SAND2019-14145C

Energy Storage Systems

Howard Passell, Ph.D.

Sandia National Laboratories

PNM Public Advisory Board 19 November 2019

Exceptional service in the national interest

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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. SAND2019-13351 C

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

Sandia National Laboratories

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

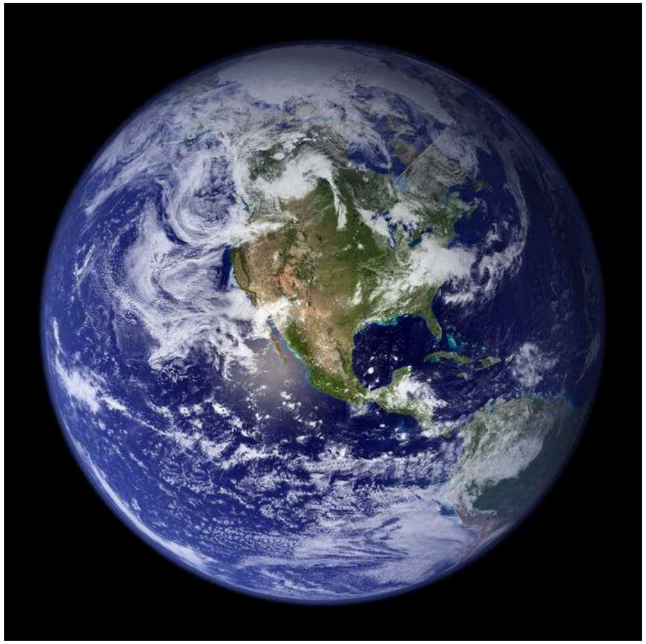
Climate crisis

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

Sandia National Laboratories

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

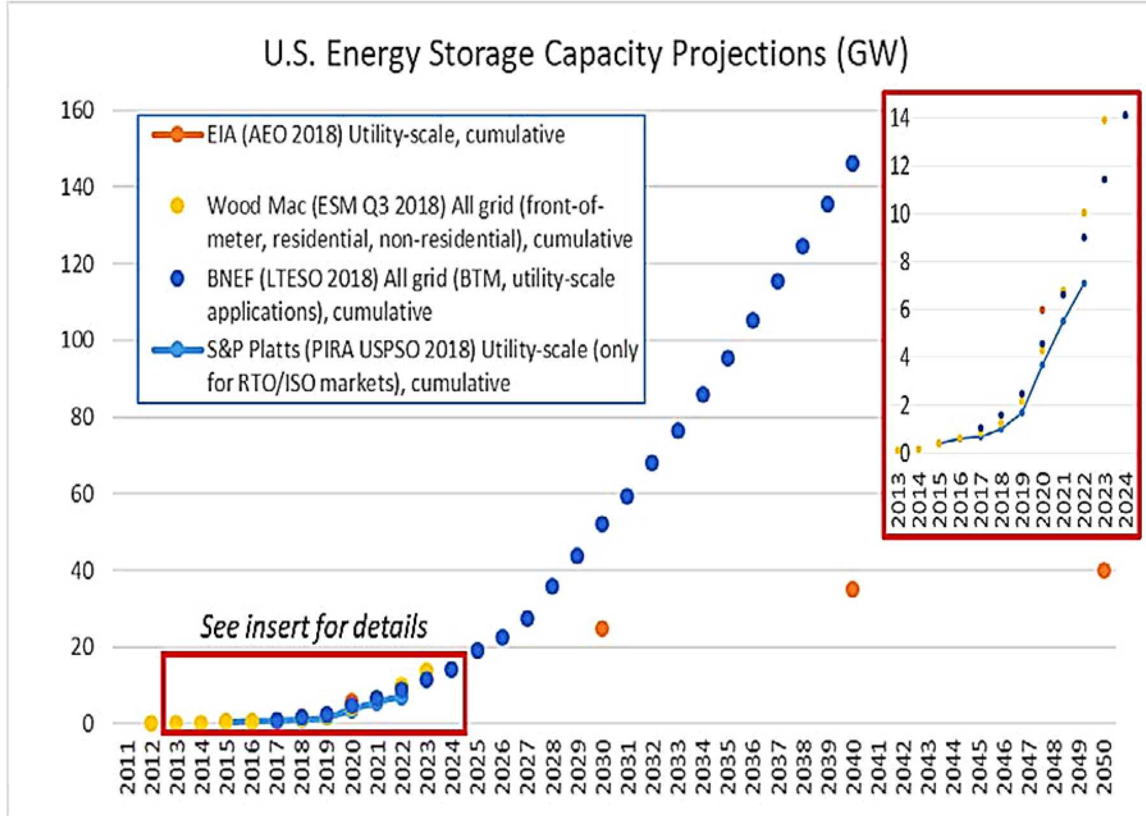
Sandia National Laboratories

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

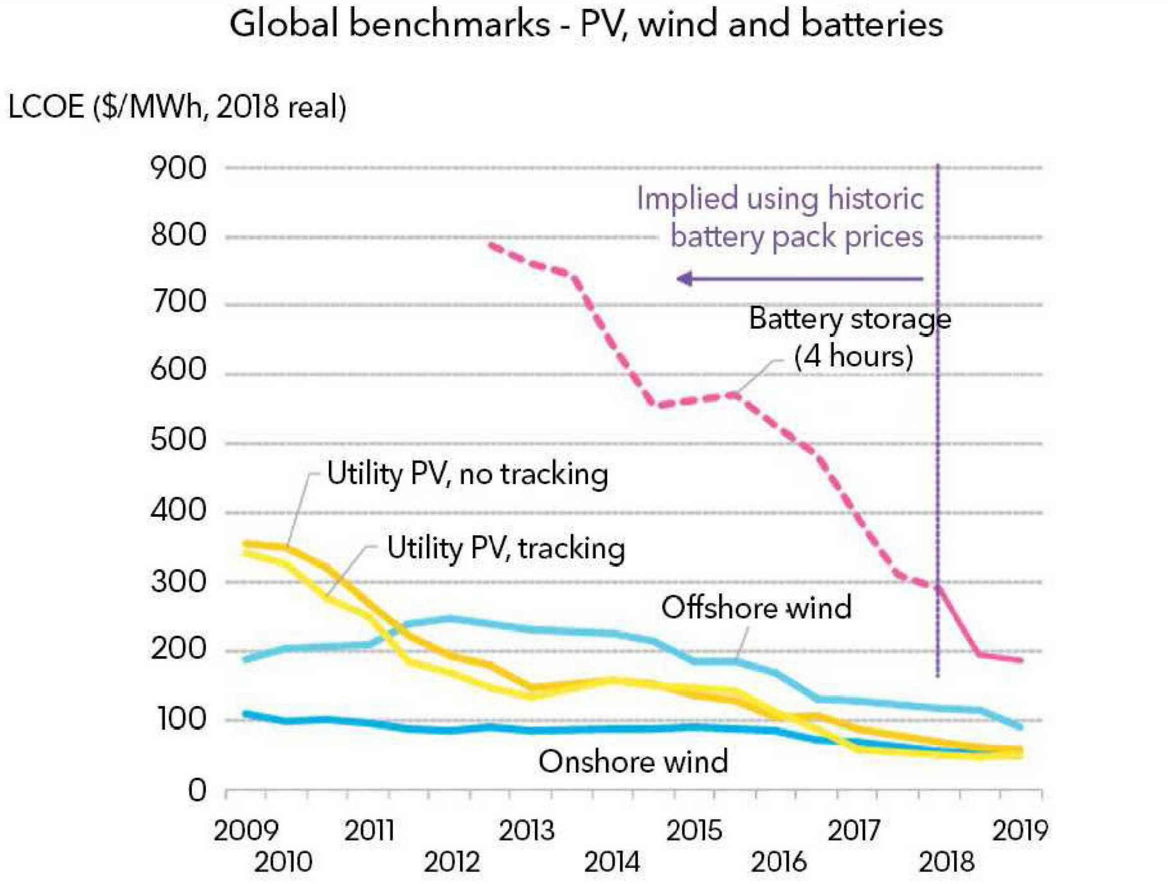


Wood Mackenzie P&R / ESA | U.S. energy storage monitor 2018 YIR and Q1

"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)."

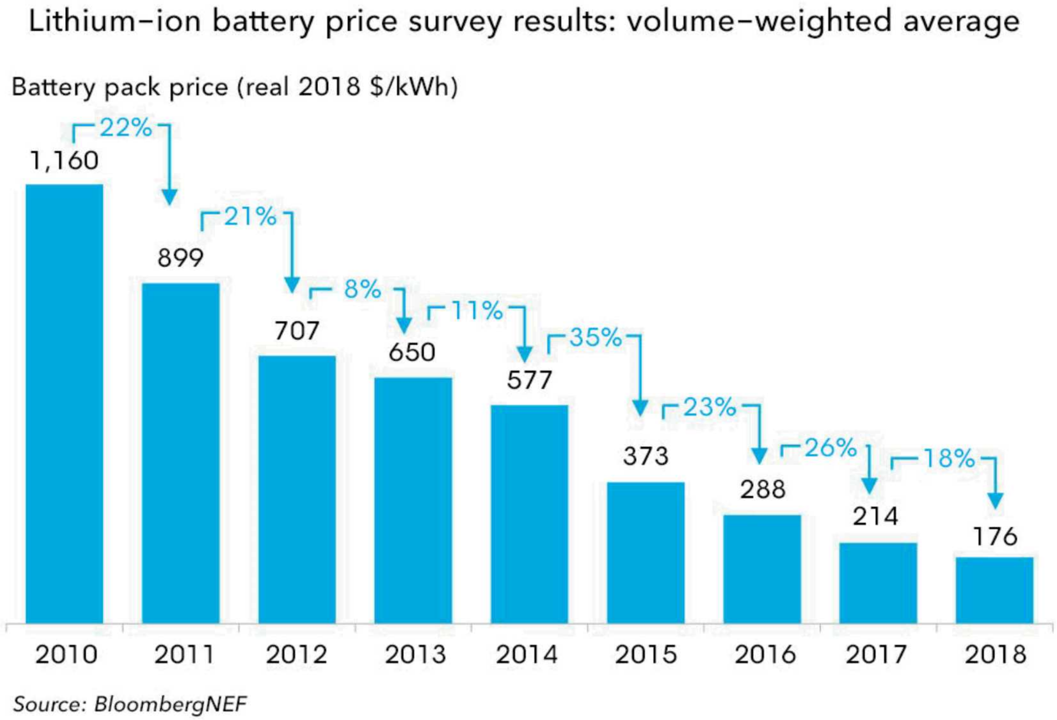
Bloomberg New Energy Frontiers

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

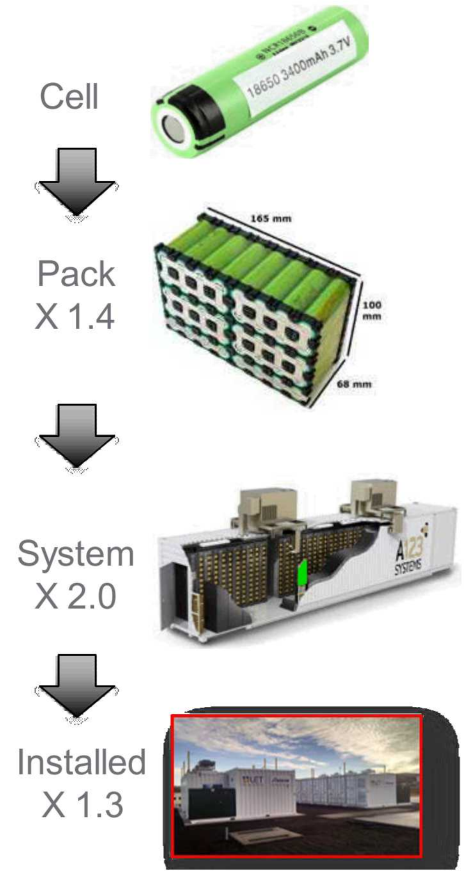
Residential PV, -55%
Utility Scale PV, -71%
Wind, -75%
EV Batteries, -79%

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

Battery costs are dropping fast



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

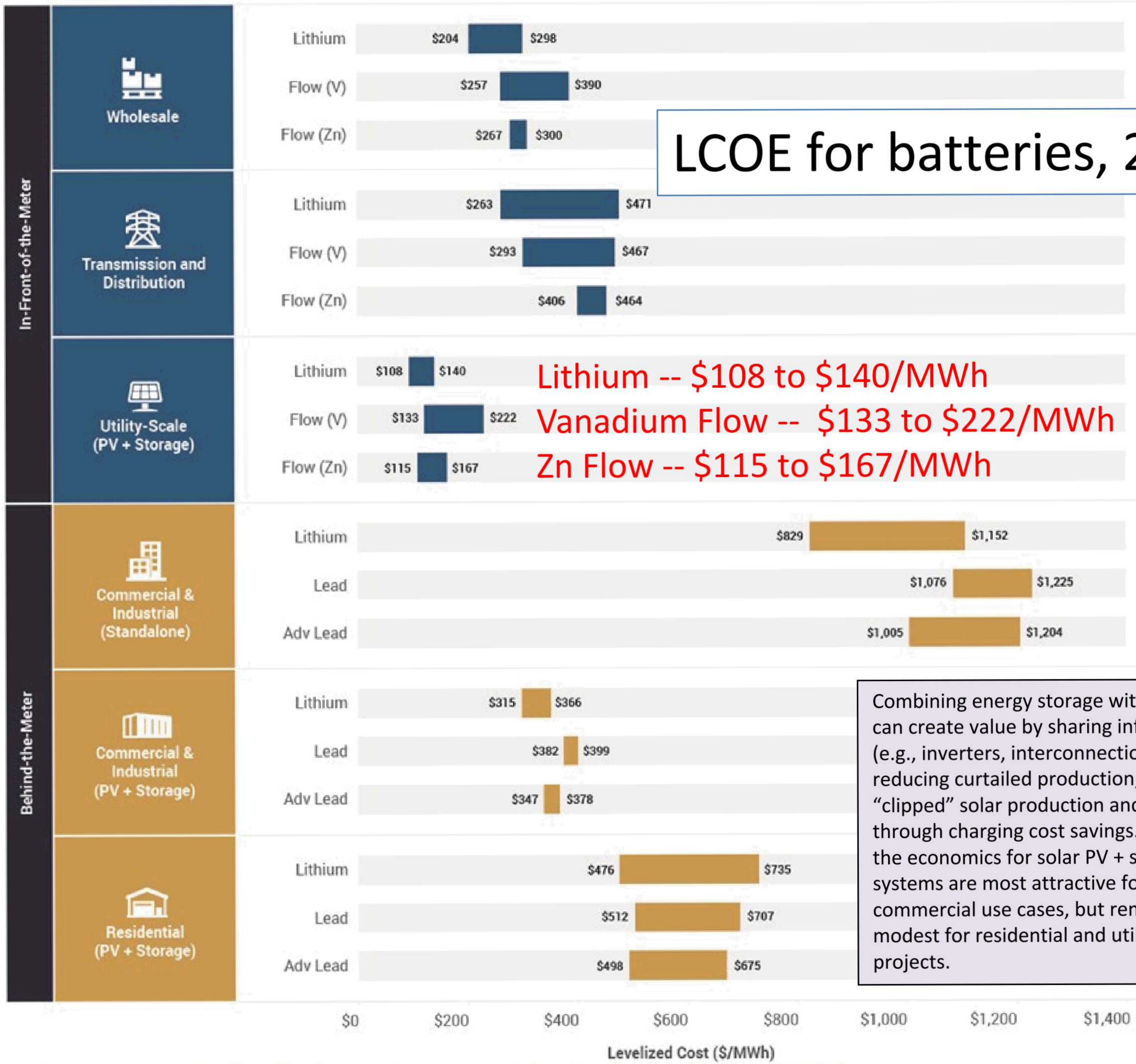


13 kWh Tesla Powerwall now sells for about $481/kWh

$200/kWh cell → **$~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

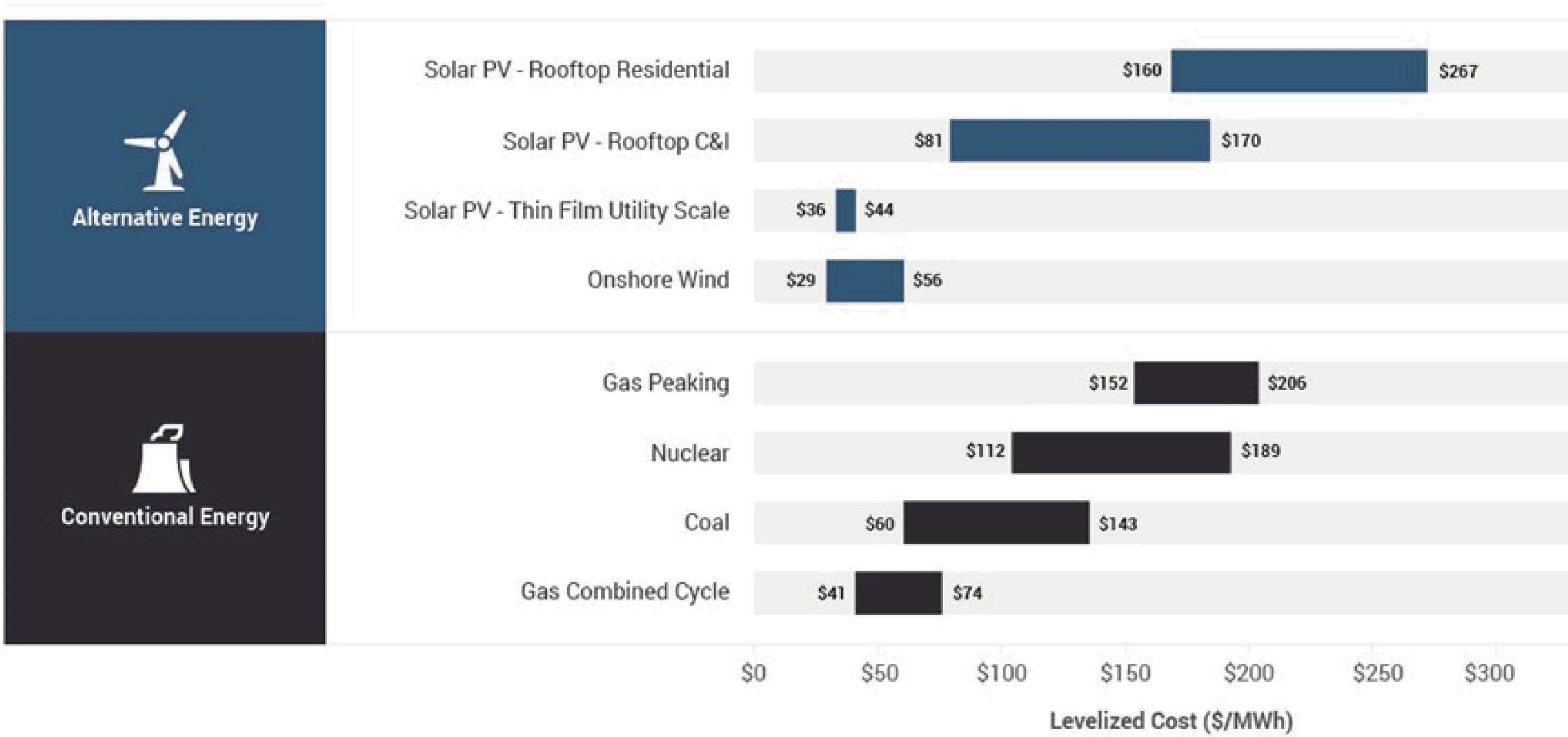
Zn Flow -- $115 to $167/MWh

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.

Sandia National Laboratories

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

LCOE for alternative and conventional energy

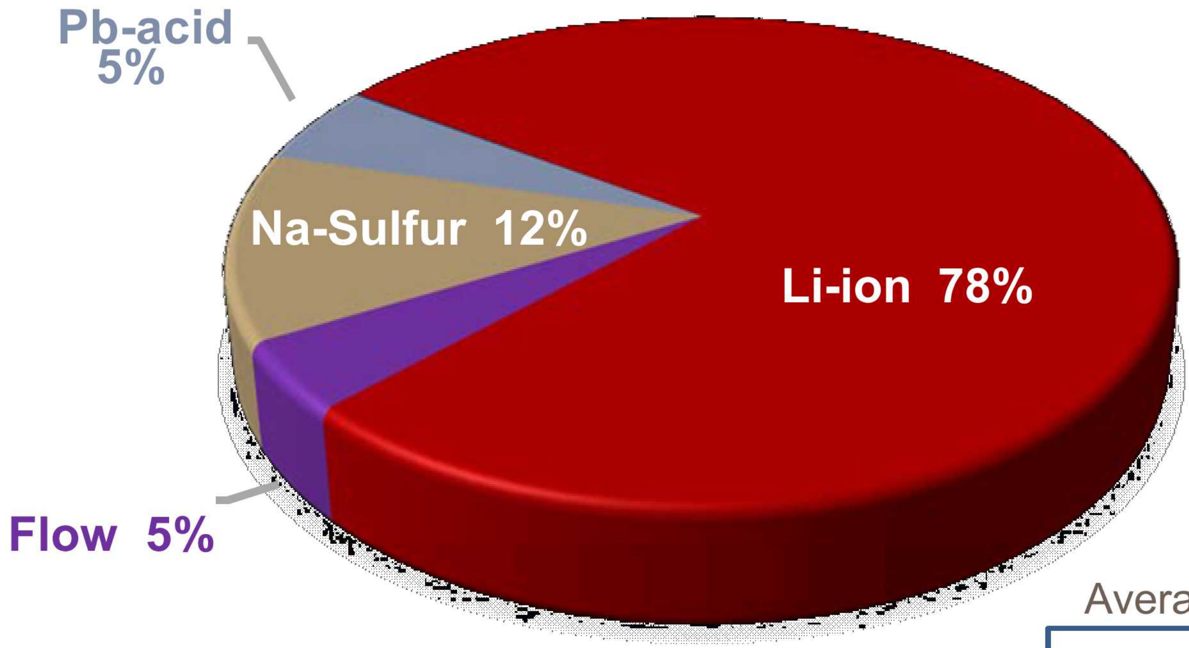


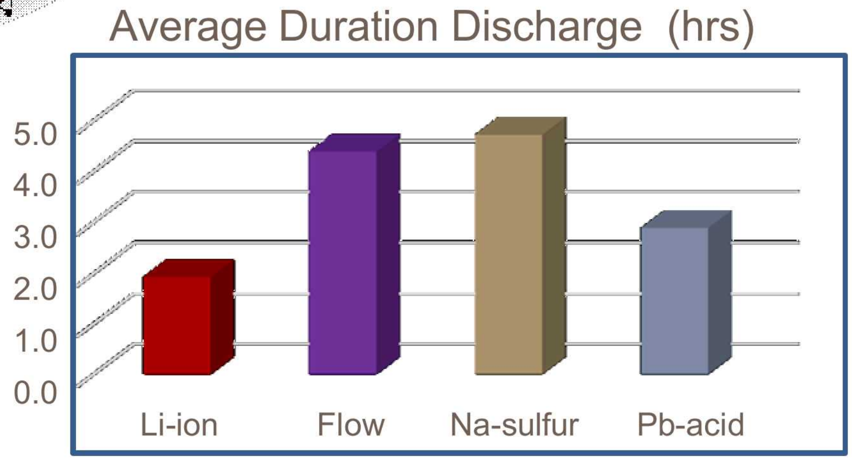
Remember, PV + Storage . . .

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



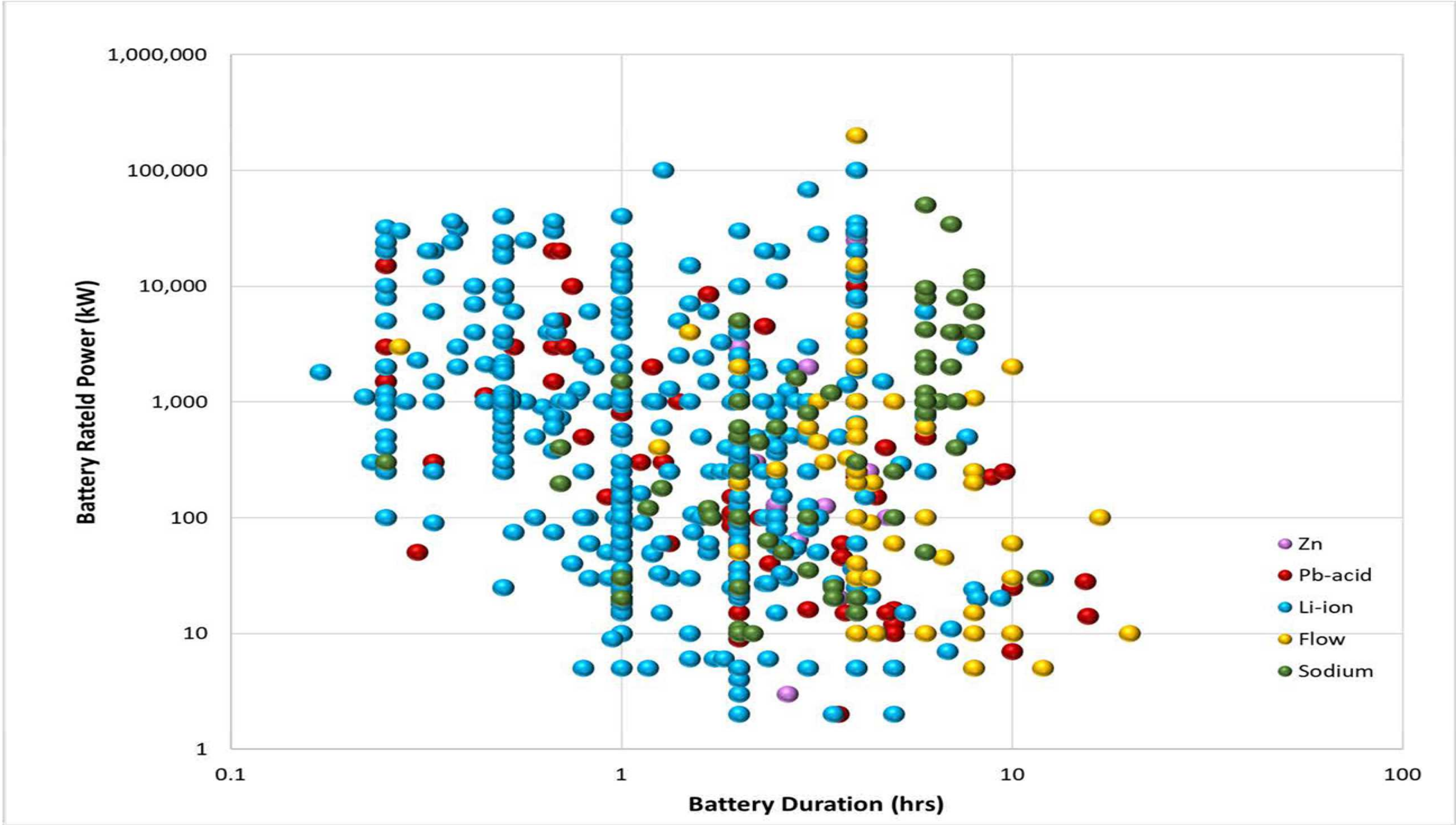


**Operational as of Nov. 2017 – being updated for 2018*

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

Energy Storage Association

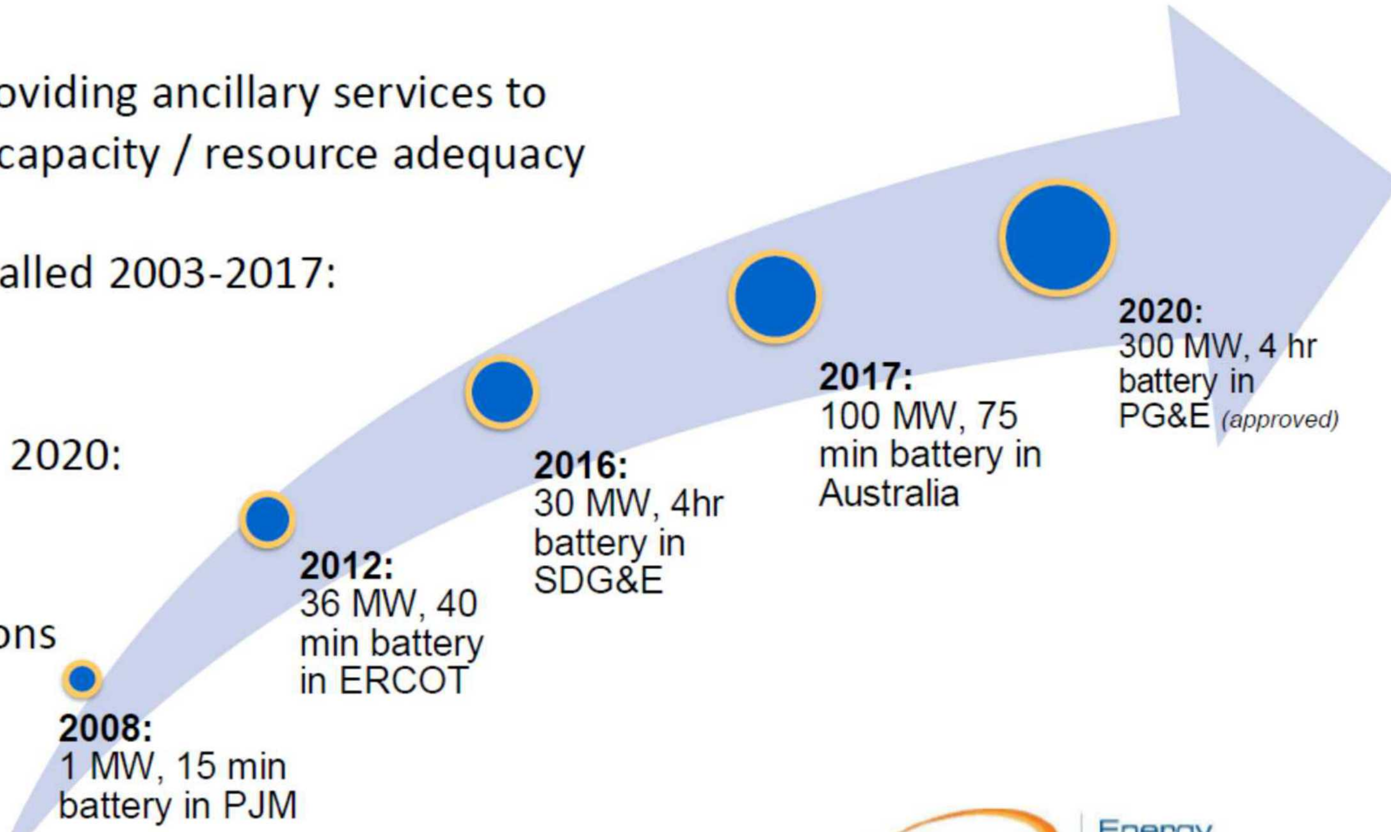
As costs go down, size and duration go up

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

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

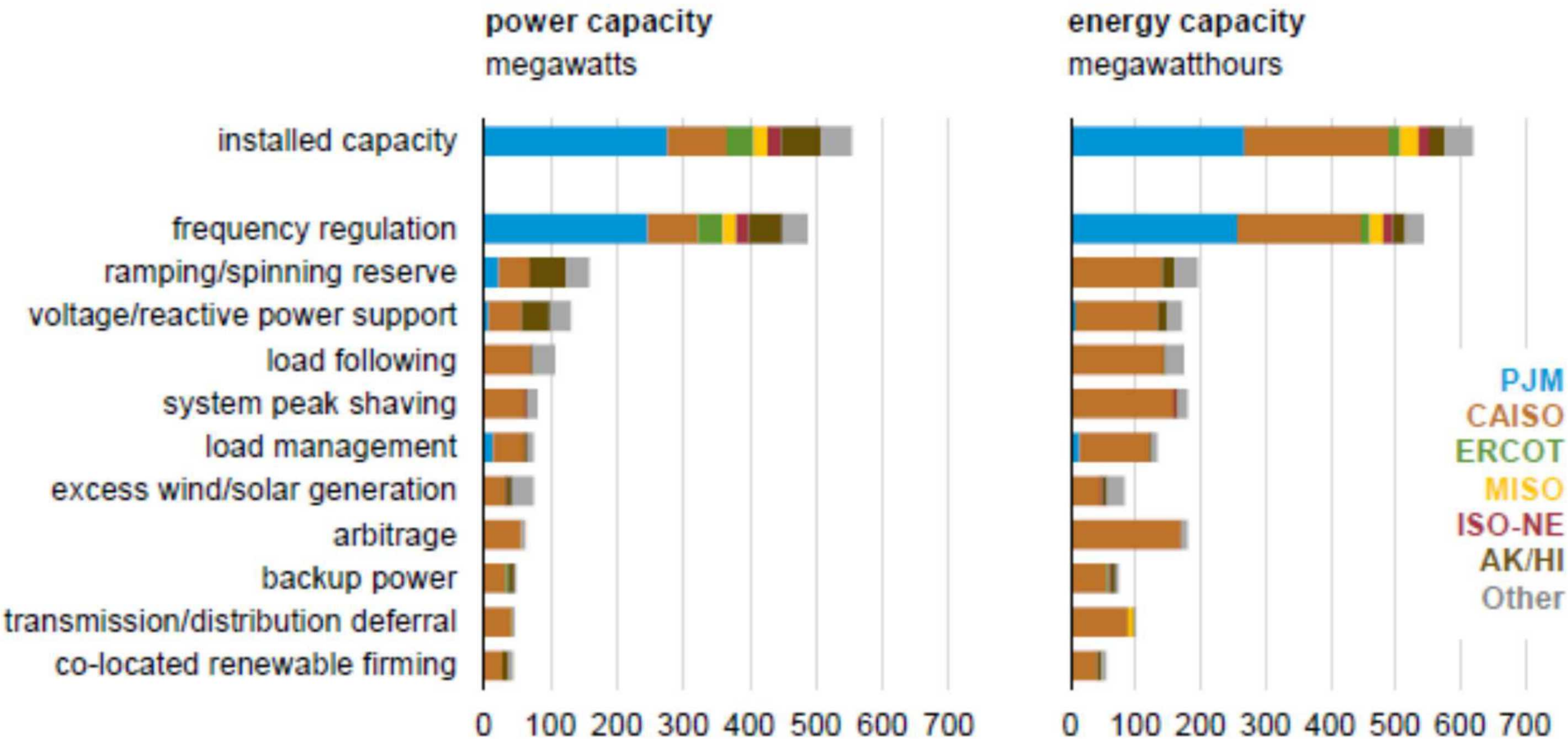
Single PG&E battery in 2020:
300 MW / 1200 MWh

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



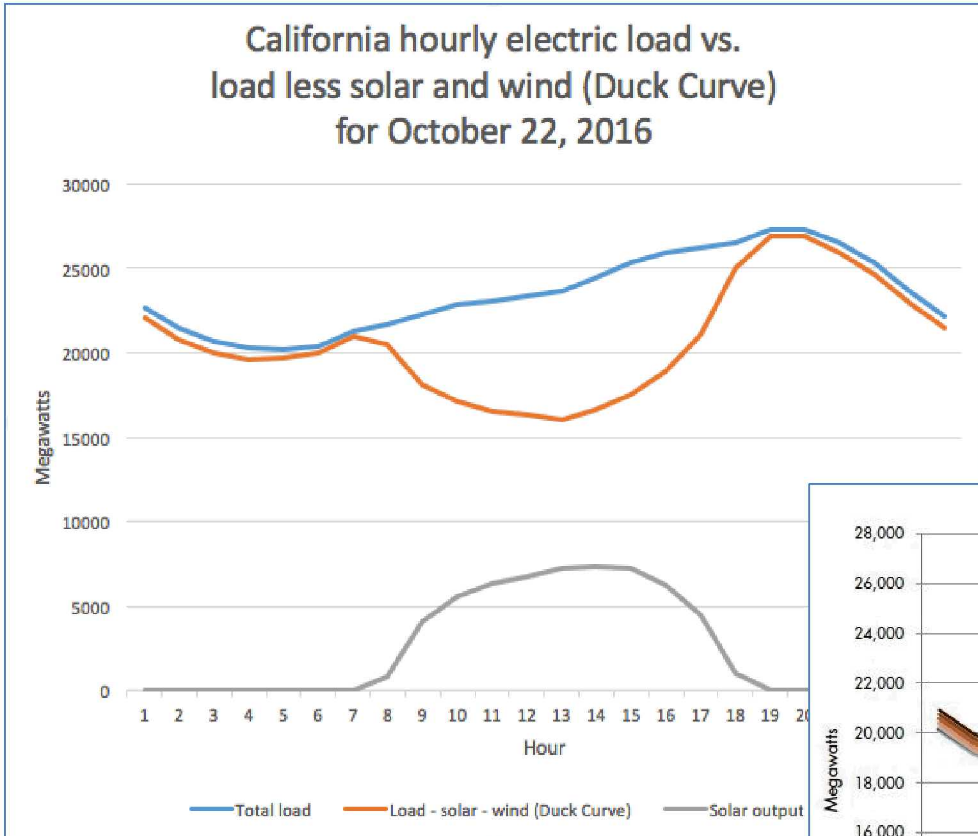
Energy Storage Association

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

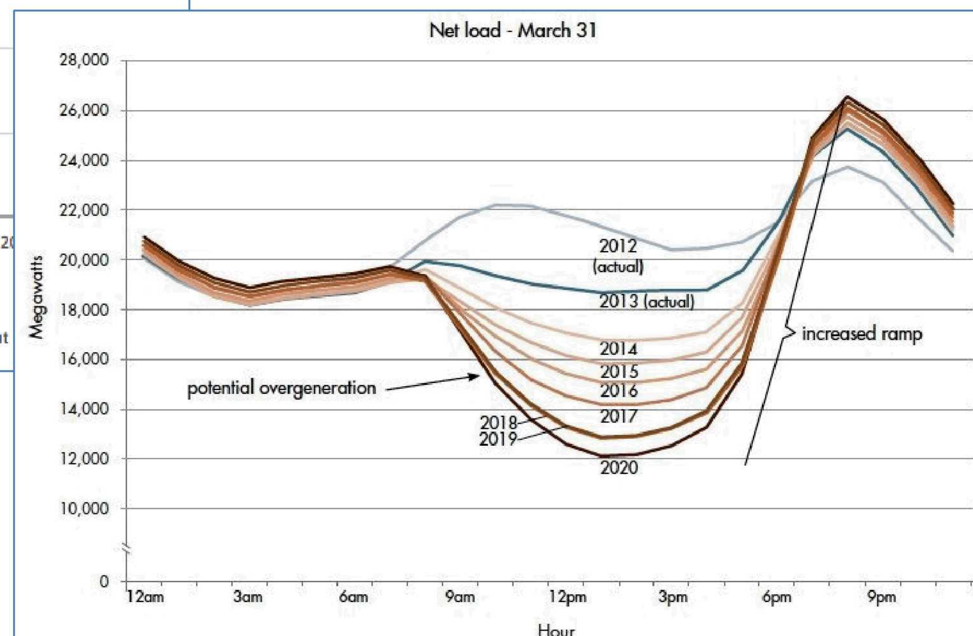


USEIA, U.S. Battery Storage Market Trends, 2018

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

ESA 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		

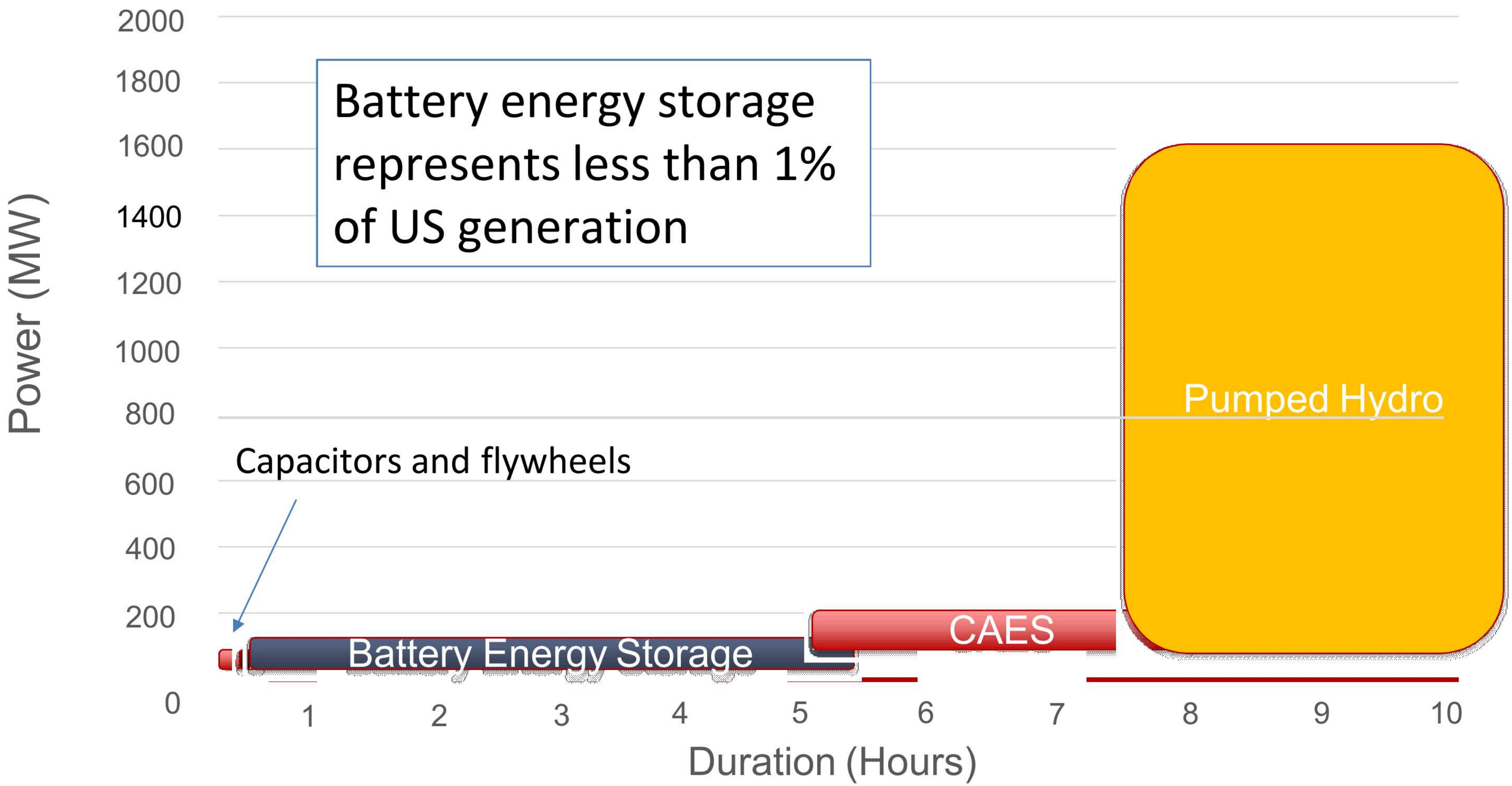
Optimal Sizing of Distributed Energy Resources for 100% Renewable Planning

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

[a]*Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-1108, USA*
[b]*Retired Fellow, NIST, Gaithersburg, MD; Current address, 250 E Alameda Apt 523, Santa Fe, NM 87501,USA*

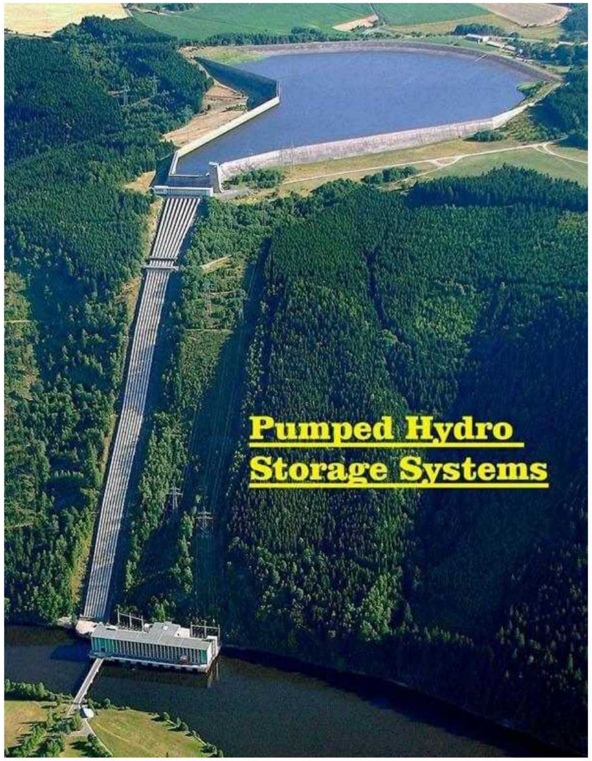
Electromechanical, Capacitor, and Thermal Technologies

Energy Storage Technologies



Pumped Hydro

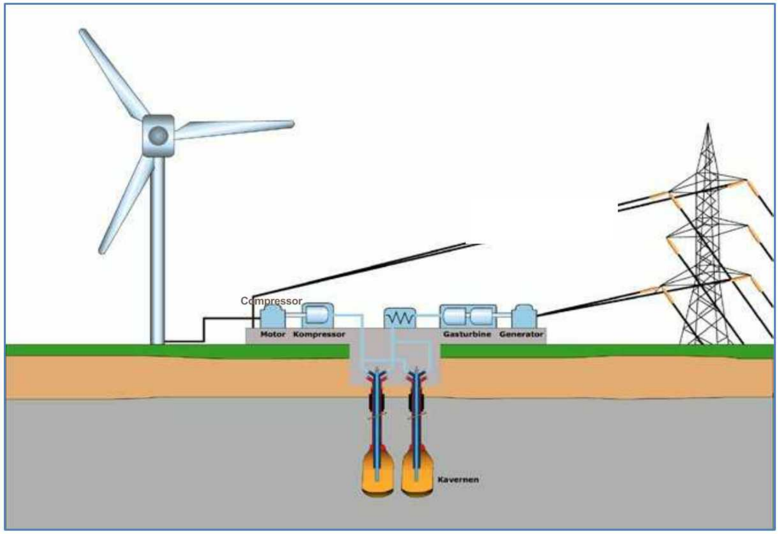
- Characteristics
  - Large global and US capacity, but difficult to site new projects in the US
  - High energy capacity (4h – 22h)
  - High power capacity (GWs)
  - Slower response (seconds to minutes)
  - Very mature technology
  - Long Life (20+ years)
  - High initial costs
- Broad applications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



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

Compressed Air (CAES)

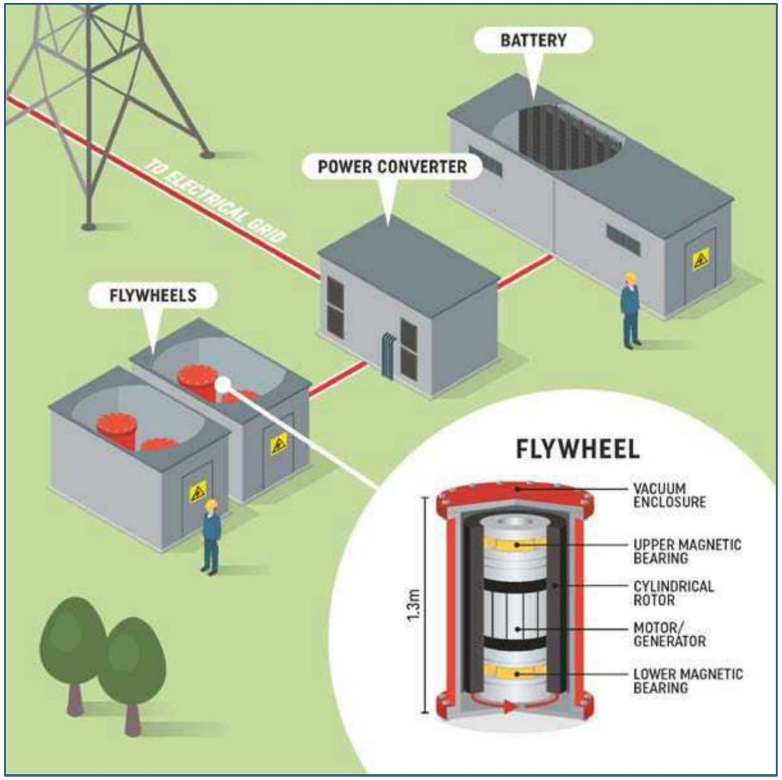
- Characteristics
  - High energy capacity (2h – 30h)
  - High power capacity (100s MW)
  - Long life (20 - 30 years)
  - Slower response (seconds)
  - Must be sited above geological repository (e.g., deep salt caverns)
  - Initial costs are high
- Broad applications



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

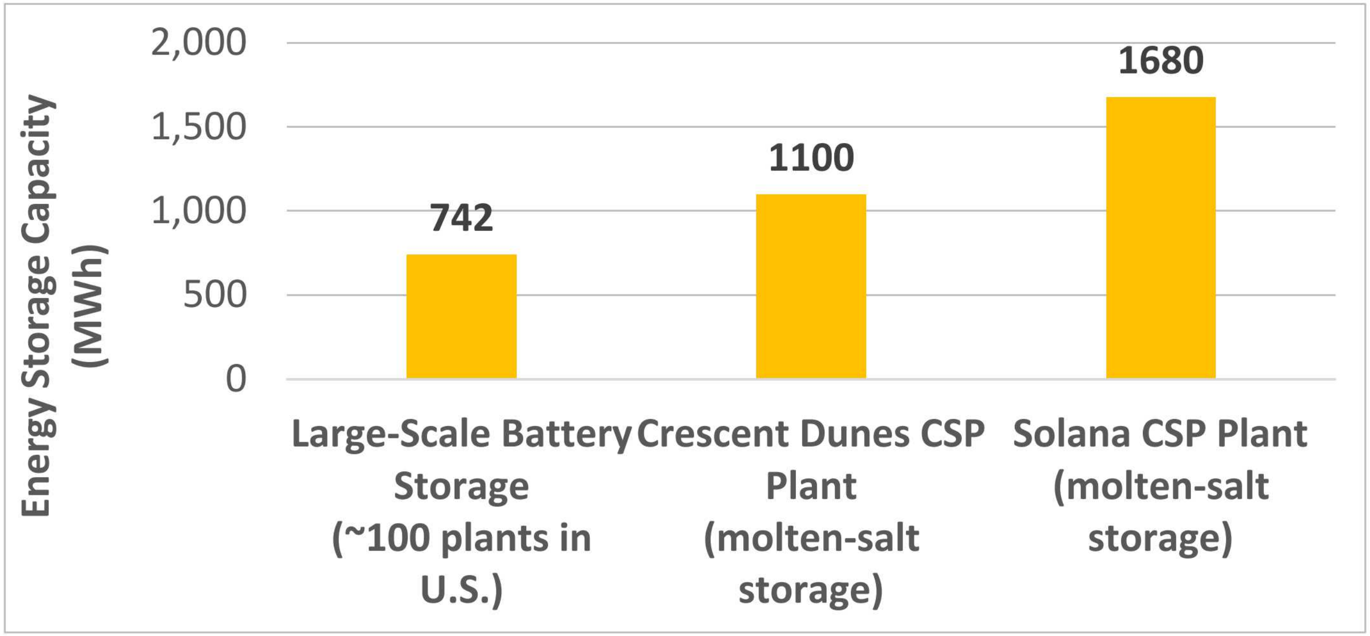
- Characteristics
  - Very long life
  - Fast discharge (milliseconds)
  - High round trip efficiency
  - High cost

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

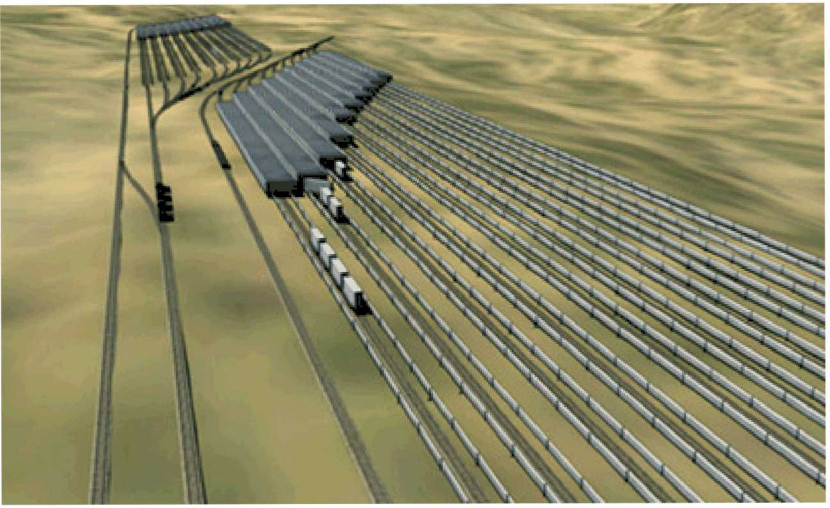
Gravity energy storage

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

Vault Energy Storage

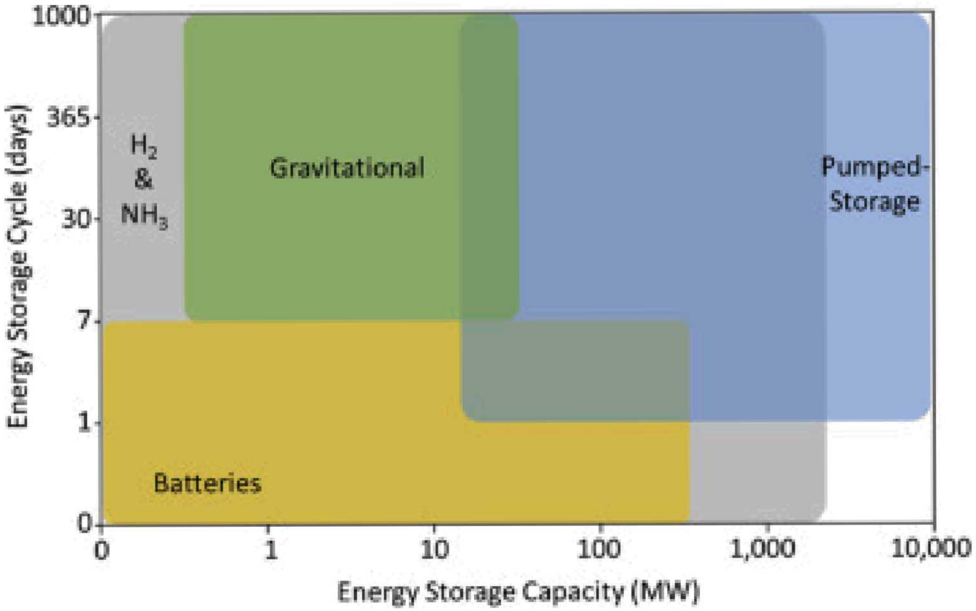
Energy Vault

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

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

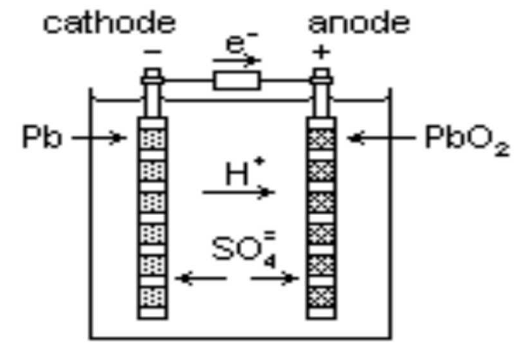
(Reduced carbon) → (Oxidized carbon)

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

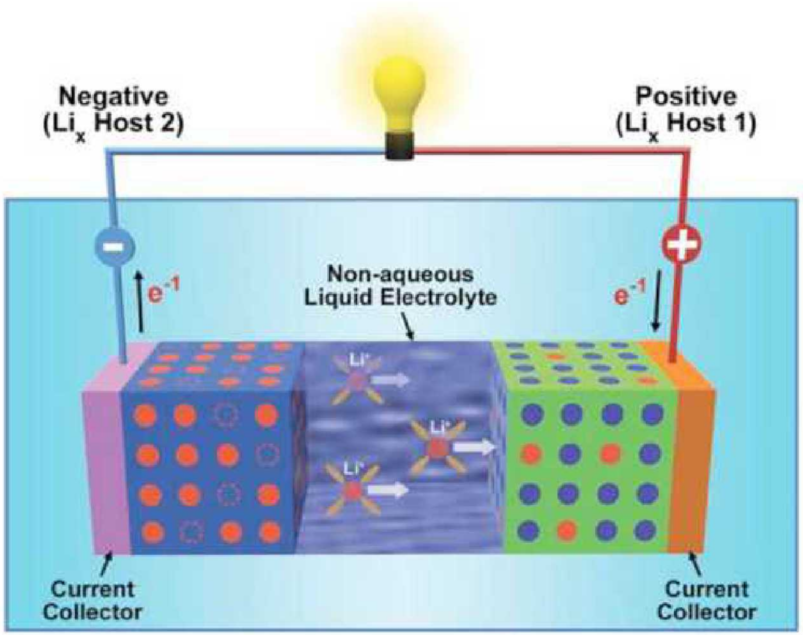
Reduced lead in the presence of oxidized lead, and in a sulfuric acid electrolyte, results in lead sulfate and water, and electrons move with a force of 2 V.

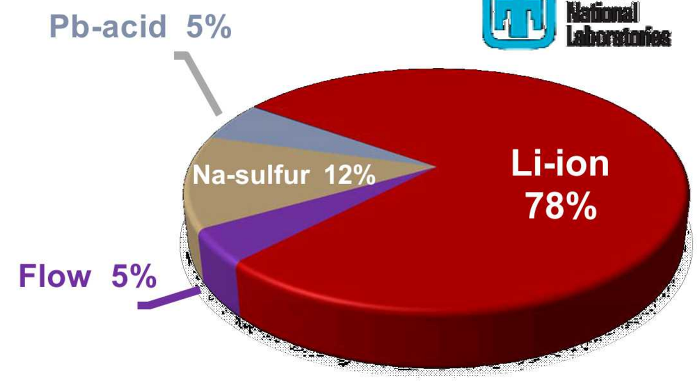


Lead Acid Cell

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.

Li-ion Batteries





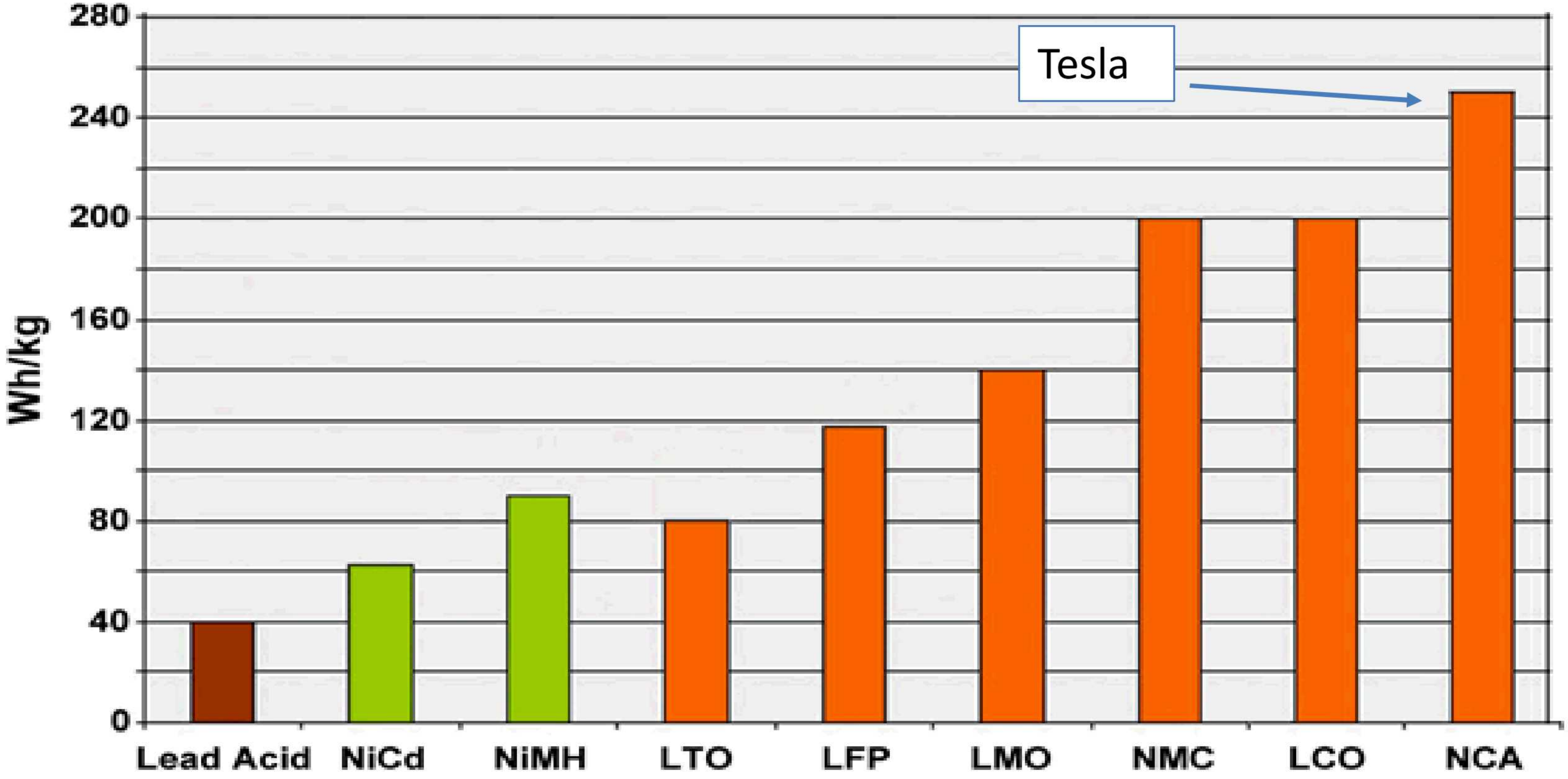
Chemistries	
$LiCoO2$	iphone
$LiNiO_2$	
$LiNi_xCo_yMn_zO_2$	Volt
$LiNi_xCo_yAl_zO_2$	Tesla
$LiMn_2O_4$	
$LiMn_{1.5}Ni_{0.5}O_4$	
$LiFePO_4$	
$LiMnPO_4$	
$LiNiPO_4$	
$LiCoPO_4$	

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.

https://batteryuniversity.com/learn/article/types_of_lithium_ion

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

Sandia National Laboratories

Tesla and the 18650 Li-ion cell

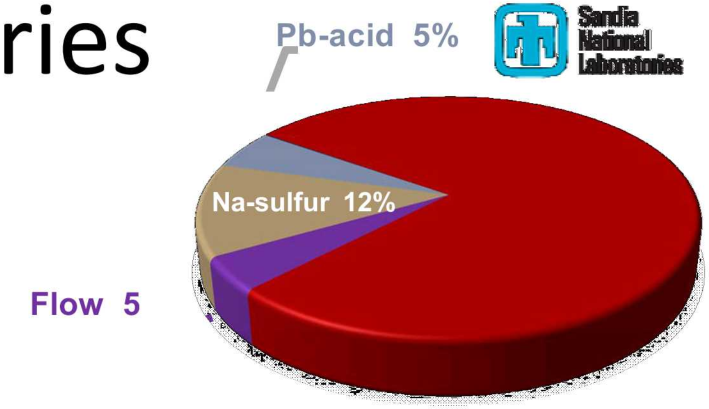
Tesla Model S Battery Pack

7104 cells

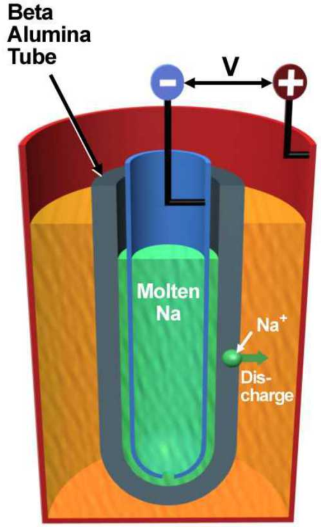
18650 cell format used in 85 kWh Tesla battery

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

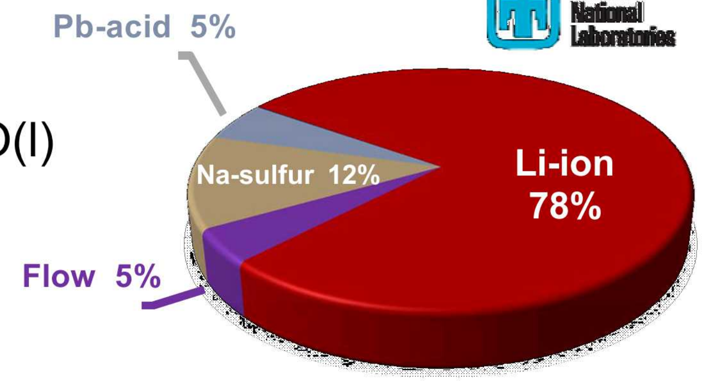
Sodium (Na) -- Sulfur Batteries



- 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



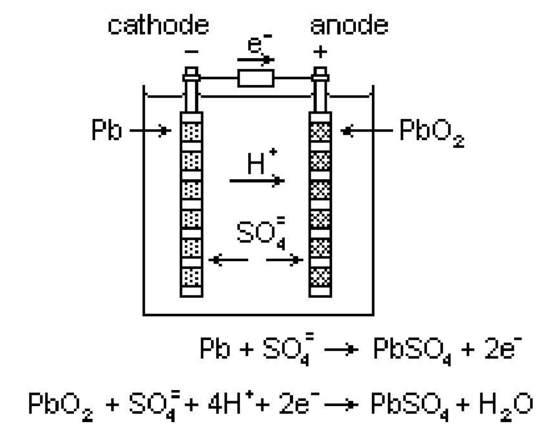
Lead Acid Batteries



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

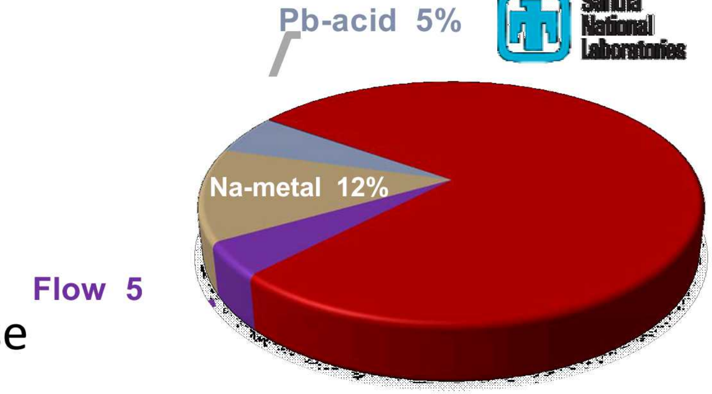
Characteristics

- 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

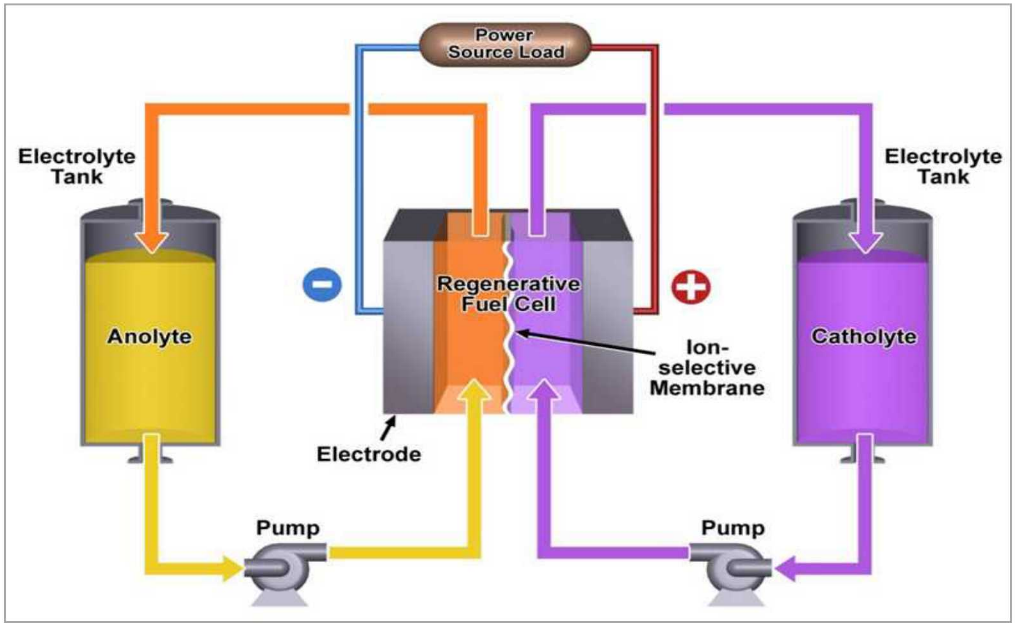


Lead-Acid Storage Cell

Flow Batteries

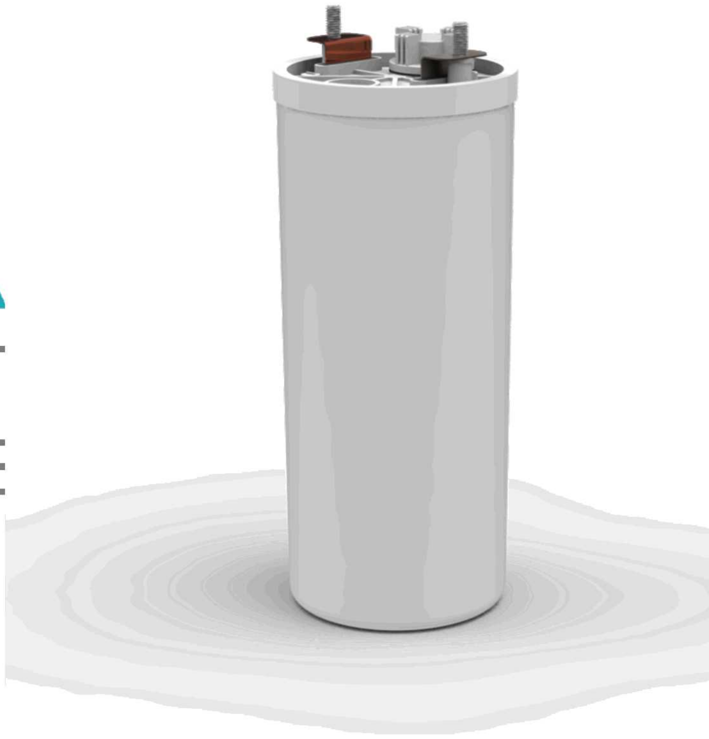


- Wide range of chemistries available
  - Vanadium, zinc bromine, iron chromium
- Flexible -- increase volume of tanks to increase energy (no new racks, no new controllers)
- Suitable for wide range of applications, 5 kW to 10s MW
- Potential long cycle life (tens of thousands) and high duration (10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



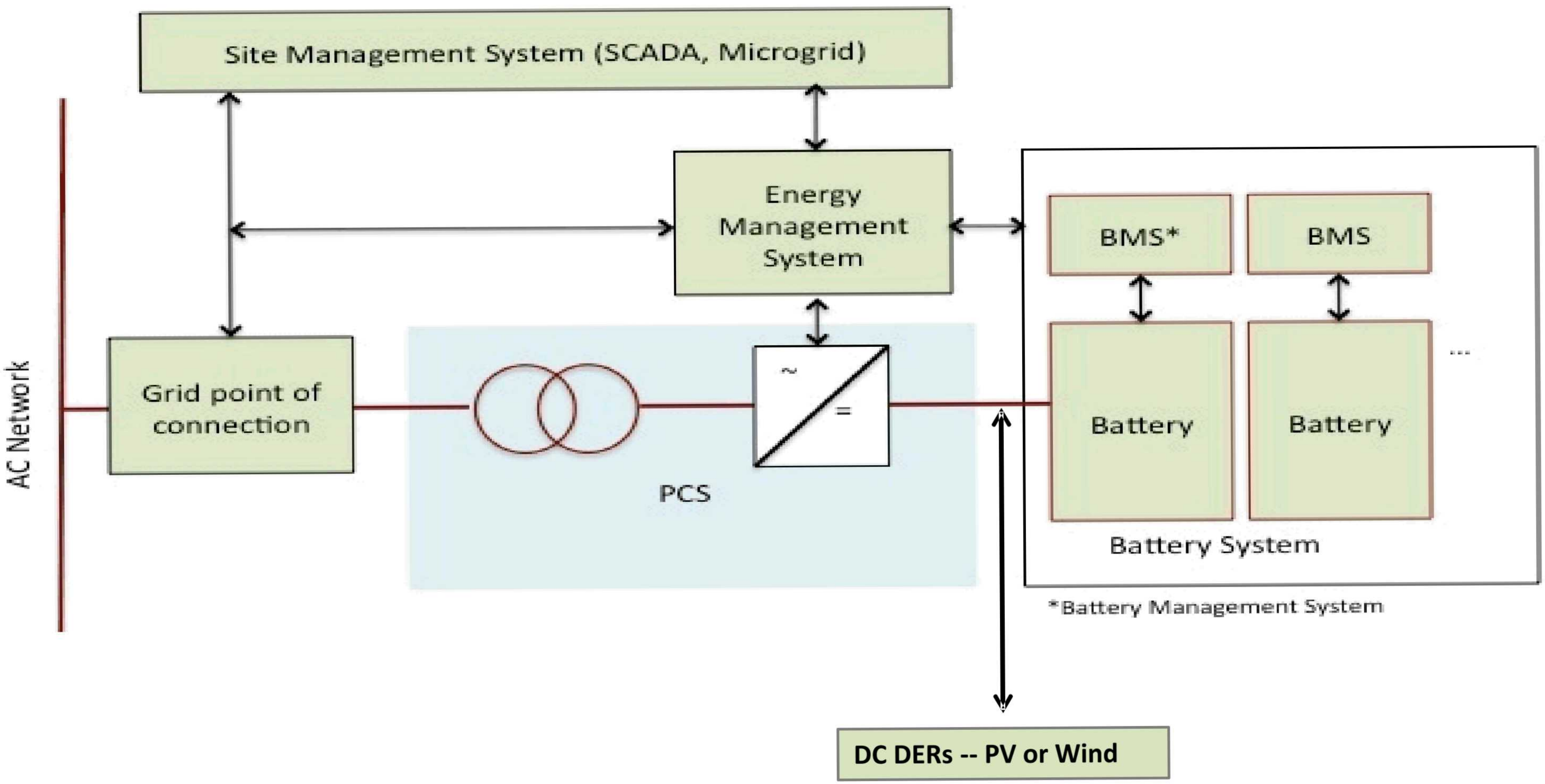
Zn-MnO_2 alkaline batteries

- 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



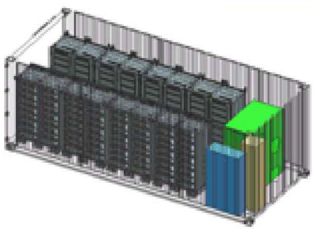
Battery Energy Storage Systems (BESSs)

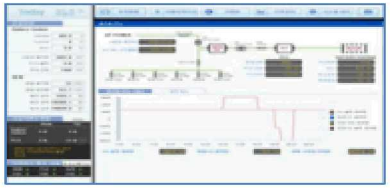
BESS topology



BESS elements

Battery Storage	Battery Management System (BMS)	Power Conversion System (PCS)	Energy Management System (EMS)	Site Management System (SMS)	Balance of Plant
• Batteries • Racks	• Mgmt. of the battery --Efficiency --Depth of Discharge (DOD) --Cycle life	• DC to AC, AC to DC ---Bi-directional Inverter --Transformer, switchgear	• Optimal monitoring and dispatch for different purposes --Charge/discharge --Load management --Ramp rate control --Ancillary services • Coordinates multiple systems	• Distributed Energy Resources (DER) control • Synchronization with grid • Islanding and microgrid control • Interconnection with grid	• Housing • HVAC • Wiring • Climate control • Fire protection • Permits • Personnel

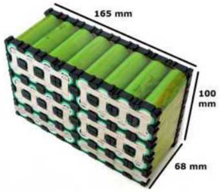




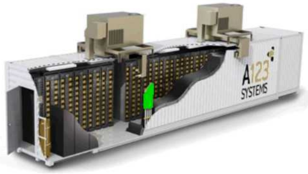
NOTE: Important to have single entity responsible for the ESS integration.

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

[DOE Energy Storage Systems Program](https://www.sandia.gov/ess-ssl/)
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

Dr. Imre Gyuk, Manager of the DOE Energy Storage Program.

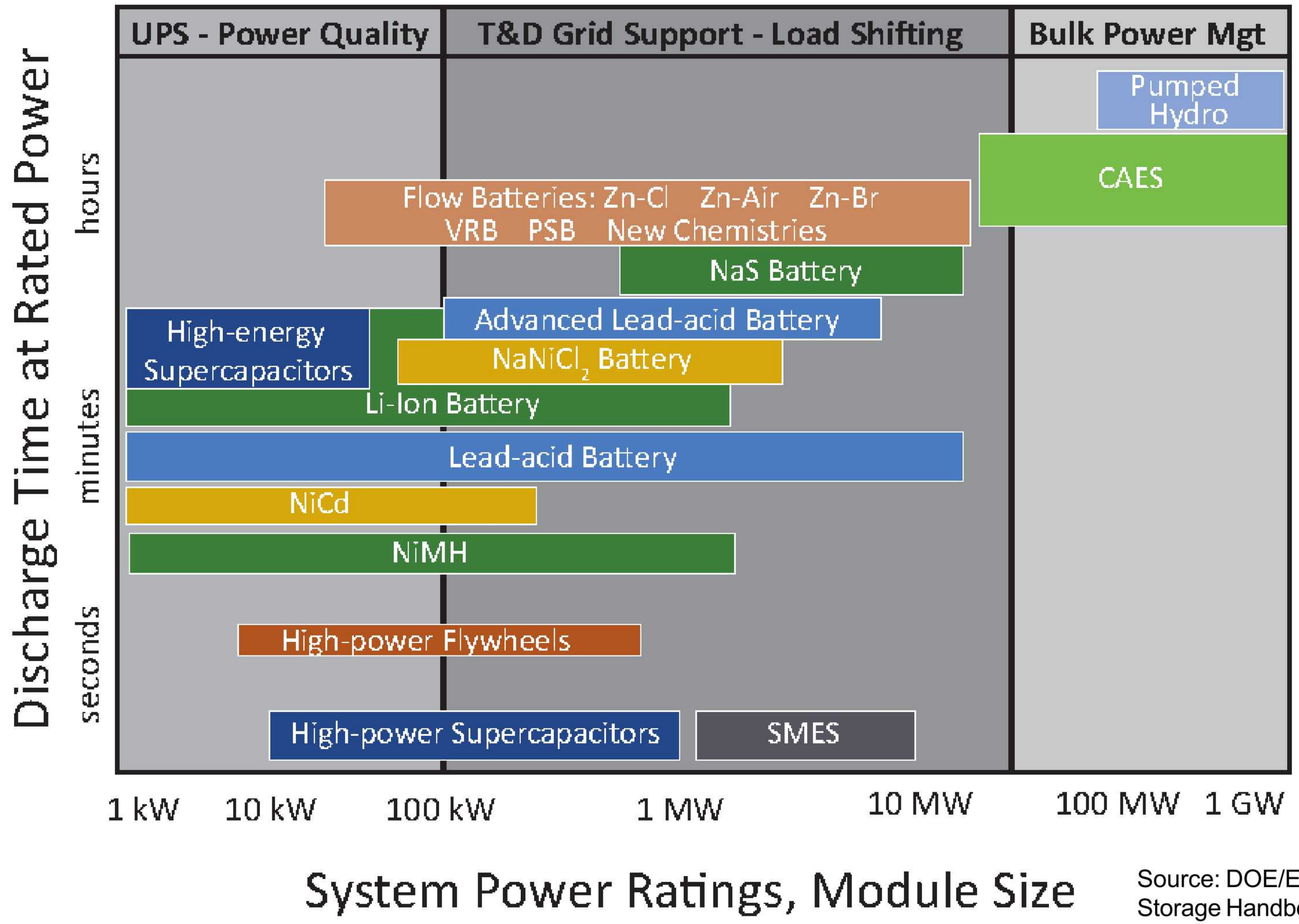
Howard Passell – hdpasse@sandia.gov – 505 284-6469

Additional Slides

ESS services and value streams

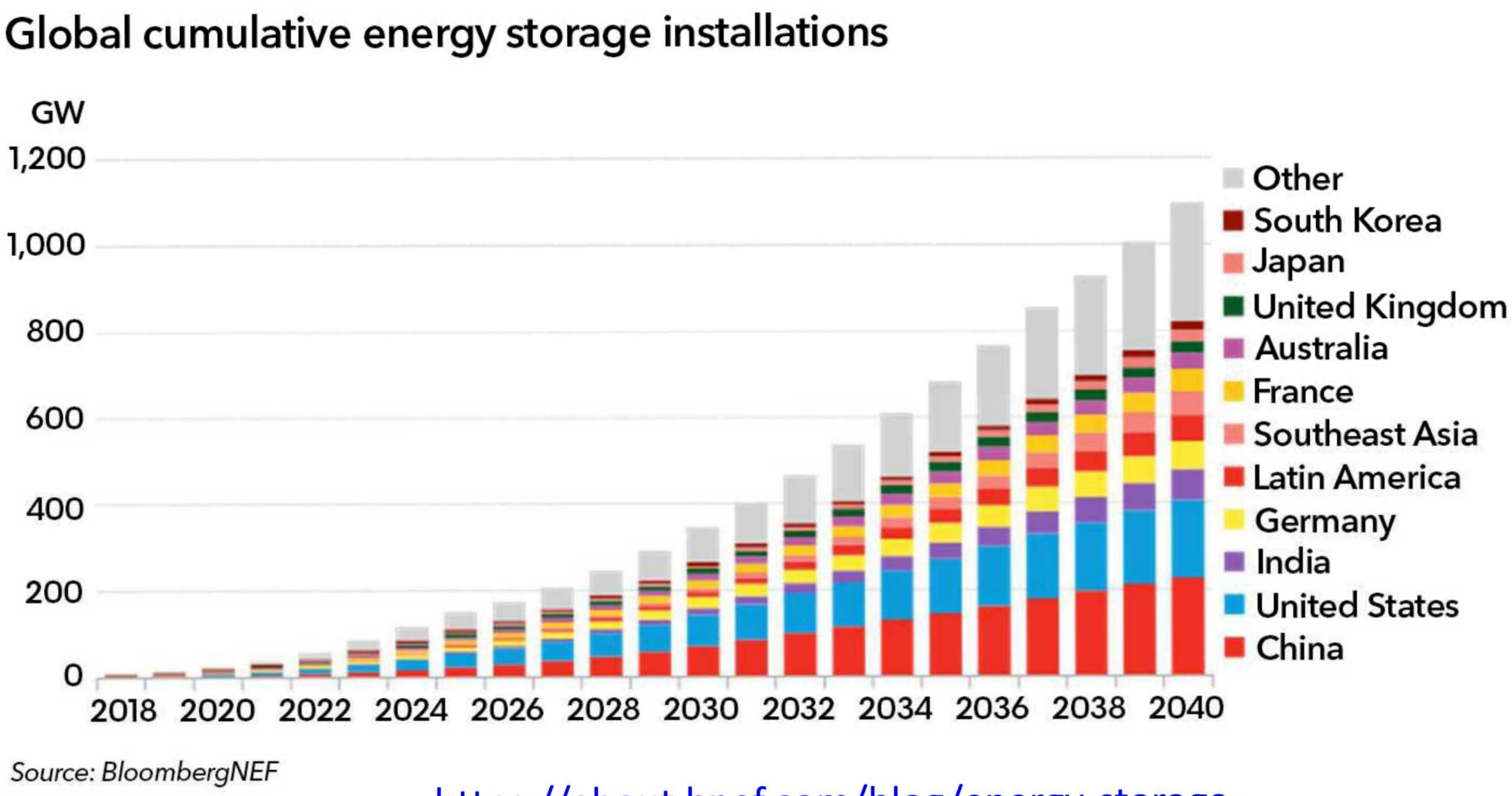
- **Frequency Regulation** – Provide *up* regulation by discharging and provide *down* regulation by charging
- **Power Quality** -- Mitigate voltage sags by injecting real power
- **Peak Shaving** - Discharge in on-peak periods and charge in off-peak periods
- **Renewables Firming** (PV, wind) -- Supplement 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

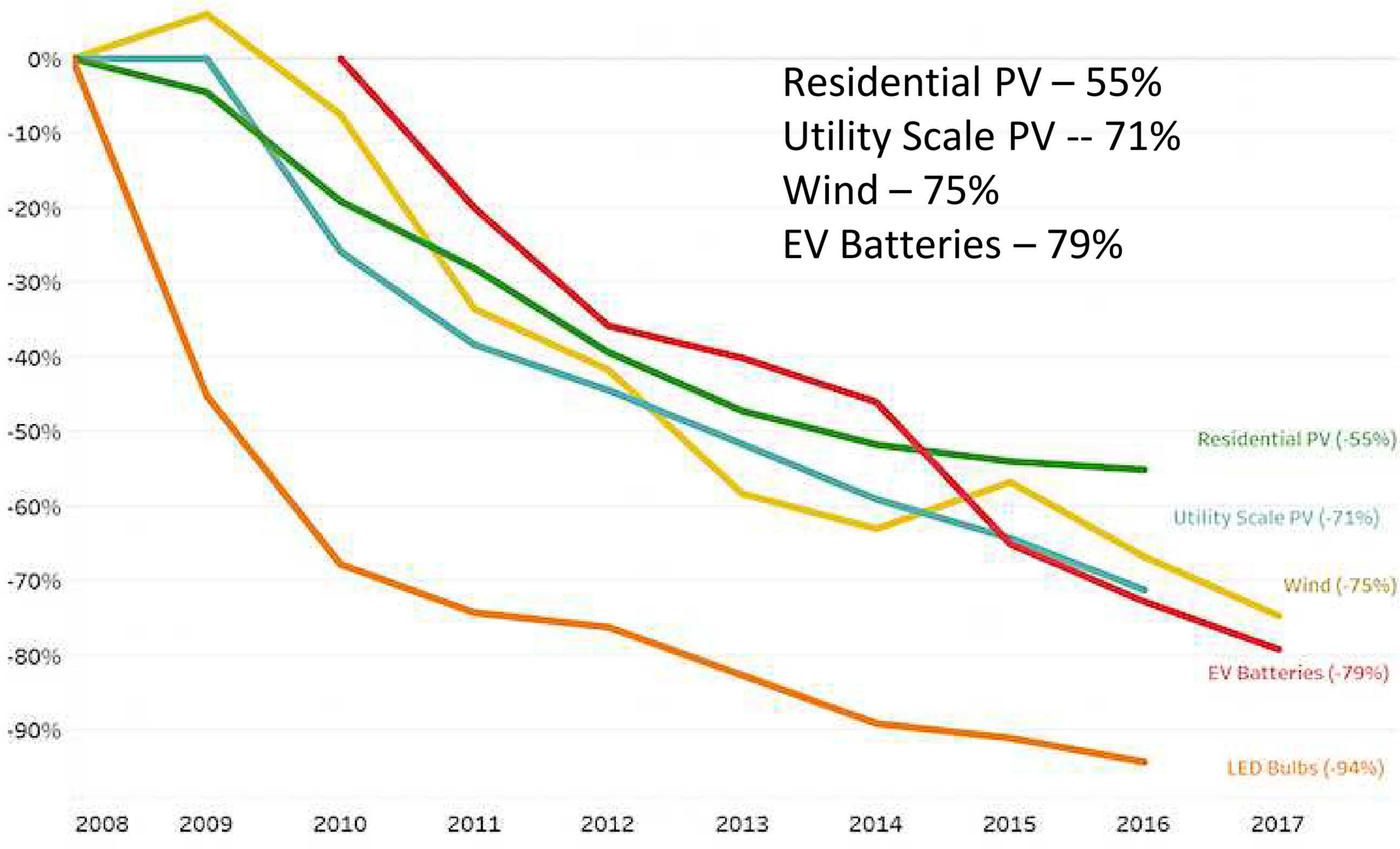
Global ES



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

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

Howard Passell, hdpasse@sandia.gov, 505 550 5752