PNM 2020-2039 Integrated Resource Plan

NOVEMBER 19, 2019

Talk to us.

PNM.com

AGENDA

2020-2039 IRP PUBLIC ADVISORY MEETING #6: BATTERY TECHNOLOGY
GUEST PRESENTATION -- SANDIA NATIONAL LABORATORIES

- Welcome and Introductions
- Safety and Ground Rules
- Battery Technology – Sandia National Labs
- Outline of future meeting topics

SAFETY AND LOGISTICS

- In case of an emergency, please follow any broadcast instructions and exit signs.
- We are required to participate in drills, just as in the case of a real emergency.
- Restrooms: Exit door to the north and down the hall.

MEETING GROUND RULES

01

- Questions and comments are welcome – One Person Speaks at a Time

02

- Reminder; today's presentation is not PNM's plan or a financial forecast, it is an illustration of the IRP process

03

- We ask that you complete the Questions/Comments sign-up sheet in advance of requesting the microphone to pose your written question or comment. All questions will be logged
- Questions and comments should be respectful of all participants

04

- These meetings are about the 2020 IRP, questions and comments should relate to this IRP. Any questions or comments related to other regulator proceedings should be directed towards the specific filing

DISCLOSURE REGARDING FORWARD LOOKING STATEMENTS

The information provided in this presentation contains scenario planning assumptions to assist in the Integrated Resource Plan public process and should not be considered statements of the company's actual plans. Any assumptions and projections contained in the presentation are subject to a variety of risks, uncertainties and other factors, most of which are beyond the company's control, and many of which could have a significant impact on the company's ultimate conclusions and plans. For further discussion of these and other important factors, please refer to reports filed with the Securities and Exchange Commission. The reports are available online at www.pnmresources.com.

The information in this presentation is based on the best available information at the time of preparation. The company undertakes no obligation to update any forward-looking statement or statements to reflect events or circumstances that occur after the date on which such statement is made or to reflect the occurrence of unanticipated events, except to the extent the events or circumstances constitute material changes in the Integrated Resource Plan that are required to be reported to the New Mexico Public Regulation Commission (NMPRC) pursuant to Rule 17.7.4 New Mexico Administrative Code (NMAC).

BATTERY TECHNOLOGY AND ENERGY STORAGE

HOWARD PASSELL & RAY BYRNE
SANDIA NATIONAL LABORATORIES

Sandia National Laboratories

Exceptional service in the national interest

Sandia National Laboratories

Energy Storage Systems

Howard Passell, Ph.D.

Sandia National Laboratories

PNM Public Advisory Board 19 November 2019

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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SNL Outreach to Regulators

Sandia is funded by the Energy Storage Programs Office in the DOE Office of Electricity to provide outreach to regulatory commissions around the U.S.

In collaboration with PNNL and other institutions . . .

Hawaii PUC, Dec. 7, 2018, Honolulu: ES Introductory Workshop

California Energy Commission (CEC), June 14, 2019, Sacramento: Energy Storage Academy

Southeastern PUCs – **Alabama**, **Arkansas**, **Florida**, **Georgia**, **Kentucky**, **Maryland**, **New Jersey**, **North Carolina**, **Virginia**, July 17-18, Birmingham: Second Southeast Energy Storage Symposium and PUC Workshop (with Southern Research)

Nevada, New Jersey, Texas, and Iowa PUC workshops are being planned

New Mexico PRC workshops are underway

The “energy transition” is happening now

If you were in a shipwreck and a piano top came floating by, you might climb up on top of it and use it as a life preserver. But if you were in the business of designing life preservers, you probably would not make one in the shape of a piano top.

Buckminster Fuller, Operating Manual for Spaceship Earth, 1969

Climate crisis

Declining costs for renewables

Public Health

Geopolitics

Ecosystem Health

Energy dynamics are fundamentally different

- Demand is flat or declining -- little demand for new generation
- “Decarbonization” and “electrification” are on the rise
- Coal is no longer king
- PV + storage is supplanting old and new gas peakers
- 100-years of one-way electricity flow is a thing of the past
- 10% EV penetration will shift demand to nighttime*
- Wholesale and retail markets are shifting

The job of regulatory commissions is way more complicated than it has ever been.

*https://www.utilitydive.com/news/with-10-penetration-evs-could-shift-all-residential-peak-load-to-night-a/565207/

Energy storage (ES) is fundamentally different

Energy storage . . .

- Is both a load and a generation source
- Provides alternative to “locational marginal price”
- Facilitates demand management
- Unleashes the power of renewables
- Provides flexibility, resilience, and reliability
- Provides various services and value streams

Energy Storage Terminology

- **Watt** (W) – 1 Joule/second (~4 Joules = 1 calorie, the energy required to raise 1 gm of water 1^{o} C)
- **kW, MW, TW** – a measure of maximum generation capacity -- **POWER**
- **kWh, MWh, TWh** – a measure of capacity * time – **ENERGY**
    - A 40 MW, 4 hr battery = 160 MWh
    - A 40 MW, 40 MWh battery = 40MW for an hour, 20 MW for 2 hours, etc. (nominal)
- **Cycles** – the number of times a storage device can be charged and discharged
- **Depth of discharge** – the depth to which discharge occurs relative to capacity
- **Energy density** -- ratio of energy from a battery to battery mass
- **Round trip efficiency** -- refers to energy losses that occur (or don't) in each cycle of the device (for batteries ~approx. 70-80% is good . . .)
- **Real power** – power that does work
- **Reactive power** (VARs – volt-ampere reactive power) – power that maintains voltage in transmission systems; power absorbed (and generated) by generators and capacitors in the grid; https://business.directenergy.com/blog/2016/may/reactive-power)

Levelized cost of energy – total energy produced over the lifetime of the project divided by the total cost over the lifetime

Grid scale ES market is growing fast, and expected to grow faster

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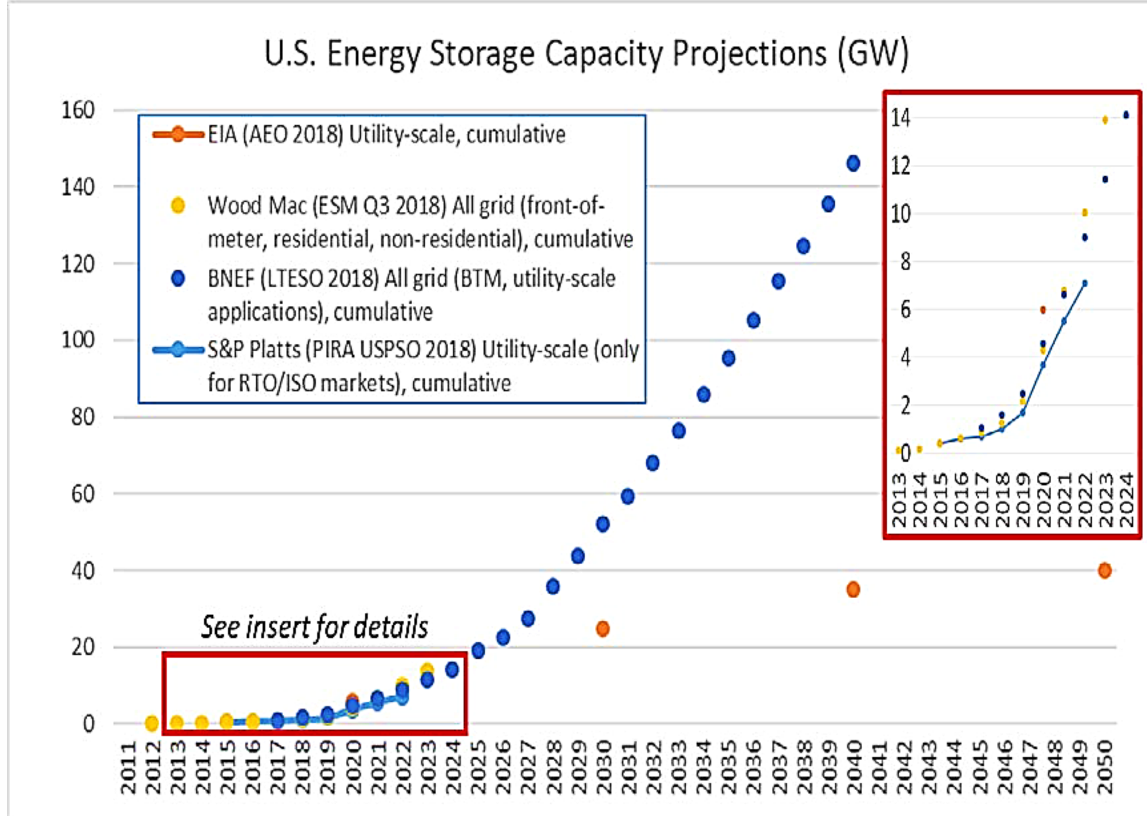
2018

- 310 MW / 777 MWh new storage deployments in US

Market Penetration

- Grid-scale battery storage still < 0.1% of U.S. generation capacity
- EV's < 1% of vehicles sold in US

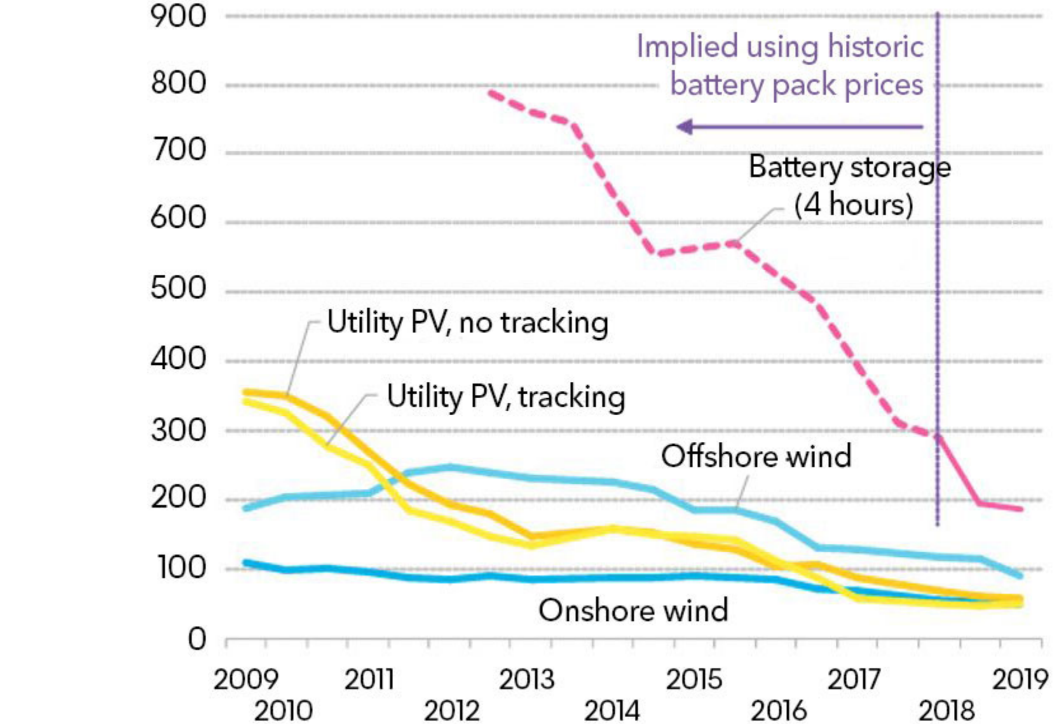


Wood Mackenzie P&R / ESA | U.S. energy storage monitor 2018 YIR and Q132

"2019 Q3 residential installations by Tesla represent a 99% growth over Q3 in 2018 . . ."

PV Magazine, 10/24/19

Declining costs. . .



Source: BloombergNEF. Note: The global benchmark is a country weighed-average using the latest annual capacity additions. The storage LCOE is reflective of a utility-scale Li-ion battery storage system running at a daily cycle and includes charging costs assumed to be 60% of whole sale base power price in each country.

"Batteries co-located with solar or wind projects are starting to compete, in many markets and without subsidy, with coal- and gas-fired generation for the provision of 'dispatchable power' that can be delivered whenever the grid needs it (as opposed to only when the wind is blowing, or the sun is shining)."

Bloomberg New Energy Frontiers

https://about.bnef.com/blog/battery-powers-latest-plunge-costs-threatens-coal-gas/

Residential PV, -55%
Utility Scale PV, -71%
Wind, -75%
EV Batteries, -79%

http://energyfreedomco.org/f4-costs.php

Battery costs are dropping fast

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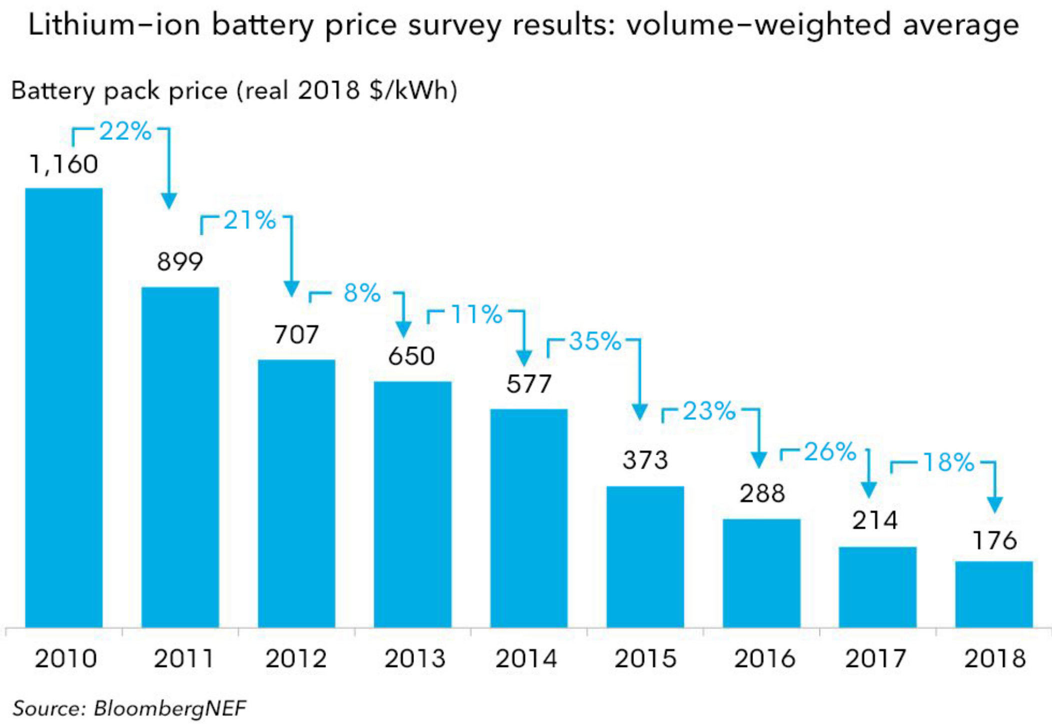
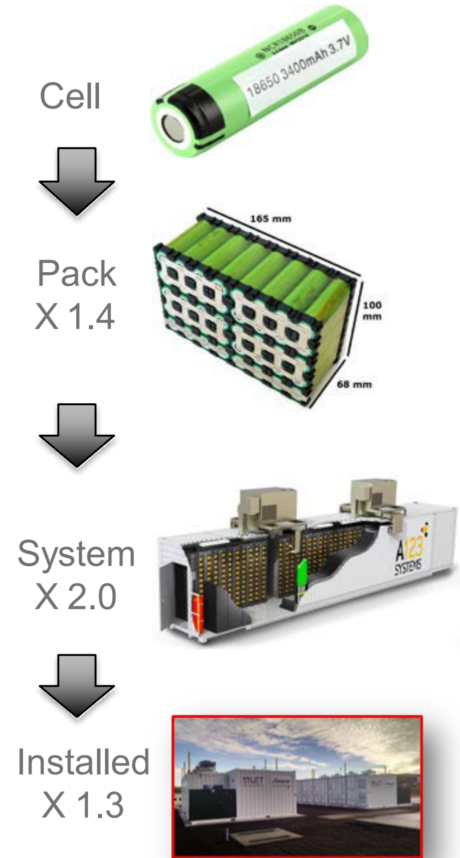


https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

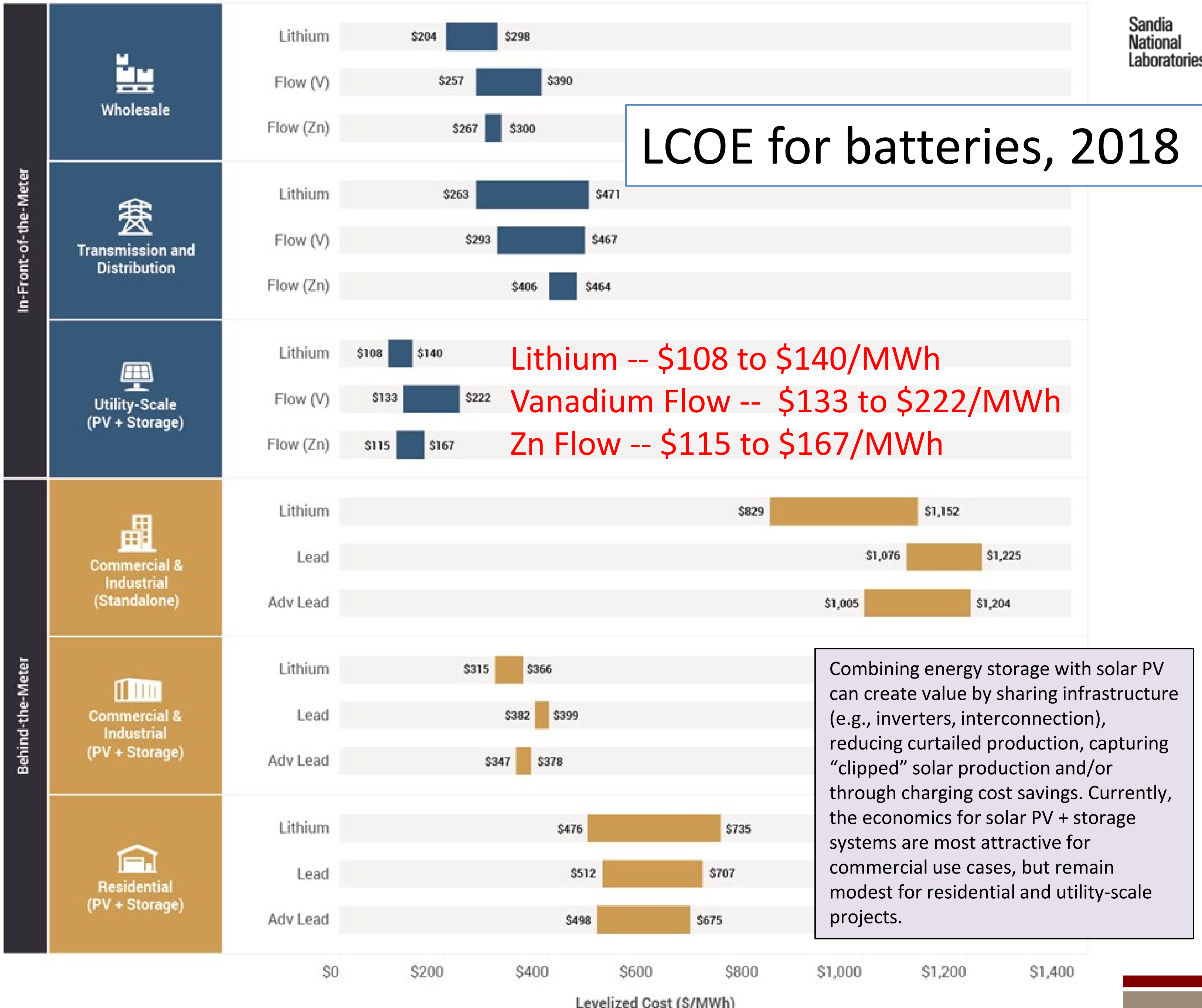


13 kWh Tesla Powerwall now sells for about $481/kWh

$200/kWh cell → $~1000/kWh system

Big savings now are not in the cells, but in the systems . . .

LCOE for batteries, 2018



Lithium -- $108 to $140/MWh
Vanadium Flow -- $133 to $222/MWh
Zn Flow -- $115 to $167/MWh

Combining energy storage with solar PV can create value by sharing infrastructure (e.g., inverters, interconnection), reducing curtailed production, capturing "clipped" solar production and/or through charging cost savings. Currently, the economics for solar PV + storage systems are most attractive for commercial use cases, but remain modest for residential and utility-scale projects.

https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/

LCOE for alternative and conventional energy

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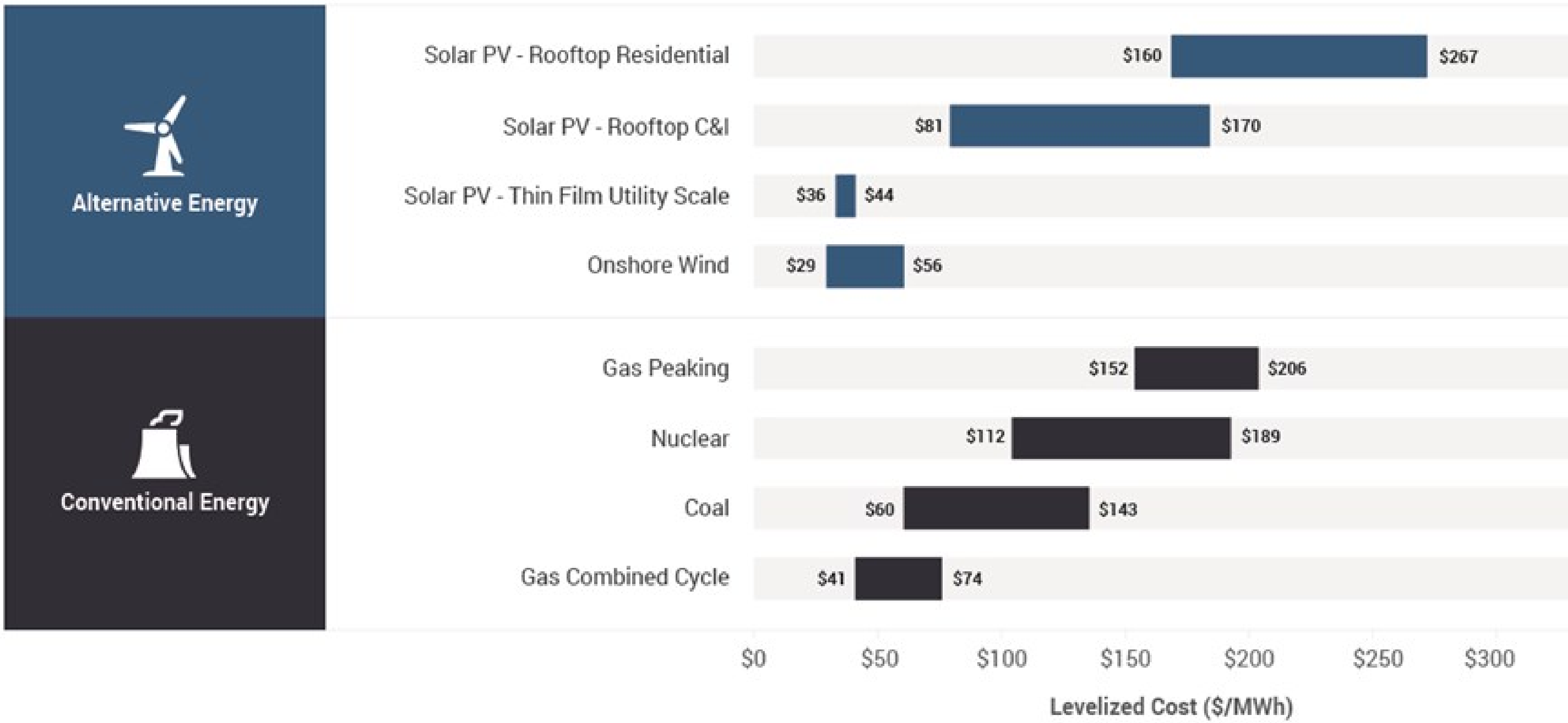
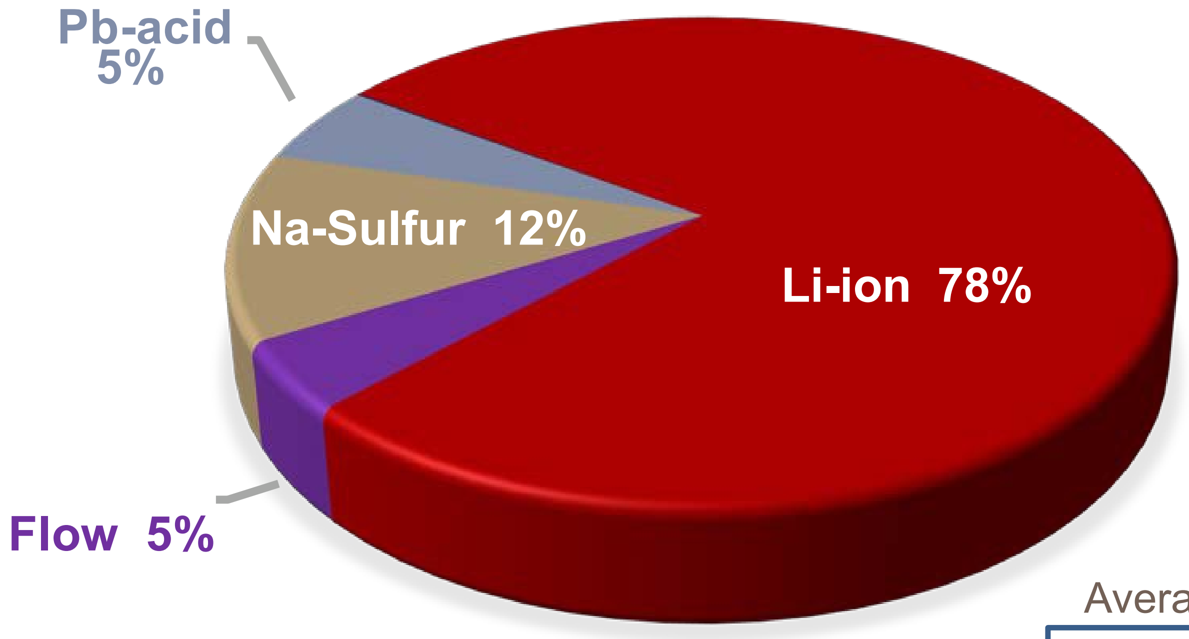


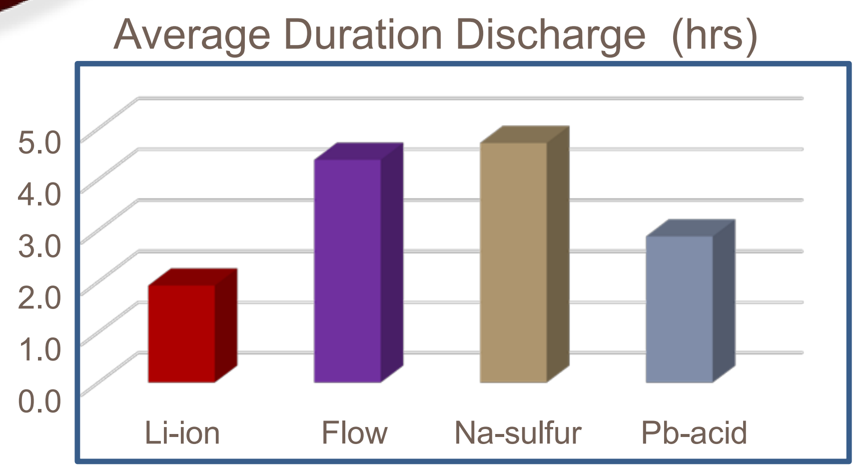
Remember, PV + Storage . . .

Lithium -- $108 to $140/MWh
Vanadium Flow -- $133 to $222/MWh
Zn Flow -- $115 to $167/MWh

https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/

Battery energy storage deployments



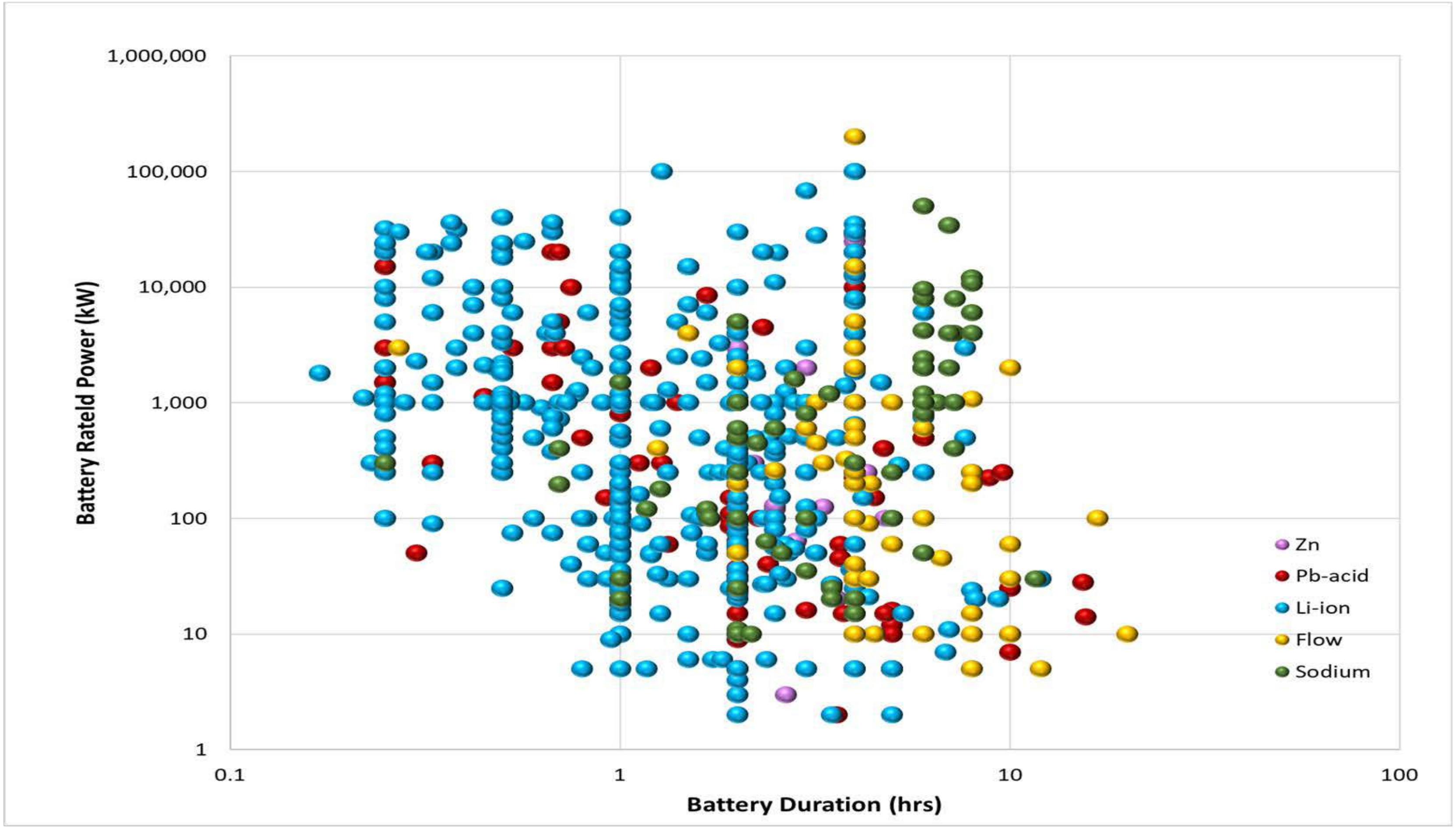


**Operational as of Nov. 2017 – being updated for 2018*

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

Mapping of Grid Scale Battery Energy Storage System (BESSs)Deployments

Sandia National Laboratories



Source: US DoE Energy Storage Database, March 2019, https://www.energystorageexchange.org/

Based on Shell International Exploration & Production (US) Inc.; analysis presented by Shell 11 March 2019, ARPA-e DAYS

US grid battery storage > 1 GW

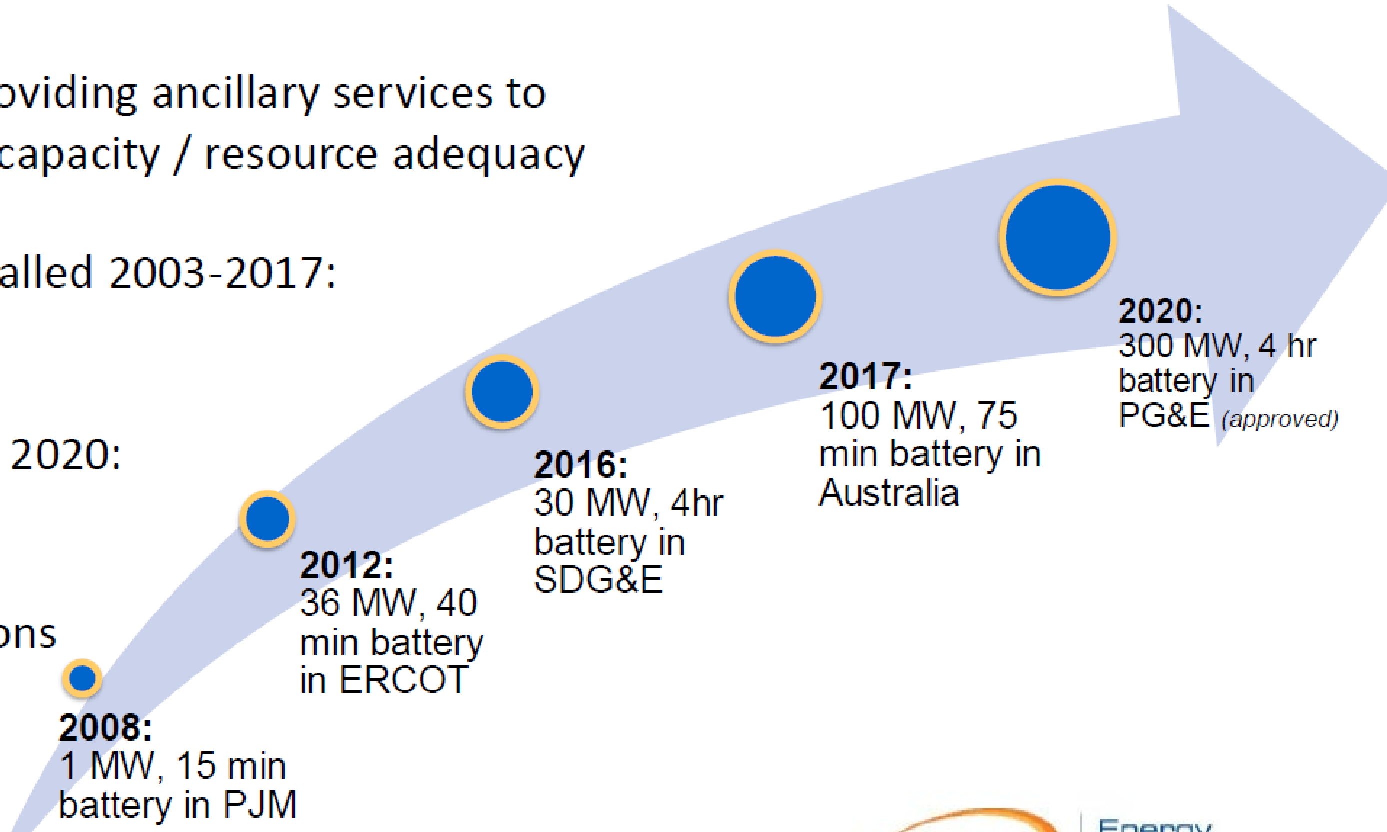
As costs go down, size and duration go up

Shift from primarily providing ancillary services to increasingly providing capacity / resource adequacy

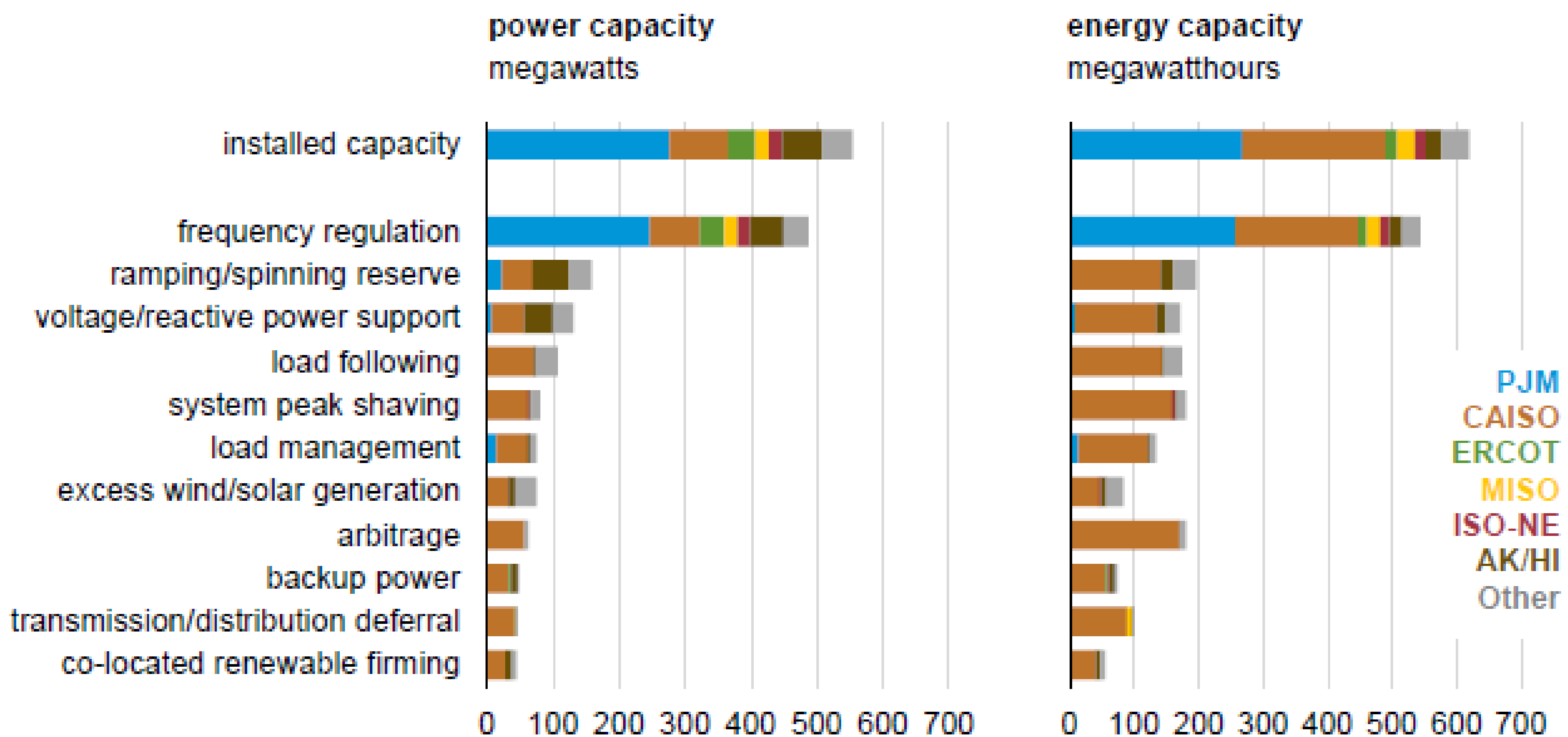
All battery storage installed 2003-2017:
800 MW / 1200 MWh

Single PG&E battery in 2020:
300 MW / 1200 MWh

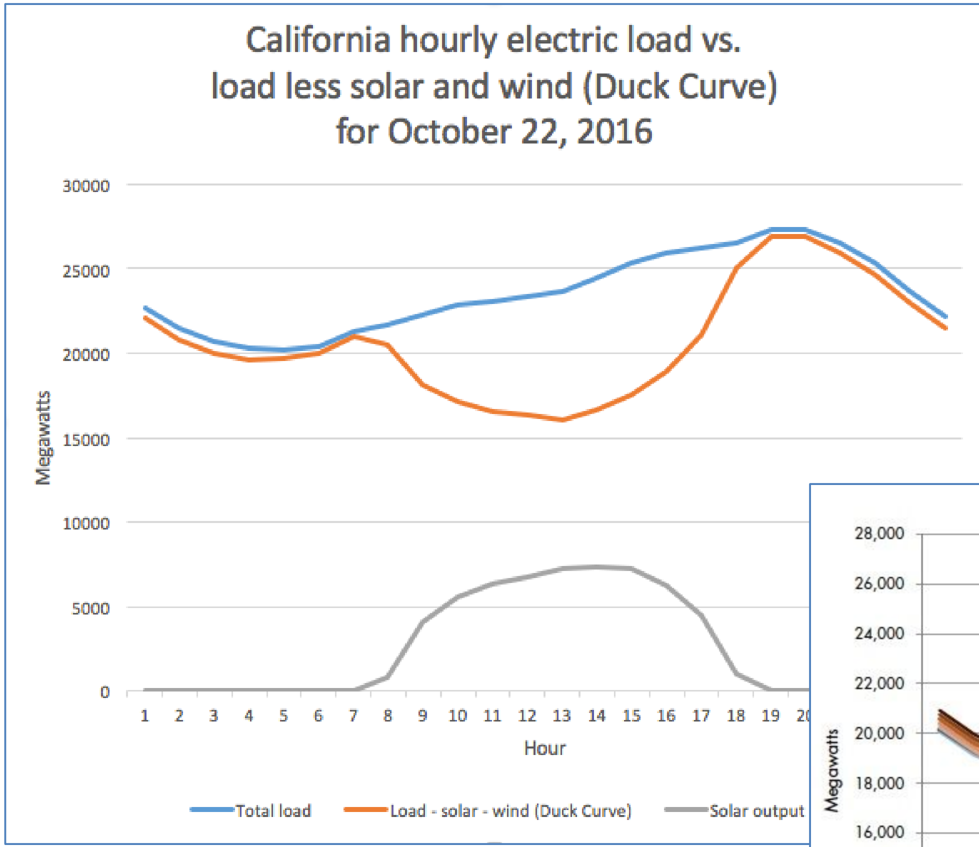
DER storage aggregations to follow (largest today ~20 MW)



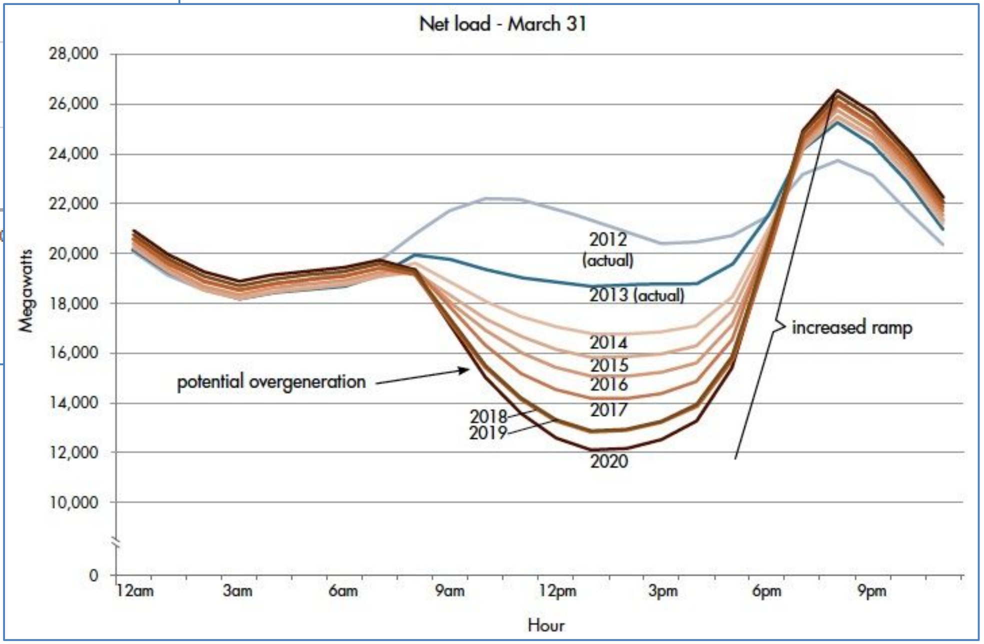
Applications served by U.S. Large Scale BESSs (2016)



The California Duck Curve

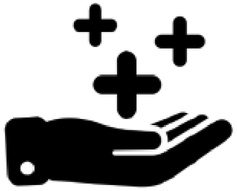


http://www.caiso.com/market/Pages/ReportsBulletins/DailyRenewablesWatch.aspx



https://www.greentechmedia.com/articles/read/californias-duck-curve-will-encourage-innovation#gs.OaaSnKE

Barriers to deployment



Cannot VALUE or compensate storage flexibility

Solutions

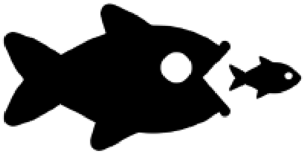
Deployment targets

Incentive programs

Tariff/rate design

Wholesale market products

Cost-benefit studies



Unable to COMPETE in all grid planning and procurements

Solutions

Long-term resource planning

Distribution planning

Transmission planning

GHG/renewables standards

Wholesale market rules

Resource adequacy rules

Cannot ACCESS grid or constrained to narrow use

Solutions

Interconnection processes

Multiple-use frameworks

Ownership rules

Energy Storage Association

NM Energy Transition Act

- 100% Carbon-Free Electricity by 2045
  - Senate Bill 489, Energy Transition Act, passed 44-22 on 03/12/2019
    - Provides process to close coal plants and provide economic relief and job training
    - Provides job training in renewables
    - Creates new Renewable Portfolio Standards
- Renewable Portfolio Standards in NM
  - 20% by 2020
  - 50% by 2030
  - 100% by 2045 (Co-ops by 2050)
- In December 2018 New Mexico Electricity was *produced* by the following sources: (http://bber.unm.edu/energy)
  - 48% coal, 33% natural gas, 19% renewable
- NM joins 8 other states, 141 cities, 11 counties with 100% goals
  - Hawaii, CA, Wash DC, Puerto Rico, Washington, Maine, NY, Nevada

How do we get there?

Optimal PV, wind, and ES capacity requirement for PNM to meet 100% carbon free goal

	Now	Needed[4]
Energy Storage	3.75 MW[1] (0.00375 GW)	5 GW/25 GWh
Solar PV	818 MW[2] (0.818 GW)	10 GW
Wind	1,953 MW[3] (1.953 GW)	5 GW

[1] Global Energy Storage Database 2019; [2] Solar Energy Industries Association 2019

[3] American Wind Energy Assoc. 2019; [4] Copp et al., in press

Optimal Sizing of Distributed Energy Resources for 100% Renewable Planning

David A. Copp[a,*], Tu A. Nguyen[a], Robb Thomson[b], Raymond H. Byrne[a], Babu R. Chalamala[a]

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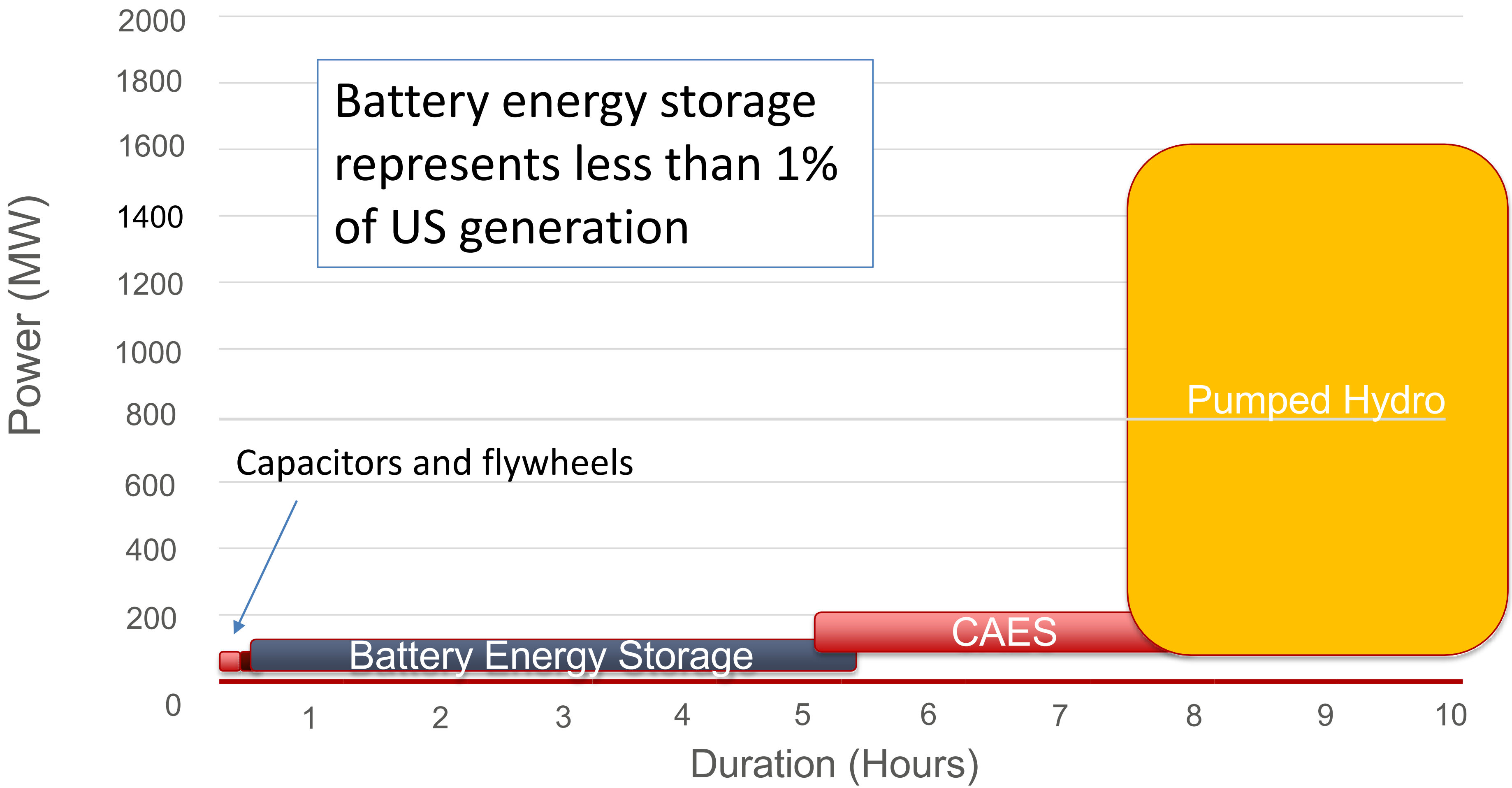
[b] *Retired Fellow, NIST, Gaithersburg, MD; Current address, 250 E Alameda Apt 523, Santa Fe, NM 87501, USA*

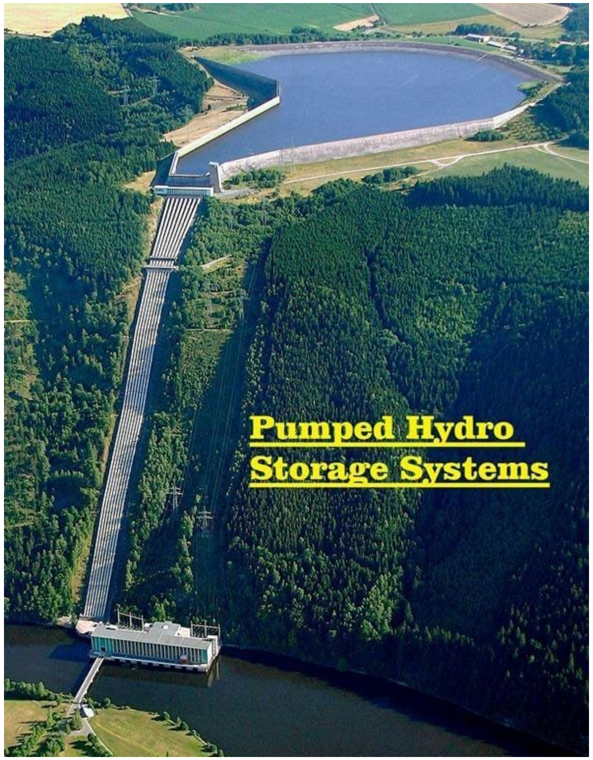
Electromechanical, Capacitor, Thermal, and Gravitational Technologies

Energy Storage Technologies



Pumped Hydro

- Characteristics
  - Large global and US capacity, but difficult to site new projects in the US
  - High energy capacity (4h – 22h)
  - High power capacity (GWs)
  - Slower response (seconds to minutes)
  - Very mature technology
  - Long Life (20+ years)
  - High initial costs
- Broad applications and services

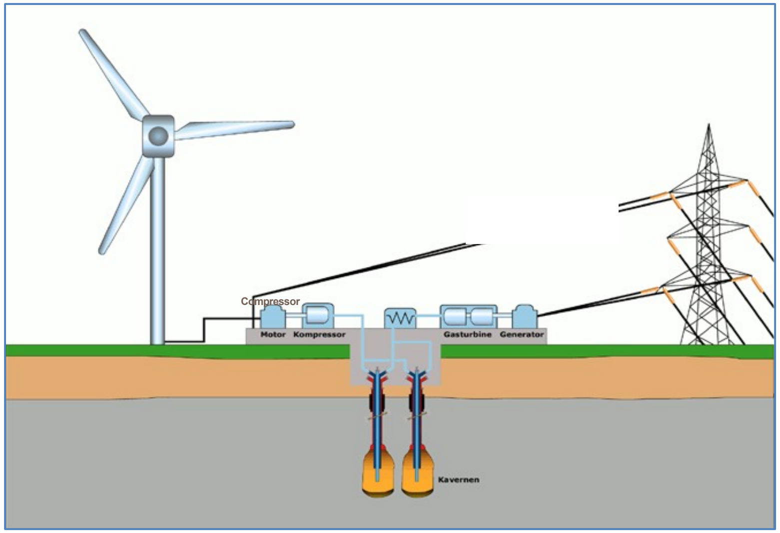


https://www.windpowerengineering.com/pumped-hydro-storage-market-to-surpass-350-billion-by-2024/

Compressed Air (CAES)

Sandia National Laboratories

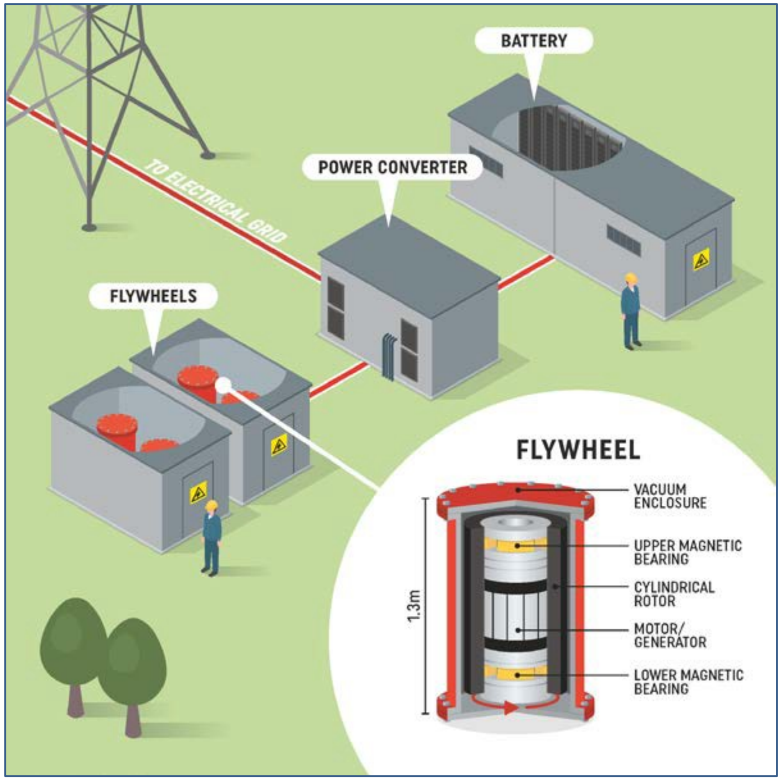
- Characteristics
  - High energy capacity (2h – 30h)
  - High power capacity (100s MW)
  - Long life (20 - 30 years)
  - Slower response (seconds)
  - Must be sited above geological repository (e.g., deep salt caverns)
  - Initial costs are high
- Broad applications



https://www.uigmbh.de/images/referenzen/CAES_animiert.gif

Flywheels

- Characteristics
  - High power capacity (kW to MW per flywheel)
  - High cycle life (millions)
  - Very fast response (milliseconds)
  - Short term storage
- Limited applications
  - Frequency and voltage regulation, transient stability, stopping and starting electric trains



Courtesy of The University of Sheffield

Super Capacitor

Sandia National Laboratories

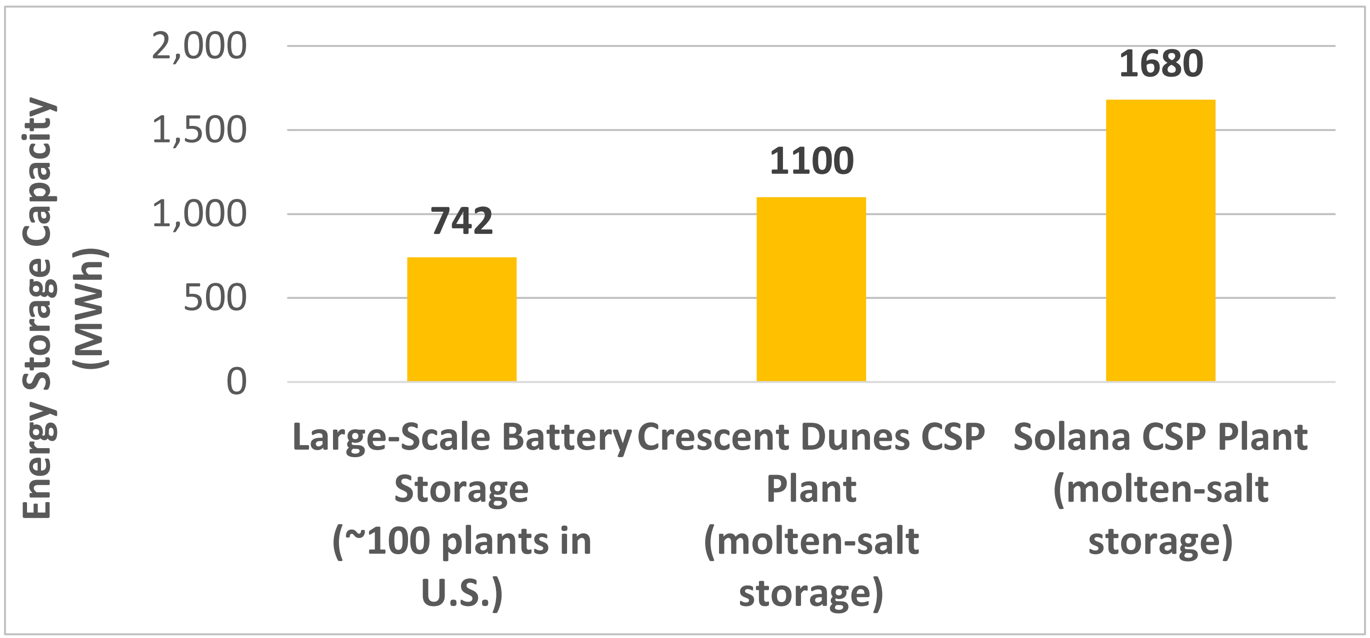
- Characteristics
  - Very long life
  - Fast discharge (milliseconds)
  - High round trip efficiency
  - High cost

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

- Limited applications
  - Power quality, frequency regulation, regenerative braking in vehicles

Concentrated Solar Power and Thermal Energy Storage

- Mirrors concentrate the sun's energy onto a receiver to provide heat to spin a turbine/generator and produce electricity
- **Hot fluid can be stored as thermal energy efficiently and inexpensively** for on-demand electricity production when the sun is not shining



Battery data from USEIA, 2018

CSP data from Cliff Ho, Sandia National Labs

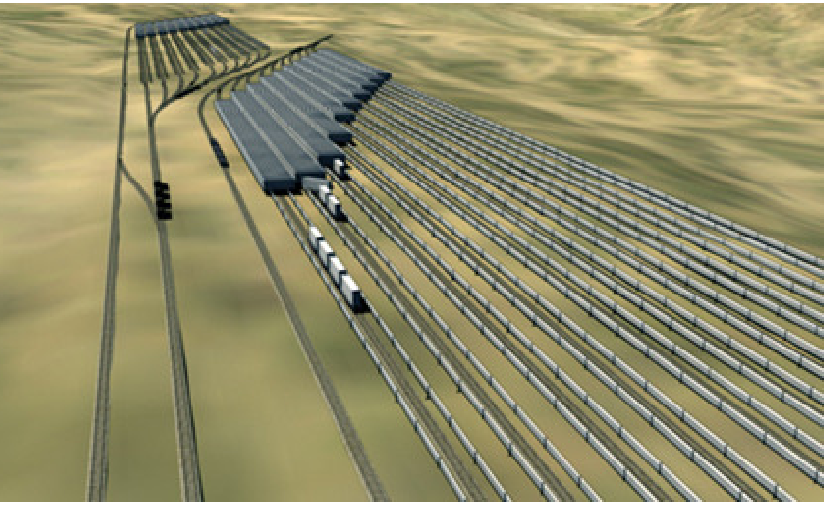
Gravity energy storage

- Long duration storage
- High capital costs
- Long cycle life (??)
  - High maintenance costs

Vault Energy Storage

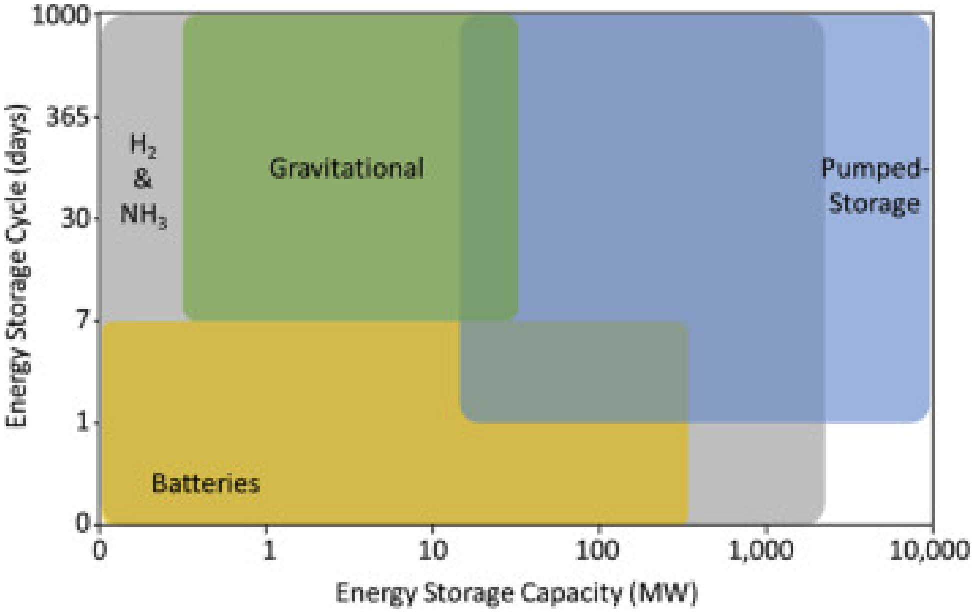
Energy Vault

Rail Energy Storage



https://www.aresnorthamerica.com/grid-scale-energy-storage

Mountain Gravity Energy Storage



Hunt et al., Energy, https://doi.org/10.1016/j.energy.2019.116419

Battery Technologies

How a battery works

- Redox (reduction – oxidation) chemistry drives all biological metabolism

$CO_2 + H_2O \xrightarrow{\text{Sunlight}} CH_2O + O_2$

(Oxidized carbon) → (Reduced carbon)

Electrons move from oxygen to carbon

$CH_2O + O_2 \xrightarrow{\text{Enzymes}} CO_2 + H_2O + \text{energy}$

(Reduced carbon) → (Oxidized carbon)

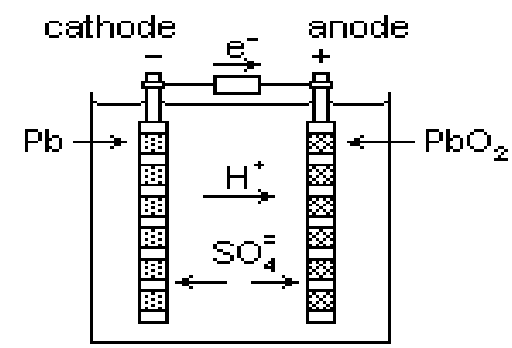
Electrons move from carbon to oxygen

- The same redox chemistry drives battery power

$Pb(s) + PbO_2(s) + 2H_2SO_4(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l)$ • OCV ~ 2.0 V

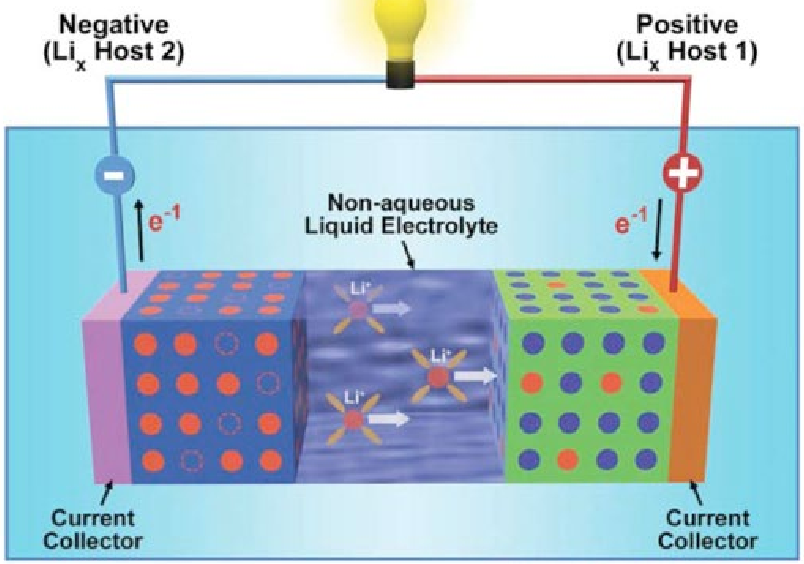
Reduced lead in the presence of oxidized lead, and in a sulfuric acid electrolyte, results in lead sulfate and water, and electrons move with a force of 2 V.

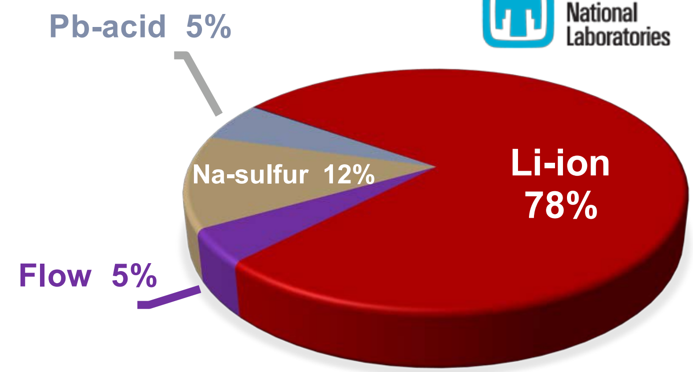
Oxidation is defined as removal of electrons from an atom leading to an increase in its positive charge, and reduction as addition of electrons resulting in a decrease (reduction) in positive charge.



Lead Acid Cell

Li-ion Batteries





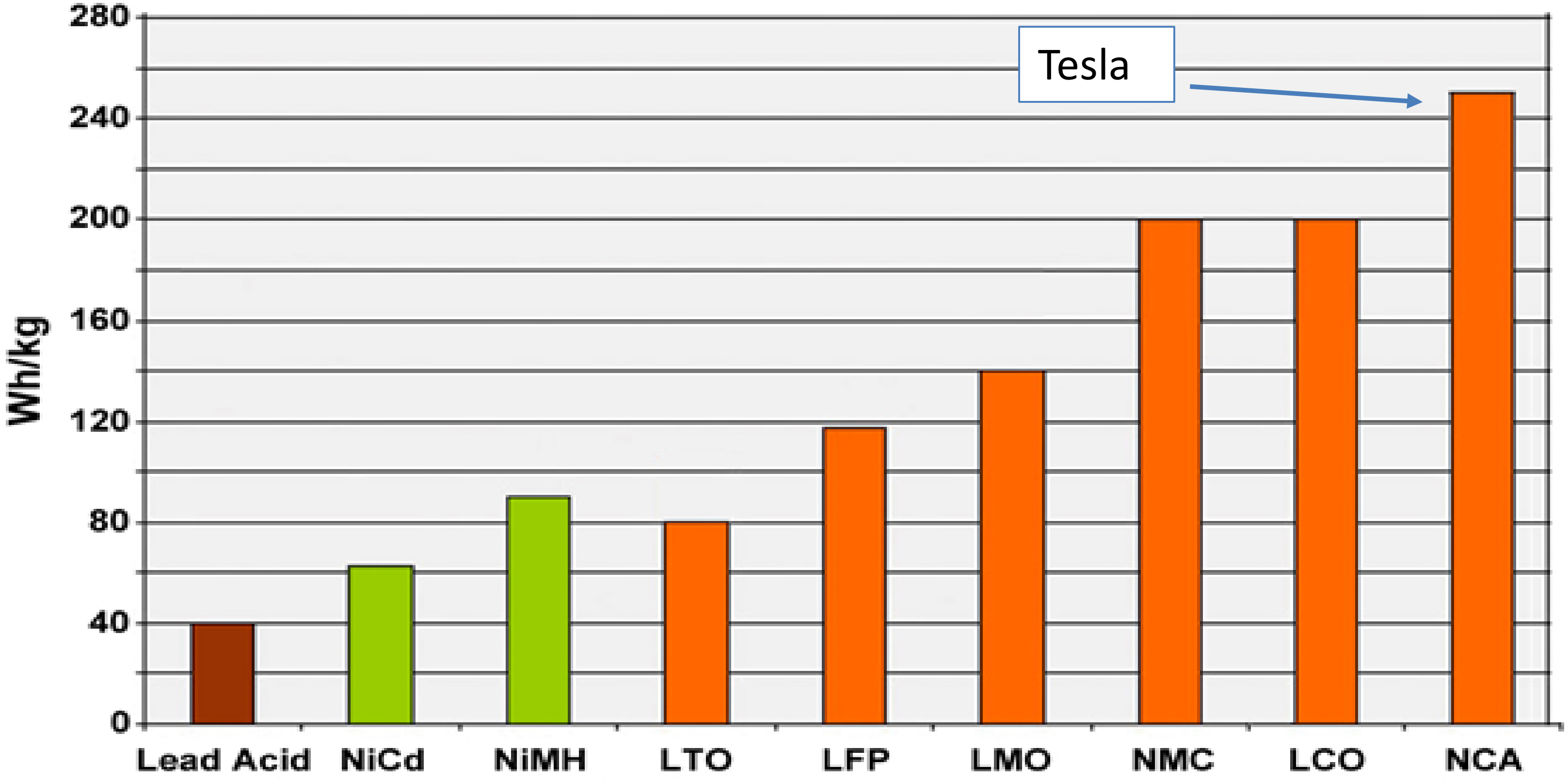
Chemistries	
$LiCoO2$	iphone
$LiNiO_2$	
$LiNi_xCo_yMn_zO_2$	Volt
$LiNi_xCo_yAl_zO_2$	Tesla
$LiMn_2O_4$	
$LiMn_{1.5}Ni_{0.5}O_4$	
$LiFePO_4$	
$LiMnPO_4$	
$LiNiPO_4$	
$LiCoPO_4$	

Cathode: $$Li_{1-x}CoO_2 + xLi^+ + xe^- \xrightarrow{discharge} LiCoO_2$$

Anode: $$Li_xC_6 \xrightarrow{discharge} xLi^+ + xe^- + C_6$$

Z. Yang JOM September 2010, Volume 62, Issue 9, pp 14-23

Li-ion chemistry energy density



Li-Al Oxide (NCA) enjoys the highest specific energy; however, Li-Mn Oxide (NMC) and Li-phosphate (LFP) are superior in terms of specific power and thermal stability. Li-titanate, LTO) has the best life span.

Li-Ion Batteries

- High energy density
- Better cycle life than Lead-Acid
  - 5000-10,000 cycles at 100% DOD
- Decreasing costs
  - Stationary follows on coattails of EV battery development
- Ubiquitous – multiple vendors
- Fast response (milliseconds)
- Broad applications
- High efficiency (85-90%)
- Safety continues to be a significant concern
- Recycling is not available yet
- Uses non-domestic rare earth metals

SCE/Tesla 20MW - 80MWh Mira Loma Battery Facility

SCE Tehachapi Plant, 8MW—32MWh

Tesla and the 18650 Li-ion cell

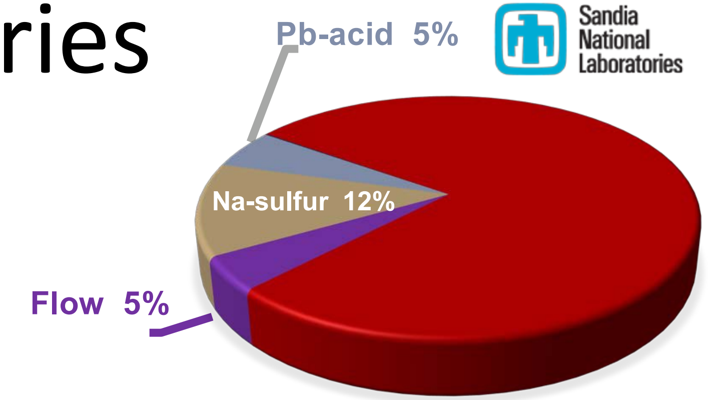
Tesla Model S Battery Pack

7104 cells

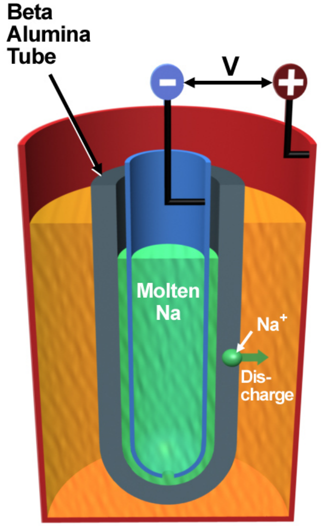
18650 cell format used in 85 kWh Tesla battery

An ESS like the 20 mW – 80 mWh Mira Loma System would require 6.7 million of the 18650 cells

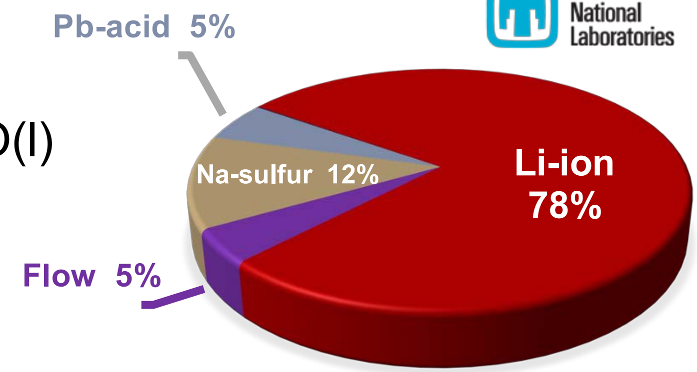
Sodium (Na) -- Sulfur Batteries



- High energy density
- Life cycles
  - 2500 at 100% DOD
  - 4500 at 80% DOD
- Fast response (milliseconds)
- 85% round trip efficiencies
- Must be kept hot!
  - 300 - 350° C
  - Stand by losses are high, battery has to keep running or be heated up
- Longer term -- 4-6 hours
- Broad applications
- Low production volumes prevent economies of scale



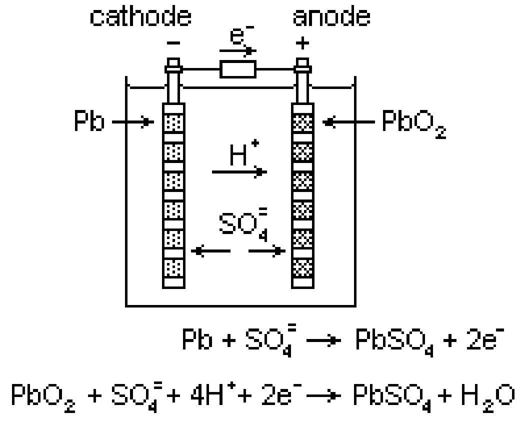
Lead Acid Batteries



$Pb(s) + PbO_2(s) + 2H2SO_4(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l)$

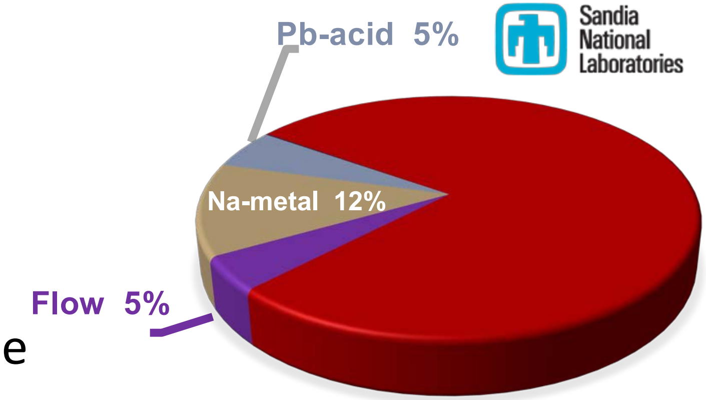
Characteristics

- The most common batteries worldwide
- Limited life time (5~15 yrs)
- Limited cycle life (500~1000 cycles)
- Degradation w/ deep discharge (>50% DOD)
- Low energy density (30-50 Wh/kg)
- Overcharging leads to H_2 evolution
- Sulfation occurs with prolonged storage
- Recyclable
- Less expensive the Li-ion
- New lead-carbon systems ("advanced lead acid") can exceed 5,000 cycles

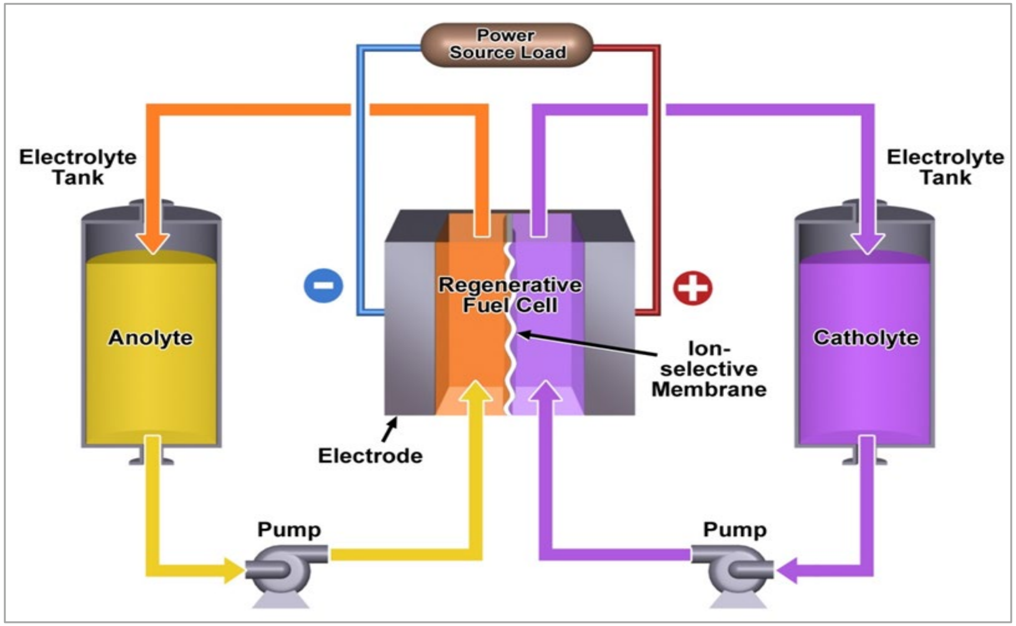


Lead-Acid Storage Cell

Flow Batteries



- Wide range of chemistries available
  - Vanadium, zinc bromine, iron chromium
- Flexible -- increase volume of tanks to increase energy (no new racks, no new controllers)
- Suitable for wide range of applications, 5 kW to 10s MW
- Potential long cycle life (tens of thousands) and high duration (10 hours)*
- Low energy density
- Lower round trip energy efficiency (50-70%)
- More expensive than Li-ion
- Safer than Li-ion
- Still nascent technology



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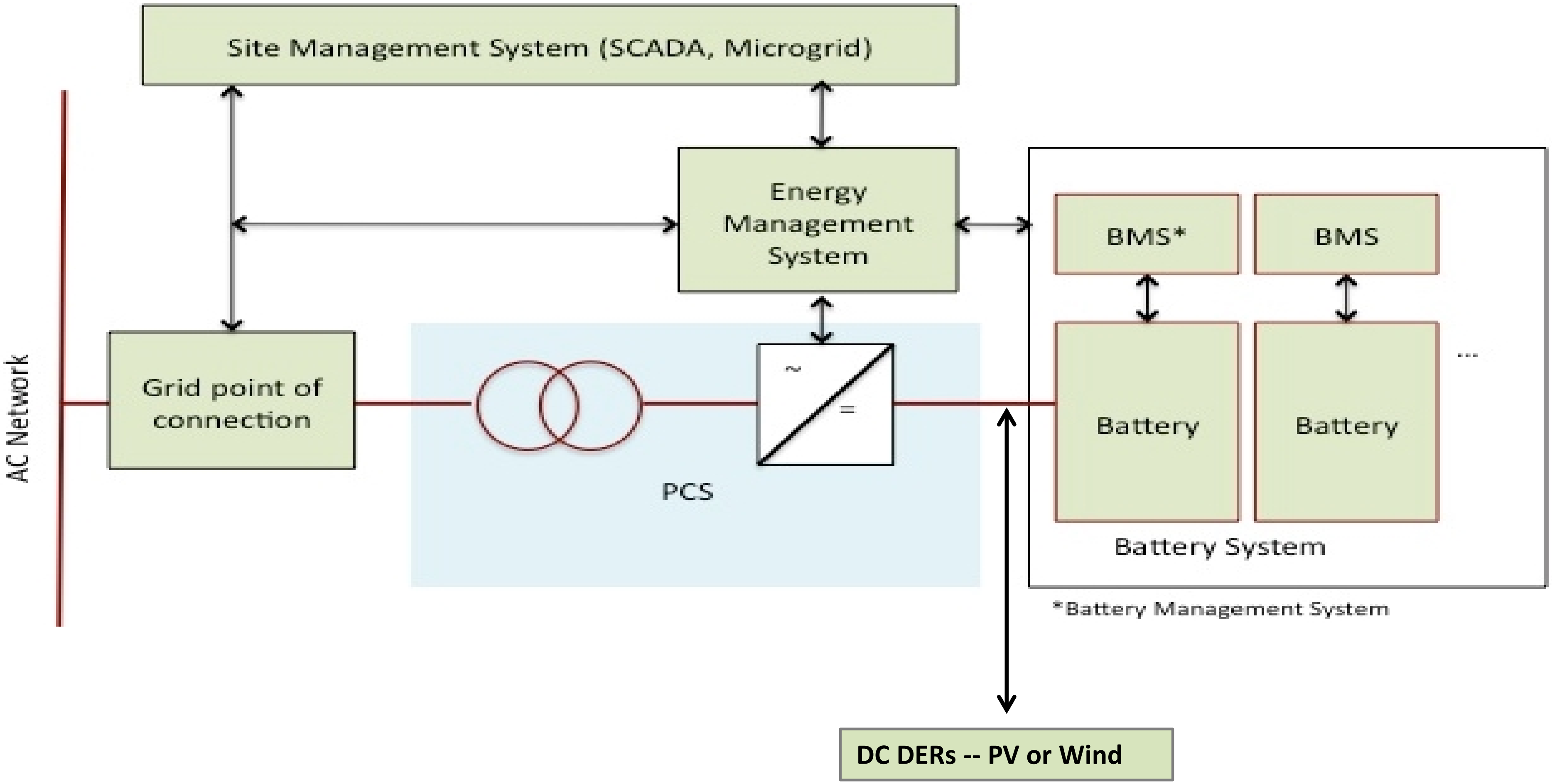
$Zn\text{-}MnO_2$ alkaline batteries

- Traditionally primary batteries, and ubiquitous
- Lowest bill of materials costs and manufacturing capital expenses
- Established supply chain for high volume
- Readily be produced in larger form factors for grid applications
- No temperature limitations of Li-ion or Pb-acid
- Environmentally benign -- EPA certified for landfill disposal
- Projected delivered costs at $50/kWh
- Reversibility has been challenging
- Cycle life must be improved

URBAN ELECTRIC POWER

Battery Energy Storage Systems (BESSs)

BESS topology



BESS elements

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Battery Storage

- Batteries
- Racks

Battery Management System (BMS)

- Mgmt. of the battery
  - --Efficiency
  - --Depth of Discharge (DOD)
  - --Cycle life

Power Conversion System (PCS)

- DC to AC, AC to DC
  - ---Bi-directional Inverter
  - --Transformer, switchgear

Energy Management System (EMS)

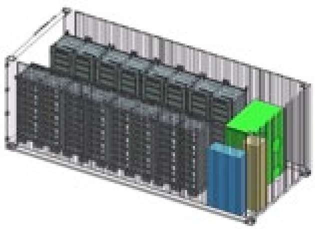
- Optimal monitoring and dispatch for different purposes
  - --Charge/discharge
  - --Load management
  - --Ramp rate control
  - --Ancillary services
- Coordinates multiple systems

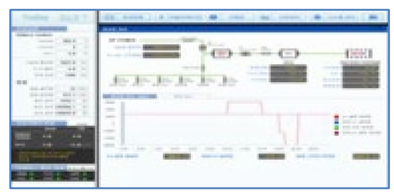
Site Management System (SMS)

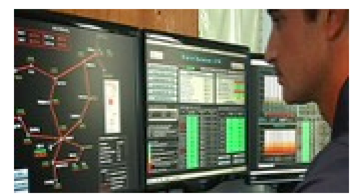
- Distributed Energy Resources (DER) control
- Synchronization with grid
- Islanding and microgrid control
- Interconnection with grid

Balance of Plant

- Housing
- HVAC
- Wiring
- Climate control
- Fire protection
- Permits
- Personnel



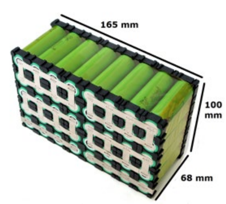




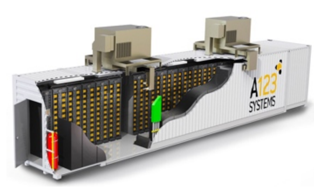
NOTE: Important to have single entity responsible for the ESS integration.

Whole system installation can increase costs by 2-5x over cost of a cell.

Cell



Pack -- X 1.4



Management Systems -- X 2.0

Balance of Plant – X 1.3

Commissioning

Factory Witness Test — In the factory -- testing of components. Often all components are not in the same factory

Operational Acceptance Test — In the field – testing components one by one as you put it together

Start-up

Functional Acceptance Test — Sequence of operation and app testing – getting baseline info on capacity, efficiency, temps . . .

Shakedown — Do all safety features work when they are supposed to?

> "It never works out of the box."
>
> Dan Borneo, SNL BESS Projects Manager

BESS Safety

Development of Inherently Safe Cells

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

Safety Devices and Systems

- Current interrupt devices
  - digital or mechanical
- Battery management system
  - Enforces limits on voltage, state of charge, and temperature

Effective Response to Off-Normal Events

- Suppressants
- Containment
- Advanced monitoring and controls

Policy, Codes, and Standards

- Testing and documenting
- Siting
- Interconnection

Yet other topics

- Design of BESSs will vary depending on intended uses
- Impact of electric vehicles on the grid
- Economics
  - Energy Storage Applications & Revenue Streams
  - Stacking benefits
- Policy
  - ES landscape for states in the US
  - Policy issues
  - Developing an ES policy roadmap

Many resources are available

Sandia National Laboratories

DOE Energy Storage Systems Program
https://www.sandia.gov/ess-ssl/

DOE Global Energy Storage Database
https://www.energystorageexchange.org/

Clean Energy States Alliance (CESA)
https://www.CESA.org

Energy Storage Technology Advancement Partnership
https://www.cesa.org/projects/energy-storage-technology-advancement-partnership/

The Energy Transition Show
https://xenetwork.org/ets/

Energy Storage Association
https://energystorage.org/

Utility Dive
https://www.utilitydive.com/

Summary points

- Battery technology is improving, spreading, getting cheaper, getting safer, and is expected to boom
- MUCH more battery capacity is required to meet 100% carbon free goals in NM and across the country
- Li-ion overwhelms the market, but many other chemistries are in development
- Batteries can provide important services to the grid
- Batteries can provide many of value streams, but many of those values are hard to quantify, and markets for most don't exist
- PV + batteries is already outcompeting new and existing gas peaker plants

Acknowledgements

This work was supported by management and staff in the Sandia National Labs Energy Storage Systems Program,

and by

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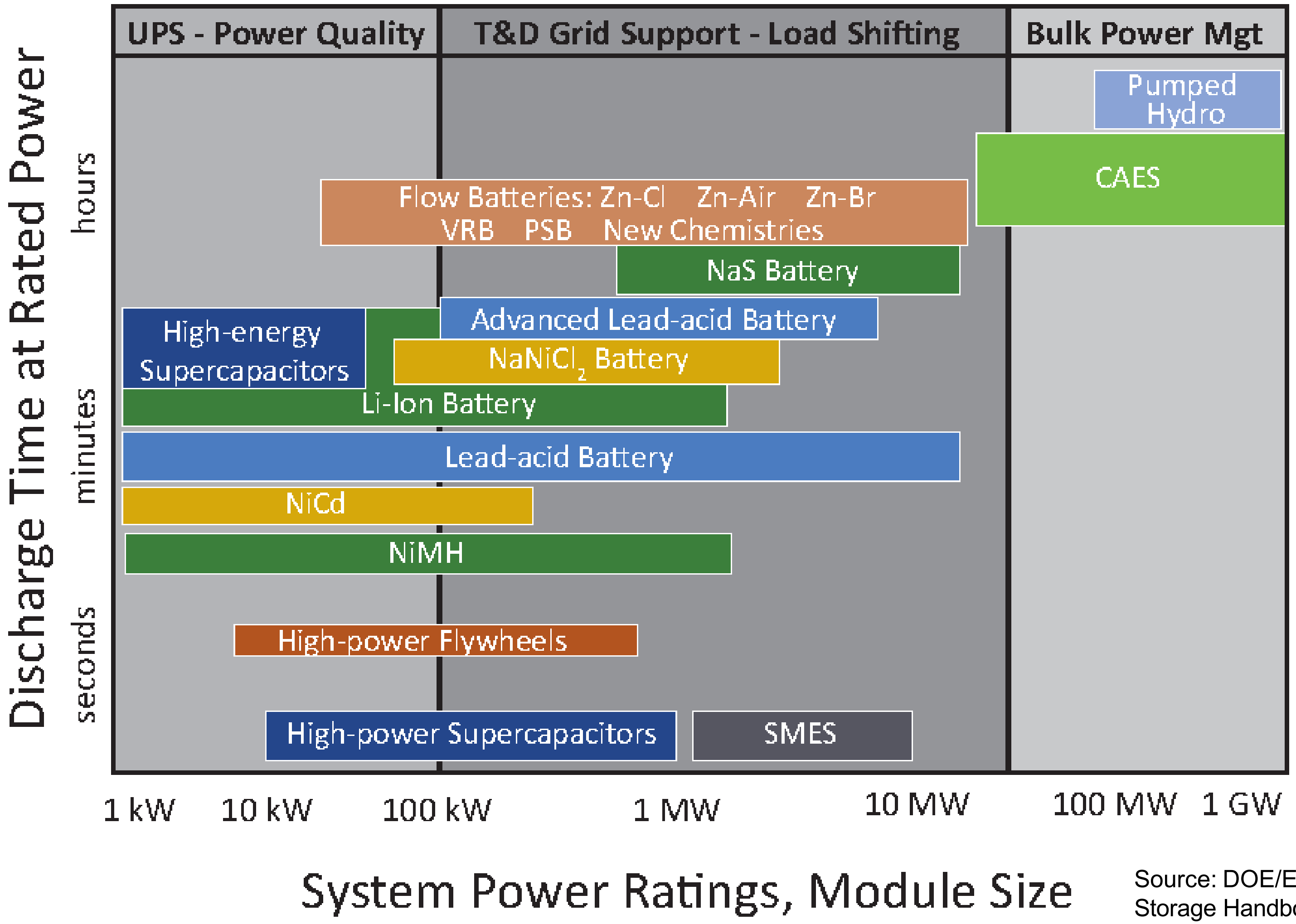
Howard Passell – hdpasse@sandia.gov – 505 284-6469

Additional Slides

ESS services and value streams

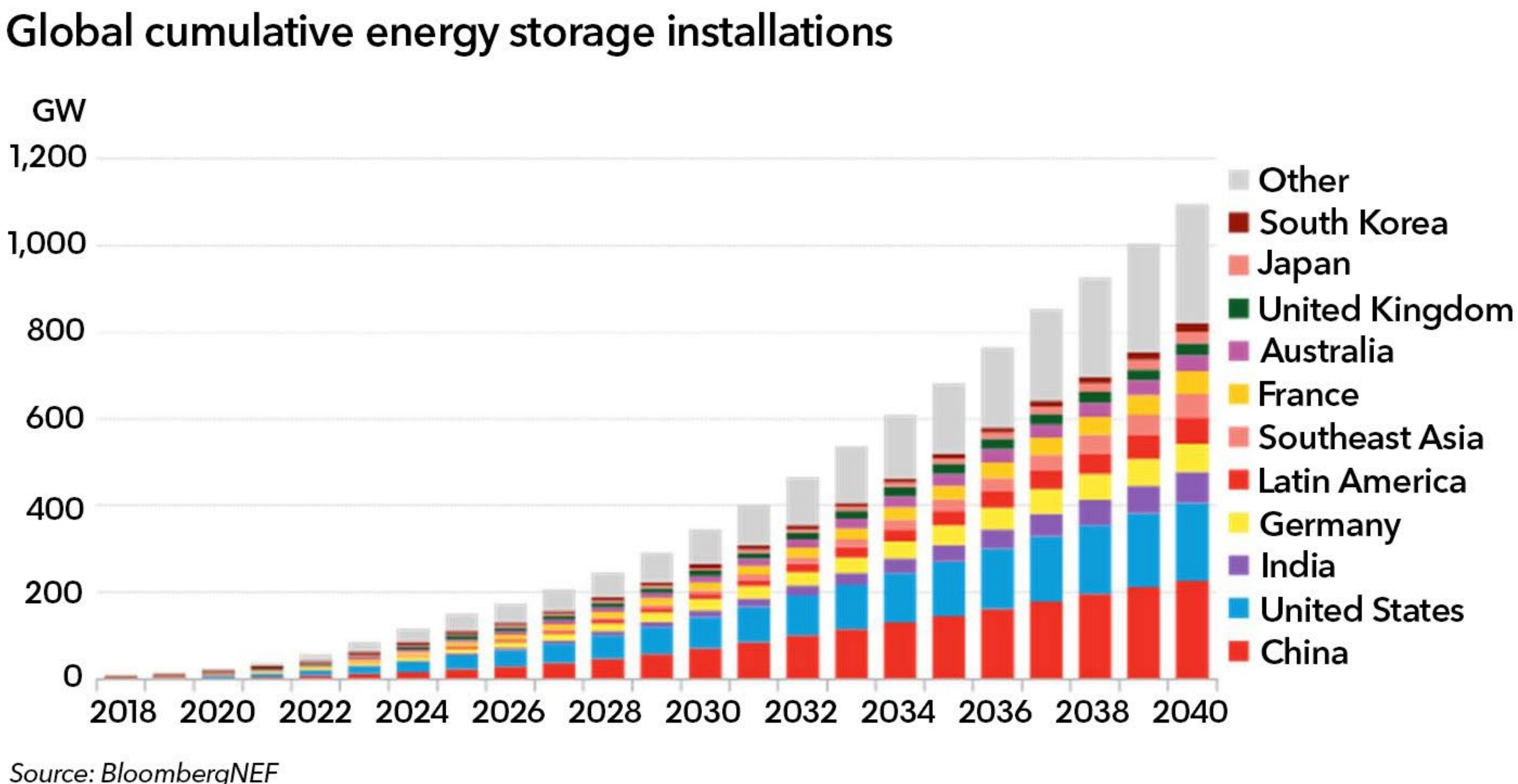
- **Frequency Regulation** – Provide *up* regulation by discharging and provide *down* regulation by charging
- **Power Quality** -- Mitigate voltage sags by injecting real power
- **Peak Shaving** - Discharge in on-peak periods and charge in off-peak periods
- **Renewables Firming** (PV, wind) -- Supplement RE to provide steady power output
- **Islanded Microgrids** – Support an electrical island separated from the grid
- **New Peakers and Transmission & Distribution Deferral** – Avoid construction of new infrastructure
- **Resilience/Reliability** – Provide power during and after natural disasters and hedge against malevolent attack

Storage Technology and Applications Markets



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

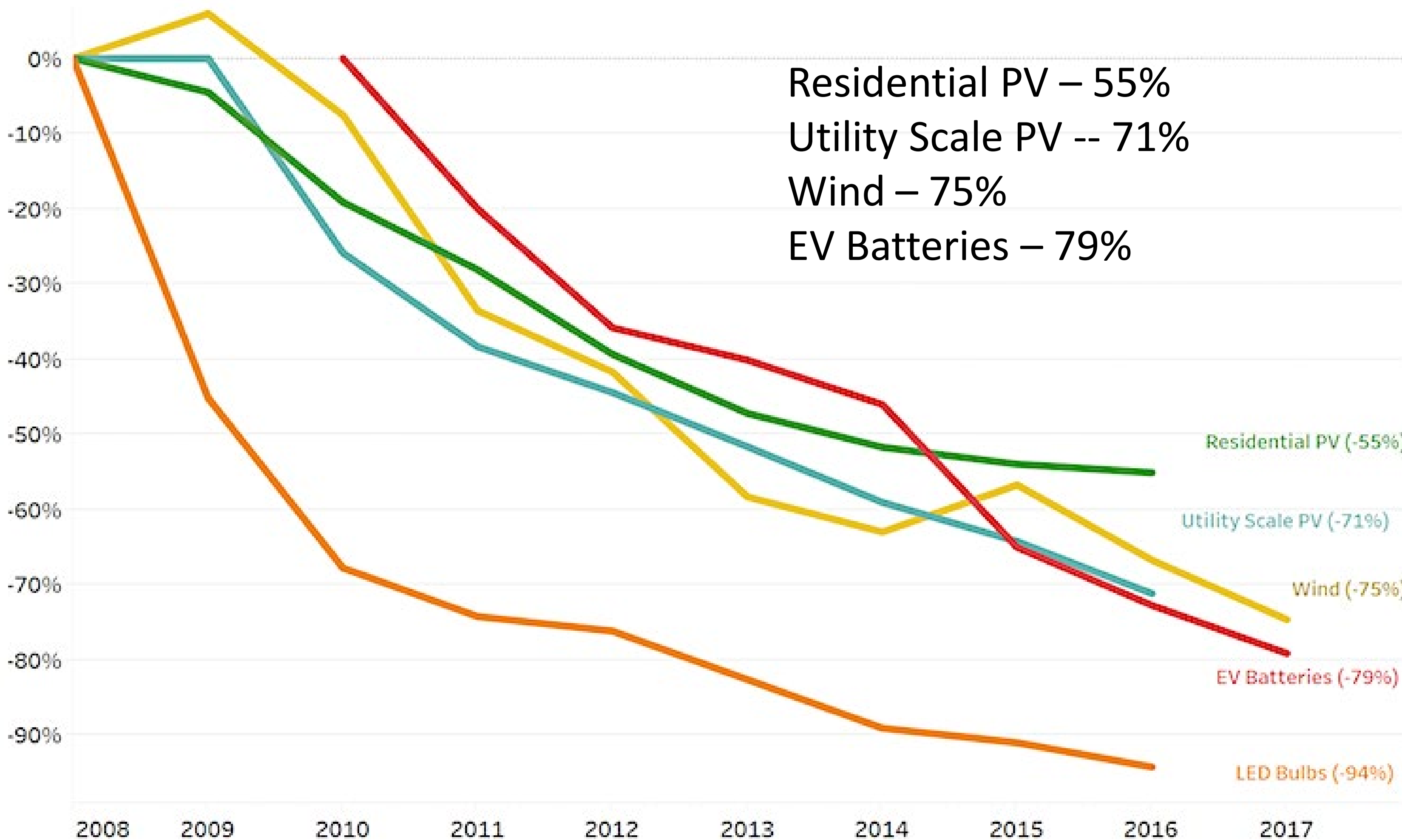
Global ES



https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/

Cost reductions -- 2008-2017

Residential PV – 55%
Utility Scale PV -- 71%
Wind – 75%
EV Batteries – 79%



http://energyfreedomco.org/f4-costs.php

Safety through Codes and Standards

- Many ESS safety issues are identical or similar to other technologies
  - Voltage, arc flash, fire hazard, chemical toxicity are all conventional hazards
- Some safety issues are unique to ES in general, some only to particular ESSs
  - NFPA 70E, Standard for Electrical Safety in the Workplace – e.g., locking out or disconnecting energy in all storage systems for maintenance
  - DC voltage safety is associated with all battery types
- Current codes and standards define system safety system safety
  - Tells a designer how far apart to space batteries or what alternative methods and materials criteria might be
- Codes and standards are being updated and new ones developed
- Sandia's Energy Storage Safety Collaborative – national-scale collaborative addressing safety issues; sandia.gov/energystoragesafety

Comparison of Energy Storage Options

Cliff Ho, 2016. A review of high-temperature particle receivers for concentrating solar power. Applied Thermal Engineering.

	Energy Storage Technology					
	Solid Particles	Molten Nitrate Salt	Batteries	Pumped Hydro	Compressed Air	Flywheels
Levelized Cost[1] ($/MWh$_e$)	10 – 13	11 – 17	100 – 1,000	150 - 220	120 – 210	350 - 400
Round-trip efficiency[2]	>98% thermal storage ~40% thermal-to-electric	>98% thermal storage ~40% thermal-to-electric	60 – 90%	65 – 80%	40 – 70%	80 – 90%
Cycle life[3]	>10,000	>10,000	1000 – 5000	>10,000	>10,000	>10,000
Toxicity/ environmental impacts	N/A	Reactive with piping materials	Heavy metals pose environmental and health concerns	Water evaporation/ consumption	N/A	N/A
Restrictions/ limitations	Particle/fluid heat transfer can be challenging	< 600 °C (decomposes above ~600 °C)	Very expensive for utility-scale storage	Large amounts of water required	Unique geography required	Only provides seconds to minutes of storage

[1]Ho, C.K., A Review of High-Temperature Particle Receivers for Concentrating Solar Power, *Applied Thermal Energy*, 2016; Kolb, G.J., Ho, C.K., Mancini, T.R., Gary, J.A., 2011, Power Tower Technology Roadmap and Cost Reduction Plan, SAND2011-2419, Sandia National Laboratories, Albuquerque, NM; Akhil et al., 2015, DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, SAND2015-1002, Sandia National Laboratories, Albuquerque, NM. For solid particles and molten salt, we assume a 30 – 50% thermal-to-electric conversion efficiency and 10,000 lifetime cycles for the thermal-to-electric storage and conversion systems; the cost includes the storage media (bulk ceramic particles and sodium/potassium nitrate salts ~$1/kg with ▯T = 400 °C and 9 hours of storage), tanks, pumps/piping/valves, other parts and contingency, and the power block at $1000/kW$_e$ with 19 operating hours per daily cycle (including 9 hrs of storage) and 90% availability. For batteries, cost is based on sodium-sulfur, vanadium-redox, zinc-bromine,lead-acid, and lithium-ion batteries capable of providing large-scale electricity.

[2]Roundtrip efficiency defined as ratio of energy in to energy retrieved from storage; Djajadiwinata, E. et al., 2014, Modeling of Transient Energy Loss from a Cylindrical-Shaped Solid Particle Thermal Energy Storage Tank for Central Receiver Applications, Proceedings of the Asme 8th International Conference on Energy Sustainability, 2014, Vol 1.; Siegel, N.P., 2012, Thermal energy storage for solar power production, Wiley Interdisciplinary Reviews-Energy and Environment, 1(2), p. 119-131.; http://energystorage.org/energy-storage/energy-storage-technologies; http://energymag.net/round-trip-efficiency/

[3]Siegel, N.P., 2012, Thermal energy storage for solar power production, Wiley Interdisciplinary Reviews-Energy and Environment, 1(2), p. 119-131.

Workshop Formats

Sandia National Laboratories

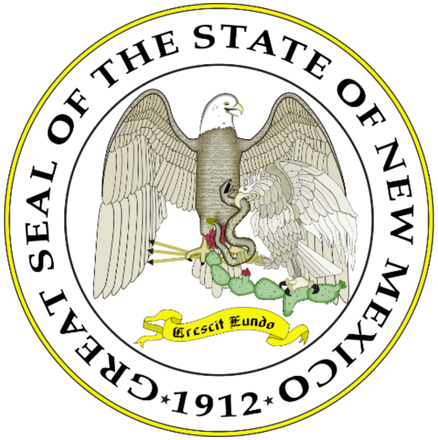
All other workshops have been 1- or 2-day events, carefully planned with Commission staff

New Mexico PRC Introductory Workshops:

- Today – Energy Storage Systems, and Energy Storage Economics and Valuation
- Dec. 4 – Energy Storage Policy

Help us identify topics for a series of future workshops

Big thanks to Commissioners Hall and Fischmann, Milo Chavez, Brian Harris, Isaac Leshin-Sullivan – and to you all



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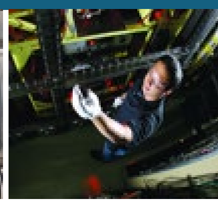
Energy Storage Applications and Value Stacking



PRESENTED BY

Ray Byrne, Ph.D.

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Energy storage application time scale

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

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

Energy Arbitrage

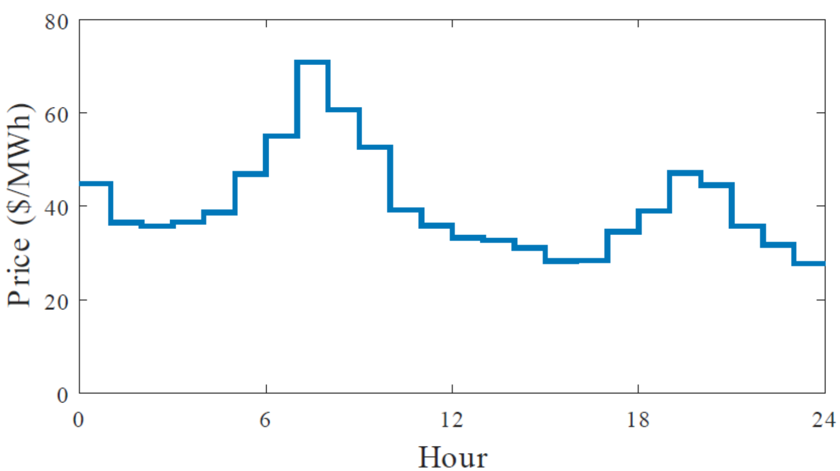
Buy low, sell high

η_c = conversion efficiency

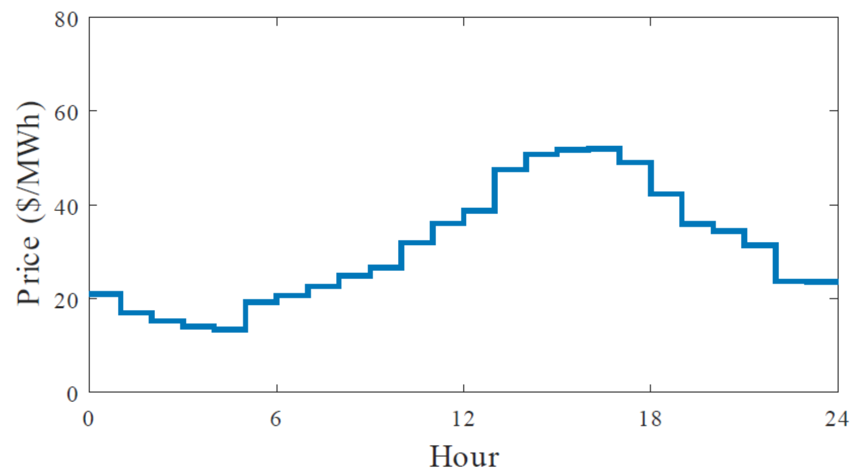
LMP_H = average high LMP, LMP_L = average low LMP

q = charge quantity

$$\text{arbitrage opportunity} = q\eta_c LMP_H - qLMP_L$$



(a) Day ahead LMP for ISO-NE node 4476 (LD.STERLING13.8), March 23, 2017.



(b) Day ahead LMP for ISO-NE node 4476 (LD.STERLING13.8), July 14, 2016.

Energy Arbitrage

Market area – market prices

Vertically integrated utility – efficiency savings

Different variants

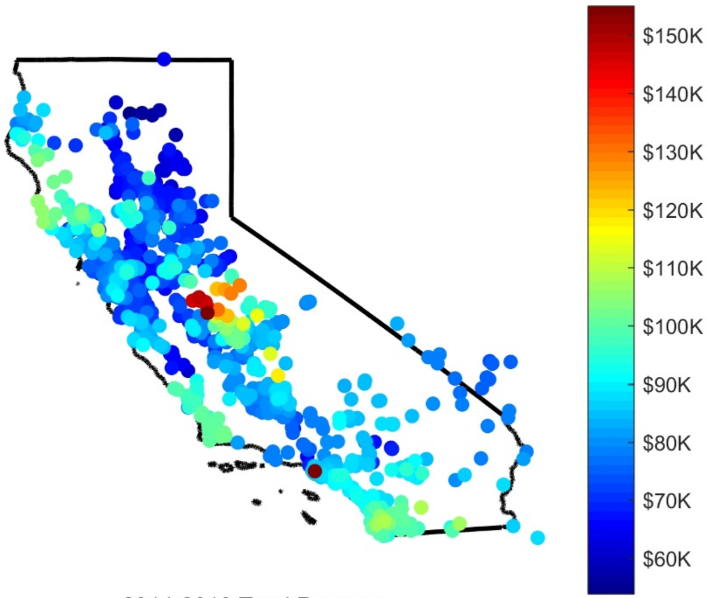
- Charge with inexpensive renewable energy
- Arbitrage day ahead and real-time markets
- Day ahead market only

Rarely the highest potential revenue stream

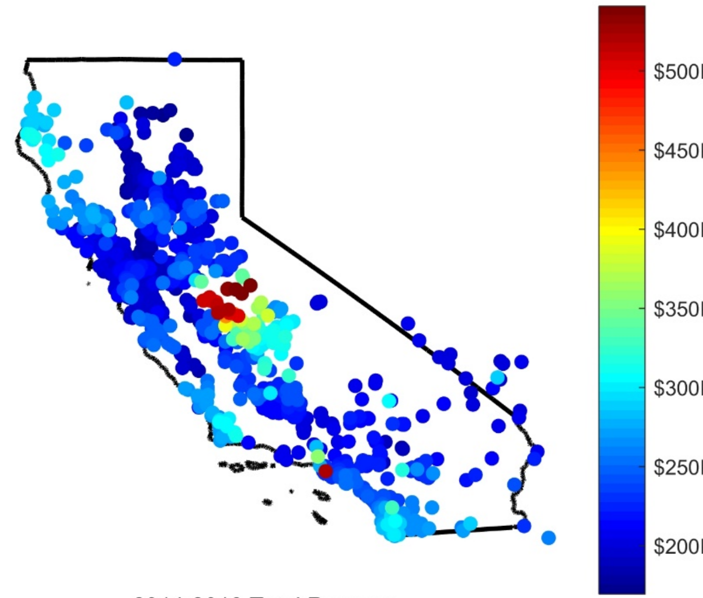
85% efficiency => 117.6% price difference

65% efficiency => 153.8% price difference

Energy Arbitrage Example - CAISO



2014-2016 Total Revenue
DA Arbitrage

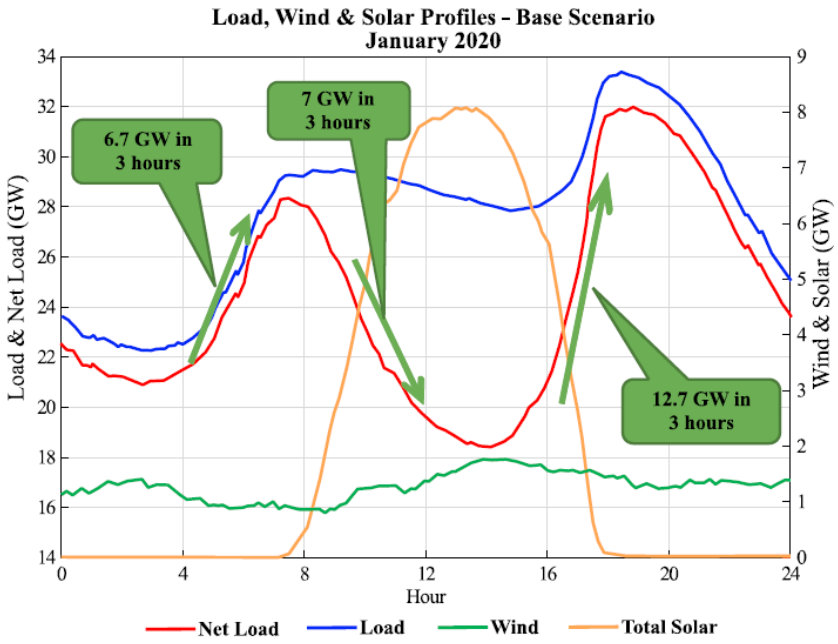


2014-2016 Total Revenue
DA+RT Arbitrage

- 1 MW, 4 MWh system, 80% efficiency
- Three year total revenue by LMP node, 2014-2016
- Assumes perfect foresight (best you can do)

Renewable Energy Time Shift

- Goal – shift renewable generation from off-peak to on-peak hours
- Example – CAISO "duck curve"
- CAISO has implemented a ramping product
- Other areas, arbitrage is your only option



Renewable Energy Time Shift

To attain the goal of 100% renewable generation, massive amounts of longer-term storage will be needed

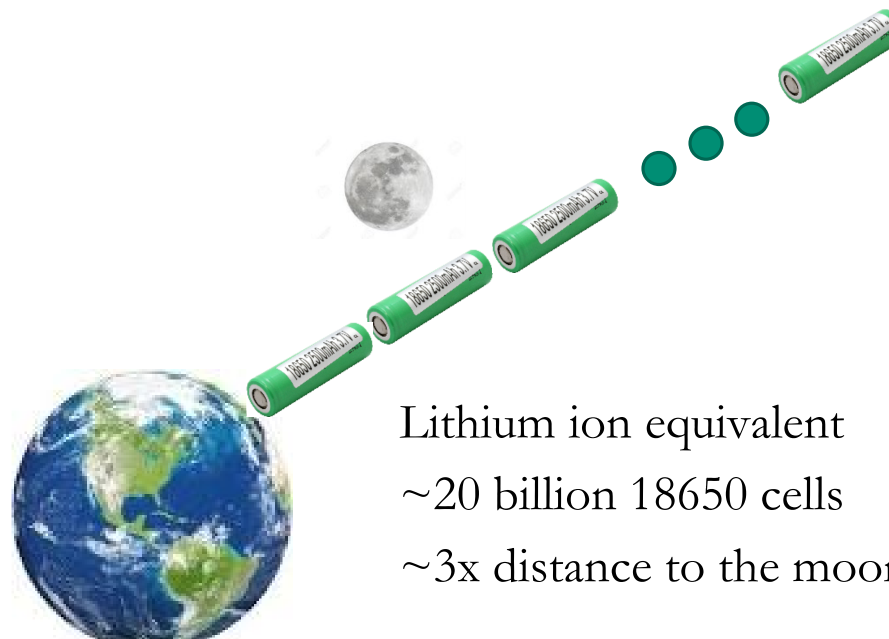
Tradeoffs between:

- Amount of storage
- Additional transmission (geographic diversity reduces variability)
- Renewable curtailment

Racoon Mountain pumped hydro

1,652 MW

22 hours



Lithium ion equivalent

~20 billion 18650 cells

~3x distance to the moon

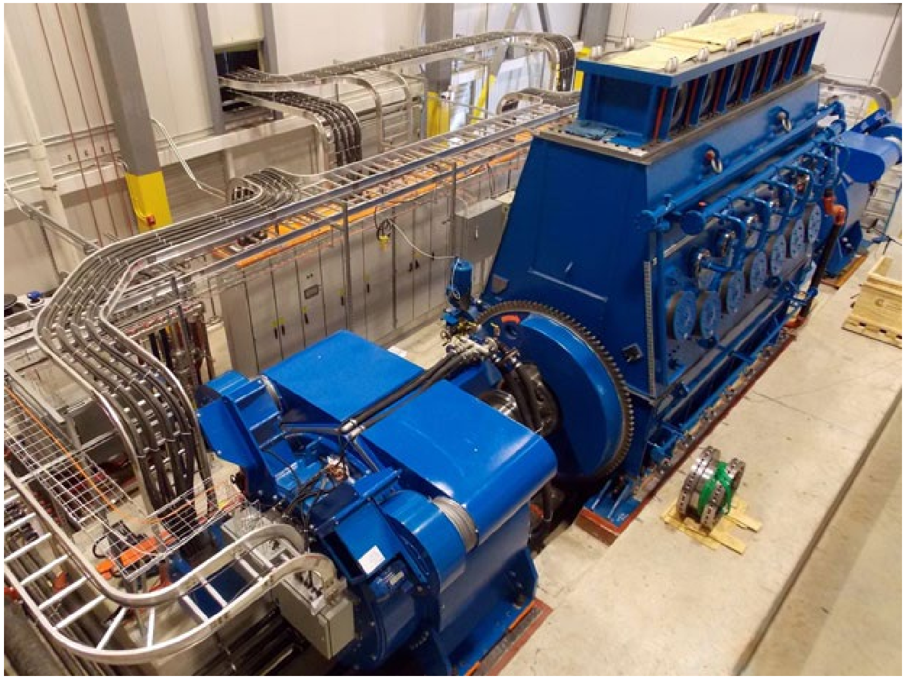
Mature Long-Term Storage Technologies

- Pumped hydro
- Compressed air energy storage
- Thermal storage (e.g., concentrated solar)

Promising Long-Term Storage Technologies

- Flow batteries
- Hydrogen electrolysis

More Research is Needed



Time-of-Use Charge Reduction

Behind-the-meter application

Arbitrage based on the rate structure

- Rates for each time period
- On-peak/off-peak pricing

Often not a significant benefit

Weekday

	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Jan	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Feb	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Mar	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Apr	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
May	2	2	2	2	2	2	2	2	3	3	3	3	4	4	4	4	4	4	3	3	3	2	2	2
Jun	2	2	2	2	2	2	2	2	3	3	3	3	4	4	4	4	4	4	3	3	3	2	2	2
Jul	2	2	2	2	2	2	2	2	3	3	3	3	4	4	4	4	4	4	3	3	3	2	2	2
Aug	2	2	2	2	2	2	2	2	3	3	3	3	4	4	4	4	4	4	3	3	3	2	2	2
Sep	2	2	2	2	2	2	2	2	3	3	3	3	4	4	4	4	4	4	3	3	3	2	2	2
Oct	2	2	2	2	2	2	2	2	3	3	3	3	4	4	4	4	4	4	3	3	3	2	2	2
Nov	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Dec	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0

Weekend

	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Jan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
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Aug	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Sep	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
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Nov	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Demand Charge Reduction

Behind-the-meter application

Demand charge typically based on the maximum rate of consumption ($/kW) over the billing period

Narrow spikes can significantly increase the electricity bill

Often results in a significant benefit

Weekday

	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Jan	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Feb	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Mar	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Apr	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
May	0	0	0	0	0	0	0	0	2	2	2	2	3	3	3	3	3	3	2	2	2	0	0	0
Jun	0	0	0	0	0	0	0	0	2	2	2	2	3	3	3	3	3	3	2	2	2	0	0	0
Jul	0	0	0	0	0	0	0	0	2	2	2	2	3	3	3	3	3	3	2	2	2	0	0	0
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Dec	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0

Weekend

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Feb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oct	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Projected load growth requires a transmission or distribution upgrade

Energy storage can be deployed to defer the investment

ES_0 = energy storage cost

T_0 = deferred transmission investment

r = interest rate

K = number of deferral years

$$ES_0 \leq T_0\left(1 - e^{-rK}\right)$$

Grid Resiliency

Events like Hurricane Sandy and Hurricane Katrina have increased the interest in grid resiliency applications

Value of Lost Load (VOLL) – typically estimated based on

- Market prices
- Surveys

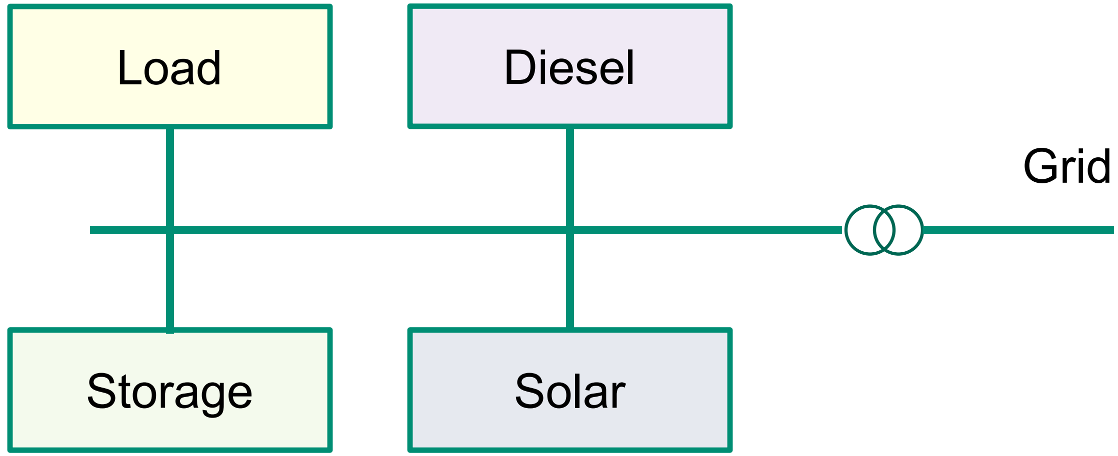
Data for public administration likely under-estimates the value

Sterling Municipal Light Department
2 MW, 3.9 MWh system

Microgrids - hybrid renewable, storage and alternative backup solutions for critical load

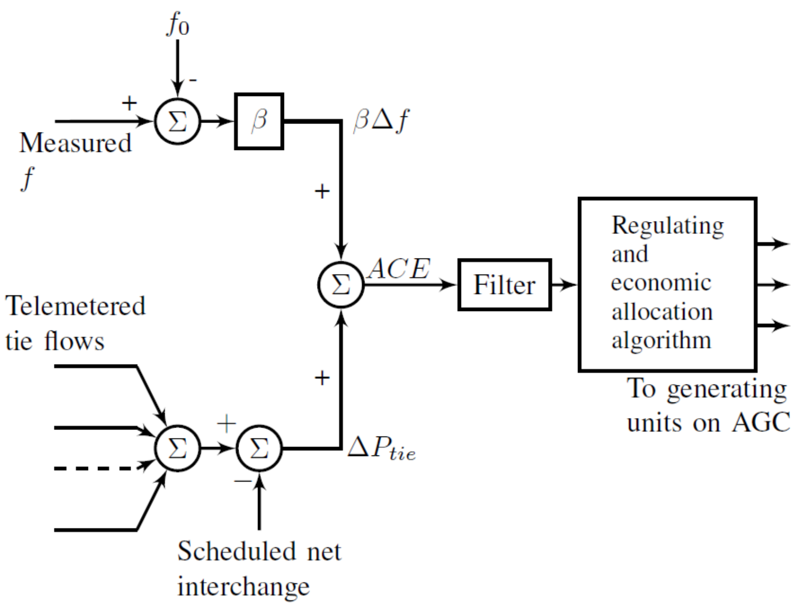
- Energy storage is a key component
- Often paired with distributed generation
  - Solar
  - Wind
  - Diesel
  - Natural gas

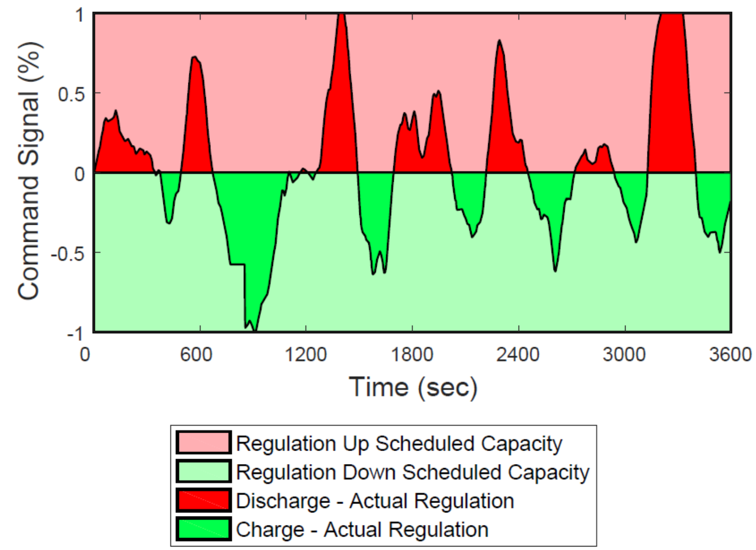
Design and operation are optimization problems



Second by second adjustment in output power to maintain grid frequency

Follow automatic generation control (AGC) signal





Representative regulation command signal (RegD from PJM)

Implementation varies by independent system operator

- Bidirectional signal – PJM
- Regulation Up, Regulation down – CAISO, ERCOT

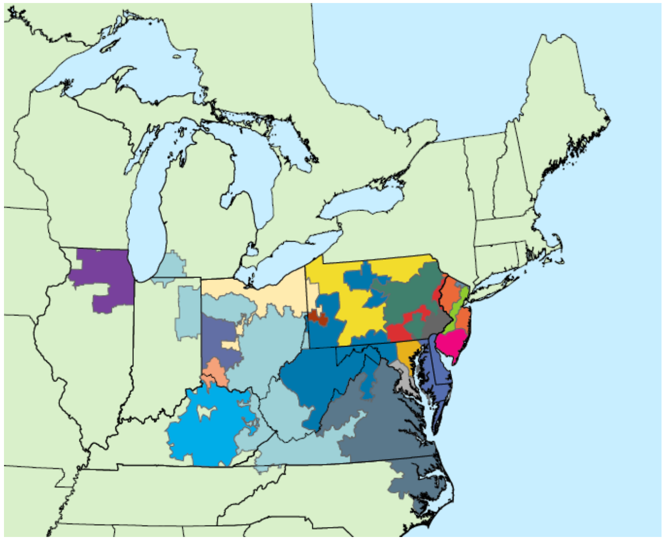
Pay-for-performance

- Performance score (how well did you track command signal)
- Mileage payment

20 MW, 5 MWh Beacon flywheel plant at Hazle Township, Pennsylvania

Often the highest potential revenue stream

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



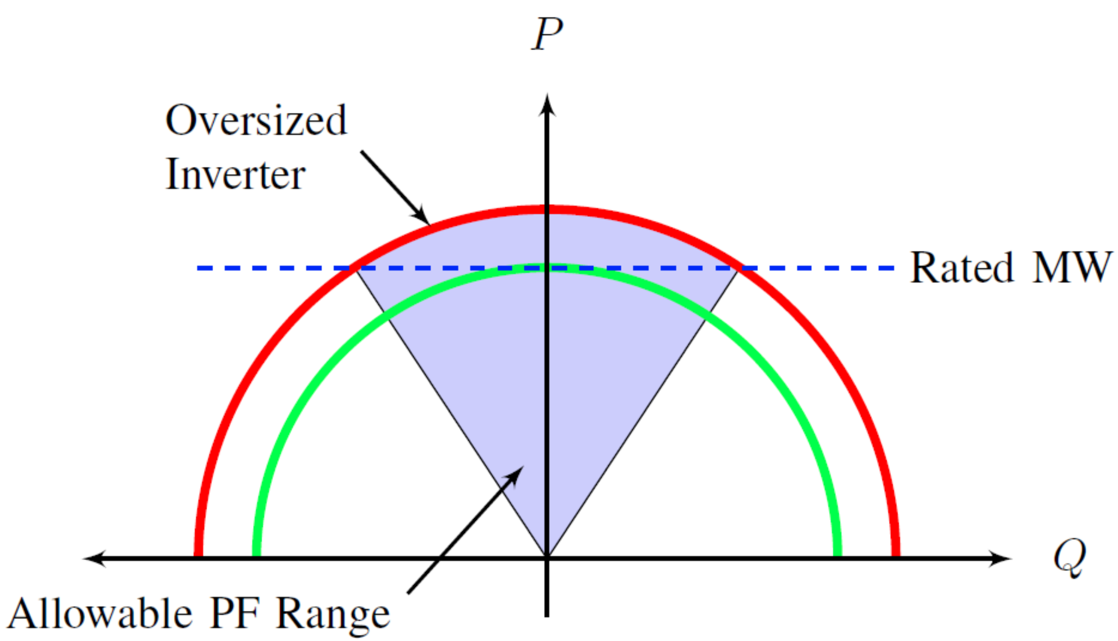
PJM results, 20MW, 5MWh 200-flywheel system

Beacon Power Flywheel

Inject real/reactive power to control voltage

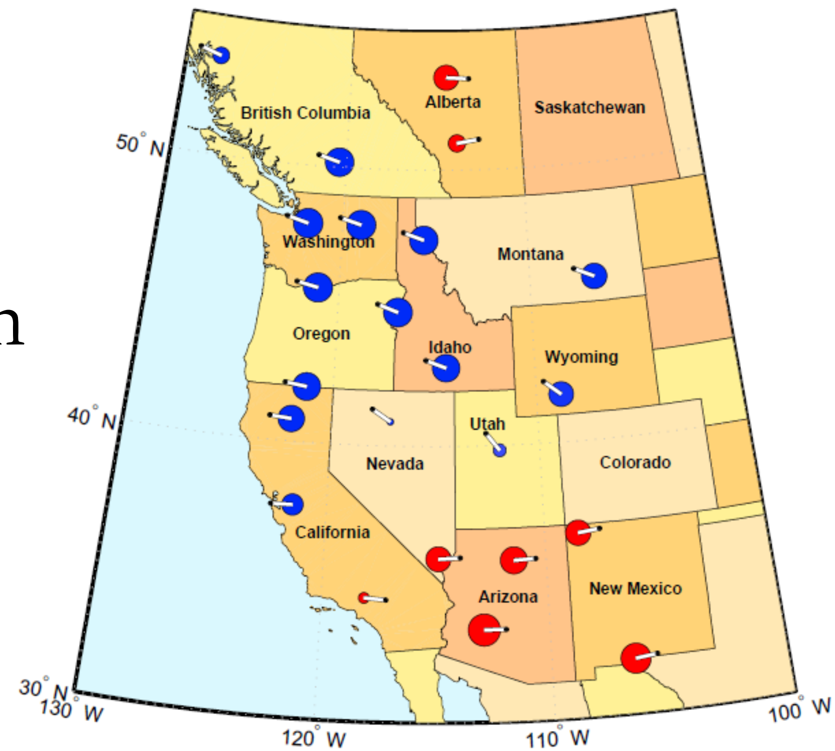
Can support reactive power over a wide state-of-charge range, limited by inverter rating

Some ISOs compensate for reactive power at the transmission level



Small Signal Stability

- All large power systems are subject to low frequency electro-mechanical oscillations (0.2-1 Hz)
- Injection of real power can provide damping
- BPA has a demonstration project underway
- Potential future revenue stream



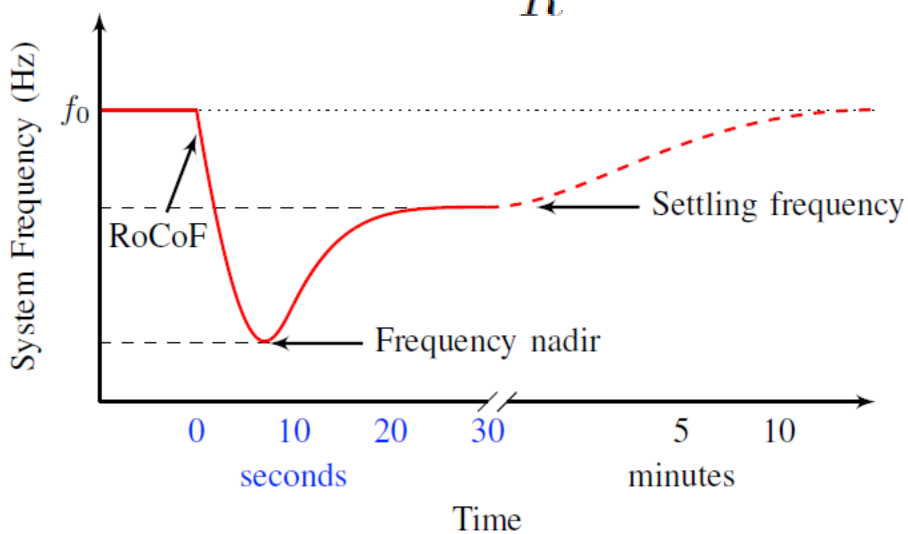
North-South Mode B (0.37 Hz) from a 2015 heavy summer WECC base case simulation

Frequency Droop

Frequency droop: generator speed control proportional to the speed (frequency) error

Energy storage can provide frequency droop via a control law

$$\Delta P = -\frac{1}{R}\Delta f$$



Frequency Droop

In the U.S., generators are not required to provide frequency responsive service

Nor are they compensated for providing the service

Eastern Interconnection suffers from a "Lazy L"

February 18, 2016, FERC issued a notice of inquiry to reform rules and regulations

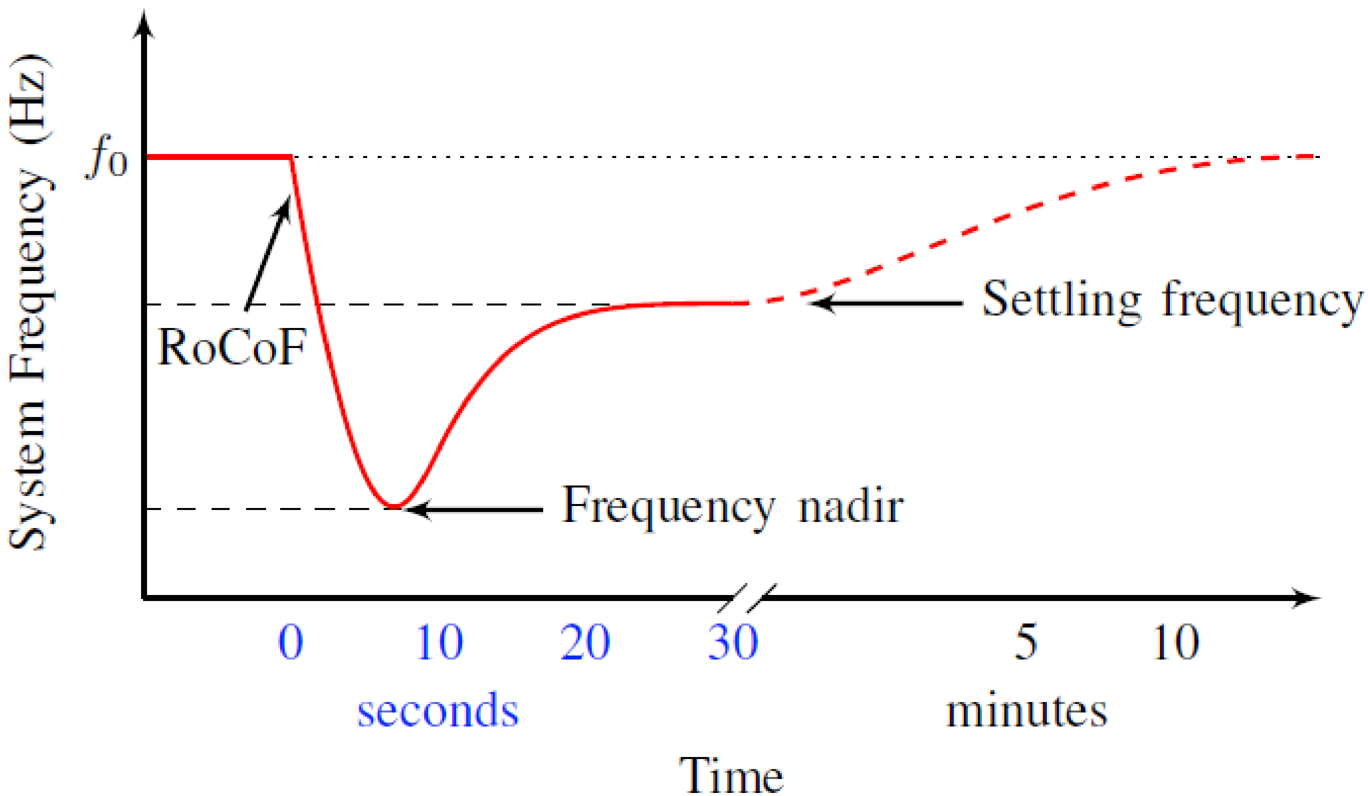
- Required service, Mechanisms for compensating service

August 8, 2017 FERC requests supplemental comments

February 15, 2018 – FERC Order 842, all new generation must be capable of providing primary frequency response as a condition of interconnection

Large rotating machines provide inertia

Rate of Change of Frequency (RoCoF) is proportional to the inertia in the system



Synthetic Inertia

Increased inverter-based generation displaces inertia

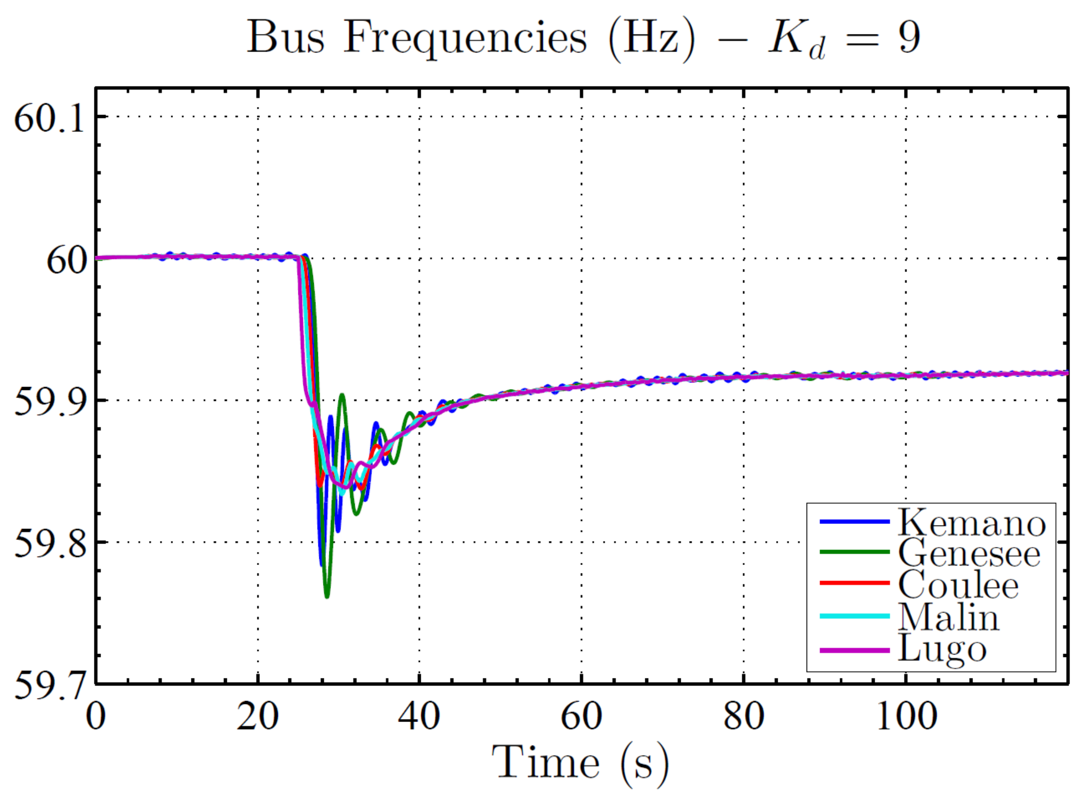
Energy storage can provide synthetic inertia via a control law

$$\Delta P = -k_{in}\frac{df}{dt}$$

No mechanisms for compensating resources that provide inertia

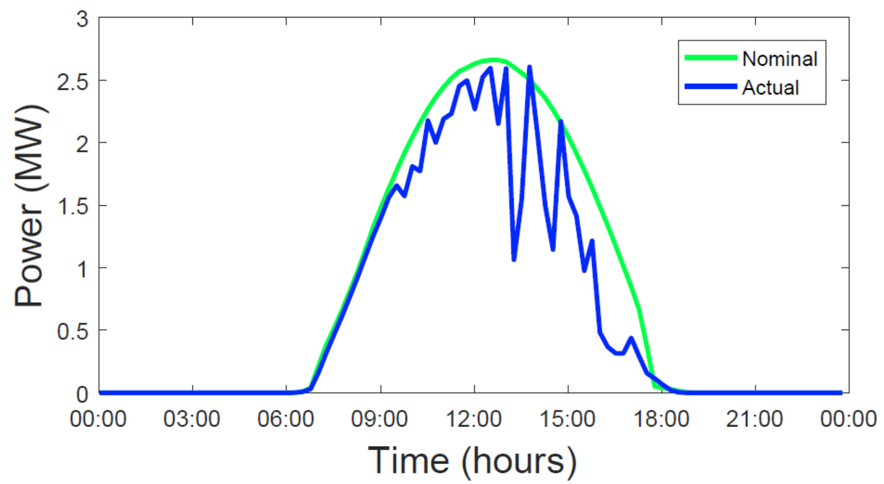
Local frequency measurement is often proposed – this can be problematic near faults

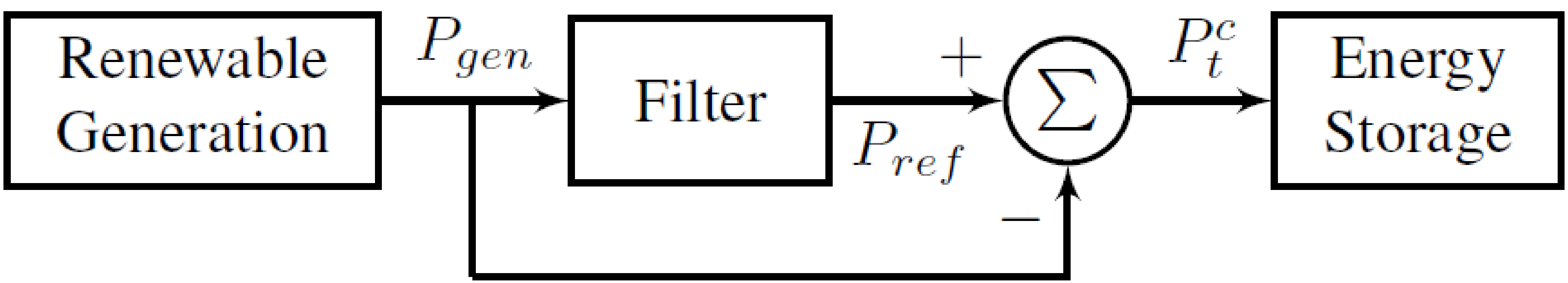
There are advantages to responding to a system frequency



Some areas are placing ramp rate limitations on renewable generation

- Puerto Rico
- Hawaii





Maximizing Revenue from Energy Storage

Revenue maximization can be formulated as an LP-optimization

First step – best possible scenario (perfect foresight)
- Gives insight into storage operation
- Starting point for developing operating strategy

In most market areas, frequency regulation is the optimum application

Exception – ISO NE
- Forward Capacity Market payments
- Regional Network Service payment

Grid resilience is a common goal
- VOLL from surveys does not yield a significant value
- Likely does not capture the value to first responders
- Definition of resilience is important

Energy Storage Model

Energy flow model

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

S_t: state of charge at time step t (MWh)

γ_s: storage efficiency (percent)

q_t^R: quantity of energy purchased for recharging at time step t (MWh)

q_t^D: quantity of energy sold for discharging at time step t (MWh)

Constraints:

$\bar{q}$	maximum discharged/recharged energy in one period (MWh)
$\bar{S}$	maximum storage capacity (MWh)
$\underline{S}$	minimum storage capacity (MWh)

$$\underline{S} \leq S_t \leq \bar{S}, \forall t$$

$$0 \leq q_t^D + q_t^R \leq \bar{q}, \forall t$$

CAISO MODEL – DA/RT Market Arbitrage

Objective function

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

Analyzed 3 years for market data (2014-2016) for ~2200 CAISO nodes

Energy storage model parameters

ENERGY STORAGE SYSTEM PARAMETERS

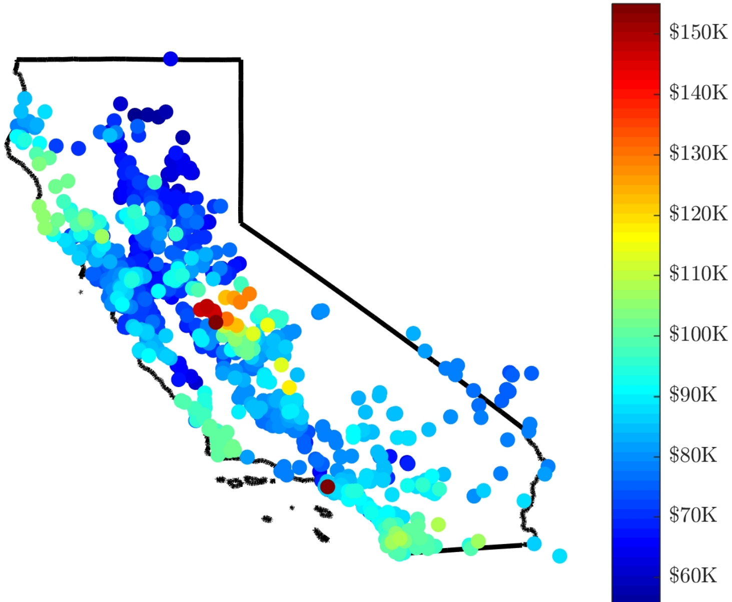
parameter	**value**
γ_c	0.80
γ_s	1.0
$\bar{q}$	1.0 MWh
$\bar{S}$	4.0 MWh
$\underline{S}$	0.0 MWh

Estimating the Value of Energy Storage – CAISO Example

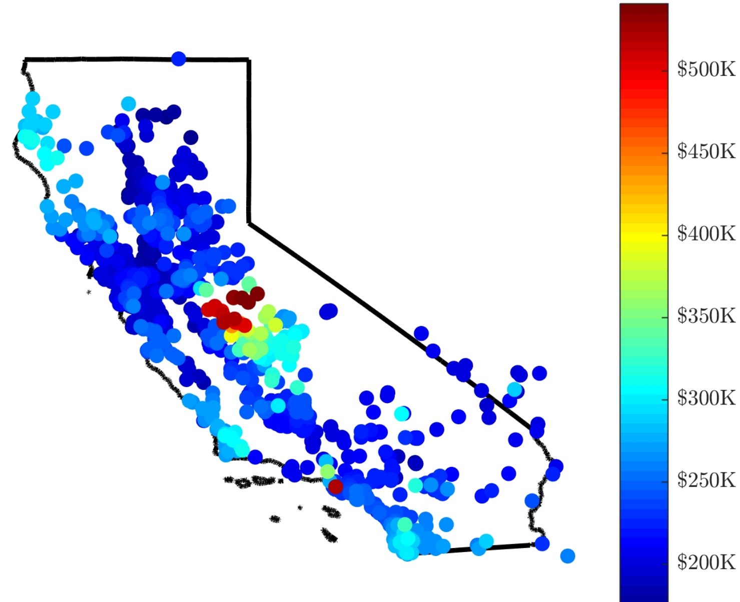
Analyzed ~2200 LMP nodes in CAISO
- Day ahead market arbitrage
- Day ahead and real time market arbitrage

Key takeaways
- Revenue opportunity is highly location dependent
- Significantly more potential revenue if the real time market is included

<u>Storage model</u>
1 MW, 4 MWh
80% efficiency



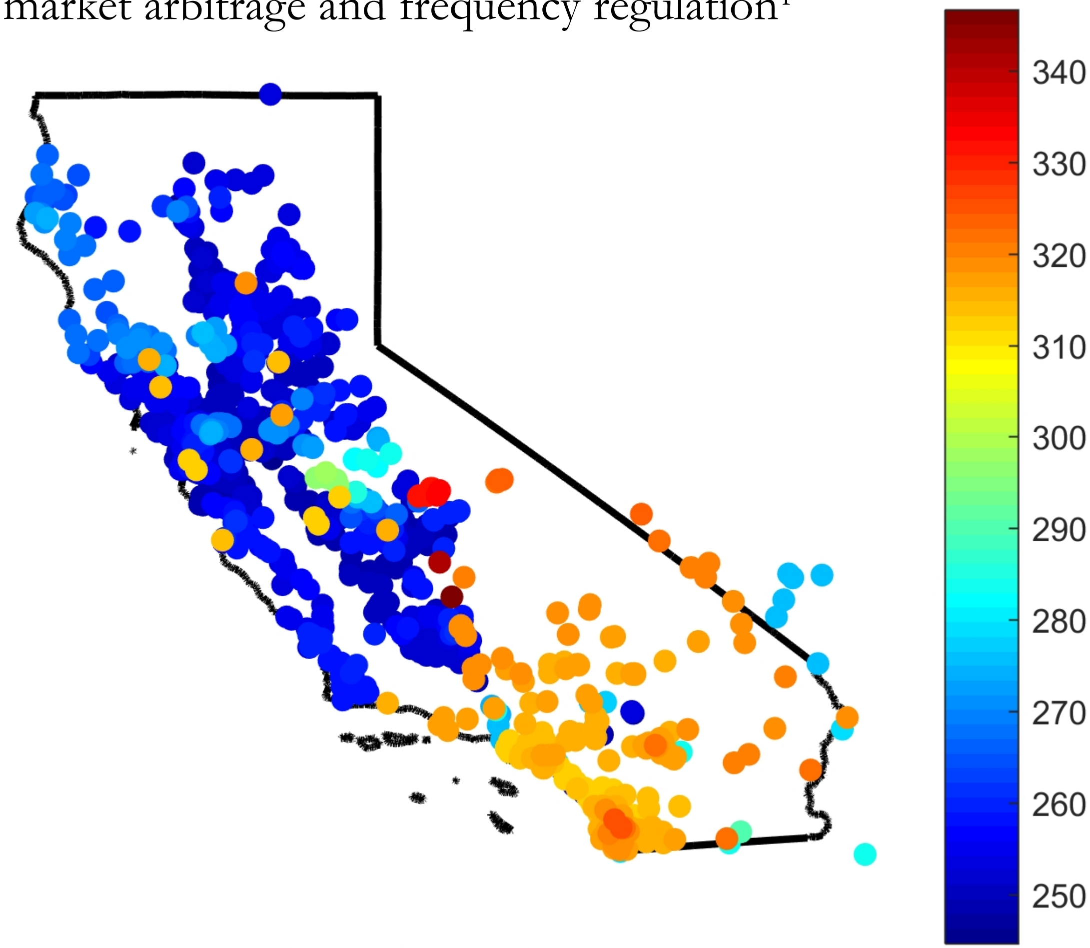
2014-2016 Total Revenue
DA Arbitrage



2014-2016 Total Revenue
DA+RT Arbitrage

Estimating the Value of Energy Storage – CAISO Example

Results for DA market arbitrage and frequency regulation[1]



2014-2016 Total DAM
Arbitrage plus Regulation Revenue ($K)

[1] R. H. Byrne, T. A. Nguyen and R. J. Concepcion, "Opportunities for energy storage in CAISO," accepted for publication in the 2018 IEEE Power and Energy Society (PES) General Meeting, August 5-9, 2018.

Sterling Municipal Light Department (SMLD)

Sterling Potential value streams:

- Energy arbitrage
- Reduction in monthly network load (based on monthly peak hour)
- Reduction in capacity payments (based on annual peak hour)
- Grid resilience
- Frequency Regulation

Grid Resilience was the primary goal – other applications help pay for the system

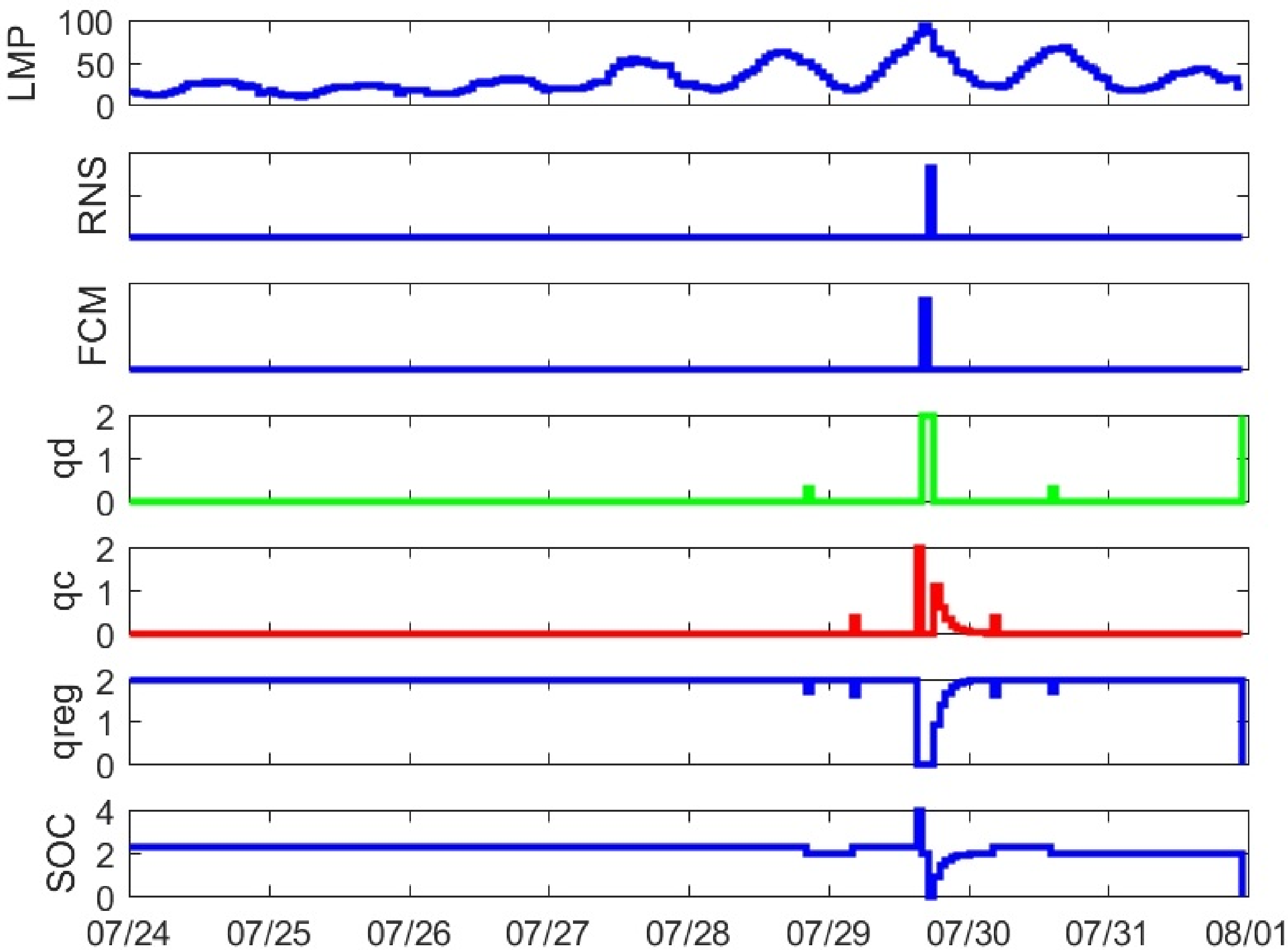
Several potential value streams (1MW, 1MWh 2017-18 data)

Description	Total	Percent
Arbitrage	$40,738	16.0%
RNS payment	$98,707	38.7%
FCM obligation*	$115,572	45.3%
Total	$255,017	100%

For more information, please refer to:

R. H. Byrne, S. Hamilton, D. R. Borneo, T. Olinsky-Paul, and I. Gyuk, "The value proposition for energy storage at the Sterling Municipal Light Department," proceedings of the 2017 IEEE Power and Energy Society General Meeting, Chicago, IL, July 16-20, 2017, pp. 1-5. DOI: 10.1109/PESGM.2017.8274631

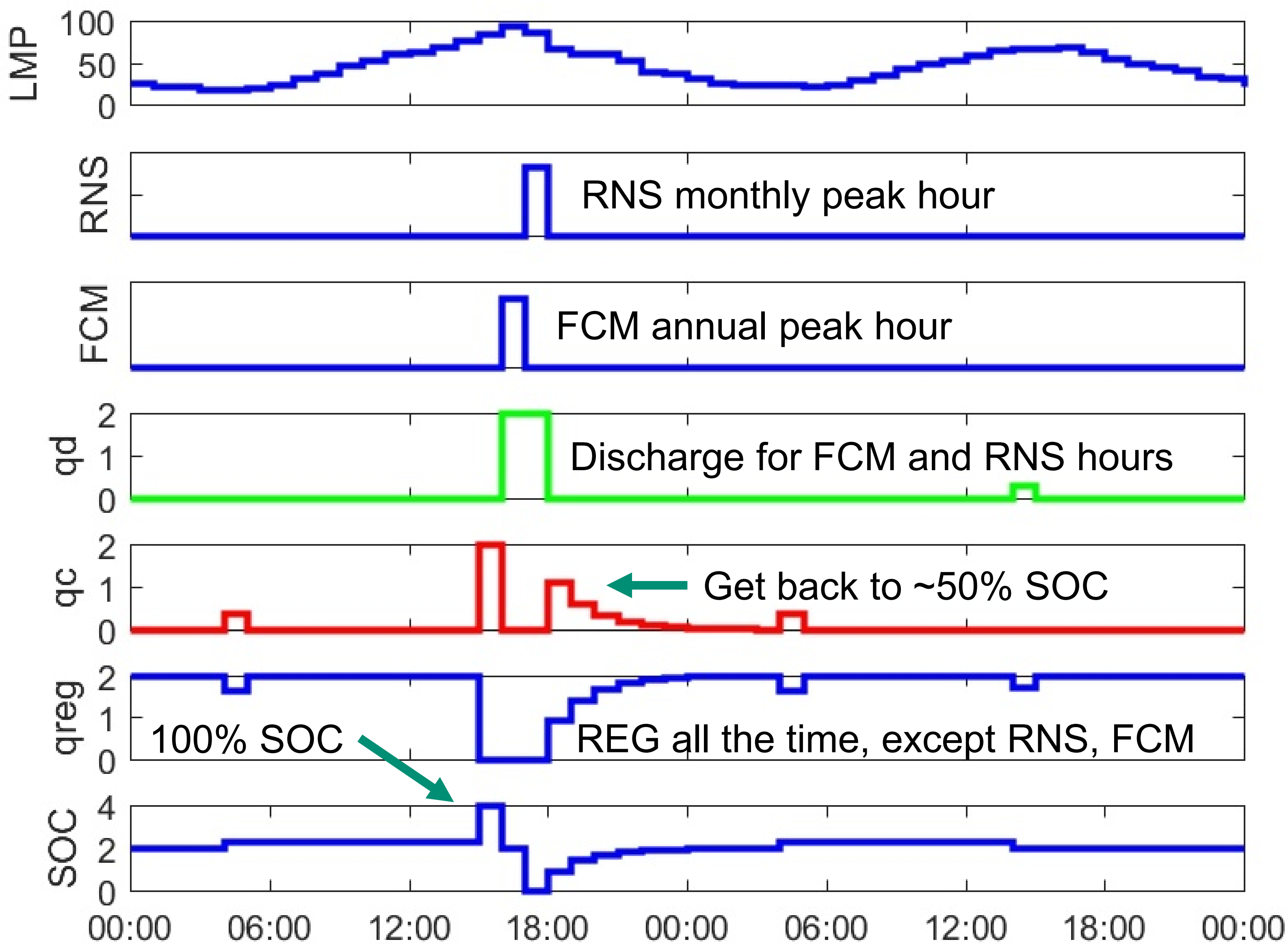
Optimization Results – Typical Week SMLD



2 MW, 4 MWh system

- Last week of July 2015
- Annual and monthly peaks
- Spend the majority of the time at 50% SOC performing frequency regulation
- Charge up to 100% SOC in hour prior to FCM peak
- Discharge for two consecutive hours (FCM and RNS peak)
- Return to 50% SOC and continue performing frequency regulation
- Note minimal arbitrage (qc, qd)
- Assumes an energy neutral (with losses) regulation signal

Optimization Results – Typical Day SMLD



Valuing Storage in a Vertically Integrated Utility

Production cost modeling is the gold standard for valuing storage in the Integrated Resource Planning Process

- Requires an accurate system mode
  - Transmission system
  - Load variability
  - Renewable variability
  - Generator models
- Primarily addresses arbitrage and reserve products

Other benefits require technical analysis & comparative economic analysis

- Primary frequency response/inertia – dynamic simulations
- Voltage support – power flow simulations
- Solar hosting capacity analysis of distribution networks
- T&D deferral – load modeling

Stacking Benefits - Takeaways

Stacking benefits can increase potential revenue …

At the expense of:

- Potentially accelerated degradation of the energy storage system
- Potentially increased complexity of the forecasting and control algorithms

Modeling the degradation as a function of charge/discharge profile is still an active research area

Summary

- Energy storage is capable of providing a wide array of grid services
- Regulatory structure is still evolving for many applications
- Different technologies for energy versus power applications
- Valuation of storage is highly location-specific
- For further reading:

www.sandia.gov/ess

FUTURE MEETINGS

NEAR TERM SCHEDULE

TENTATIVE MEETING SCHEDULE THROUGH MAY 2020

July 31:	Kickoff, Overview and Timeline
August 20:	The Energy Transition Act & Utilities 101
August 29:	Resource Planning Overview: Models, Inputs & Assumptions
September 6:	Transmission & Reliability (Real World Operations)
September 24:	Resource Planning “2.0”
October 22:	Demand Side/EE/Time of Day
November 19:	Battery Technology & Energy Storage
January 14:	Technology Review
TBD:	Load Forecast & Price Projections / Finalize Scenarios
March 10:	Process Update
April 14:	Process Update / Public Draft
May 12:	Advisory Group Comments

MAKE SURE WE HAVE UP TO DATE CONTACT INFORMATION FOR YOU

www.pnm.com/irp for documents

irp@pnm.com for e-mails

Register your email on sign-in sheets for alerts of upcoming meetings and notices that we have posted new information to the website.

Meetings Schedule:

Tuesday, November 19, 2019, 8 a.m. to 4 p.m.

Tuesday, January 14, 2020, 1 p.m. to 4 p.m.

Thank you

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