

Exceptional service in the national interest



Energy Storage Overview

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Outline

- Grid scale energy storage
- Value streams
- Storage on the grid today
- Technology overview
- Energy storage analytics at Sandia

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



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)



Recent Storage Policy Breakthroughs

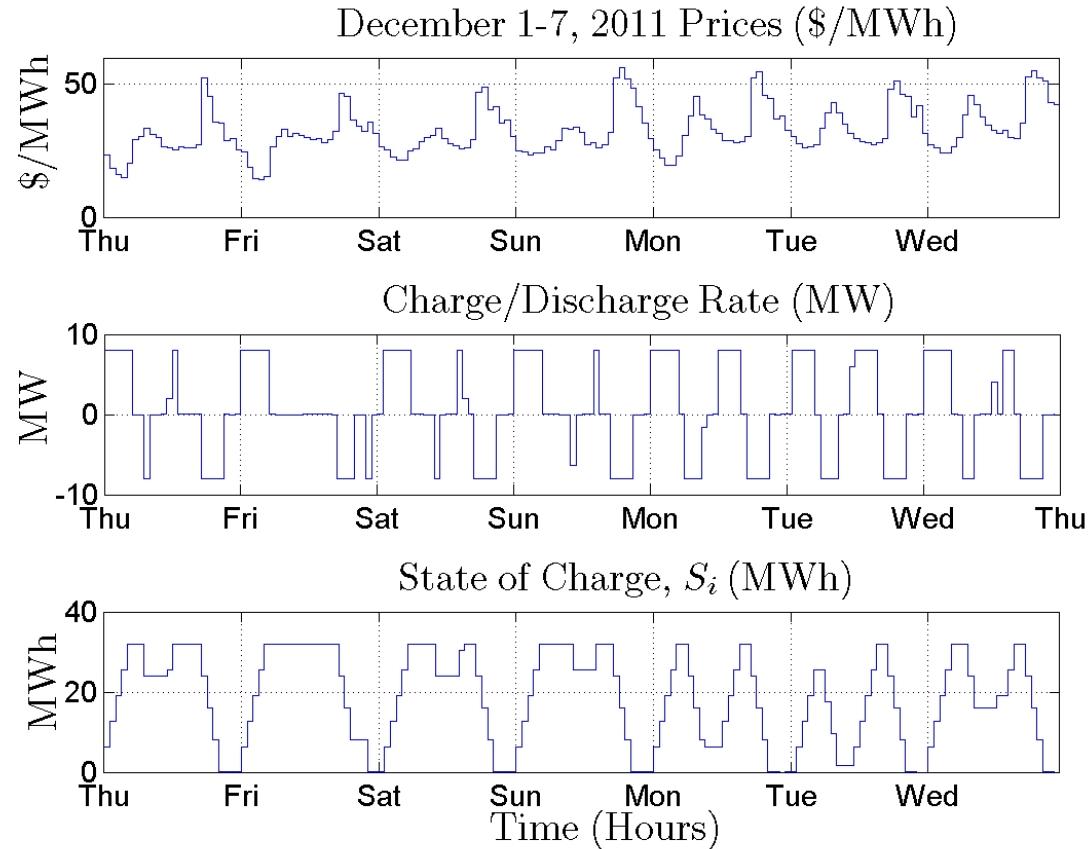
- American Recovery and Reinvestment Act (ARRA) of 2009 Energy Storage Demonstration Projects
 - 16 projects
 - Varying levels of technology maturity
 - 50% federal cost share (\$600M for all 21 SGDPS)
- FERC order 755 and FERC order 784: “pay-for-performance”
 - More fairly compensates “fast responding”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

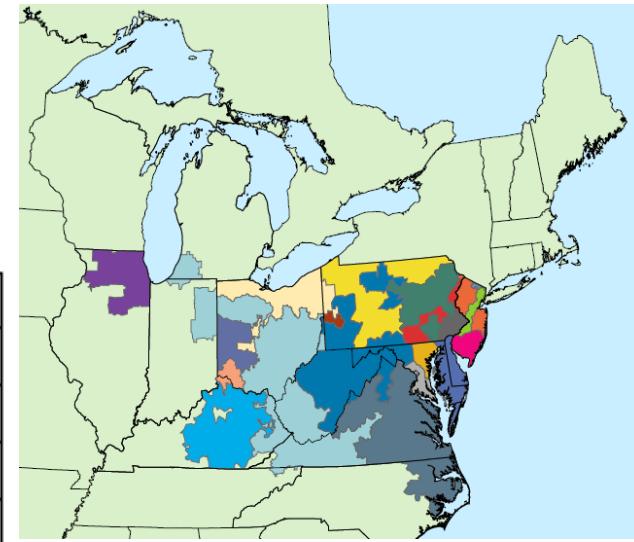
- Energy arbitrage – buy low, sell high
- Energy price swings must be larger than efficiency losses
- Rarely captures the largest value



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



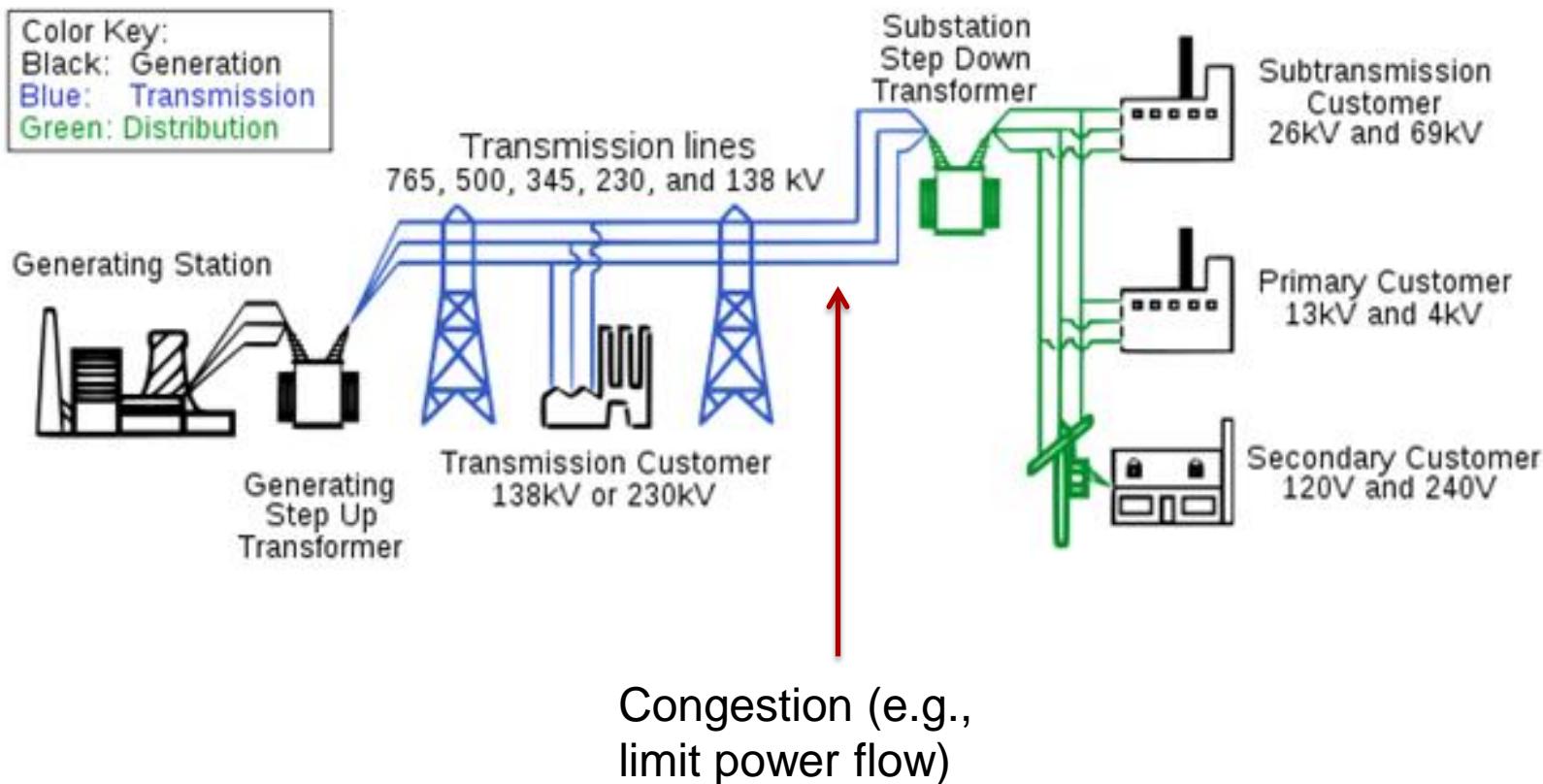
PJM results, 20MW, 5MWh
200-flywheel system



Beacon Power Flywheel

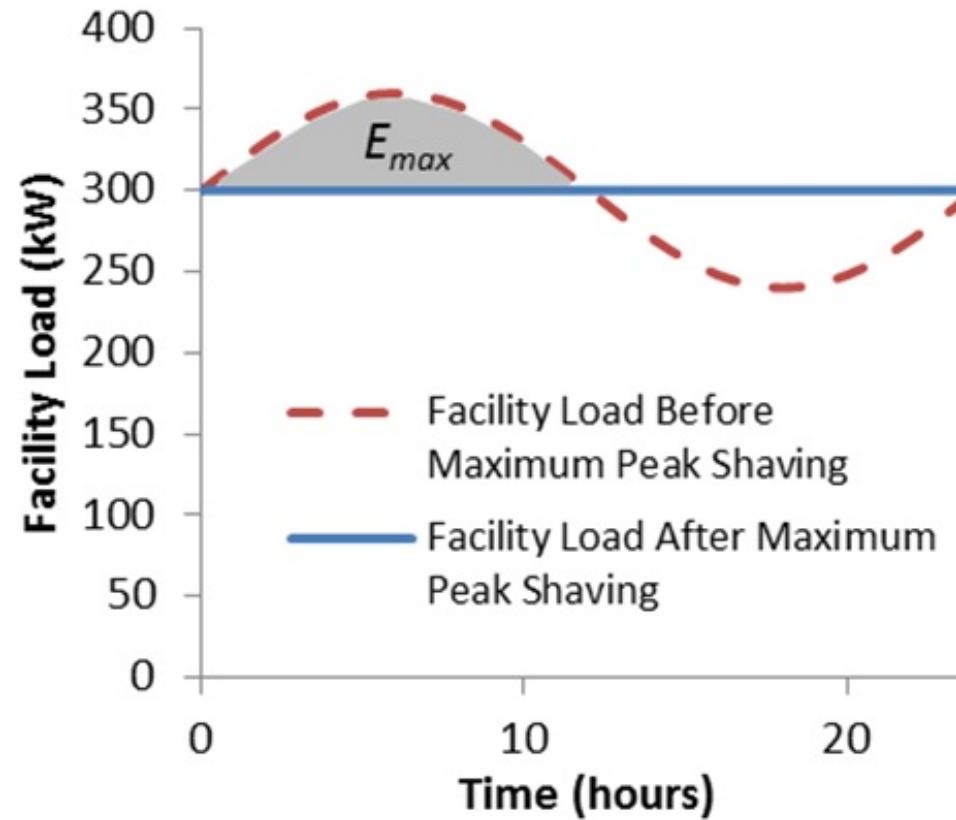
Energy Storage Value Streams

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



Energy Storage Value Streams

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



Energy Storage Value Streams

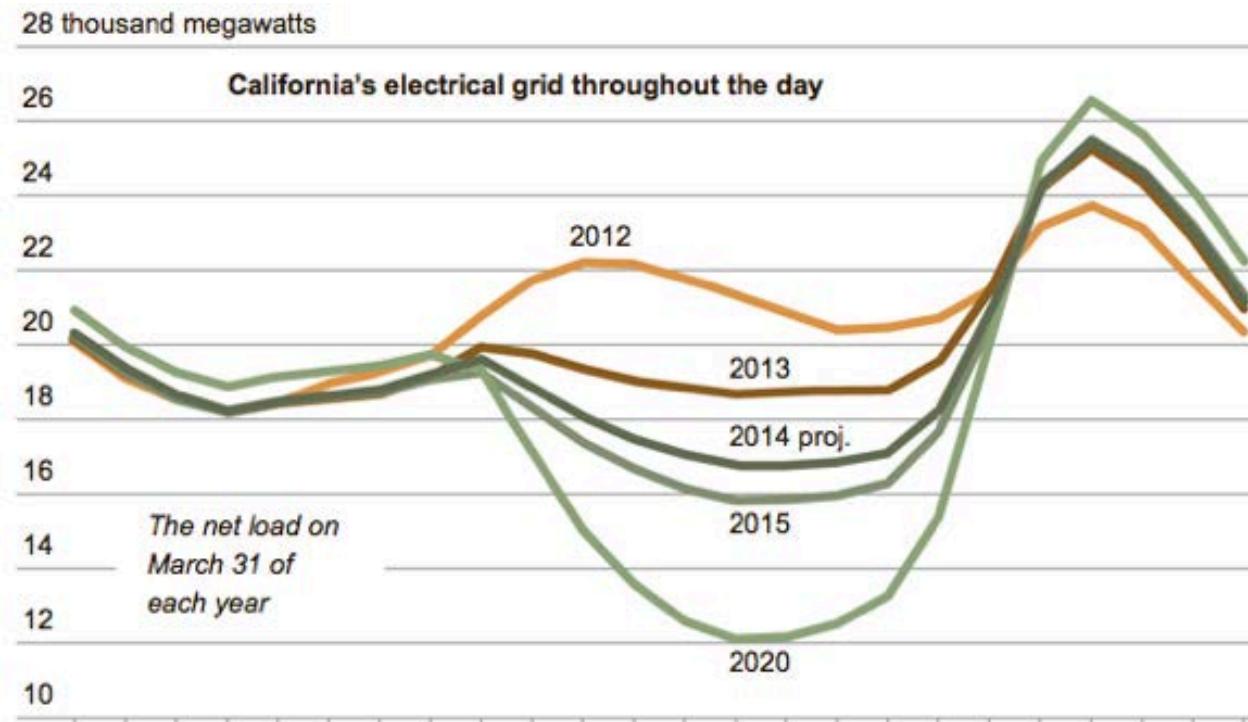
- Distribution level energy storage
 - Volt/VAR support
 - Islanding during outages
 - Frequency regulation
 - Renewable time shift
 - Peak shaving
 - Arbitrage



DTE ARRA energy storage demonstration project

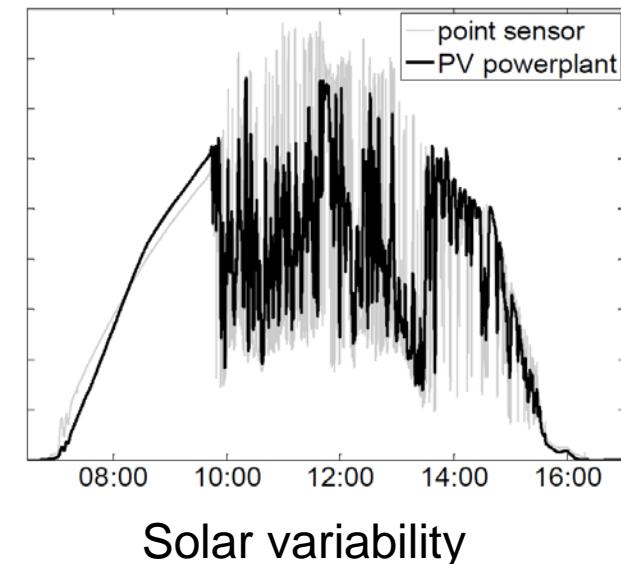
Energy Storage Value Streams

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



CA “duck” curve

Source: CalISO

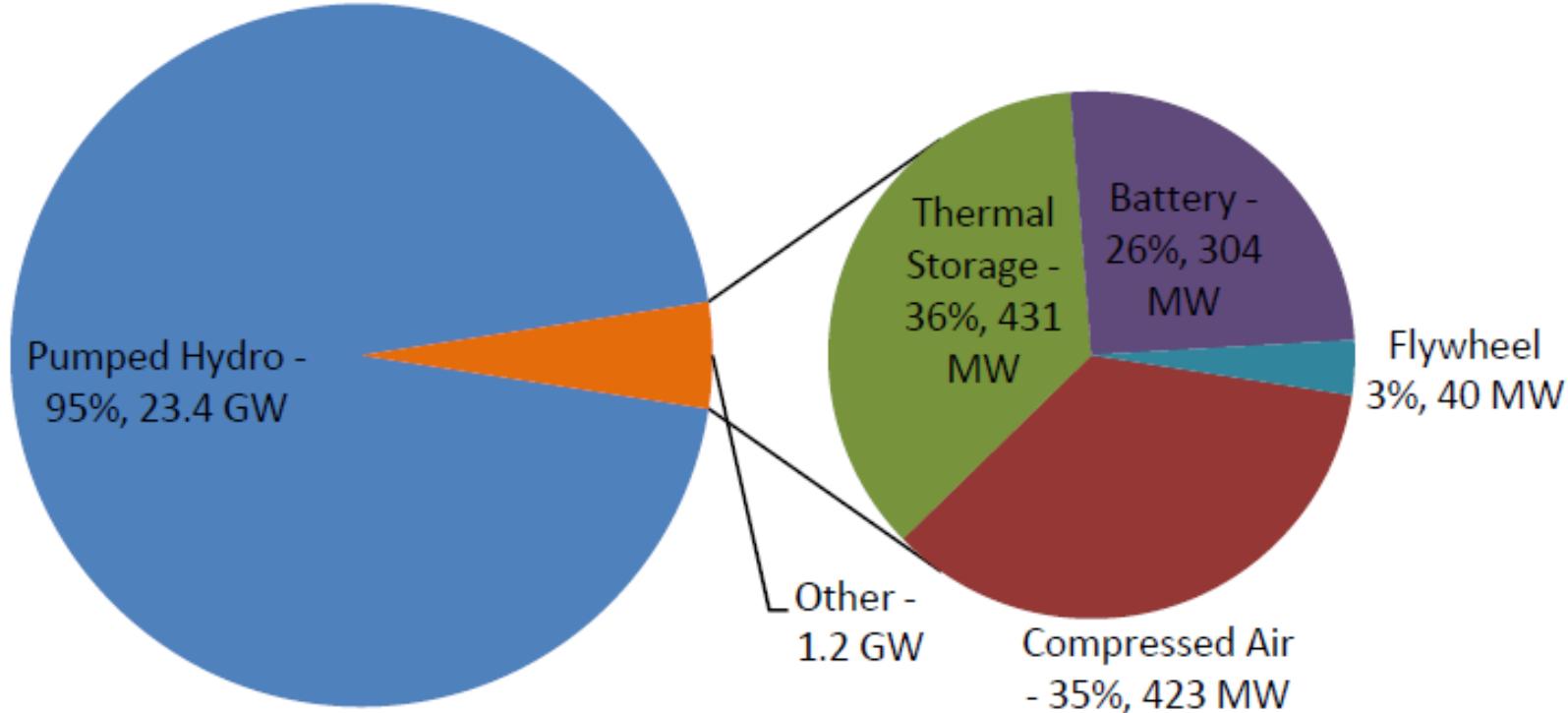


For vertically integrated utilities – increased regulating and spinning reserves. In market areas, adding ramping products.

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

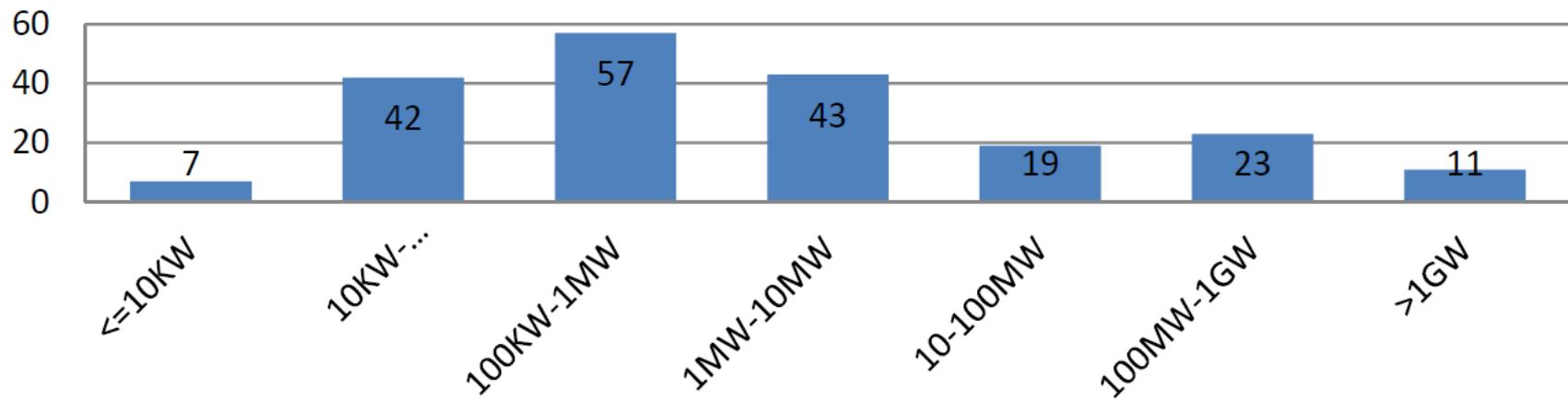
Energy Storage on the Grid Today



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

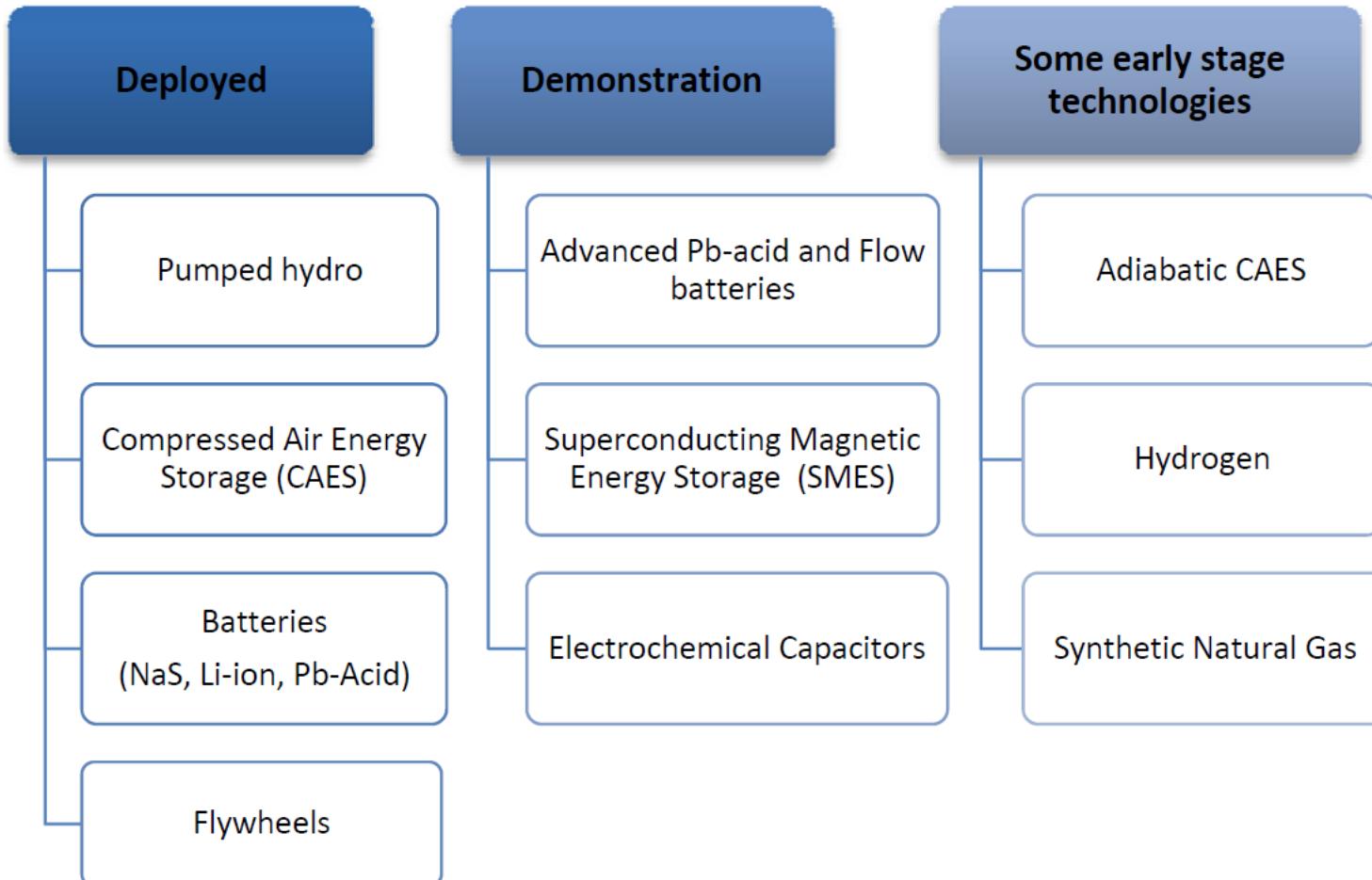
Energy Storage on the Grid Today

Installations by Rated Power (includes announced)



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

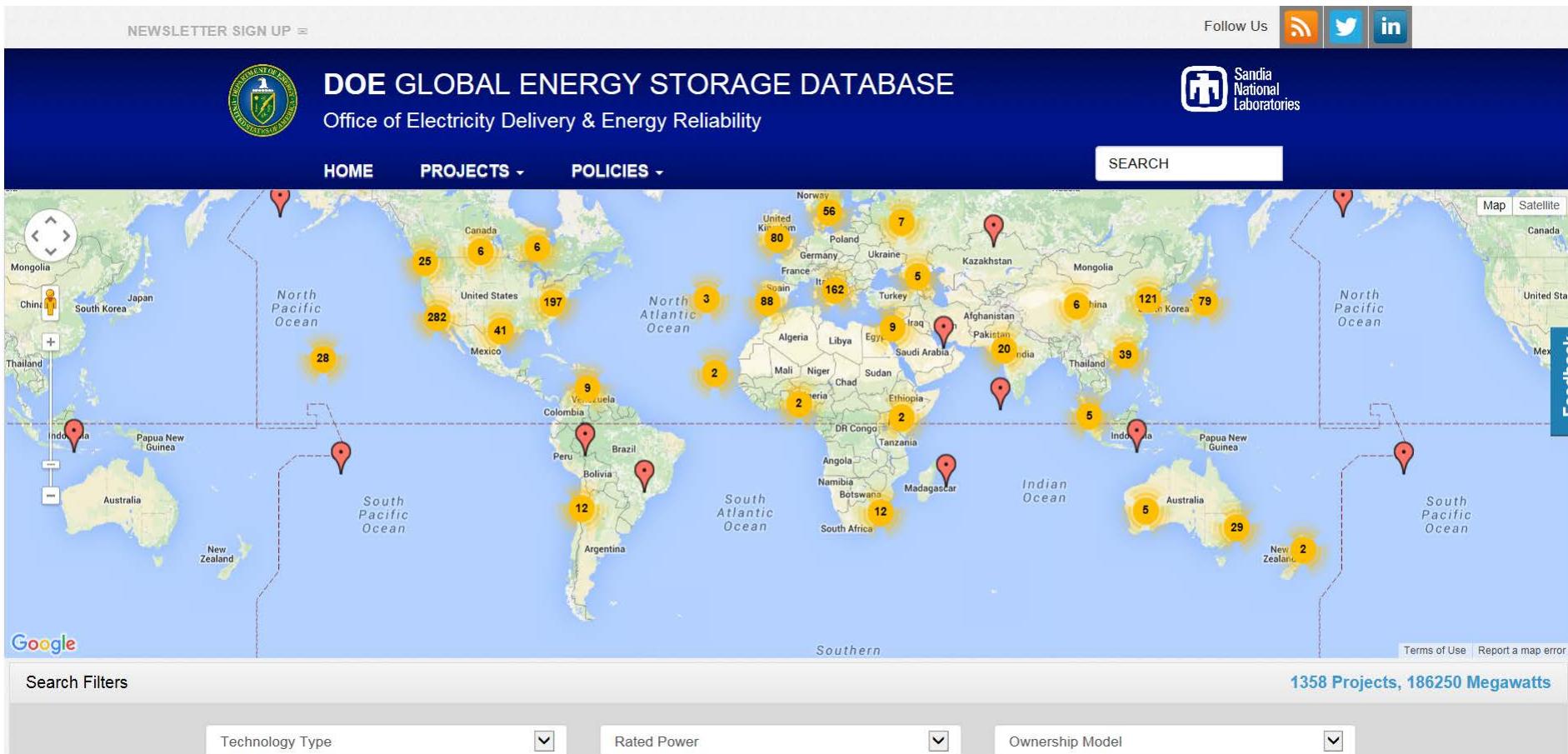
Technology Maturities



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

DOE Energy Storage Database

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

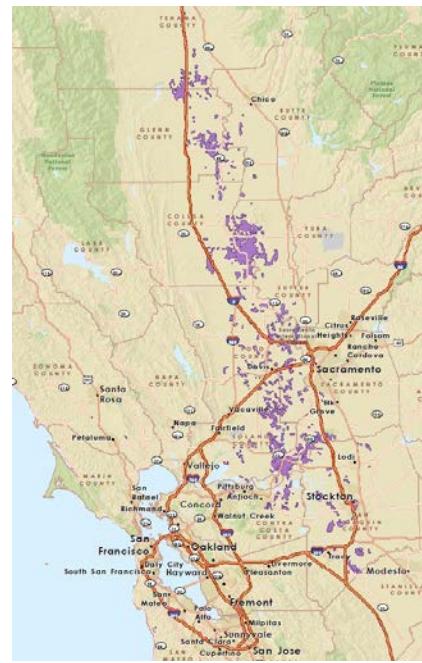


Technology Overview - CAES

- 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

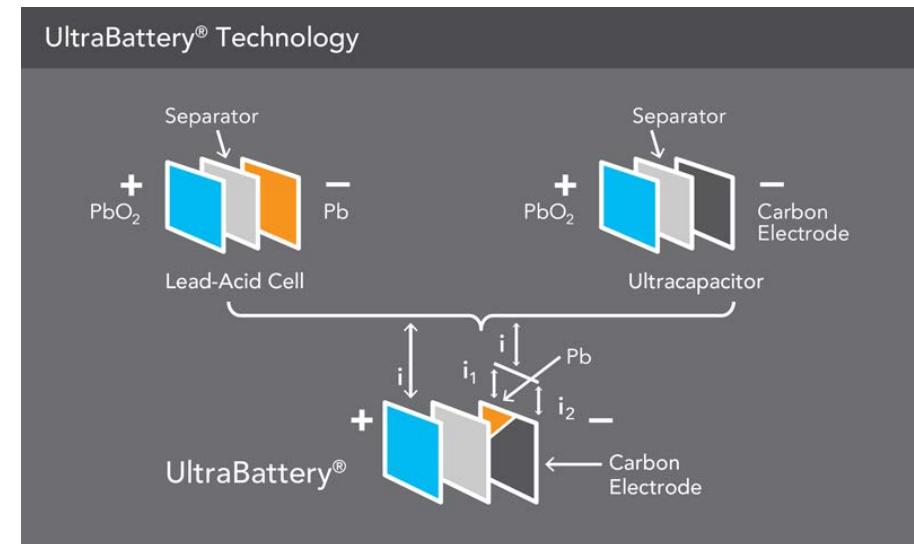
- Flywheel energy storage
 - Modular technology
 - Long cycle life
 - High peak power
 - Rapid response
 - High round trip efficiency (~85%)
- Applications
 - Load leveling
 - Frequency regulation
 - Peak shaving
 - Transient stability
- Challenges
 - Rotor tensile strength limitations ($E \approx \omega^2$)
 - 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

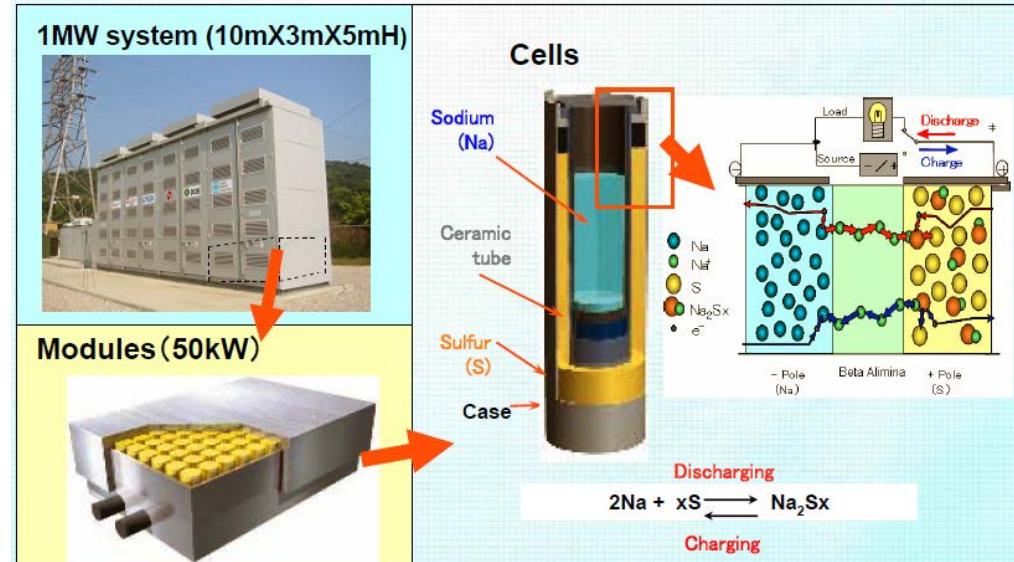
Technology Overview - NaS

- 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



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

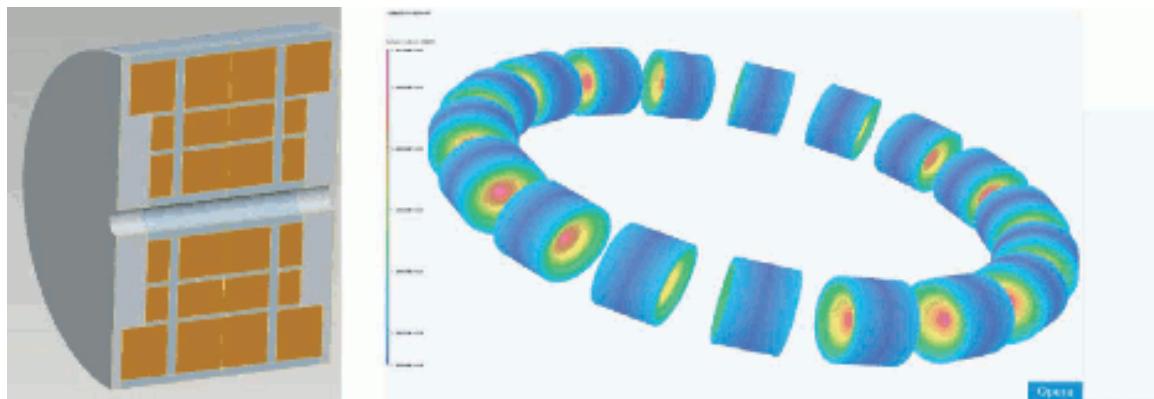


Ultra capacitor module, designed for vehicle applications (e.g., buses, trains)



Technology Overview - SMES

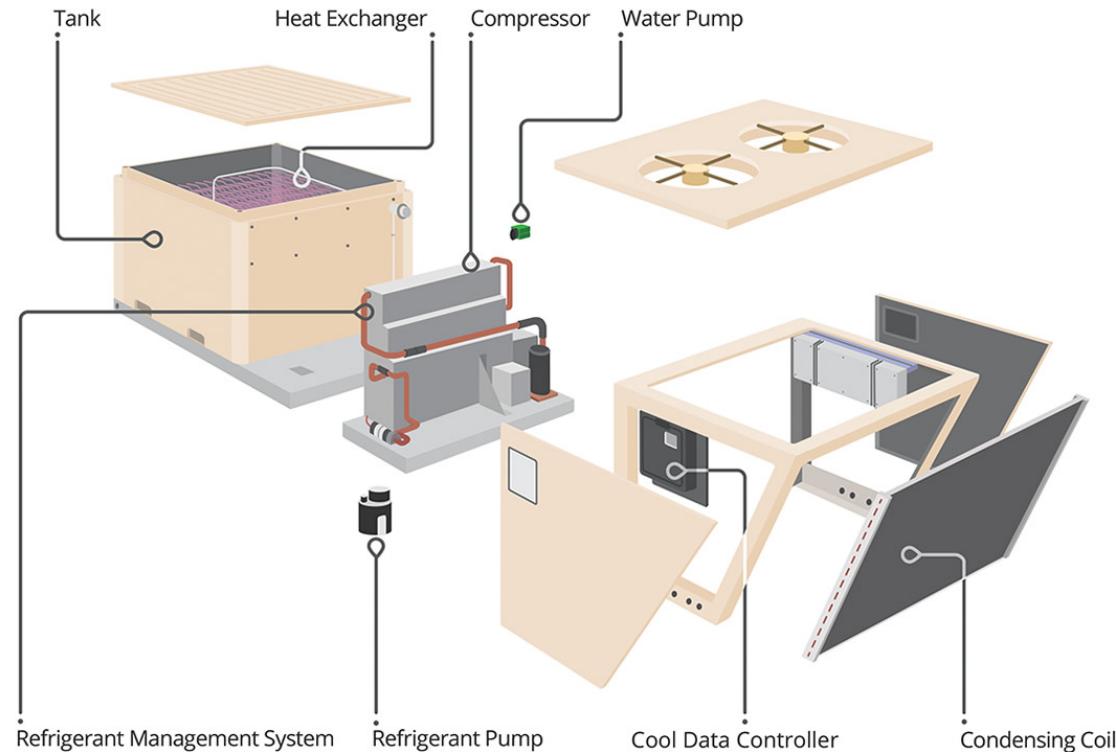
- Super Conductive Magnetic Energy Storage
 - Highest round trip efficiency (~95%)
- Applications
 - Power quality
 - Frequency regulation
- Challenges
 - Low energy density
 - Component and manufacturing cost



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

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

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

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

$$0 \leq S_t \leq \bar{S}, \quad \forall t \in T$$

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

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

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

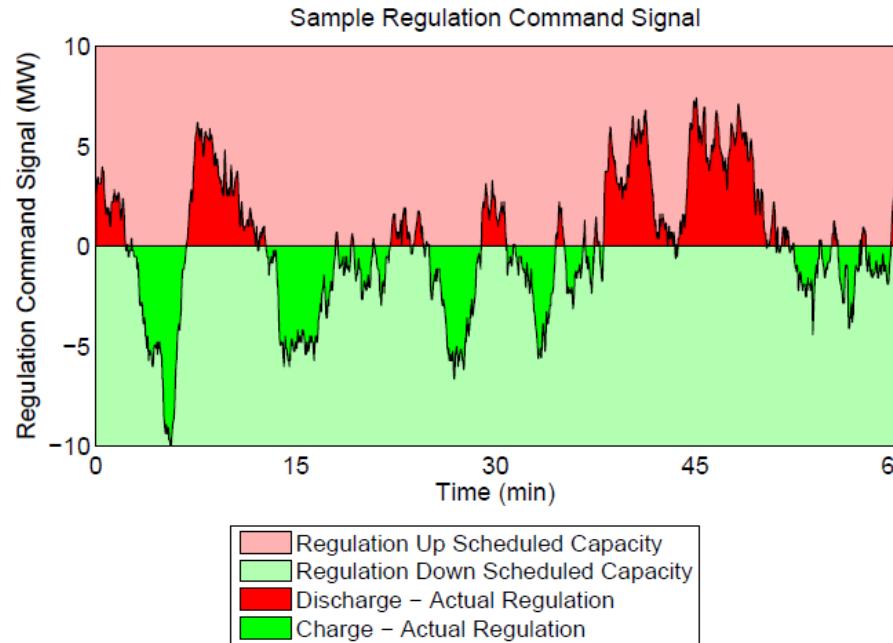
$$0 \leq S_t \leq \bar{S}, \forall t \in T$$

$$0 \leq q_t^R + q_t^{RD} \leq \bar{q}^R, \forall t \in T$$

$$0 \leq q_t^D + q_t^{RU} \leq \bar{q}^D, \forall t \in T$$

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

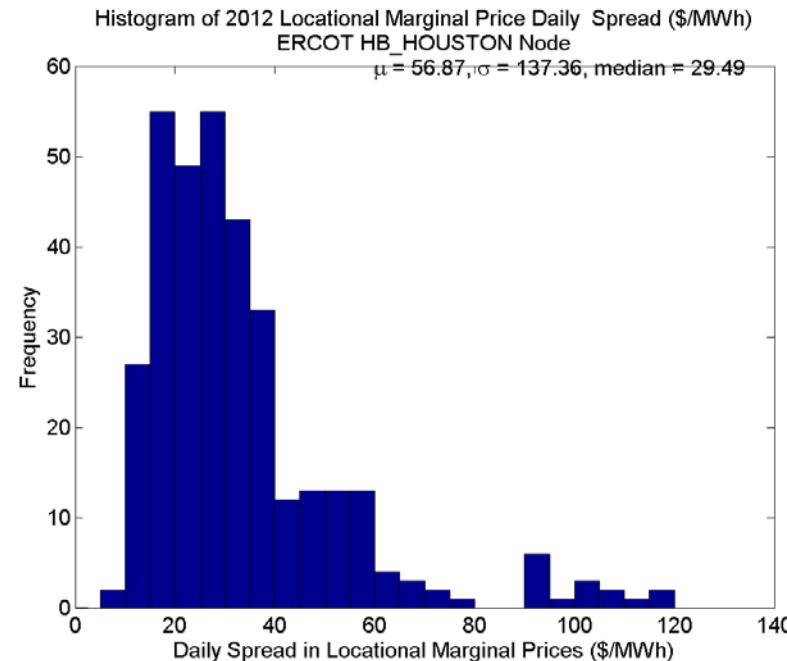
$$\max \sum_{t=1}^T [(P_t - C_d)q_t^D - (P_t + C_r)q_t^R] e^{-rt}$$

- Cost function – arbitrage + regulation

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

Maximizing Revenue – Market Area

- Studied two regions
 - CAISO [1] (included sensitivity analysis to parameters)
 - ERCOT [2]
- Plant parameters
 - 32MWh
 - 8MW
 - Efficiency 80%
 - Regulation call fraction 50%



- [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.

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



- 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

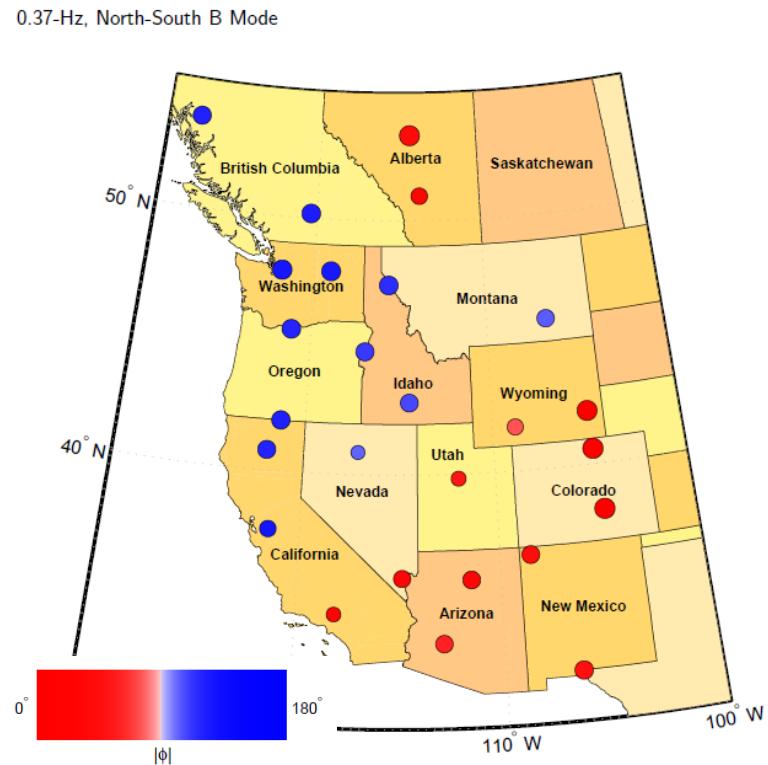
[1] J. F. Ellison, D. Bhatnagar, N. Saaman *et al.*, *NV Energy Electricity Storage Valuation*, SAND2013-4902, Sandia National Laboratories, Albuquerque, NM 87185, 2013.

[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

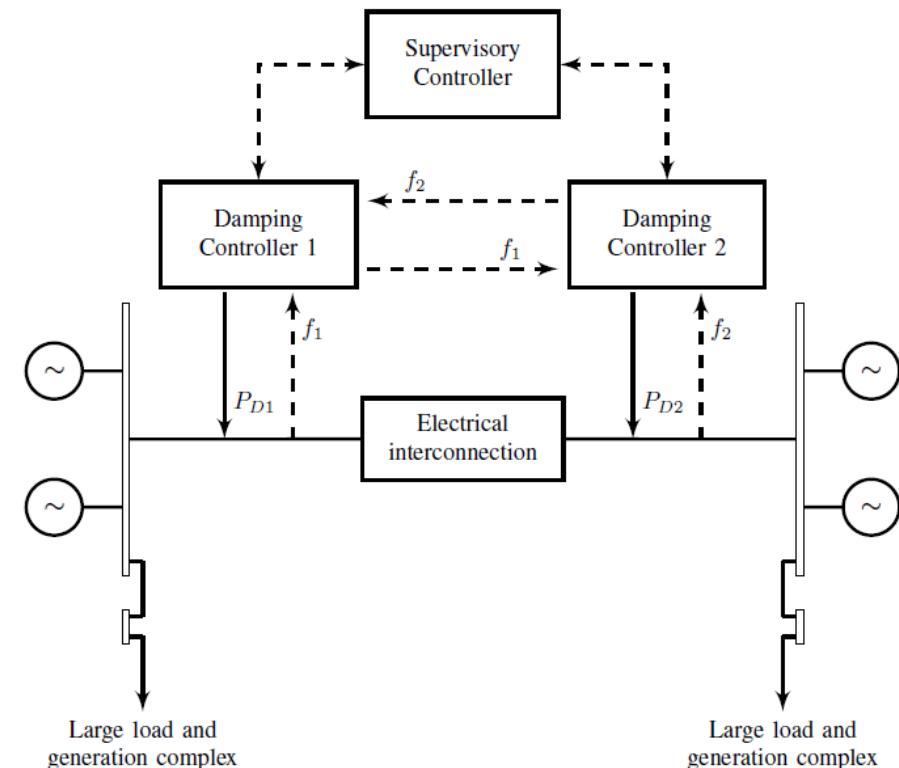
- Inter-area oscillations are present in all large power systems
- Electro-mechanical oscillations
 - 0.2-0.8Hz
 - Can be lightly damped
 - 1996 west coast blackout partially attributed to undamped inter-area oscillations



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
Brider	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 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
- Most effort is focused on the “supervisory control system”



Optimal Placement for Damping Control

- Two-area system model

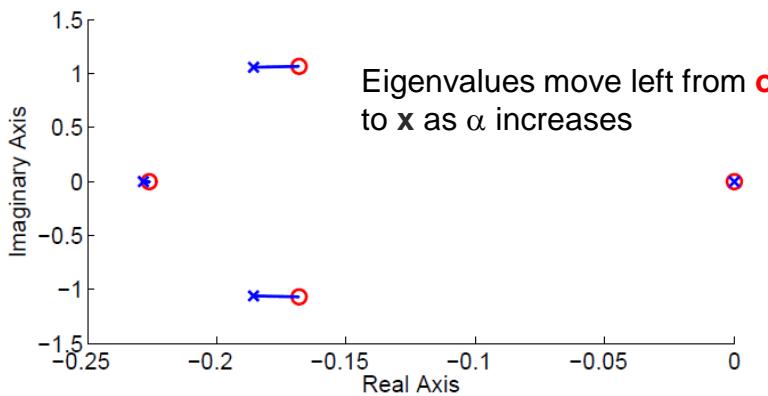
$$\Delta P_{D1} = -K\alpha(f_1(t) - f_2(t - \tau))$$

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

- 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]

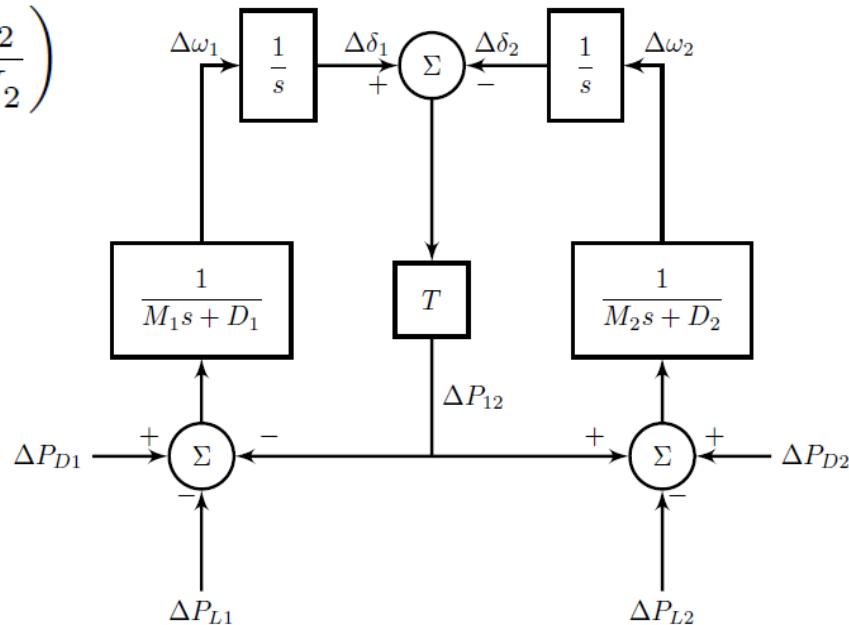


[1]

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.

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



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

Related Efforts

- Small signal stability analysis for high penetrations of renewables
- Coordination with wind/solar groups at Sandia

Summary

- The grid needs energy storage – right now there are several barriers
 - Too expensive
 - Electricity markets/utilities do not properly allocate payments/costs for services provided
 - Voltage support
 - Inertia
 - Renewable integration
 - Reliability
- The future
 - Higher energy prices – storage starts looking better
 - Lower technology costs – storage starts looking better
 - Efficient market design – helps pay for storage costs

