

*Exceptional service in the national interest*



# Energy Storage Overview

Ray Byrne, Ph.D.  
December 9, 2017

**Acknowledgment:** this work was supported by the DOE energy storage program under the guidance of Dr. Imre Gyuk.



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

# Outline

- Grid scale energy storage
- Value streams
- Storage on the grid today

# Why Do We Need Energy Storage?

- Major reasons for installing 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 (not the topic of this presentation)



# Grid Scale Energy Storage

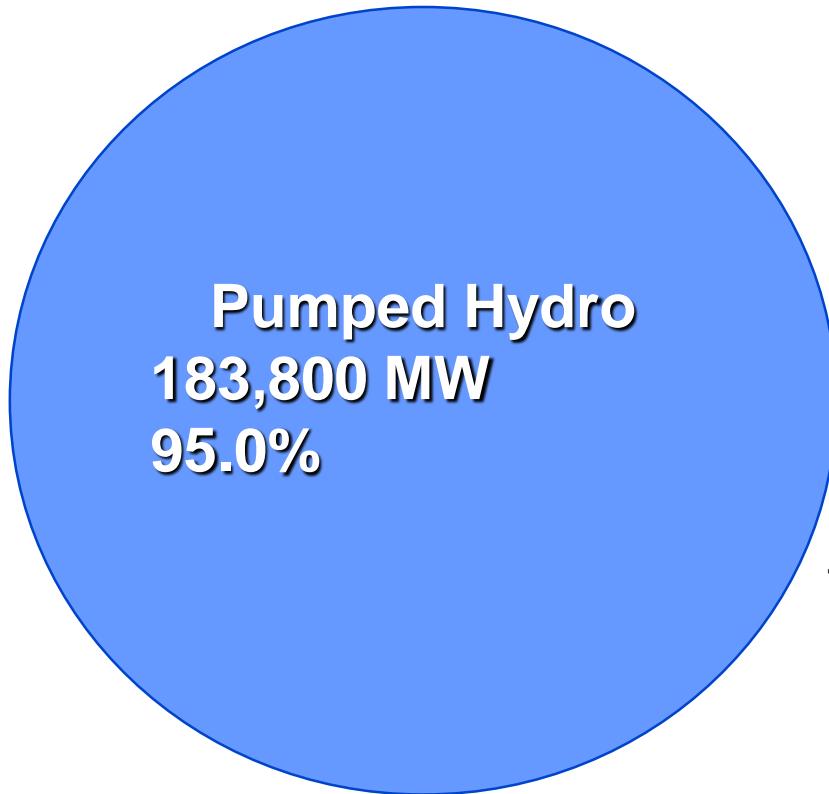
- Primary methods for energy storage
  - Electrochemical
    - Lithium batteries
    - Lead acid batteries
    - Flow batteries
  - Mechanical
    - Compressed air
    - Pumped hydro
    - Flywheels
  - Thermal
    - Molten salt
    - Ice
  - Electrical
    - Ultra Capacitors



SCE Tehachapi Plant, 8MW, 32 MWh



# Energy Storage in the Grid



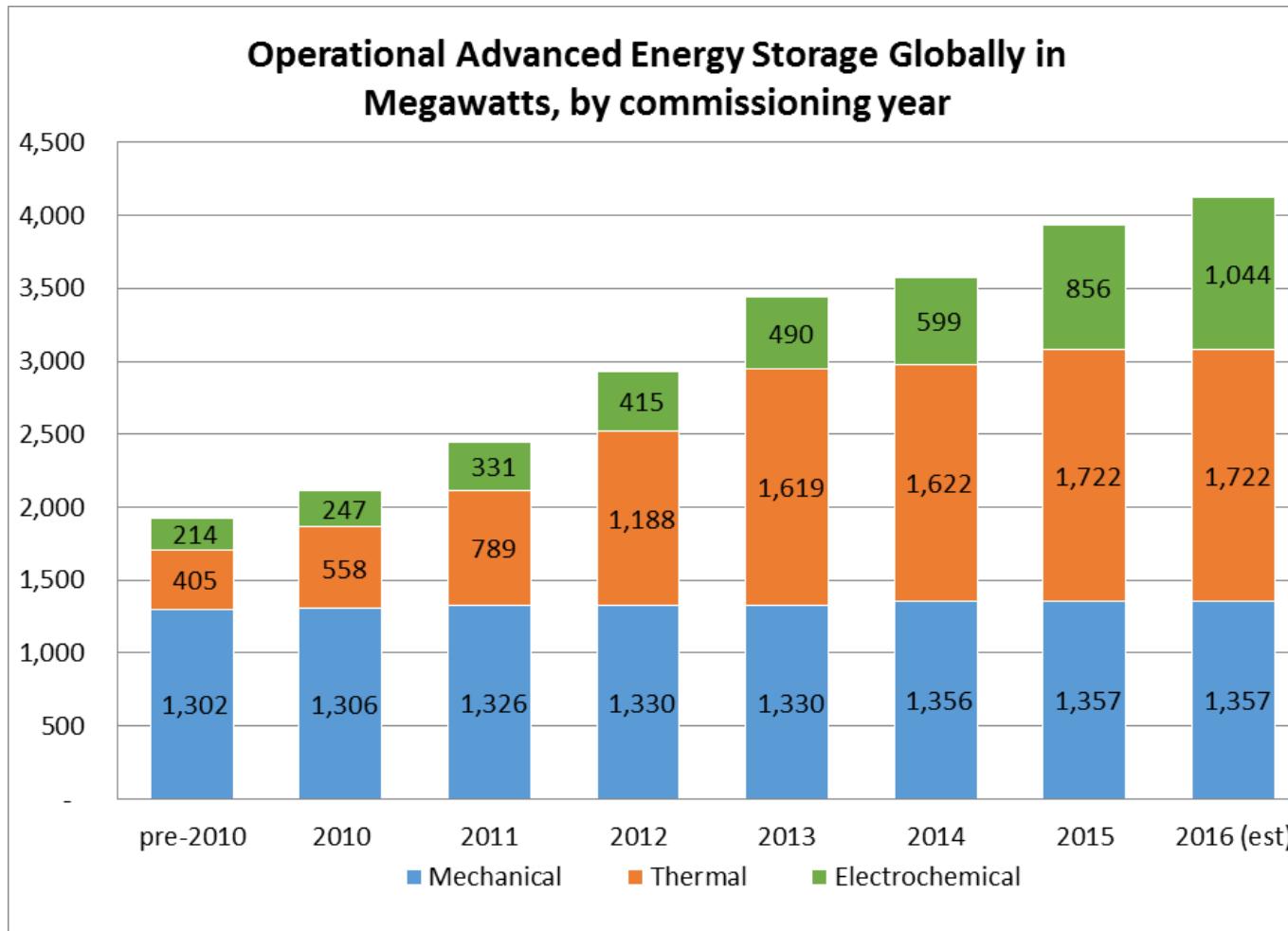
- Electro-chemical 1.7%
- Thermal Storage 1.9%
- Electro-mechanical 1.4%

Technology Type	Project s	Rated Power (MW)	
Electro-chemical	993	3,279	*Numbers reflect projects reported to the Energy Storage Global Database as of (May 2017)
Pumped Hydro Storage	352	183,800	
Thermal Storage	206	3,622	
Electro-mechanical	70	2,616	

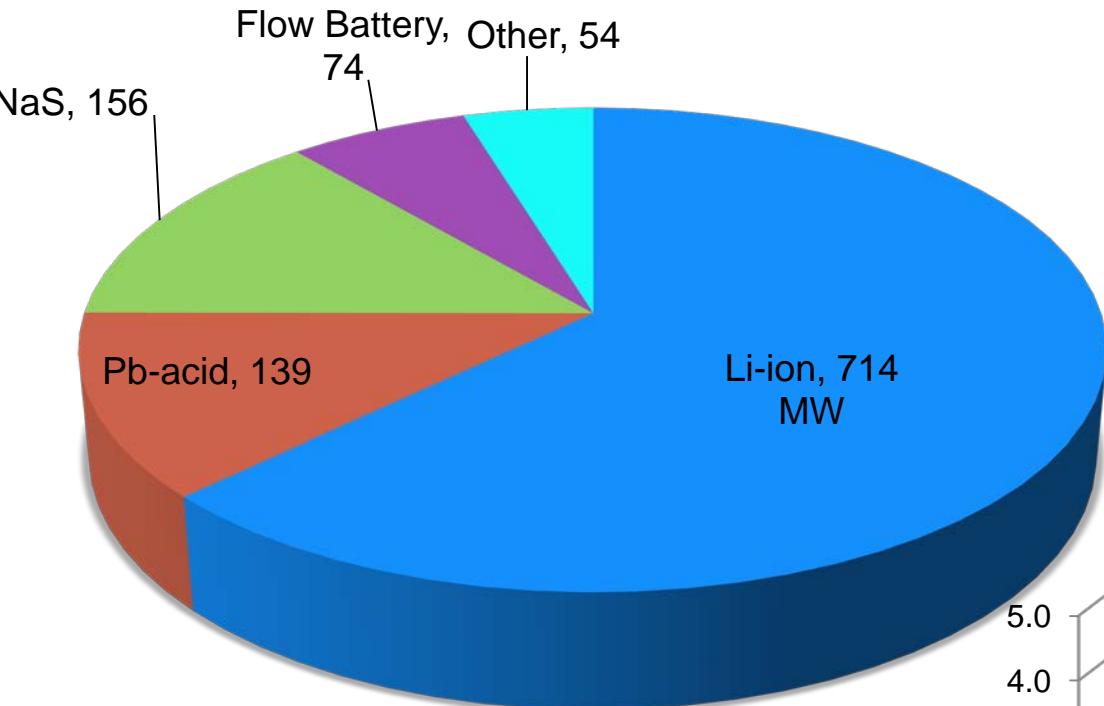
DOE ESS Database  
<http://www.energystorageexchange.org/>

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

# Operational Advanced Energy Storage (MW)

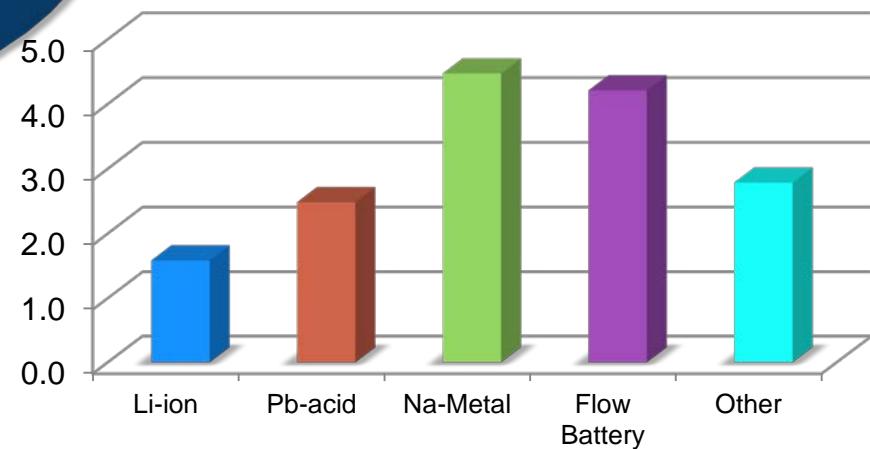


# Current Stationary ESS deployments (Battery Only)



**~ 1.1 GW of Battery Energy Storage (US)**

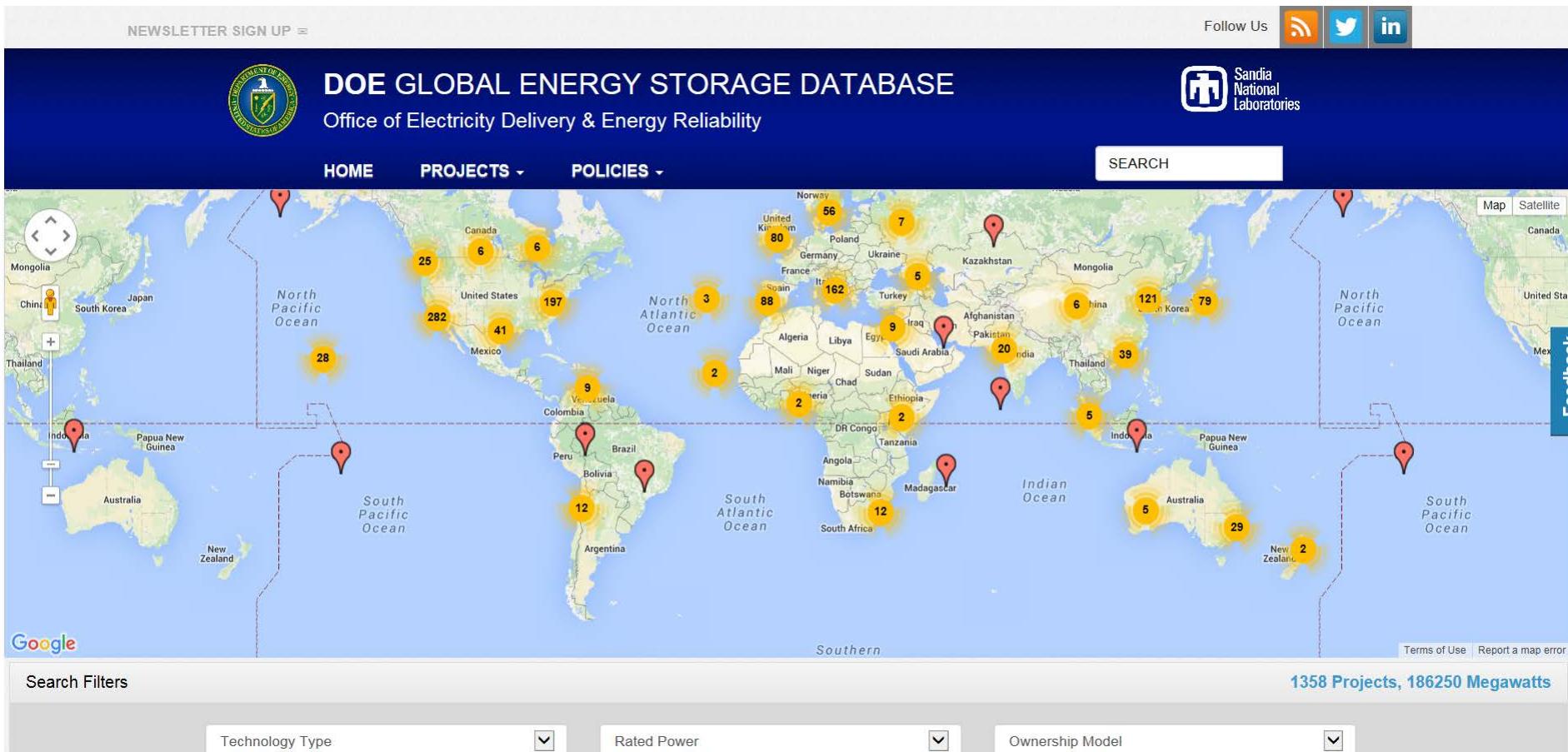
**Average Duration (hrs)**



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

# DOE Energy Storage Database

- Two ways to find the web site:
  - <http://www.energystorageexchange.org/>
  - Google “DOE energy storage database”



# Recent Storage Policy Breakthroughs

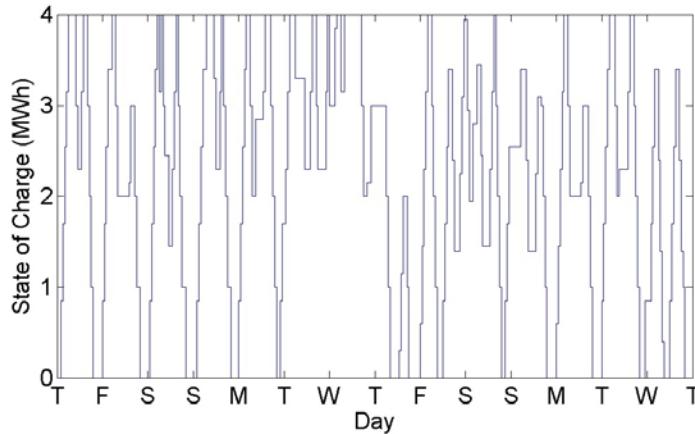
- American Recovery and Reinvestment Act (ARRA) of 2009 Energy Storage Demonstration Projects
  - 16 projects
  - Varying levels of technology maturity
  - 50% federal cost share (\$600M for all 21 SGDPs)
- FERC order 755 and FERC order 784: “pay-for-performance”
  - More fairly compensates “fast responding” 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

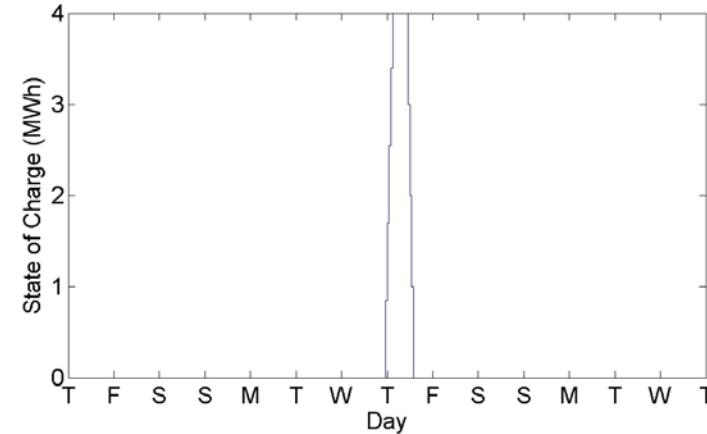
Storage Grid Domain Point of Interconnection	2014	2016	2018	2020	Total
<b>Southern California Edison</b>					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
<b>Subtotal SCE</b>	<b>90</b>	<b>120</b>	<b>160</b>	<b>210</b>	<b>580</b>
<b>Pacific Gas and Electric</b>		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

# Energy Storage Efficiency

- *Round Trip Efficiency* = 
$$\frac{\text{output MWh}}{\text{input MWh}}$$
- Quoted efficiency can be confusing:
  - Typically AC-to-AC, sometimes quoted DC-DC
  - Does it include balance of plant (e.g., air conditioning, heating, etc.)?
  - What type of charge/discharge cycle?
- Example: 1MW, 4MWh system, 2 weeks, 85% efficiency, balance of plant = 2.9762 kW



$$\text{Efficiency} = \frac{78.95 \text{ MWh}}{92.8820 + 1 \text{ MWh}} = 84.1\%$$



$$\text{Efficiency} = \frac{4 \text{ MWh}}{4.7059 + 1 \text{ MWh}} = 70.1\%$$

# Electricity Storage Services

<b>Bulk Energy Services</b>		<b>Transmission Infrastructure Services</b>
Electric Energy Time-Shift (Arbitrage)		Transmission Upgrade Deferral
Electric Supply Capacity		Transmission Congestion Relief
<b>Ancillary Services</b>		<b>Distribution Infrastructure Services</b>
Regulation		Distribution Upgrade Deferral
Spinning, Non-Spinning and Supplemental Reserves		Voltage Support
Voltage Support		<b>Customer Energy Management Services</b>
Black Start		Power Quality
Other Related Uses		Power Reliability
		Retail Electric Energy Time-Shift
		Demand Charge Management

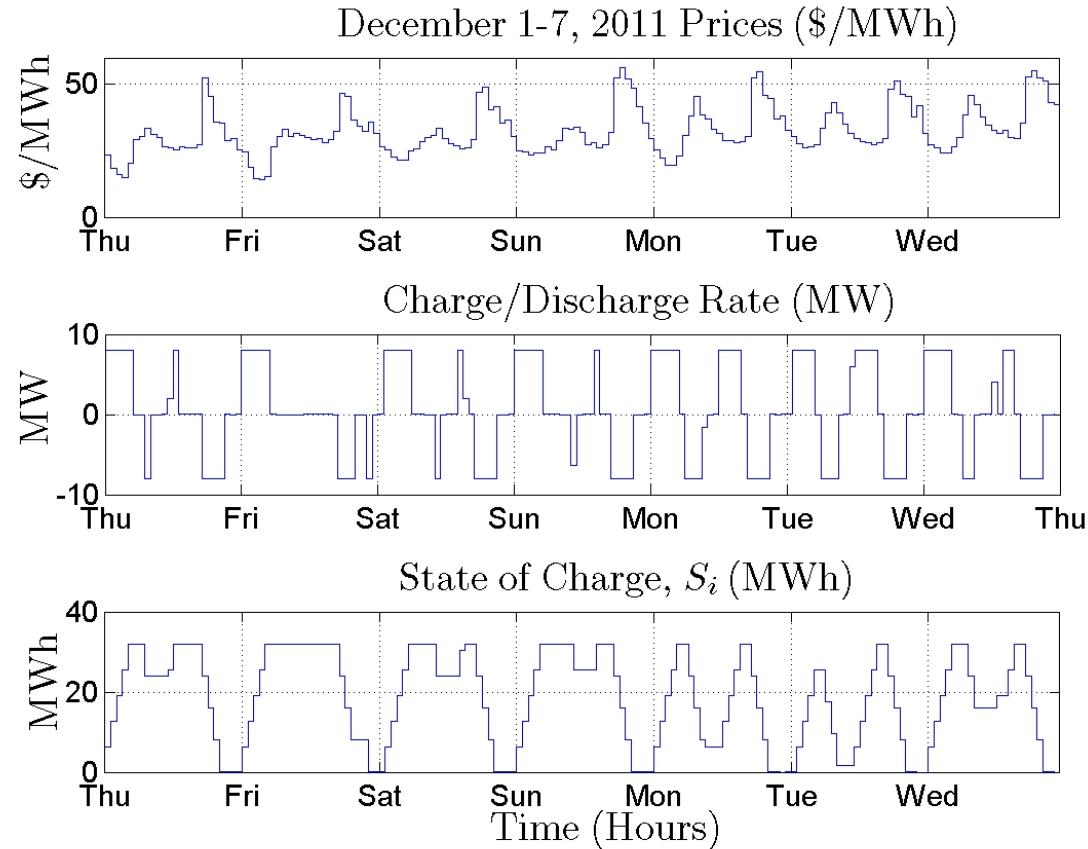
Source: DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA

## Additional information:

**“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

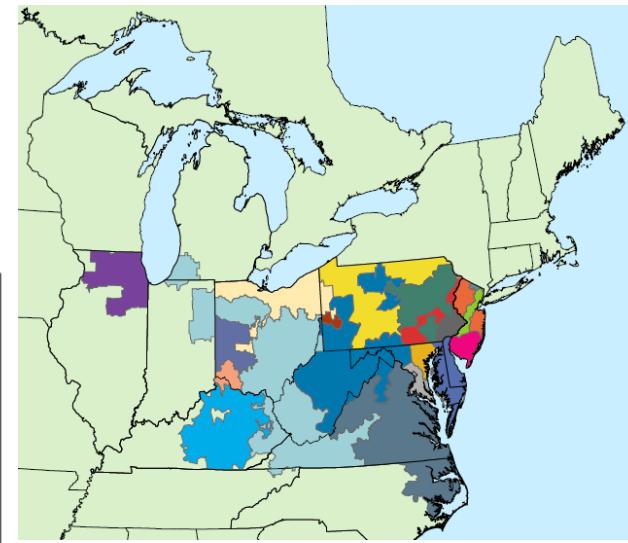
- Energy arbitrage – buy low, sell high
- Energy price swings must be larger than efficiency losses
- Rarely captures the largest value



# 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
				<b>Total</b>	<b>\$6,394,098.97</b>



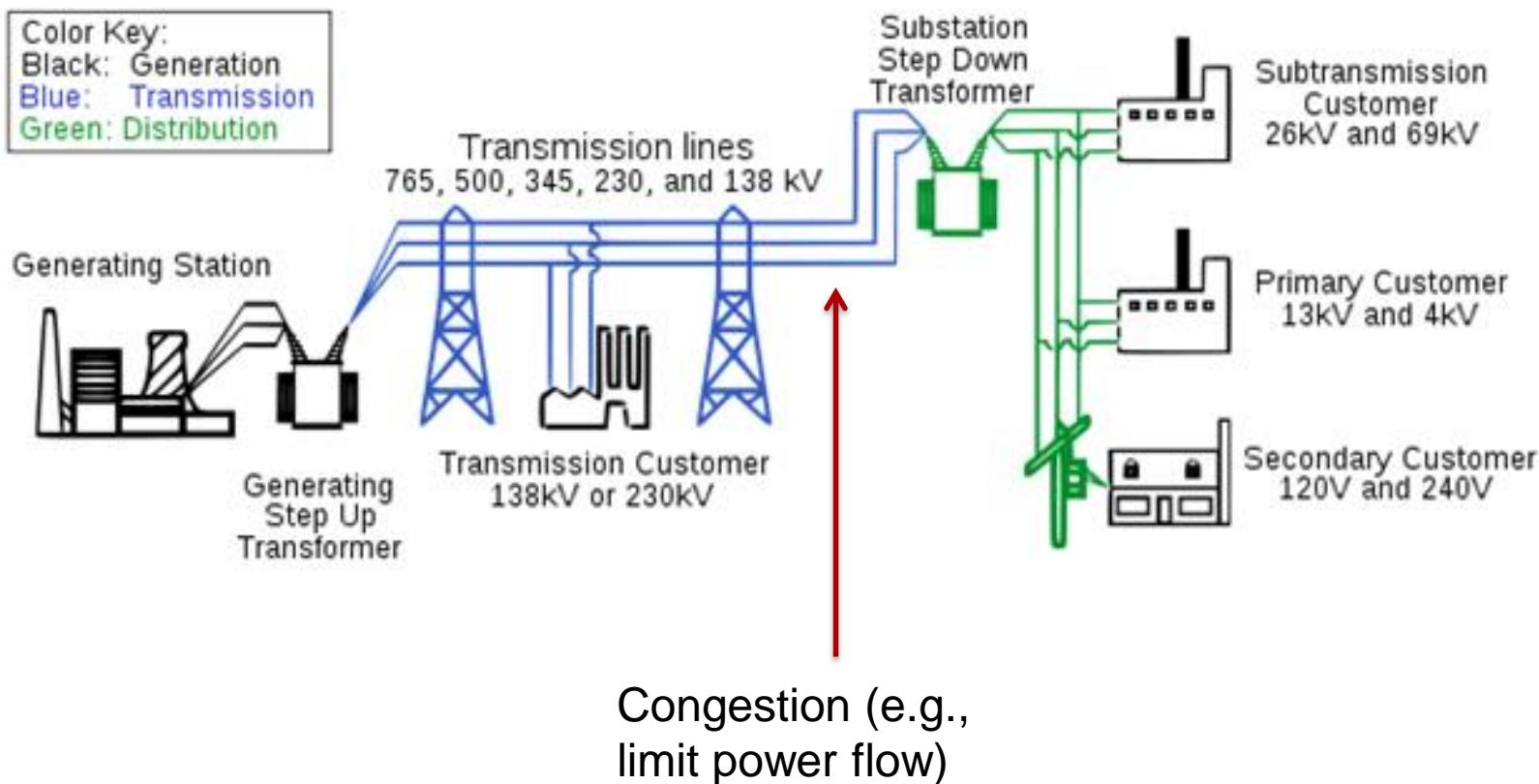
PJM results, 20MW, 5MWh  
200-flywheel system



Beacon Power Flywheel

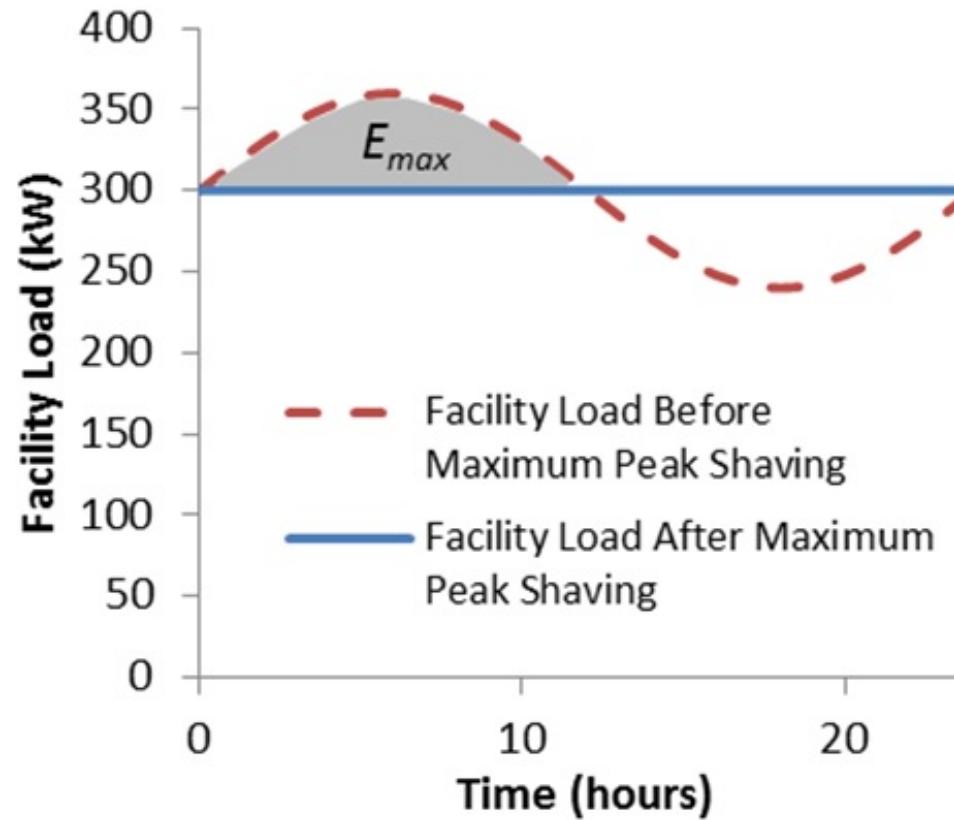
# Energy Storage Value Streams

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



# Energy Storage Value Streams

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



# Energy Storage Value Streams

- Pool transmission and capacity payments
- Example: ISO-NE
- Regional Network Service (RNS) payment for using pool transmission services – based on monthly peak load (\$98.70147/kW-yr )
- Forward capacity market payment – based on annual peak load

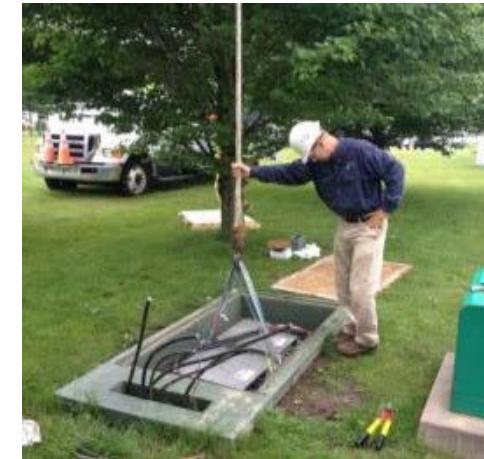
ISO-NE Capacity Clearing Price	
Year	Price (\$/kW-Month)
2010-2011	\$4.254
2011-2012	\$3.119
2012-2013	\$2.535
2013-2014	\$2.516
2014-2015	\$2.855
2015-2016	\$3.129
2016-2017	\$3.150
2017-2018	\$7.025
2018-2019	\$9.551

Year	Price (\$/kW-Month)	1 MW	2 MW	3 MW	4 MW
2015-16	\$3.129	\$51,477	\$102,958	\$154,443	\$205,932
2016-17	\$3.150	\$51,822	\$103,649	\$155,479	\$207,315
2017-18	\$7.025	\$115,572	\$213,153	\$346,744	\$462,344
2018-19	\$9.551	\$157,128	\$314,269	\$471,424	\$628,591

Assumptions: 9.6MW base load

# Energy Storage Value Streams

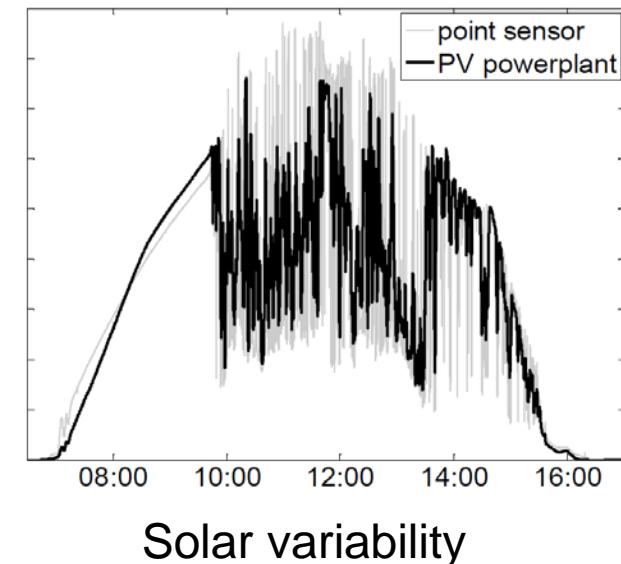
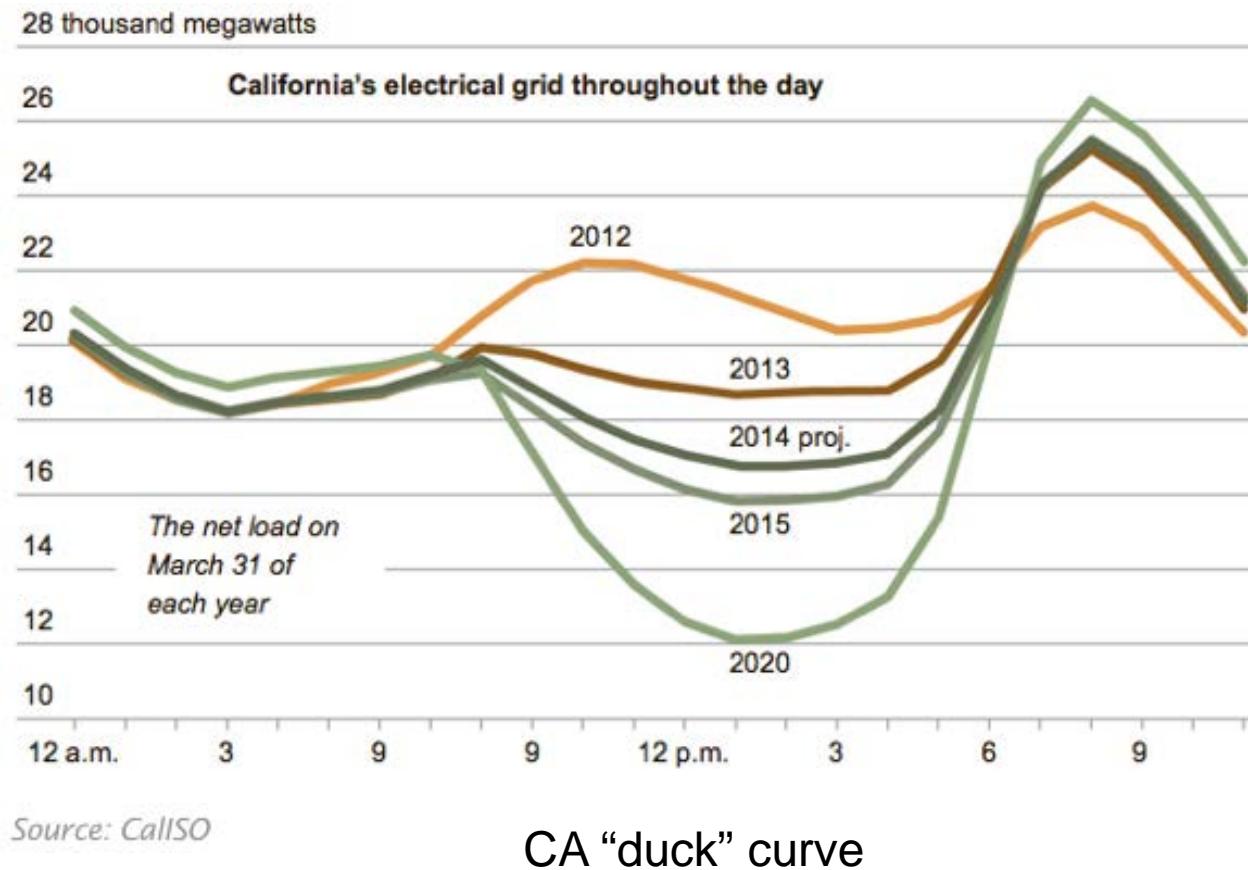
- Distribution level energy storage
  - Volt/VAR support
  - Islanding during outages
  - Frequency regulation
  - Renewable time shift
  - Peak shaving
  - Arbitrage



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)

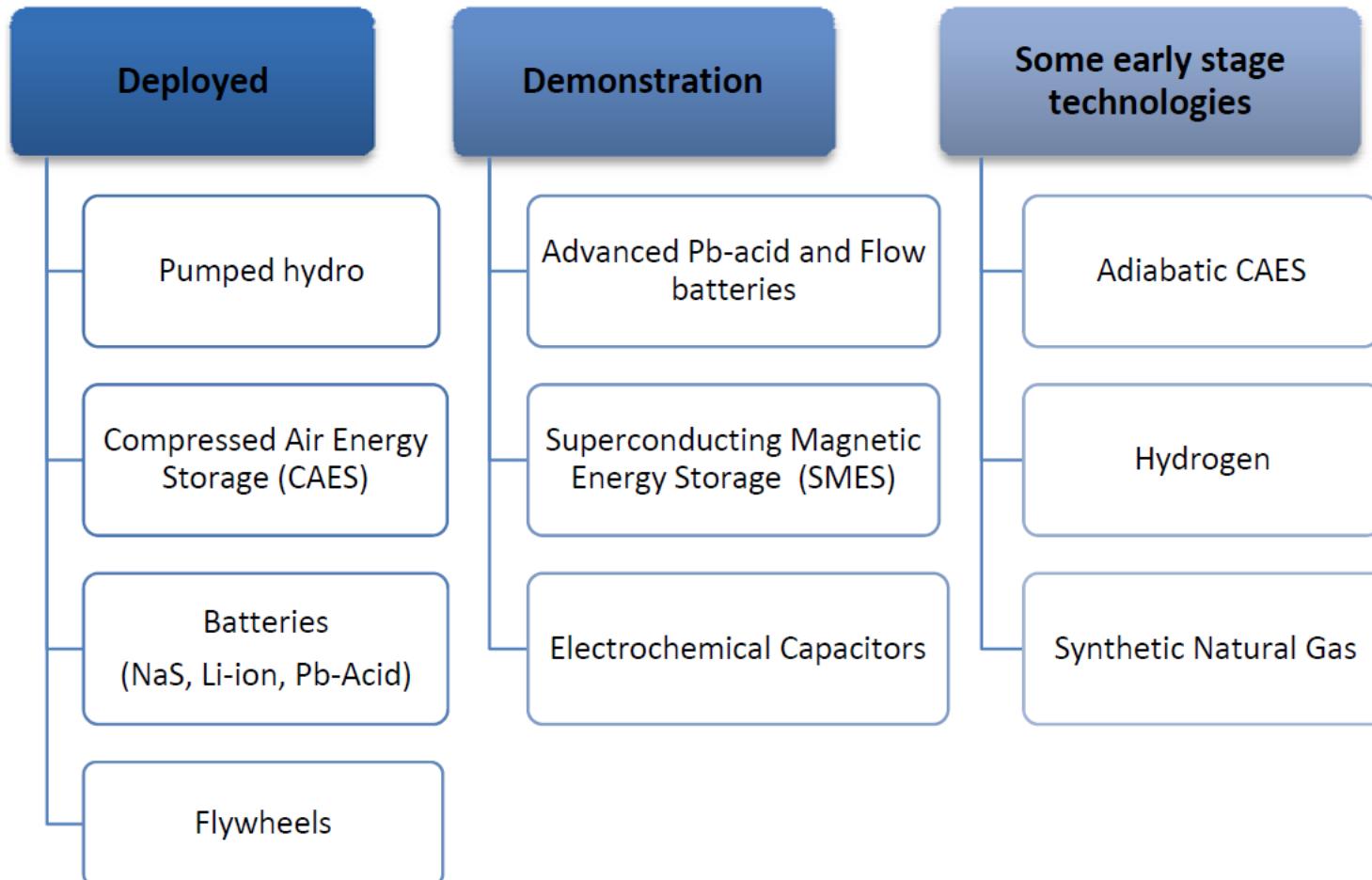


For vertically integrated utilities – increased regulating and spinning reserves. In market areas, adding ramping products.

# 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

# Technology Maturities



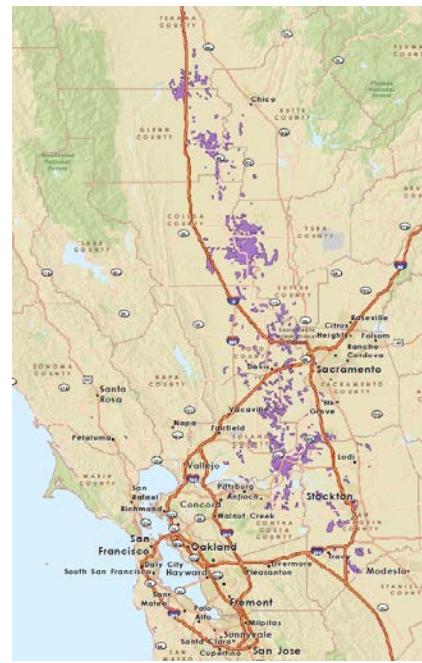
**Source:** U.S. Department of Energy, “Grid Energy Storage”, December 2013.

# 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 – 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 - Flywheels

- 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
  - Rotor tensile strength limitations ( $E \approx \omega^2$ )
  - Limited energy storage time (frictional losses)



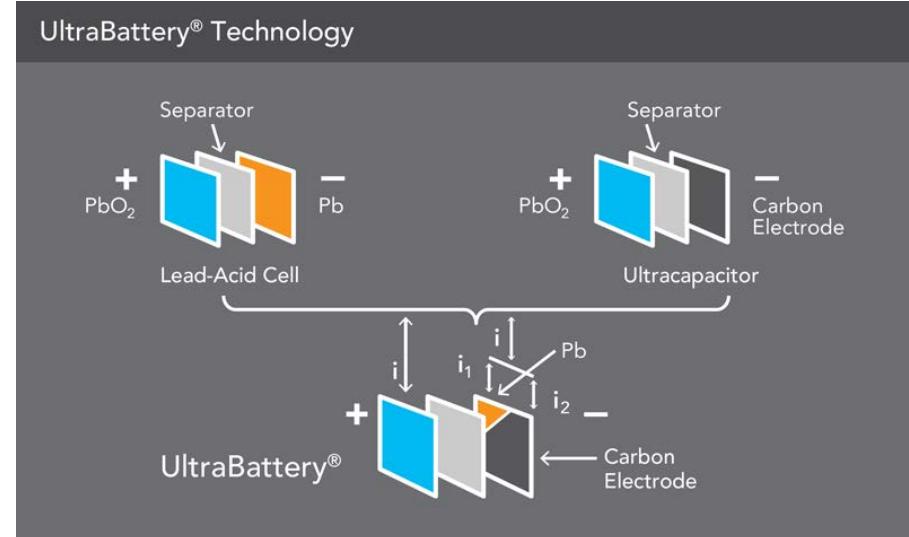
Beacon Power Hazle Township, PA plant. 20 MW, 5MWh. Operational September 2013. Stephentown, NY plant was built first.

# Technology Overview – Lead Acid

- Advanced Lead Acid Energy Storage
  - Developed by Ecoult/East Penn Manufacturing
  - Carbon plates significantly improve performance
  - Mature technology
  - Low cost
  - High recycled content
  - Good battery life

- Applications
  - Load leveling
  - Frequency regulation
  - Grid stabilization

- Challenges
  - Low energy density
  - Limited depth of discharge
  - Large footprint



Albuquerque, NM



East Lyons, PA

# Technology Overview - NaS

- Sodium Sulphur Energy Storage

- High energy density
- Long discharge cycles
- Fast response
- Long life
- 190 sites in Japan
- Developed by Ford in 1960's
- Sold to Japan (NGK is largest manufacturer)



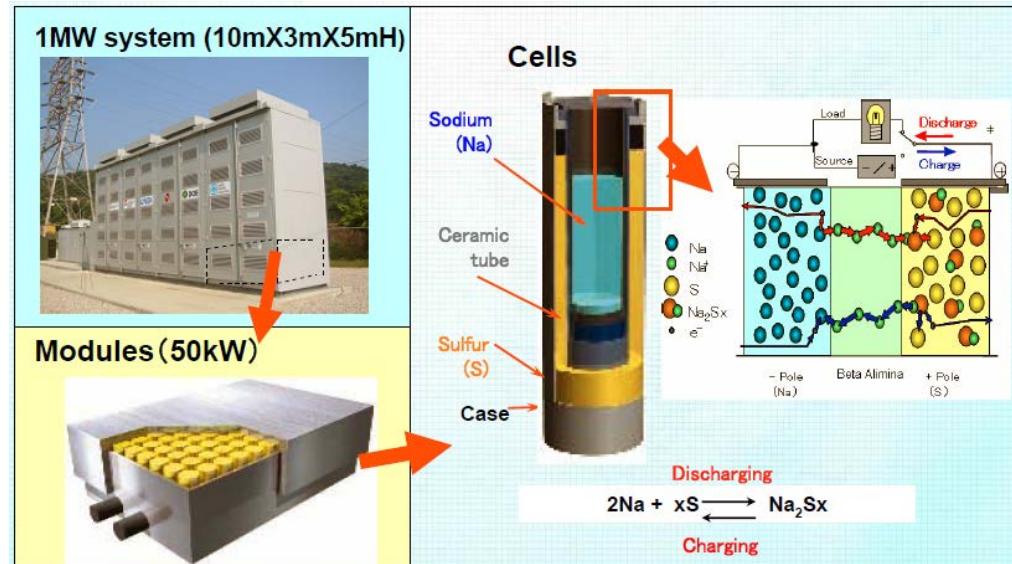
Los Alamos, NM. 1 MW, 6MWh.

- Applications

- Power quality
- Congestion relief
- Renewable integration

- Challenges

- High operating temperature (250-300C)
- Liquid containment issues



Source: NGK

# Technology Overview – Li-ion

- 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.

# 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

# 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

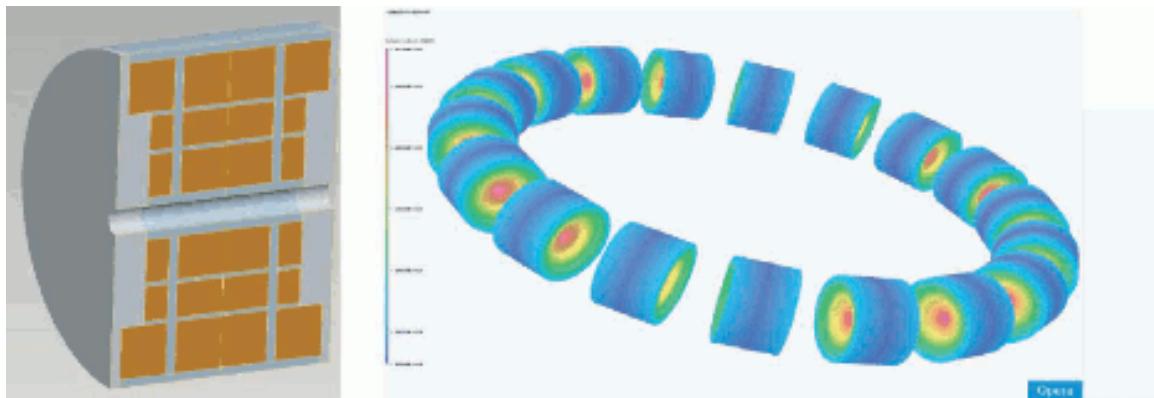


Ultra capacitor module, designed for vehicle applications (e.g., buses, trains)



# Technology Overview - SMES

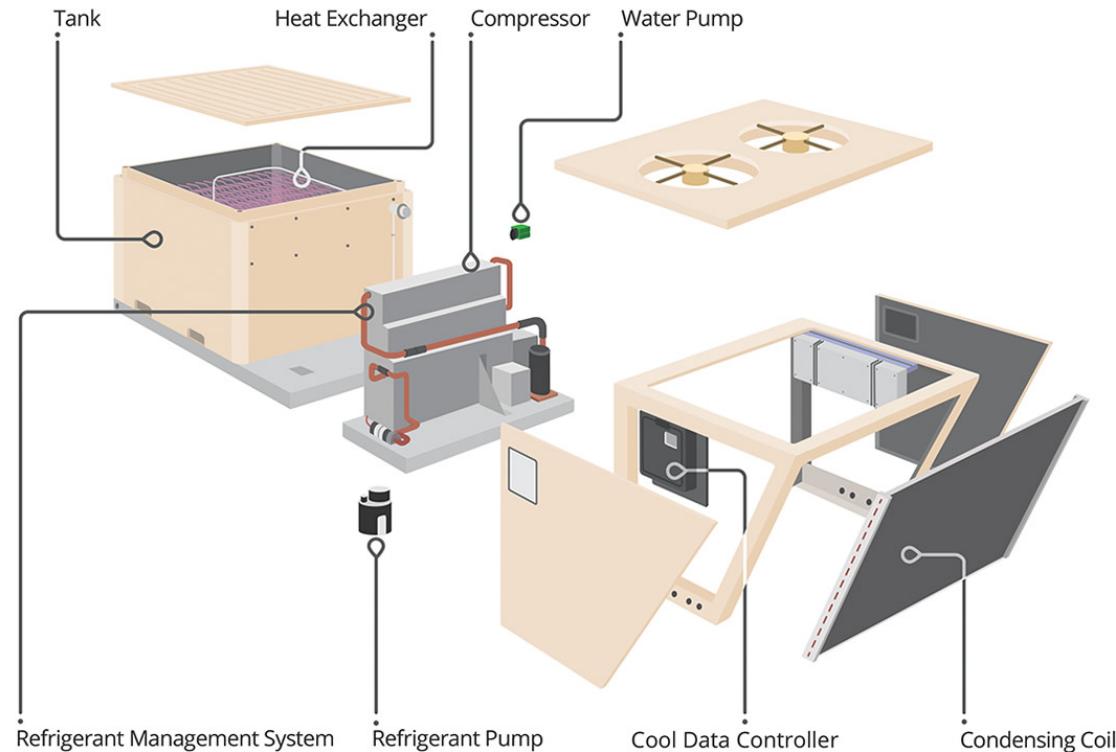
- Super Conductive Magnetic Energy Storage
  - Highest round trip efficiency (~95%)
- Applications
  - Power quality
  - Frequency regulation
- Challenges
  - Low energy density
  - Component and manufacturing cost



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](http://www.ice-energy.com)

# Summary

- Energy storage can improve the flexibility, reliability, and efficiency of the electric power grid
- Additional information can be found at:  
<http://www.sandia.gov/ess/>
- Information on ARRA energy storage demonstration projects:  
[https://www.smartgrid.gov/recovery\\_act/program\\_impacts/energy\\_storage\\_technology\\_performance\\_reports.html](https://www.smartgrid.gov/recovery_act/program_impacts/energy_storage_technology_performance_reports.html)