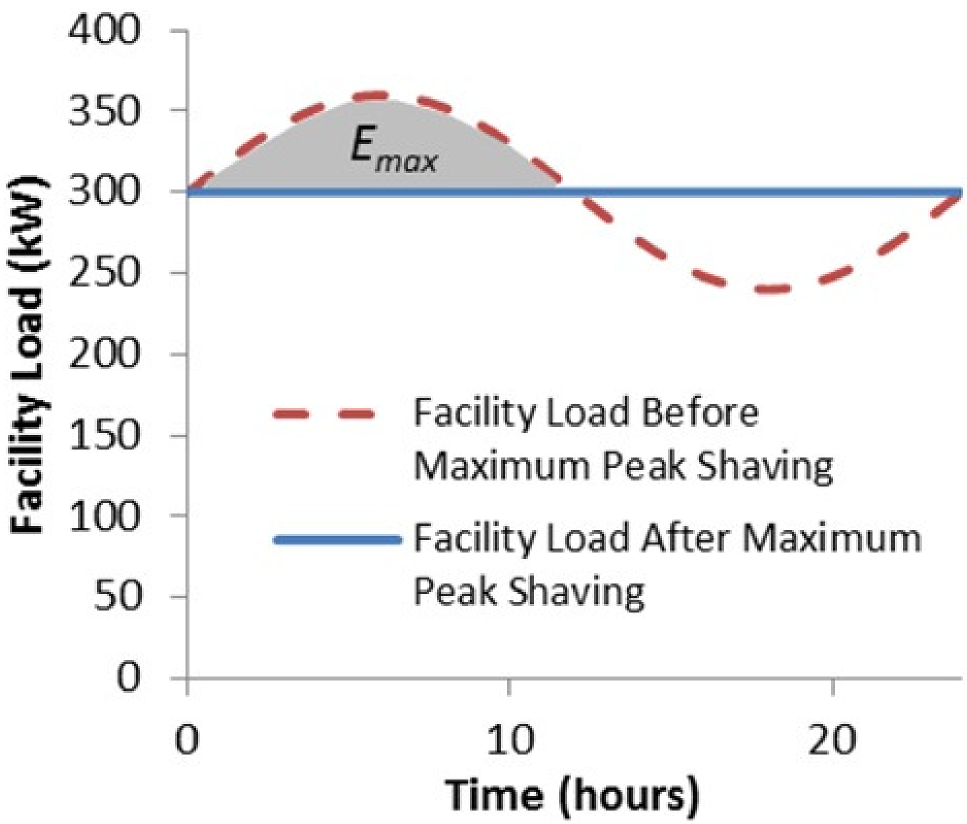


Energy Storage Value Streams - Grid Resiliency



Energy Storage Value Streams

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



Energy Storage Value Streams

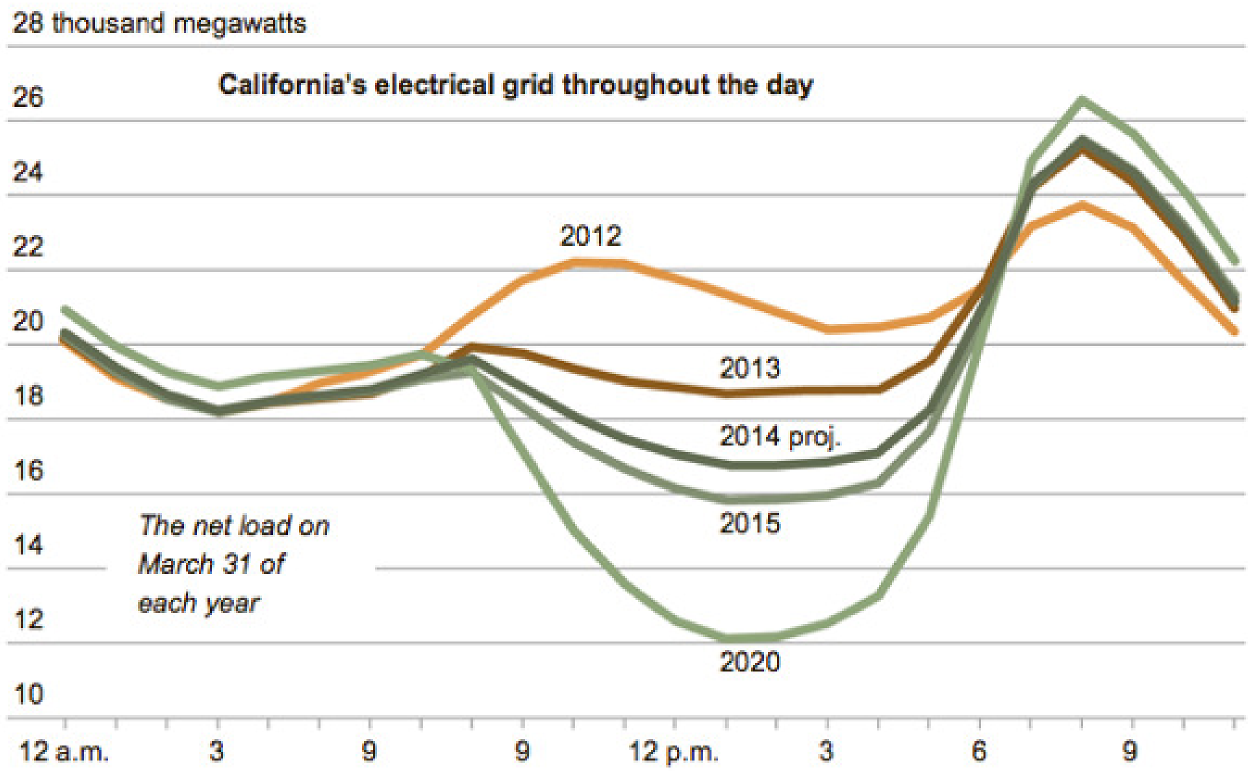
Sandia National Laboratories

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

DTE ARRA energy storage demonstration project

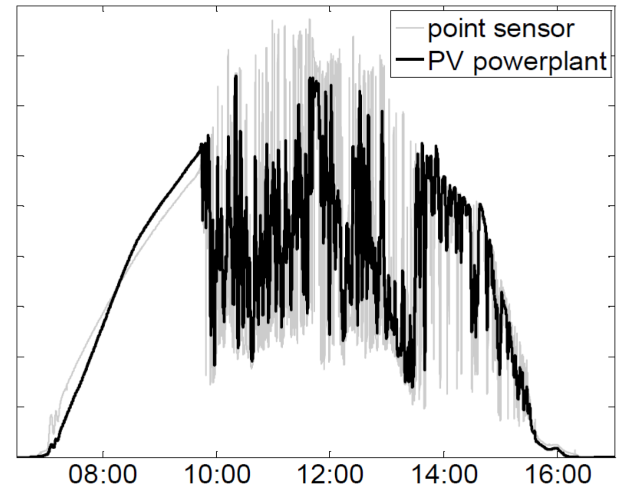
Energy Storage Value Streams

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



Source: CalISO

CA "duck" curve



Solar variability

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

Why is Storage Valuation Difficult?

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

Energy Storage Analytics

- Estimating the value of energy storage
  - Production cost modeling (vertically integrated utility)
  - LP Optimization (market area)
  - Stochastic unit commitment/planning studies (vertically integrated utility)
- 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)

Maximizing Revenue - Market Area

- Linear Program Optimization
  - MATLAB
  - Python/Cooper
- Typically look at the following revenue streams
  - Arbitrage
  - Arbitrage + Regulation
  - Allocate charge to avoid double counting
- Typically look at maximizing revenue
- Can incorporate cost data (if available)
  - Penalty for charge/discharge
  - Variable O&M costs

Maximizing Revenue - Market Area

- Assume price insensitive to supply (if not -> production cost modeling)
- Typically use 1 hour data
- Energy storage model – arbitrage

$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D \ \forall t \in T$$

  - Constraints on:
    - Total capacity
    - Maximum hourly charge/discharge quantity

$$0 \leq S_t \leq \bar{S}, \ \forall t \in T$$
$$0 \leq q_t^R \leq \bar{q}^R, \ \forall t \in T$$
$$0 \leq q_t^D \leq \bar{q}^D, \ \forall t \in T$$

Maximizing Revenue - Market Area

- Assume price insensitive to supply (if not -> production cost modeling)
- Typically use 1 hour data
- Energy storage model – arbitrage + regulation

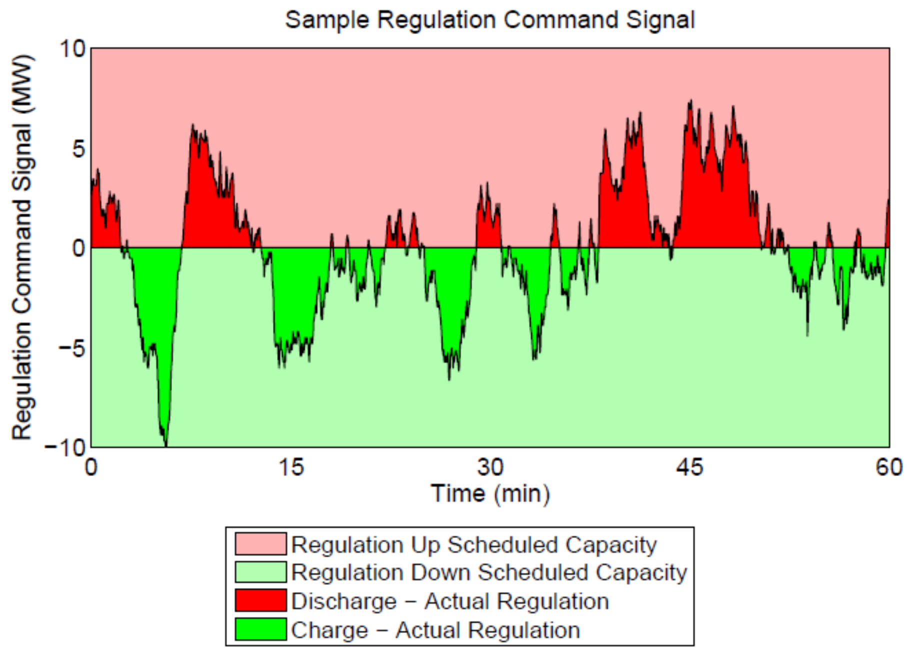
$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D + \gamma_c \gamma_{rd} q_t^{RD} - \gamma_{ru} q_t^{RU}$$

  - Constraints on:
    - Total capacity
    - Maximum hourly charge/discharge quantity

$$0 \leq S_t \leq \bar{S}, \; \forall t \in T$$
$$0 \leq q_t^R + q_t^{RD} \leq \bar{q}^R, \; \forall t \in T$$
$$0 \leq q_t^D + q_t^{RU} \leq \bar{q}^D, \; \forall t \in T$$

Maximizing Revenue - Market Area

- Modeling regulation – need to assume fraction that is assigned



$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D + \gamma_c \gamma_{rd} q_t^{RD} - \gamma_{ru} q_t^{RU}$$

Account for fraction called

Maximizing Revenue - Market Area

- Cost function – arbitrage

$$\max \sum_{t=1}^{T} \left[(P_t - C_d) q_t^D - (P_t + C_r) q_t^R \right] e^{-rt}$$

- Cost function – arbitrage + regulation

$$\max \sum_{t=1}^{T} [(P_t - C_d) q_t^D + (P_t^{RU} + \gamma_{ru}(P_t - C_d)) q_t^{RU} +$$
$$(P_t^{RD} - \gamma_{rd}(P_t + C_r)) q_t^{RD} - (P_t + C_r) q_t^R] e^{-rt}$$

Maximizing Revenue – Market Area

- Studied four regions
  - CAISO [1] (included sensitivity analysis to parameters)
  - ERCOT [2]
  - PJM [3] – Prize paper award at 2016 IEEE PES GM
  - MISO [4]
- Look at:
  - Arbitrage
  - Arbitrage + regulation
  - Consider perfect foresight and the case of forecasting

[1] R. H. Byrne, and C. A. Silva-Monroy, *Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation,* SAND2012-3863, Sandia National Laboratories, Albuquerque, NM 87185, 2012.

[2] R. H. Byrne, and C. A. Silva-Monroy, "Potential Revenue from Electrical Energy Storage in the Electricity Reliability Council of Texas (ERCOT)," in IEEE Power and Energy Society (PES) General Meeting, Washington, DC, 2014.

[3] R. H. Byrne, R. J. Concepcion, C. A. Silva Monroy, "Estimating Potential Revenue from Electrical Energy Storage in PJM," in IEEE Power and Energy Society (PES) General Meeting, Boston, MA, 2016.

[4] T. Nguyen and R. Byrne, "Estimating Potential Revenue from Electrical Energy Storage in MISO," submitted to the 2017 IEEE Power and Energy Society (PES) General Meeting.

Maximizing Revenue – Market Area

- Results for ERCOT (HB_Houston Node)

ARBITRAGE OPTIMIZATION RESULTS USING PERFECT KNOWLEDGE, 2011-2012, ERCOT HB_HOUSTON NODE.

Year	Revenue	% Discharging	% Charging
2011	\$1,054,905.61	18.86%	23.57%
2012	\$375,841.62	17.95%	22.44%

ARBITRAGE AND REGULATION OPTIMIZATION RESULTS USING PERFECT KNOWLEDGE, 2011-2012, ERCOT HB_HOUSTON NODE.

Year	Revenue	% q^D	% q^R	% q^{RU}	% q^{RD}
2011	\$2,360,994.81	0.14%	0.81%	69.49%	85.84%
2012	\$928,265.14	0.10%	0.79%	63.90%	78.53%

ARBITRAGE STRATEGY BASED ON PREVIOUS DAY PRICES, 2011-2012, ERCOT HB_HOUSTON NODE.

Year	Revenue	% of Maximum
2011	\$1,010,082.08	95.75%
2012	\$362,244.88	96.38%

ARBITRAGE AND REGULATION STRATEGY BASED ON PREVIOUS DAY PRICES, 2011-2012, ERCOT HB_HOUSTON NODE.

Year	Revenue	% of Maximum
2011	\$2,023,828.56	85.72%
2012	\$830,319.64	89.45%

Estimating Value – Vertically Integrated Utility

Sandia National Laboratories

- Production cost modeling used to evaluate different scenarios
- “Value” of energy storage is the cost savings resulting from the operation of the energy storage system
- PLEXOS© (Energy Exemplar) production cost modeling software
- Sandia is also developing a stochastic unit commitment program based on Pyomo (Python optimization software developed by Sandia)

  https://software.sandia.gov/trac/coopr

Estimating Value – Vertically Integrated Utility

- Sandia has performed studies for the following
  - Nevada Energy [1]
  - Southern Company [2]
  - Maui Electric Company [3]
- A study is currently under way for the Hawaiian Electric Company
- Typical cost savings come from being able to turn off expensive "must run" units (spinning reserve, regulation) and replace with energy storage

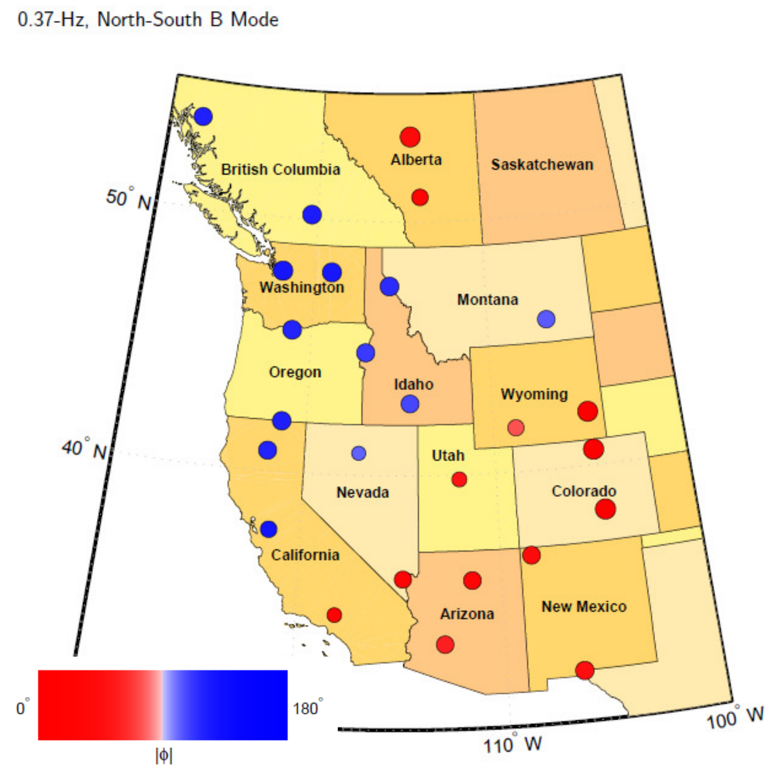
[1] J. F. Ellison, D. Bhatnagar, N. Saaman *et al.*, *NV Energy Electricity Storage Valuation,* SAND2013-4902, Sandia National Laboratories, Albuquerque, NM 87185, 2013.

[2] J. Ellison, D. Bhatnagar, C. Black *et al.*, *Southern Company Energy Storage Study: A Study for the DOE Energy Storage Systems Program,* SAND2013-2251, Sandia National Laboratories, Albuquerque, NM 87185, 2013.

[3] J. Ellison, D. Bhatnagar, and B. Karlson, *Maui Energy Storage Study,* SAND2012-10314, Albuquerque, NM 87185, 2012.

Control Strategies for Energy Storage

- Inter-area oscillations are present in all large power systems
- Electro-mechanical oscillations
  - 0.2-0.8Hz
  - Can be lightly damped
  - 1996 west coast blackout partially attributed to undamped inter-area oscillations



Bus	Amp.	Shape(*Deg.*)	Bus	Amp.	Shape(*Deg.*)
Ault	1.00	0.0	Monroe	0.80	126.3
Comanche	0.99	−2.1	Coulee	0.78	124.9
Laramie	0.95	2.1	Big Eddy	0.71	118.1
Genesee	0.92	−43.1	Nicola	0.71	122.4
Newman	0.66	−47.5	Taft	0.71	114.6
Moenkopi	0.58	−34.4	Malin	0.67	120.1
Four Corners	0.58	−45.6	Brownlee	0.65	110.3
Hassyampa	0.56	−60.6	Kemano	0.63	119.4
Mead	0.52	−32.7	Round Mt.	0.61	118.7
Langdon	0.45	−30.7	Midpoint	0.58	106.6
Bridger	0.42	75.9	Colstrip	0.56	102.5
Mona	0.29	52.6	Tesla	0.45	128.2
Vincent	0.27	−26.8	Valmy	0.22	101.2

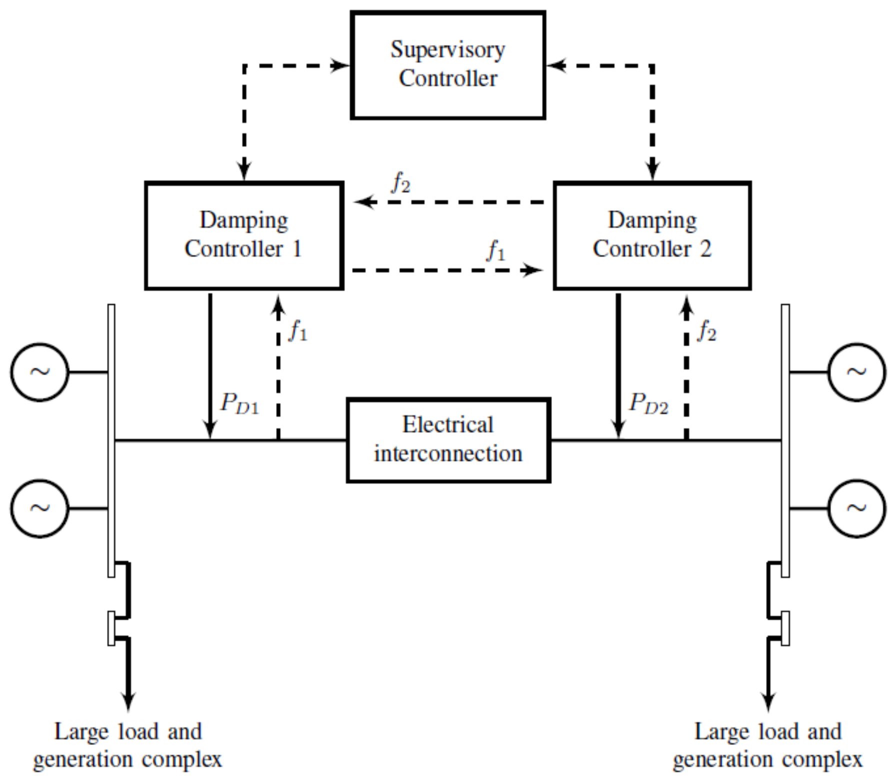
Control Strategies for Energy Storage

Sandia National Laboratories

- Sandia is collaborating with the Bonneville Power Administration (BPA) to develop wide-area damping control algorithms (BPA Technology Innovation Program)
  - PDCI modulation
  - Distributed energy storage
- Straightforward control law

$$\Delta P_{D1} = -K\big(f_1(t) - f_2(t-\tau)\big)$$
$$\Delta P_{D2} = -K\big(f_2(t) - f_1(t-\tau)\big)$$

- Most effort is focused on the "supervisory control system"



Optimal Placement for Damping Control

- Two-area system model

$$\Delta P_{D1} = -K\alpha\big(f_1(t) - f_2(t-\tau)\big)$$

$$\Delta P_{D2} = -K(1-\alpha)\big(f_2(t) - f_1(t-\tau)\big)$$

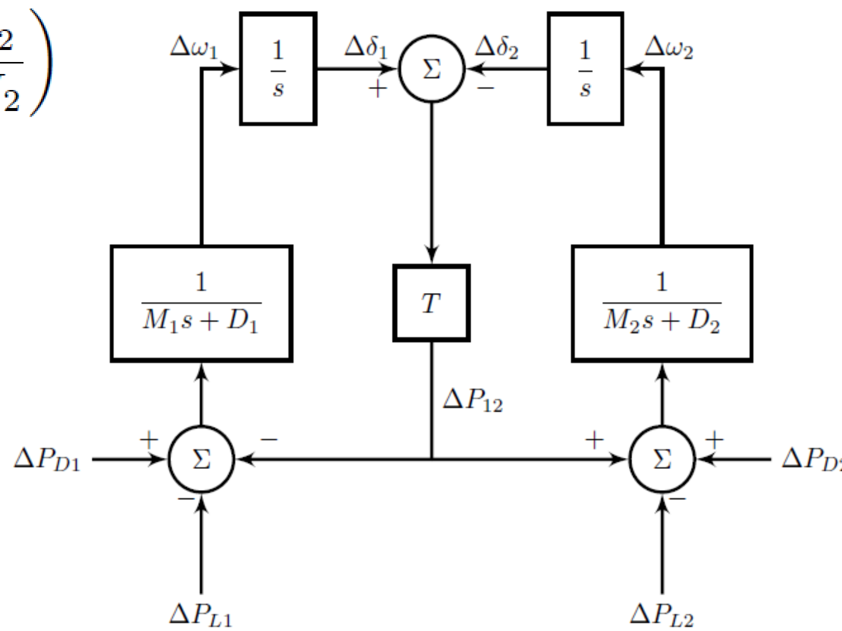
- Solve for damping ratio

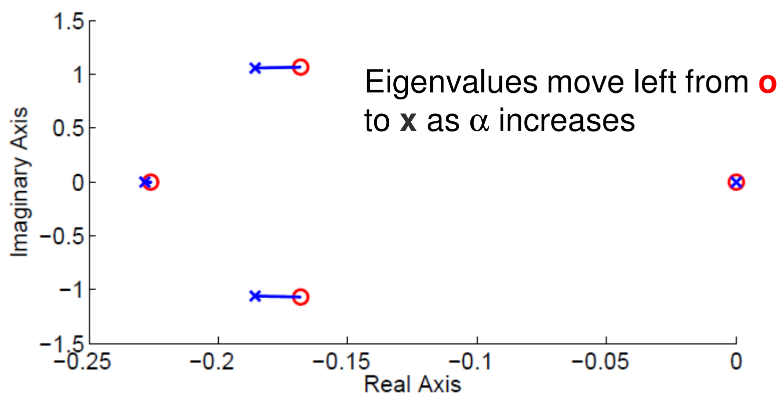
$$\zeta\omega_n \approx \frac{1}{2}\left(\frac{D_2}{M_2} + \frac{D_1}{M_1} + \frac{K(1-\alpha)}{M_2} + \frac{K\alpha}{M_1} - \frac{D_1 + D_2}{M_1 + M_2}\right)$$

- Place storage in the area with the lower inertia [1]

Two-Area System Model Quantities

Quantity	Description
M_i	Area i inertia
D_i	Area i damping
T	Synchronizing torque coefficient
ΔP_{Li}	Area i load variation
ΔP_{Di}	Area i damping torque
$\Delta\omega_i$	Area i change in speed
$\Delta\delta_i$	Area i change in angle





[1] R. H. Byrne, D. J. Trudnowski, J. C. Neely *et al.*, "Optimal Locations for Energy Storage Damping Systems in the Western North American Interconnect," in IEEE PES General Meeting, Washington, DC, 2014.

Project Evaluation

- Member of the data analysis team (DAT) for ARRA energy storage demonstration projects
  - Review project reports
  - Site visits
- Guidelines for testing energy storage systems [1]
  - Performance requirements for different applications
  - Recommend testing strategies
  - Analysis focuses on identifying system components from a control systems perspective
- Synergistic with commissioning activities (Dan Borneo)

[1] R. H. Byrne, M. K. Donnelly, V. W. Loose *et al.*, *Methodology to Determine the Technical Performance and Value Proposition for Grid-Scale Energy Storage Systems*, Sandia National Laboratories, Albuquerque, NM 87185, 2012.

Standards Development

- Working with PNNL to develop performance protocols for the energy storage industry
  - Micro-grids (completed)
  - Frequency regulation (completed)
  - Peak shaving (completed)
  - PV smoothing (in progress)
- Working to generate a U.S. standard based on the protocols
  - ANSI
  - NEMA
  - IEC
- Industry user group is test driving the protocols

Sandia National Laboratories

Exceptional service in the national interest

Developing Energy Storage Projects

Daniel Borneo, P.E.

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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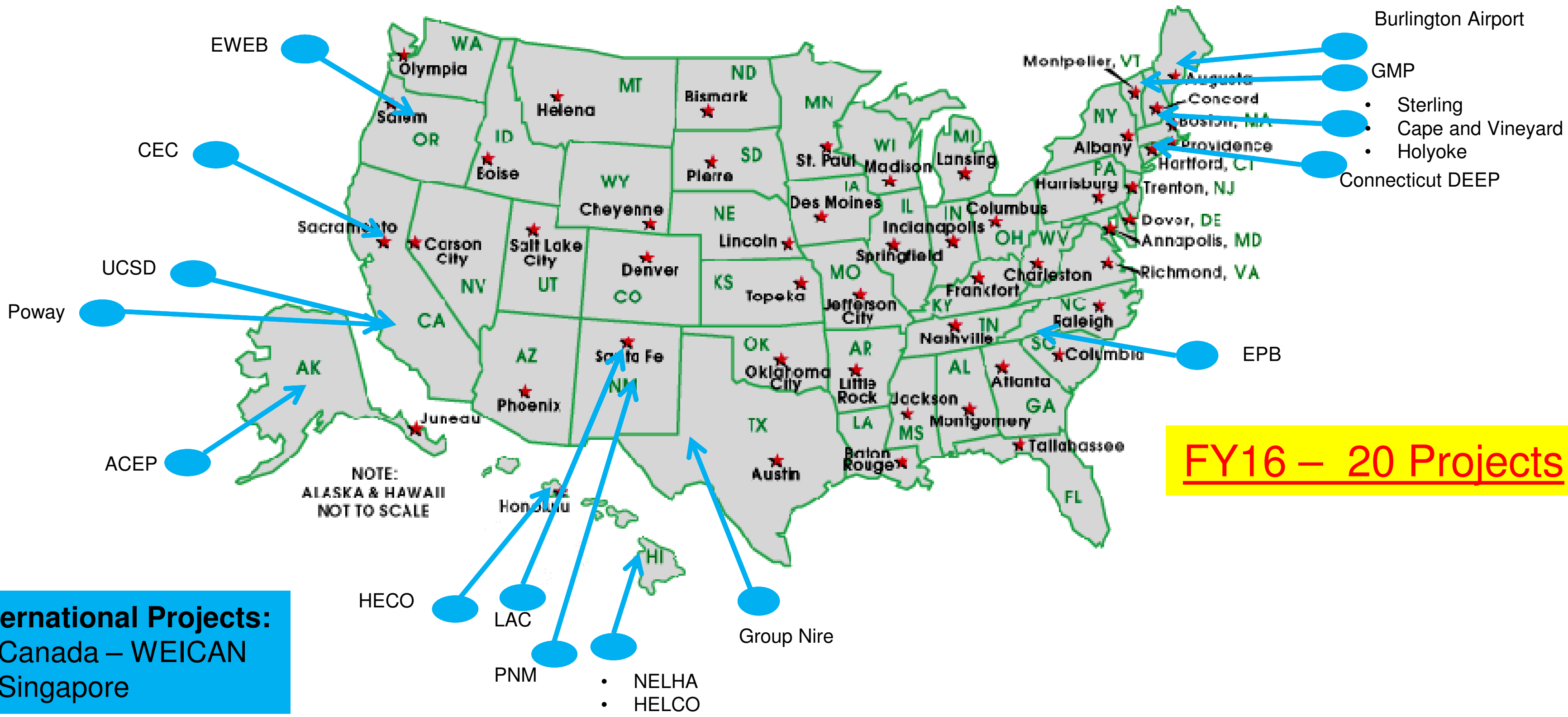
SANDIA Document SAND2017-0203 C

What we do

- Work with National and International entities to:
  - Provide third party independent analysis for cells and systems
  - Support grid-tied field projects to monitor and analyze ES technologies in differing applications
  - Support Utility, Industrial, State and International initiatives for grid modernization
  - Develop public information programs

- Goal
  - Encourage investment by making sure ES is safe, reliable, cost effective, and understood.

DOE-OE Demonstration Projects 2016



FY16 – 20 Projects

International Projects:
- Canada – WEICAN
- Singapore

Stock Image source: http://www.devarticles.com/c/a/Web-Services/Cooking-With-Web-Services-PHP-and-GD/3/

Project Programming
Problem(s) to solve, How to accomplish, Initial Analysis,

Design
Site, Interconnection, DAS, BOP, Specifications, Codes and Standards, Permitting, Cost Estimation

Procurement
System KW/KWH, DAS, BOP, Construction services, Integration services,
- Warranty

Construction
Installation per design, code, specifications. Design verification.

Commissioning/ Testing
Factory tests, operational (OAT), Start-up, Functional (FAT), Shakedown, baseline measurements

Operation
- Ongoing monitoring, Warranty, Predictive maintenance

Programing

- What are we trying to do:
  - Problem(s) to solve
  - Initial Analysis – Application(s), Power (KW) and Energy (KWh) requirements
  - Charge and Discharge cycle profiles
  - In-front-of (FTM) or behind the (BTM) meter
  - Own/operate or do PPA

Programing (cont.)

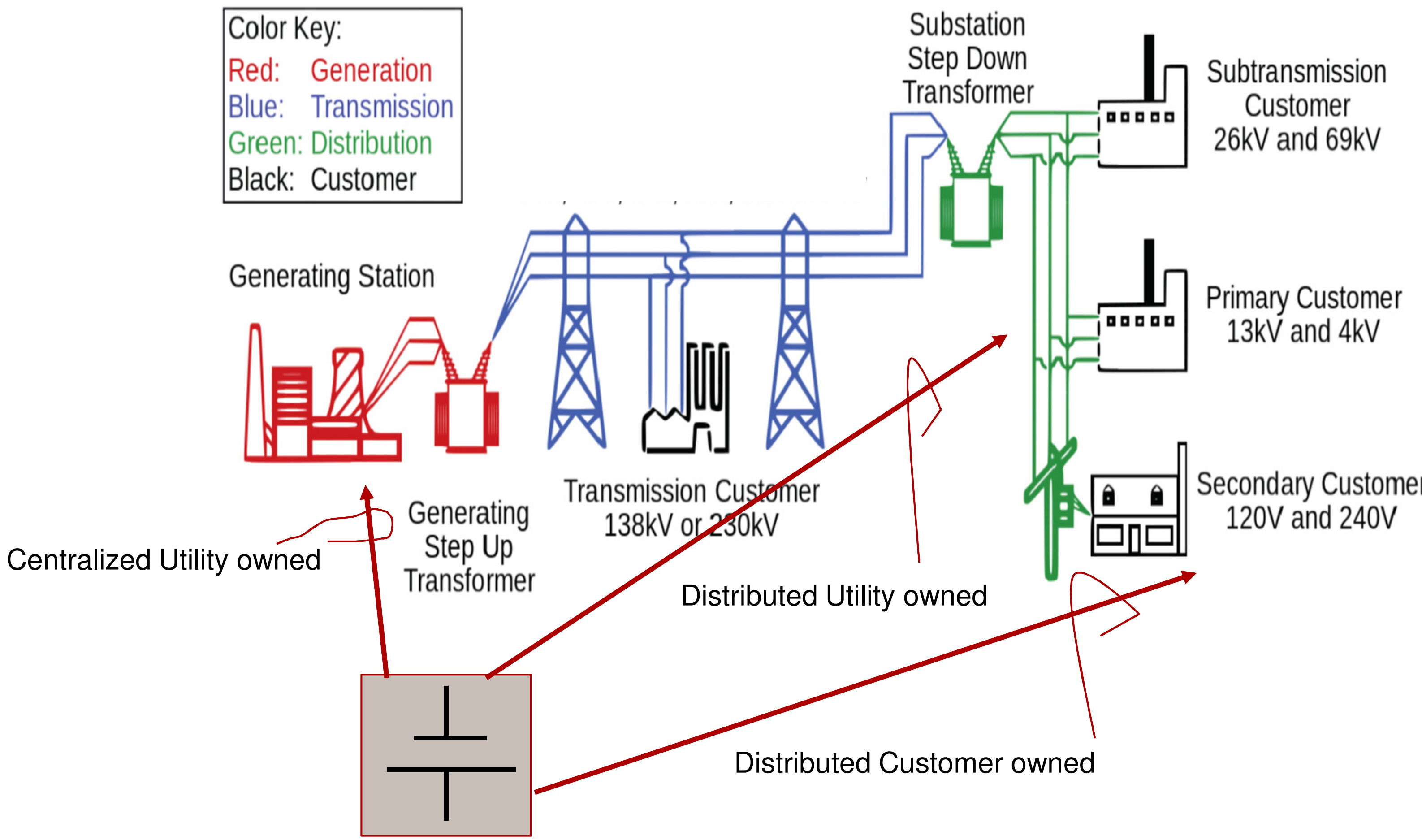
- Project team development
  - Owner/Owner's Engineer, Design Engineer, Construction personnel, Safety, Utility, building inspector (trades), first responders, insurance, other stakeholders
- Project Delivery method
  - Design/Bid/Build (DBB) aka Engineer/Procure/Construct (EPC)
  - Design/Build (DB)
  - Design/Build/Operate (Power Purchase Agreement - PPA)
  - Construction Manager/General Contractor CMGC
  - Construction Manager at risk

NOTE: Integrated Team with one owner

Programing (cont.)

- Do we have a clear knowledge of what we want to do?
    - If NO use RFI – A means to collect information about services, products, potential solutions and to understand the capability of potential vendors
    - If YES RFP – Is a request for a proposal based upon defined requirements and project details.
        - http://energy.sandia.gov/sandia-national-laboratories-develops-guidance-document-for-energy-storage-procurement/
- RFP Procurement Methods
    - Sole Source – Tried and true partner
    - Low Bid – You get what you pay for
    - Best value – Selection criteria matrix and scoring
    - Qualifications base – Most experienced for particular work
    - Unit Price or Time & Material (T&M)– Can have a not to exceed amount. Need to measure. Need to manage
    - Negotiated – All of the above should have this component

The Grid Today



Multiple locations for placement of Energy Storage

Business Models

1) Centralized utility-owned or merchant-owned storage (economic benefit to utility, little or no resiliency benefit)

2) Distributed utility-owned storage, customers purchase resiliency services (economic benefits to utility, resiliency benefit to customer)

3) Distributed customer-owned (or third-party owned) storage, utility purchases (or aggregates control of) demand response services (economic benefits to utility and customer, resiliency benefit to customer) Advantages of this model:

    - Works in **regulated or deregulated** electricity markets
    - Engages the greater **resources of the utility** (LSE) in deploying distributed storage
    - Benefits the LSE, the participating customer, and **ratepayers at large** (who end up paying for capacity)
    - From the customer's POV, this looks like simple demand response
    - From the LSE's POV, there is **no diminishing return** for deploying larger systems (which can provide greater resiliency benefits)

- **Early adopters win!**

Design

- Could be a prior separate Procurement (DBB or EPC) or
- Could be part of the procurement (DB or PPA)
- Site infrastructure
  - Grounding
  - Equipment pad or building
- Point of connection – 1- lines, detail drawings
  - Main & Aux Transformers
  - Electrical distribution switchgear and panels
  - Fault current and Arc flash calculations
  - Protection coordination
- Balance of Plant
  - HVAC
  - Fire protect
  - DAS

Design (cont.)

- System Design –
  - Energy Storage (ES) – Type and size (kw/Kwh) of storage
  - Storage management system (BMS), Magement of the storage system, i.e., charge discharge, temperature, capacity
  - Power Control (PCS), AC/DC conversion and control
  - Energy management system (EMS), Control of the applications the ES is to perform
  - Sequence of operation (SOO)
  - Data Collection System (DAS) – Provides monitoring of system performance and specification adherence
  - and Balance of Plant (BOP) – Fire protection, HVAC, ancillary loads

NOTE: Important to have single entity responsible for the ESS components - design, install and integrate.

Energy Storage System Design

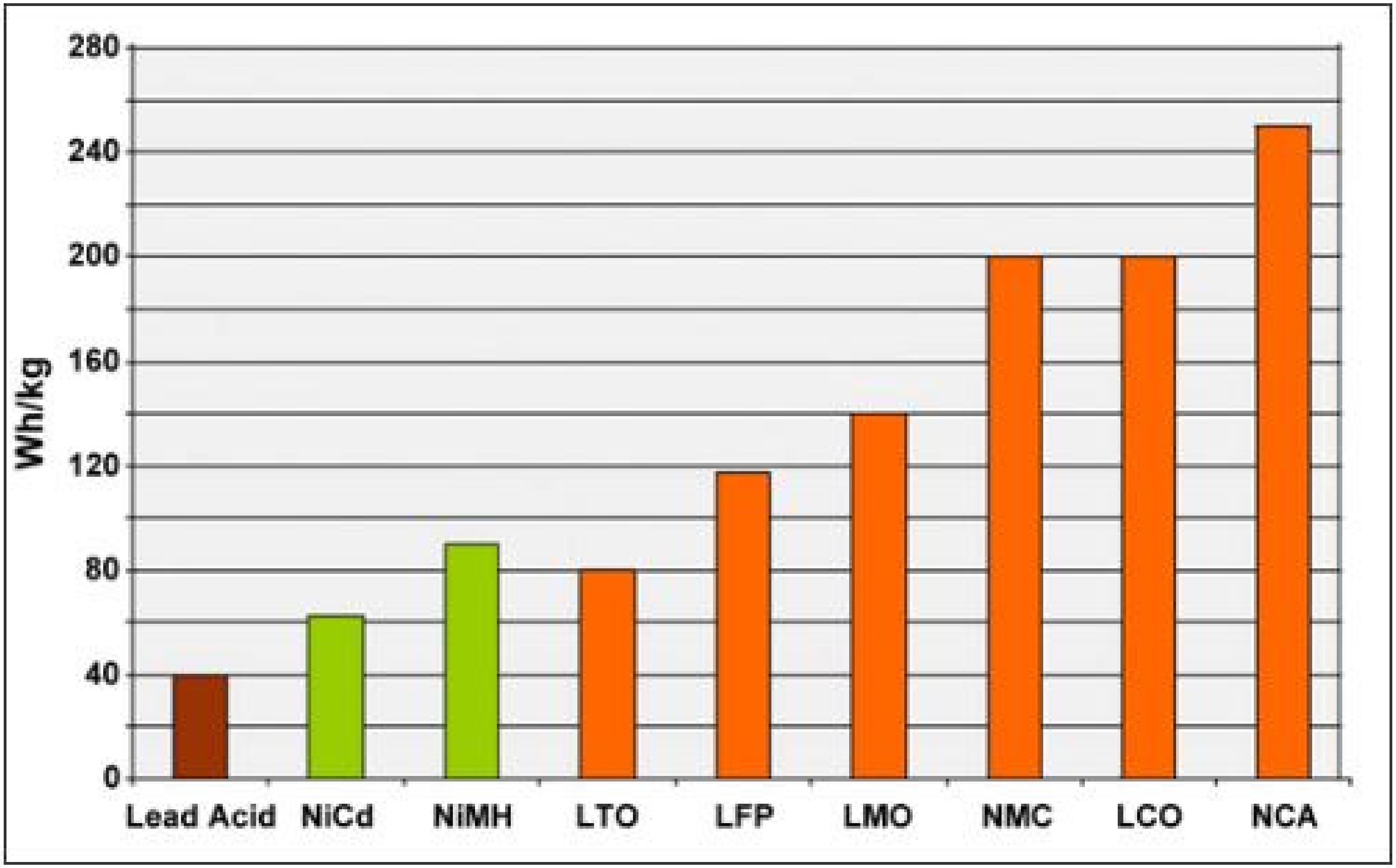
- Understand the applications and design ES Appropriately
  - Optimize the kW and kWh
  - Some technologies better suited for long durations rather than short
    - Short – Mid: Li-ion; Lead Acid
    - Long: Flow
  - Environmental concerns (extreme heat vs. cold)
- Design the control to perform the various applications (Stack) and integrate with DER
  - Centralized vs. Decentralized controller
  - Utilize ES to offset demand charges, energy shifting, capacity constraints/requirements, and fuel charges
- Does system have (need) necessary certifications
  - UL listed - If not, need to get buy-in from AHJ
- What codes and standards are required to install ES
  - Local and National

Application and Benefits of ES in a Microgrid

- Power Quality/ Reliability/UPS: Can provide instantaneous ride through during power glitches or momentary interruptions.
- Demand Reduction: Can be utilized to decrease peaking load on the grid, which may eliminate need to upgrade distribution equipment.
- Energy Shifting: PV or cheap power stored and dispatched after dark or in times of high costs
- Renewable Energy and Distributed Energy support: Can provide steady source of energy during any variability caused by Renewables or other Distributed Energy Resources (DER).
- Generator Support: Can provide generator load to increase generator efficiency and if matched to load, ES can be used to reduce generator run time.

- **ES SERVING MULTIPLE APPLICATIONS IS THE MOST COST EFECTIVE.**

Specific energy of battery technologies



Typical specific energy of lead-, nickel- and lithium-based batteries.

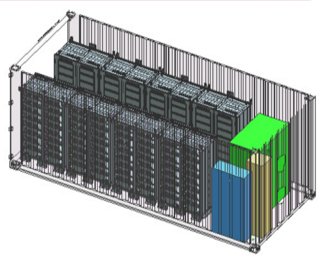
NCA enjoys the highest specific energy; however, manganese and phosphate are superior in terms of specific power and thermal stability. Li-titanate has the best life span.

Courtesy of Cadex Source: “Types of Lithium Batteries- A Handy Summary” and “BU-205: Types of Lithium-ion”, Battery University

Elements of an Energy Storage System

Storage

- Cell
- Battery Management & Protection
- Racking



Integration

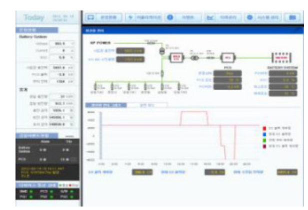
- Container / Housing
- Wiring
- Climate control

PCS

- Bi-directional Inverter
- Switchgear
- Transformer
- Skid
- DAS

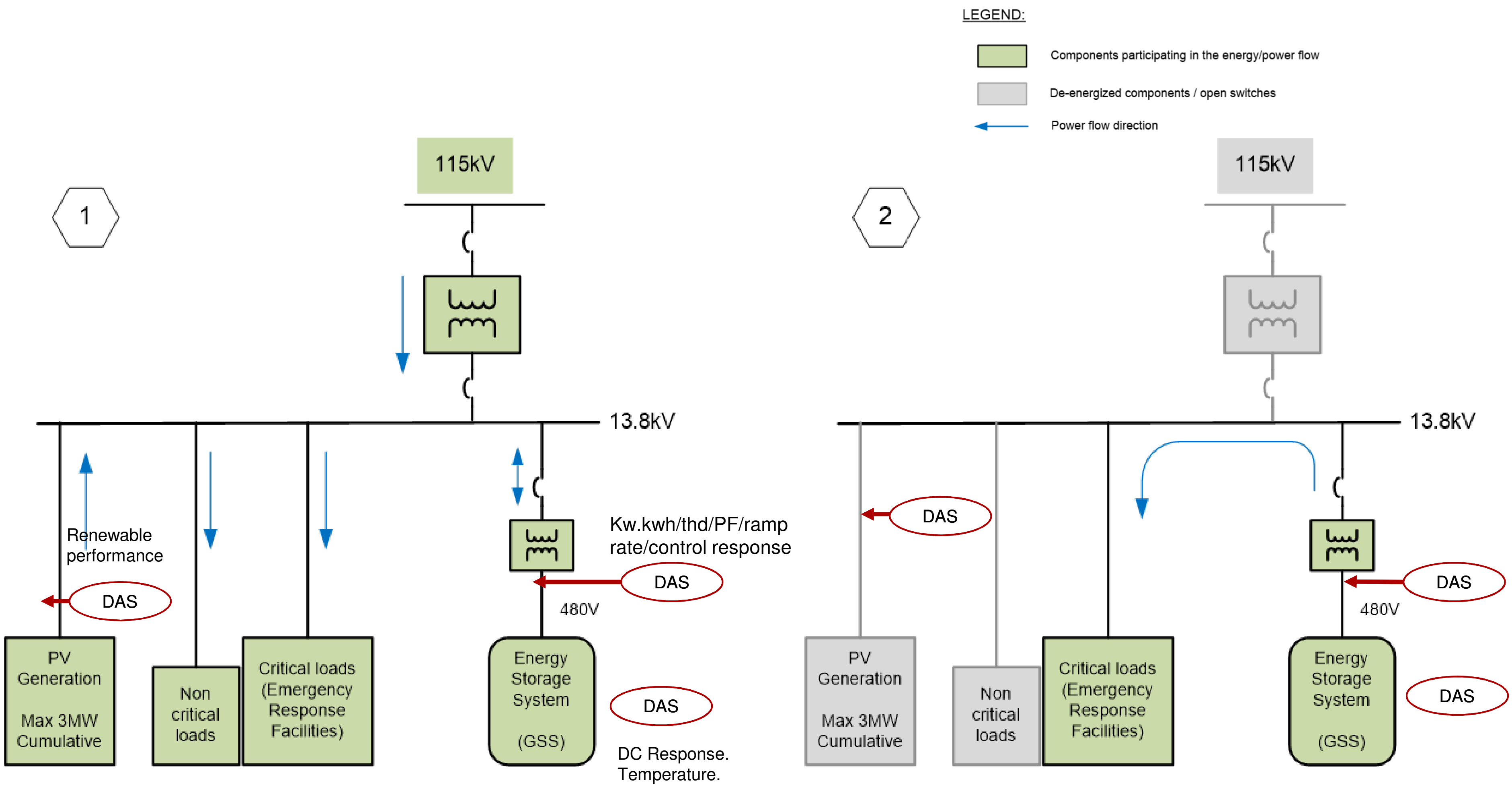
EMS

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



NOTE: Important to have single entity responsible for the ESS components - design, install and integrate.

Overview of DAS connections



SMLD operating modes Courtesy of NEC

ES Cost Considerations

Sandia National Laboratories

Capital Costs

- Design/permitting/Studies
- Site and infrastructure prep
- ES System - $/kW and/or $/kWh
- Balance of Plant
- Installation
- Commissioning
- Warranty

Operating Costs

- Efficiency factors
- Cycle life/replacement
- Operations
- Maintenance/
- Ongoing Warranty
- Debt Service
- Disposal Cost

Codes and Standards

Application	Standard Org	Standard	Standard Title
ESS Commisioning	ANSI	Z535	Safety Alerting Standards
ESS Commisioning	IEEE	450	Recommended Practice for Maintenance, Testing and Replacement of VRLA Batteries for Stationary Applications
ESS Commisioning	IEEE	1106	Recommended Practice for Installation, Maintenance, Testing and Replacement of Vented NiCd Batteries for Stationary Applications
ESS Commisioning	IEEE	1188	Recommended Practice for Maintenance, Testing and Replacement of VRLA Batteries for Stationary Applications
ESS Commisioning	IEEE	1578-2007	Recommended Practice for Stationary Battery Electrolyte Spill Containment and Management
ESS Commisioning	IEEE	1657	Recommended Practice for Personnel Qualifications for Installation and Maintenance of Stationary Batteries
ESS Installation	AS	2676-1983	Installation and Maintenance of Batteries in Buildings
ESS Installation	AS	4777-1-2005	Grid Connection of Energy Systems via Inverters
ESS Installation	IEC	62935	Planning and Installation of Electrical Energy Storage Systems
ESS Installation	IEEE	519-1992	Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems
ESS Installation	IEEE	1145-1999	Recommended Practice for Installation and Maintenance of Nickel-Cadmium Batteries for Photovoltaic Systems
ESS Installation	IEEE	1187-2013	Recommended Practice for Installation Design and Installation of VRLA Batteries for Stationary Applications
ESS Installation	ICC		International Building Code
ESS Installation	ICC		International Fire Code
ESS Installation	ICC		International Wildland Urban-Interface Code
ESS Installation	IEEE	937	Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for PV Systems
ESS Installation	IEEE	1184	Guide for Batteries for UPS Systems
ESS Installation	IEEE/ASHRAE	1635-2012	Guide for the Ventilation aand Thermal Management of Batteries for Stationary Applications
ESS Installation	IEEE	1547	Standard for Interconnecting Distributed Resources with Electric Power Systems
ESS Installation	IEEE	C2-2012-2012	National Electrical Safety Code (NESC)
ESS Installation	NFPA	70-2017	National Electrical Code (NEC) (Updated section on Energy Storage)
ESS Installation	NFPA	70E-2012	Standard for Electrical Safety in the Workplace
ESS Installation	NFPA	400-2013	Hazardous Material Code
ESS Installation	IEC	62485-2	Safety Requirements for Stationary Batteries
ESS Installation	UL	96A	Installation Requirements for Lightning Protection Systems
ESS System	ANSI	C84-1	Electric Power Systems and Equipment
ESS System	IEC	62040-1 Ed.1	UPS General and Safety Requirements in operator access areas
ESS System	IEC	62040-1 Ed.2	UPS General and Safety Requirements installed in restricted access locations
ESS System	IEC	62257-9-5	Small renewable energy and hybrid systems for rural electrification - protection against electrical hazards
ESS System	IEC	62257-9-1	Small renewable energy and hybrid systems for rural electrification - Micropower systems
ESS System	IEC	62932-2-1	Flow Battery Systems for Stationary Applications - performance requirements and methods of tests
ESS System	IEEE	485	Lead-Acid Batteries for Stationary Applications
ESS System	IEEE	1375?	Guide for the Protection of Stationary Battery Systems
ESS System	IEEE	1491	Guide for Selection and Use of BMS in Stationary Applications
ESS System	NFPA	111-2013	Standard on Stored Electrical Energy Emergency and Standby Power Systems
ESS System	NFPA	791-2014	Recommended Practice and Procedures for Unlabeled Electrical Equipment Evaluation
ESS System	UL	1741	Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy
ESS System	UL	1778	Uninterruptible Power Sources
ESS System	UL	9540	Outline for Investigation for Safety for Energy Storage Systems and Equipment

Courtesy of PNNL/Sandia edited by Schenkman/Borneo. for exhaustive list see **http://www.sandia.gov/ess/publications/SAND2016-5977R.pdf**

Additional C&S' List (Laurie Florence, UL)

Document No.	Title
ANSI UL 1973	Batteries for Use in Light Electric Rail (LER) and Stationary
UL 3001,	Distributed Energy Generation and Storage Systems
IEEE 3575	Guide for the Protection of Stationary Battery Systems
IEEE 1679	Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications
IEC CD 62619	Secondary cells and batteries containing alkaline or other non-acid electrolytes. - Safety requirements for secondary lithium cells and batteries, for use in industrial applications (under development)
IEC NP 62897	Stationary Energy Storage Systems with Lithium Batteries – Safety Requirements (under development)

Commissioning Activities During Design

- Identify commissioning team and roles and responsibilities and **integrate** with project team
  - Construction team
  - Energy Storage (ES) System integrator – (**Important position**)
  - Engineering designer – (**ES installation and balance of plant)**
  - Inspectors /EHS representatives/First Responders/Insurance
  - Operations and Maintenance
  - Utility Representative – (**Point Of Connection**)
  - ES Equipment Vendor
  - Construction contractor (Depending on Procurement Strategy)
- Review equipment specifications and applicable codes & standards
  - what is the KW/KWh rating, why?
  - Parameters that system needs to meet
- Develop and/or review the system Sequence Of Operations (SOO)
  - What application(s) will system be used for
- Develop equipment list of items that will be commissioned
- Review and/or establish ESH requirements
  - What safety systems need to be installed
  - Develop Site Incident Prevention Plan-Authorization POC, LOTO, Hot-work

Procurement

- Did anything change for the decisions made in the programing phase? To refresh:
  - Do we have a clear knowledge of what we want to do?
    - If NO use RFI – A means to collect information about services, products, potential solutions and to understand the capability of potential vendors
    - If YES RFP – Is a request for a proposal based upon defined requirments and project details.
      - http://energy.sandia.gov/sandia-national-laboratories-develops-guidance-document-for-energy-storage-procurement/
  - RFP Procurement Methods
    - Sole Source
    - Low Bid
    - Best value
    - Qualifications base
    - Negotiated

Construction

- Construction Management
  - Manage to Scope, Schedule, Budget
- Design and Shop Drawings
  - Measure twice cut once
- Design Verification – Is is built as it was designed/specified
- Coordination Meetings
- Change order Process
  - Who initiates, who authorizes, who pays
- Contingency plans and work arounds
  - When things don't go as planned

Commissioning Activities during Construction

- Factory Acceptance Tests
  - Vendor conducts factory Acceptance testing using SOO
- Develop start-up procedures
  - Based on equipment list, system manuals, SOO and operating specifications
    - Operating Specifications – Parameters that the system should operate within.
- Develop testing procedures
  - Based on SOO and applications
  - PNNL/Sandia Testing Protocol
    - **http://www.sandia.gov/ess/publications/SAND2016-3078R.pdf**
- Develop installation review checklists and perform inspections
  - Design Verification – Installed as designed & specified; labeling and signage in place, clearances,
  - Code adherence
  - Punchlist items noted
- Develop Training and emergency response procedures
  - MSDS
- Implement Lock-out/Tag-out process

Commissioning/Testing Process

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COMMISSIONING

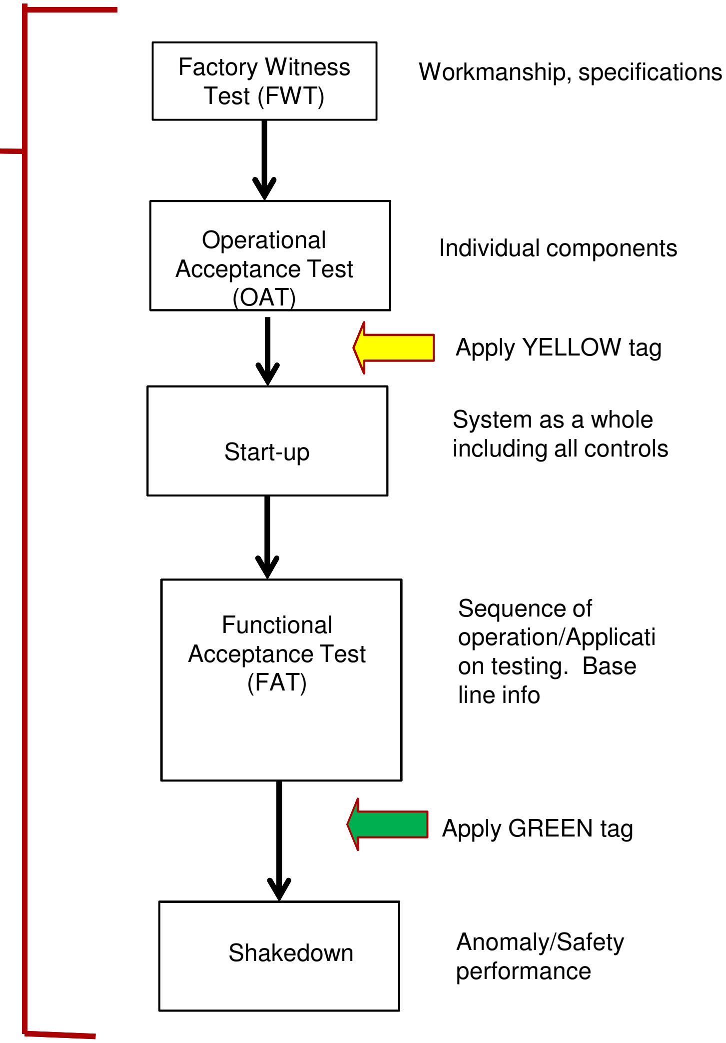
GOAL: To Ensure a **Safe and Reliable** System is Installed as designed and is verified operational.

NOTES on Tags

Tags act as gates to advance pivotal events for the owner in the following manner:

(**Pick** a **Color**)
YELLOW Tag: Owner-Operated, Not Transitioned
GREEN Tag: Transition (Hand-Off) to operations completed

The yellow tag is removed once a green tag is applied.
The green tag may be removed at the owner's discretion AFTER the project is completed and signed off.



Commissioning Process- Operational Acceptance Testing (OAT)

Do the Individual components of the system operate?

- Verify and test that the individual electrical, mechanical components of the system are ready for start-up
  - Meggering, torqueing, rotation/phasing, covers and barriers
- Verify that the controls are in place and test operation
    - Point to point check
- Verify electrical protection and relays are coordinated and are operational
- Verify and test that all safety systems are installed and operating.
  - Temperature, leak, security, fire alarm, flow, pressure
- Verify and test that all communication systems are operating
- Emergency procedures are in place and Lock/out tag out process implemented
- **Tag and sign off – System is ready to operate**

Note: Is 3rd party testing required?

Commissioning Process - Start-up

Do the components operate as a system?

- Using start-up procedures, operate all components as a system
  - Record base-line data
    - Voltage, currents, temperatures, flows, pressures
    - Perform initial IR scan
  - Record and repair punch list items

✓ Does Automatic and remote control operate as required

✓ Is Data Acquisition system operating, recording data and transmitting/Saving as required

Commissioning Process- Functional Acceptance Test (FAT)

- Using Testing plans and procedures test to insure systems performs the functions/applications for which it was designed.
  - Are all components and sub-systems operating in unison
  - Do controls operate as intended
  - Is communication system sending and receiving data as intended- type and frequency. Are anomalies being annunciated
  - Is data collected adequate to determine system performance
  - Record and repair punchlist items
  - Is training complete for operators, maintenance and first responders
  - Is operation and maintenance plan in place
  - Is warranty in place
  - Is emergency response procedures in place- 1-800 number in the event of an emergency
  - Log additional baseline data

✓ **Tag and sign off that system is now owned and operated by customer/owner**

Commissioning Process - Shakedown

When any site utility is interrupted, and then restored (e.g., electricity, gas, water, data, communication, etc.), does the system operate in such a manner as to protect the people, the environment, the equipment, and the facilities?

- *Turn off major utilities serving project.*
  - Determine if safety systems work as designed or needed.
  - Evaluate if systems fail in a safe mode.
  - Assess if back-up systems operate as needed.
  - Do alarms serve the purpose
- *Turn on major utilities*

  Determine if the systems come up in a safe manner.

  Assess if backup systems turn off in a safe/ready mode.

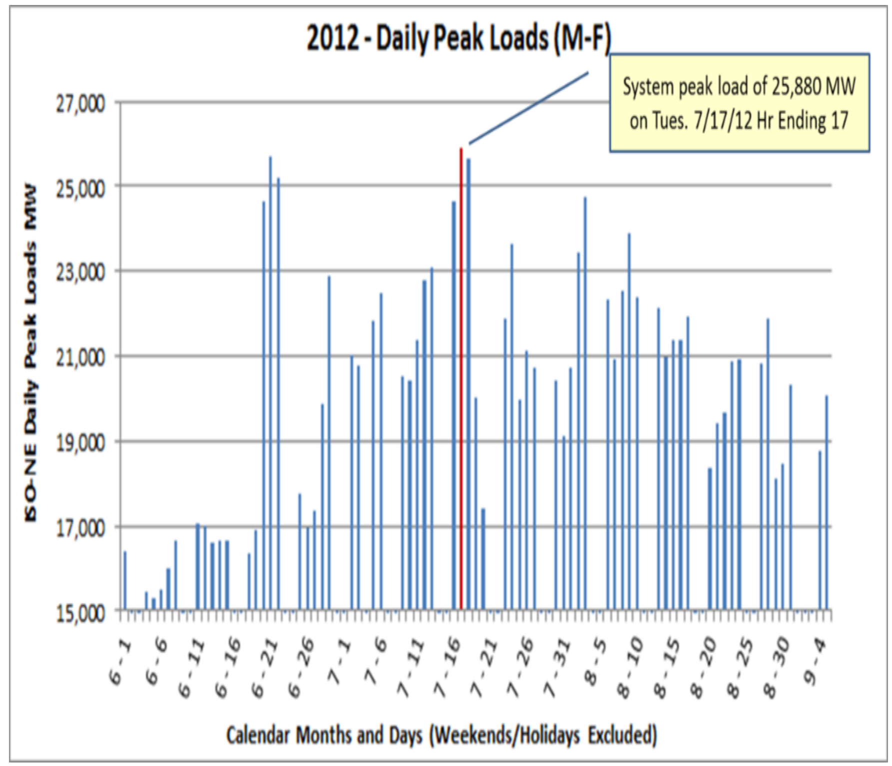
Operation

- Monitor capacity fade
- Predictive maintenance adventure
- Warranty
- Data Collection, Monitoring
  - Remote Access
  - On-board Storage

Case Study: Green Mountain Power ES Use to Reduce Peak Capacity & Transmission Payments to NE-ISO

- GMP current obligation is $80-90 million/year, based on one annual capacity peak and 12 monthly transmission peaks
  - Capacity portion (one annual peak) is $30 - $40 million/year now, will triple by 2018.
  - Transmission portion (12 monthly peaks) is $50 - $60 million/year now, will increase as transmission gets built in NE

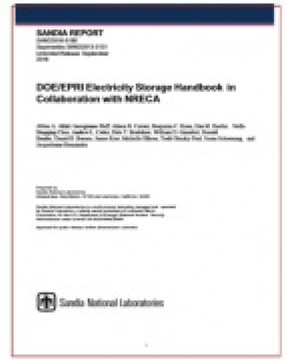
GMP calculates it will soon be paying $150 million/year to NE-ISO.



VALUE OF STORAGE?

- GMP calculates the value of storage at \$300,000 - \$500,000 /MW/year for peak capacity shaving, plus revenue from frequency regulation
- GMP site overall is valued up to \$1 million/MW/year (Solar has other value streams from RECs, generation etc.)
- Batteries cost around \$5-6 million
- GMP is seeing a **5-10-year payback**
- **And by the way, this system also provides backup power to School that is a designated emergency shelter**

DOE ESS Website Resource with examples of Available Tools



- DOE / ESS Website:
- http://www.sandia.gov/ess/

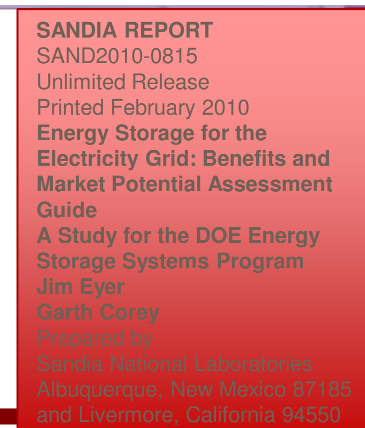
- 2015 DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA

- DOE /Strategen Global Energy Storage Database

- Energy Storage Grid: Benefits & Market Guide

- ES Demonstration Projects Summary

- ES Strategic Safety Plan


SANDIA REPORT
SAND2010-0815
Unlimited Release
Printed February 2010
Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide
A Study for the DOE Energy Storage Systems Program
Jim Eyer
Garth Corey
Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185
and Livermore, California 94550

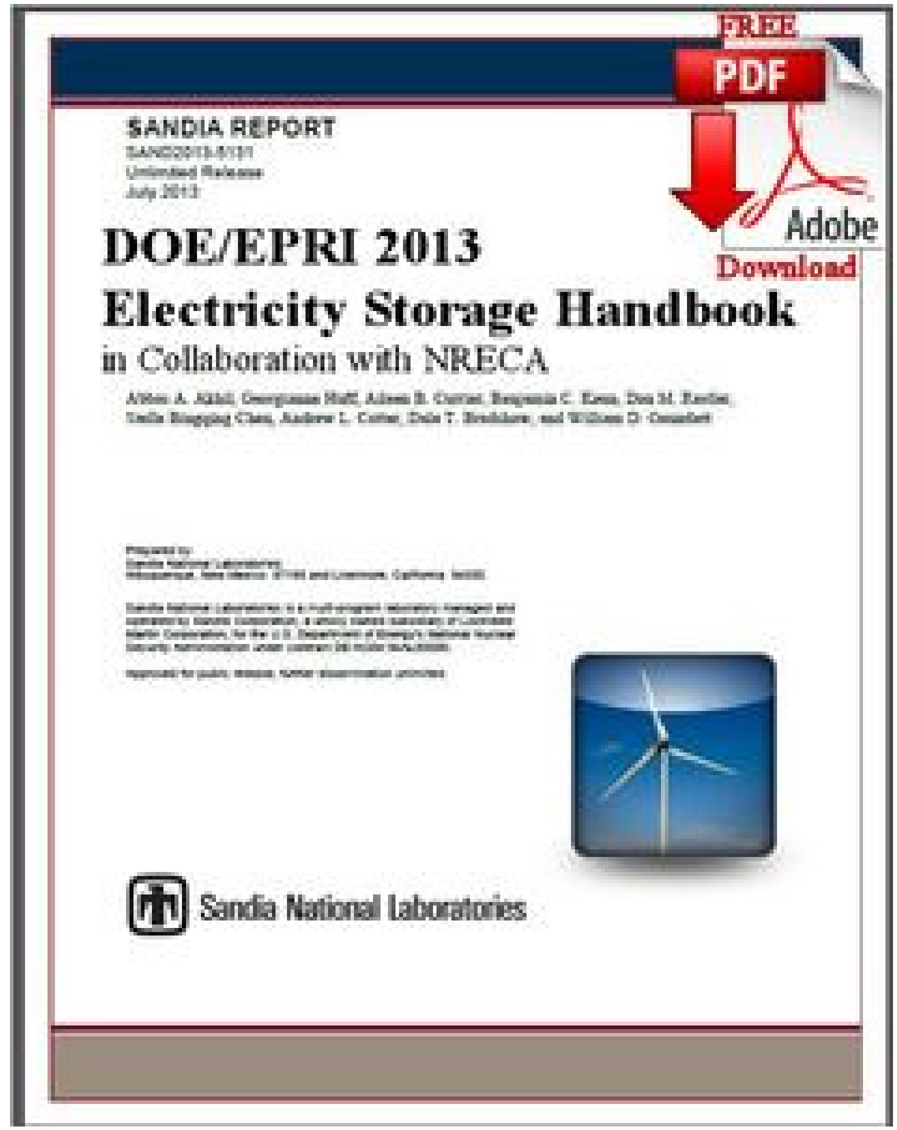
Outreach and Industry Tools

- ***DOE/EPRI Electricity Storage Handbook*** is a how-to guide for utility and rural cooperative engineers, planners, and decision makers to plan and implement energy storage projects safety in communities
- ***DOE Global Energy Storage Database*** provides free, up-to-date information on grid-connected energy storage projects and relevant state and federal policies.
- ***DOE Performance Protocol*** focuses on developing uniform methods of measuring ESS performance for specific applications.

DOE/EPRI Energy Storage Handbook

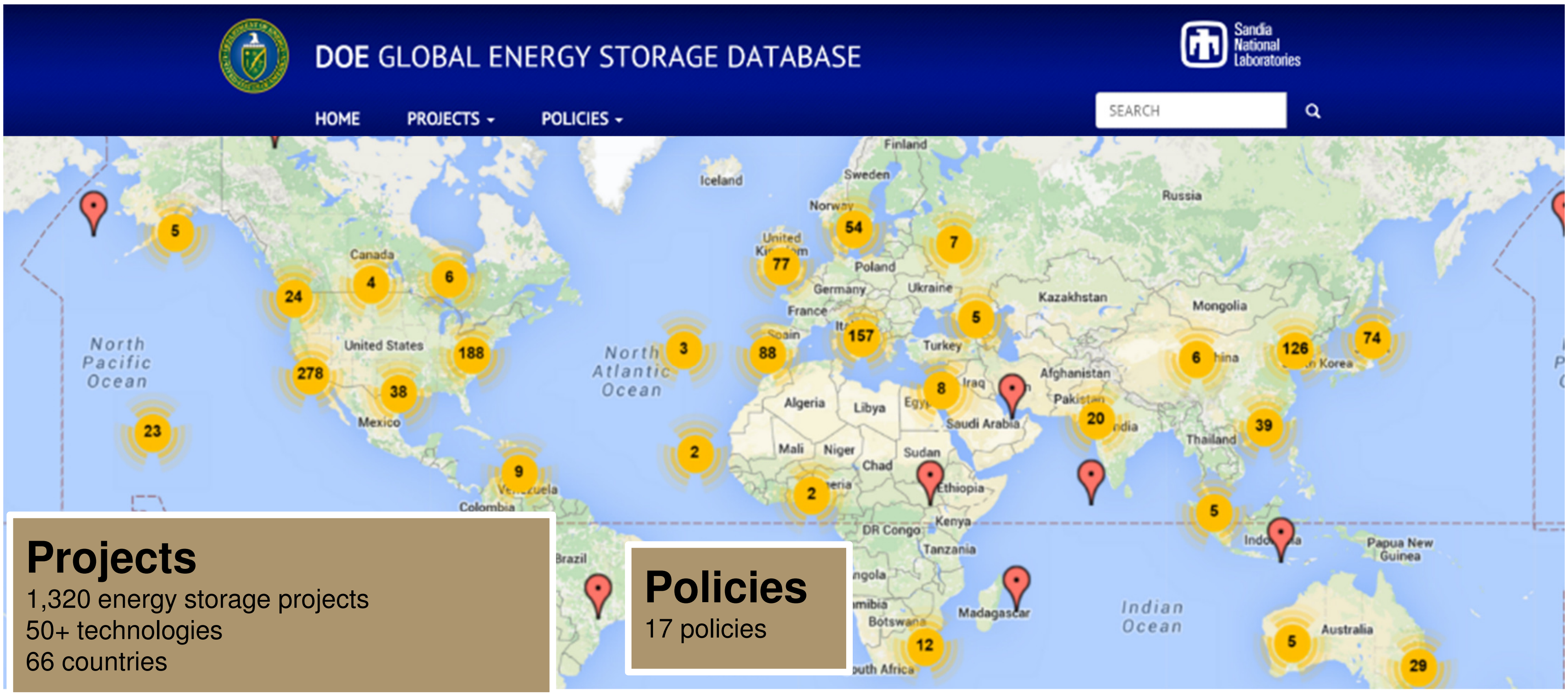
Sandia National Laboratories

- Fills an industry-wide need
- Establishes single-point resource for making decisions and stakeholders
- Handy reference on current and emerging technologies and applications
- Describes the services and applications of energy storage
  - in/on the grid
  - commercial status
  - system costs
  - performance metrics



DOE Energy Storage Database

Sandia maintains a comprehensive online resource of energy storage projects and policies.

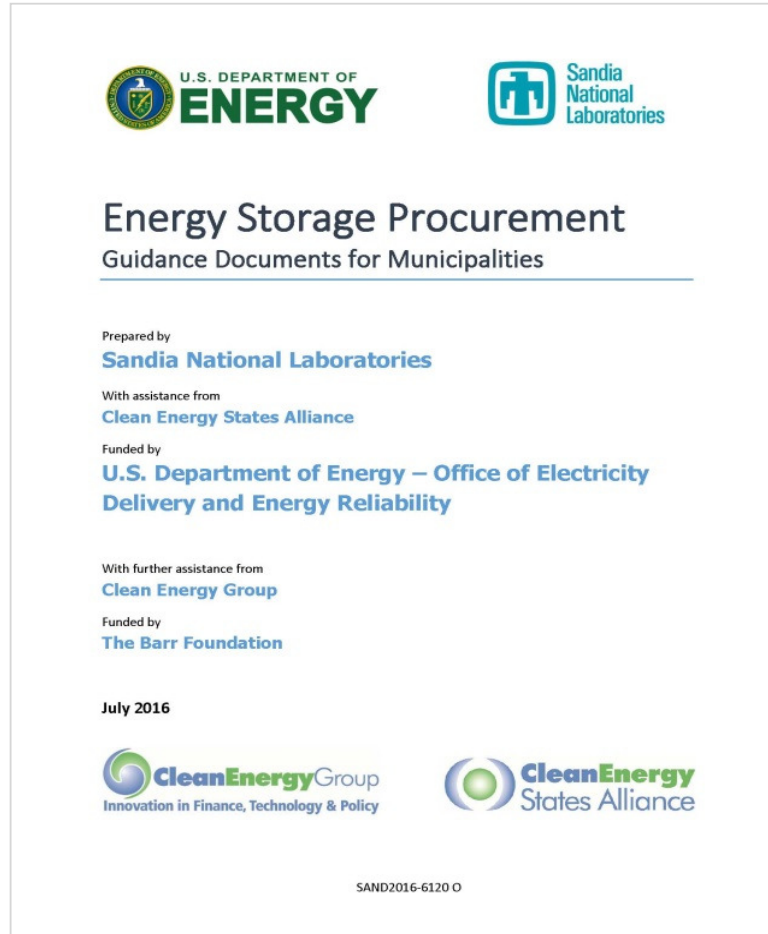


Projects
1,320 energy storage projects
50+ technologies
66 countries

Policies
17 policies

Procurement Guide for Energy Storage

- Useful reference for states, municipalities, project developers, and end users to consider as they develop solicitations for energy storage projects.
  - Checklist of information to provide in the RFP, suggests questions that should be asked of potential vendors, and includes information on what to look for in vendor responses.
  - Includes two sample RFP templates


U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories

Energy Storage Procurement

Guidance Documents for Municipalities

Prepared by

Sandia National Laboratories

With assistance from

Clean Energy States Alliance

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http://www.sandia.gov/ess/sandia-national-laboratories-publications/

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ESS Safety FORUM 2017
MEETING THE CHALLENGE

Feb. 22-24, 2017
Santa Fe, NM

The 2017 ESS Safety Forum: Meeting the Challenge will be Feb 22nd and 23rd and will provide a platform to discuss timely solutions and emerging ESS technologies. Successful grid-level implementation of variable source energy generation technology necessitates the integration of energy storage to ensure grid stabilization involving backup power, frequency regulation, and load leveling.

Interested in submitting your work?

Submit your abstract to essforum@sandia.gov.

Topics of interest include, but are not limited to,

- Battery failure modes and propagation,
- Battery safety through inherently safe design,
- Battery chemistry,
- State of health monitoring,
- Fail-gracefully technologies,
- Hardware, designs, and devices for safer systems,
- Power electronics,
- Risk assessment and management,
- Safety system integration, commissioning, and/or validation, and
- Software design and/or optimization.

Join us in historic Santa Fe, NM.

2017 ESS Safety Forum: Meeting the Challenge will be held at the historic La Fonda Hotel in Santa Fe, New Mexico from February 22-24, 2017. The La Fonda hotel is the only hotel on the historic Santa Fe Plaza. It is just moments away from authentic and exciting Santa Fe shopping and dining experiences. The La Fonda was awarded a four diamond award from AAA and has roots that date back 400 years.

ESS Safety WORKING GROUP

Join us on Feb. 24th for an in-person ESS Safety Working group meeting. For more information on the ESS Safety Working Group contact energystorage@sandia.gov.

The ESS Safety Working Groups provide a single location for information relevant to people and organizations engaged or with interest in R&D efforts in grid storage safety and to maintain an updated, relevant, and prioritized list of work needed to help the industry in understanding issues relevant to grid storage safety.

For more information, check out the 2017 ESS Safety Forum website at http://energy.sandia.gov/meeting-the-challenge-2017-ess-safety-forum/