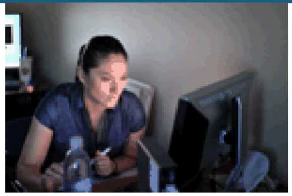
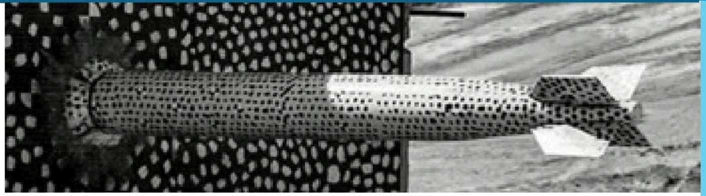
SAND2020-0523C

Energy Storage Overview





Howard Passell, Ph.D.

Sandia National Laboratories

Nevada Public Utilities Commission, 1/22/20

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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

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)
New Mexico PRC workshops are ongoing
NECPUC, New Jersey, Texas, and Iowa PUC workshops are being planned

Clean Energy States Alliance
Pacific Northwest National Laboratory
Oak Ridge National Laboratory
Georgia Public Service Commission
Florida Public Service Commission
New Jersey Board of Public Utilities
State of California Energy Commission
New England Conference of Public Utilities Commissioners necpuc
State of Hawaii
Kentucky Public Service Commission
PRC New Mexico Public Regulation Commission

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 phasing out
- PV + storage is supplanting old and new gas peakers
- Wholesale and retail markets are shifting
- 100-year-old electricity business model is history

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

Energy storage (ES) is fundamentally different

Energy storage . . .

- Is both a load and a generation source
- Facilitates demand management
- Defers new generation and transmission infrastructure
- Unleashes the power of renewables
- Provides various services and value streams
- Provides flexibility, resilience, and reliability

ES Terms & Language

- 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.

"Energy" applications >30 min. time scale, long duration of energy

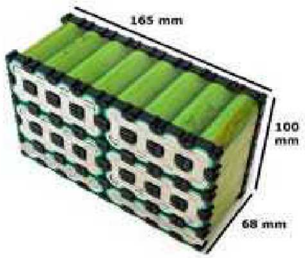
"Power" applications <15 min. time scale, fast control of the electric grid

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

ES Terms & Language, cont'd

ES evaluation focuses on:

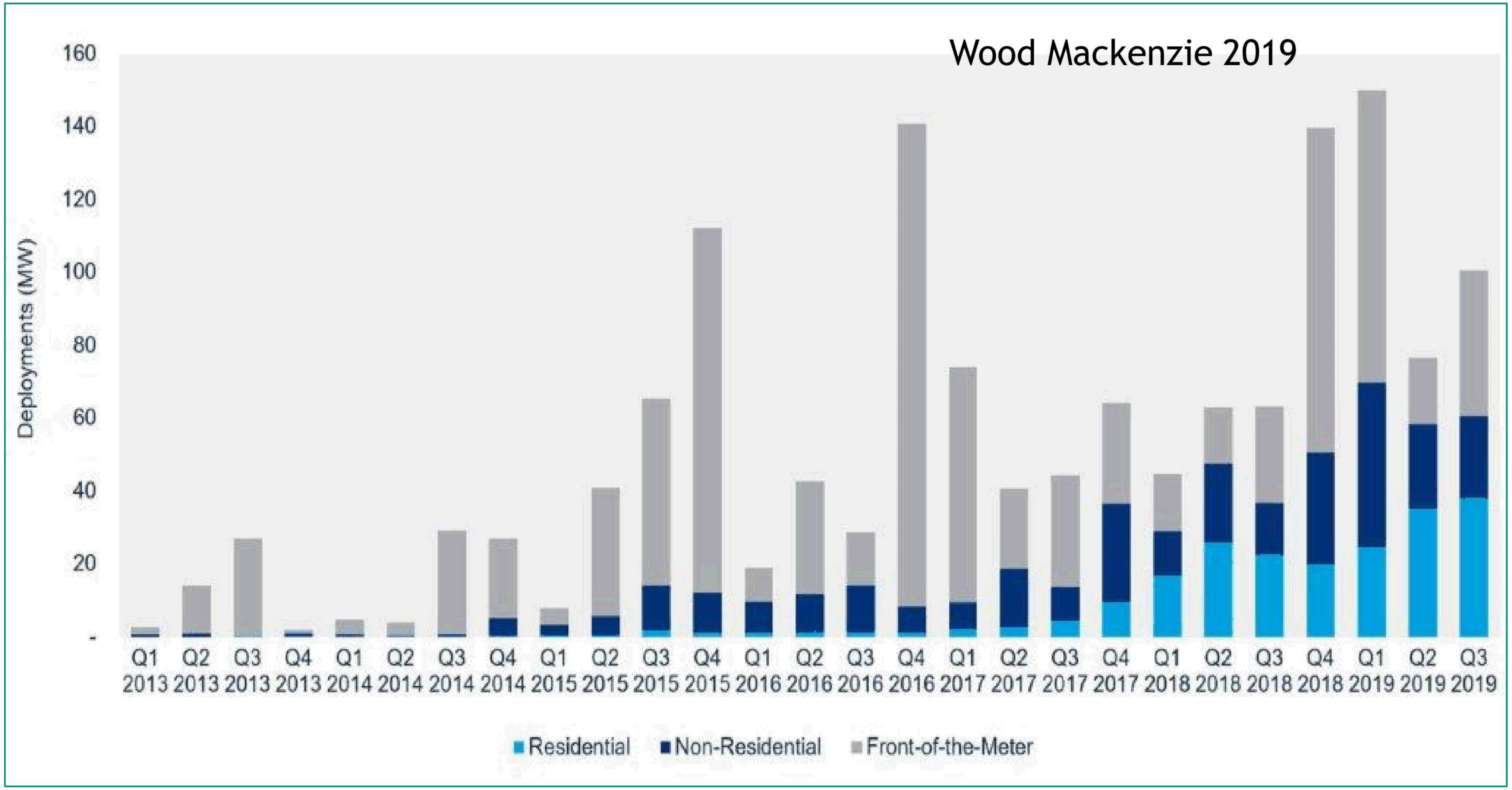
Cost, Capacity, Duration, and Lifetime



- **Cost** -- $/kWh/cell
- **Capacity -** kW, MW, TW
- **Duration** – kW/h, MW/h, etc.
- **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 . . .)

U.S. Battery Deployments, 2013 - 2019

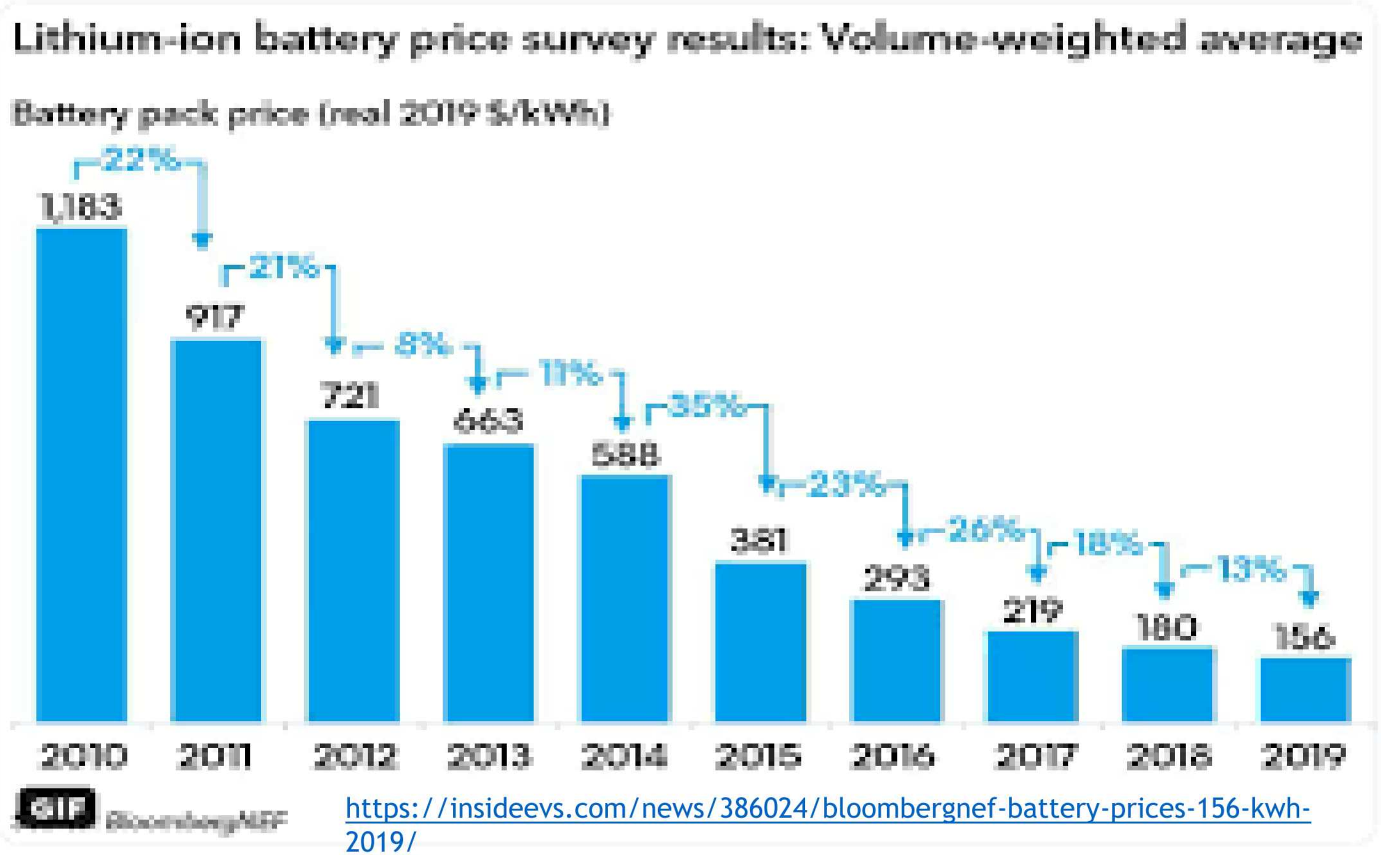


899 MW of grid-scale storage deployment in US by 2019, 2.5 GW projected for 2023 (US EIA)

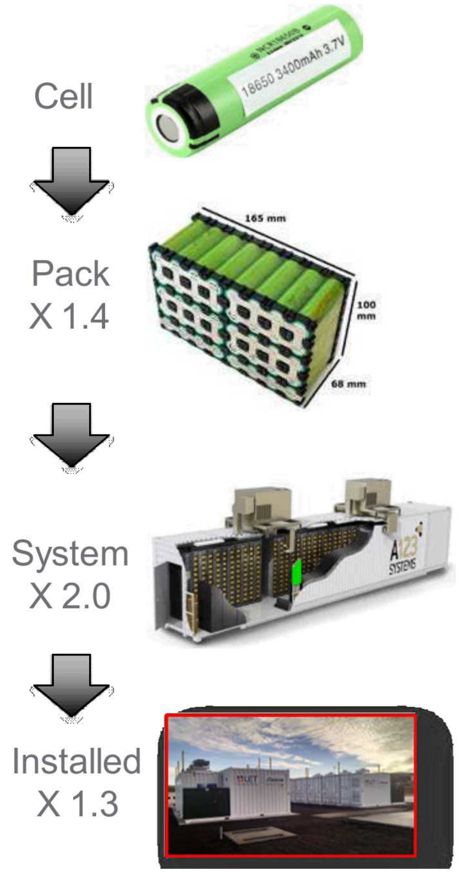
Grid-scale battery storage still < 0.1% of U.S. generation capacity

EV's < 1% of vehicles sold in US

Battery costs are dropping fast



https://insideevs.com/news/386024/bloombergnef-battery-prices-156-kwh-2019/

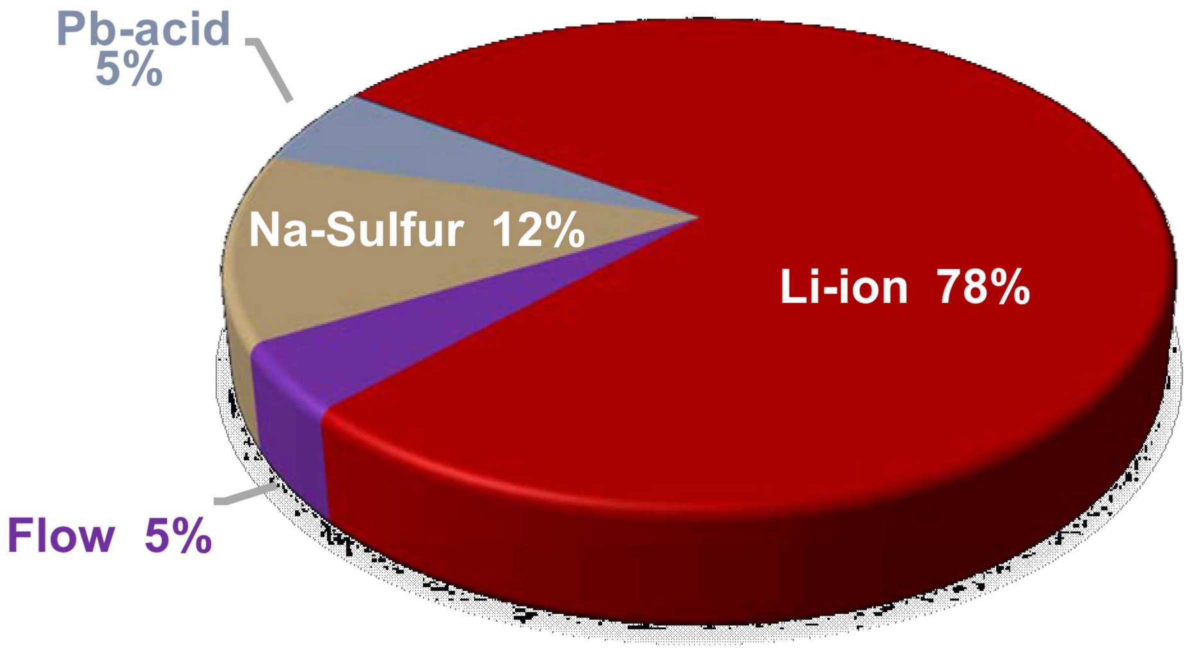


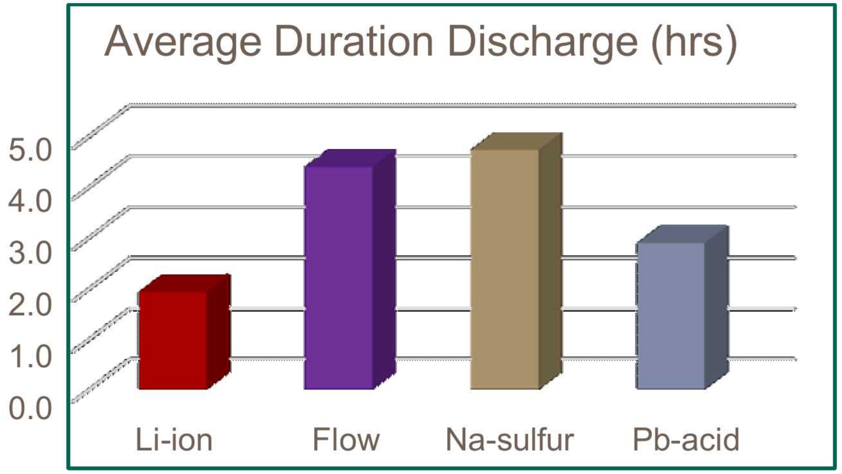
13 kWh Tesla Powerwall now sells for about $481/kWh

$150/kWh cell → **$~750/kWh system**

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

Battery energy storage deployments

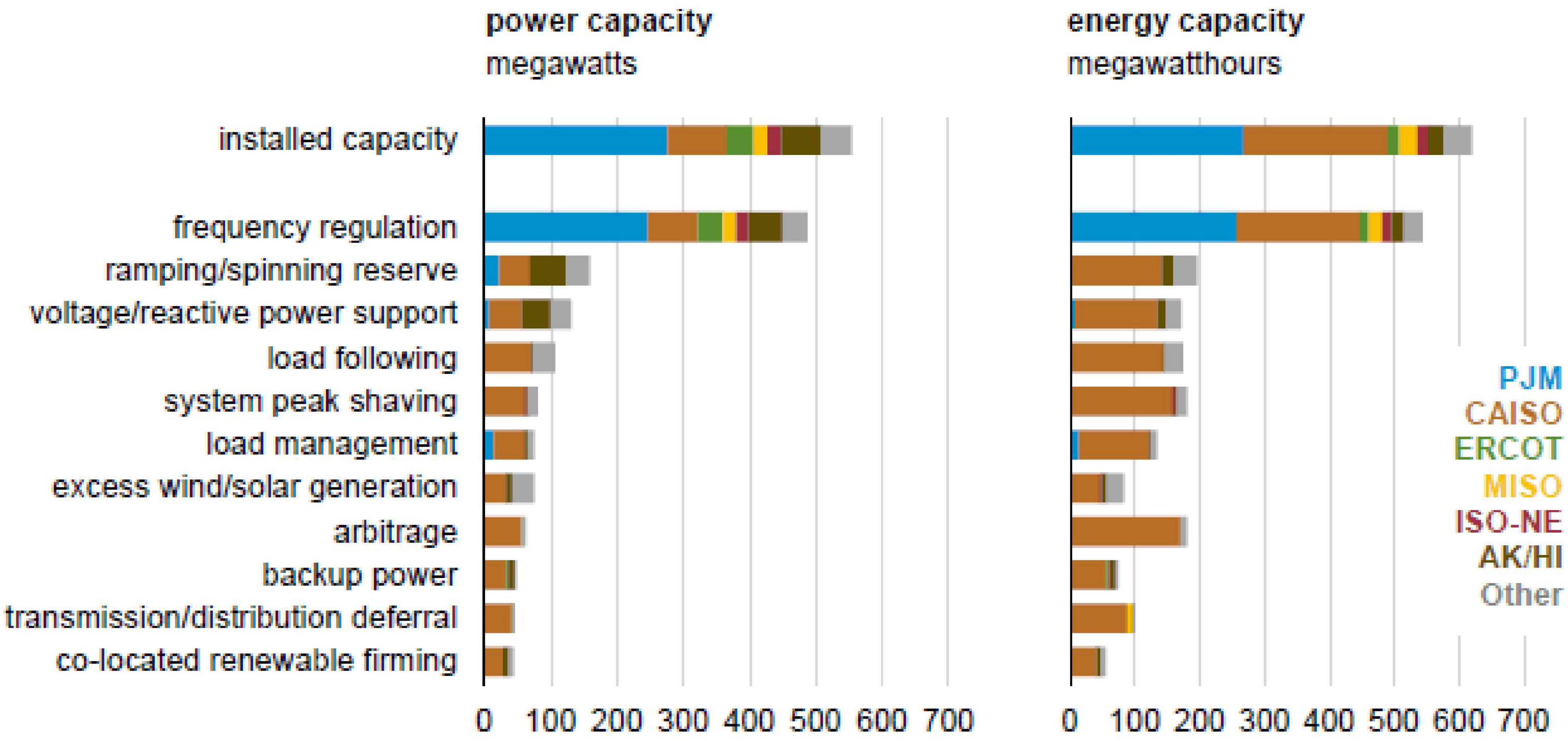




**Operational as of Nov. 2017 – being updated for 2018*

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

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



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

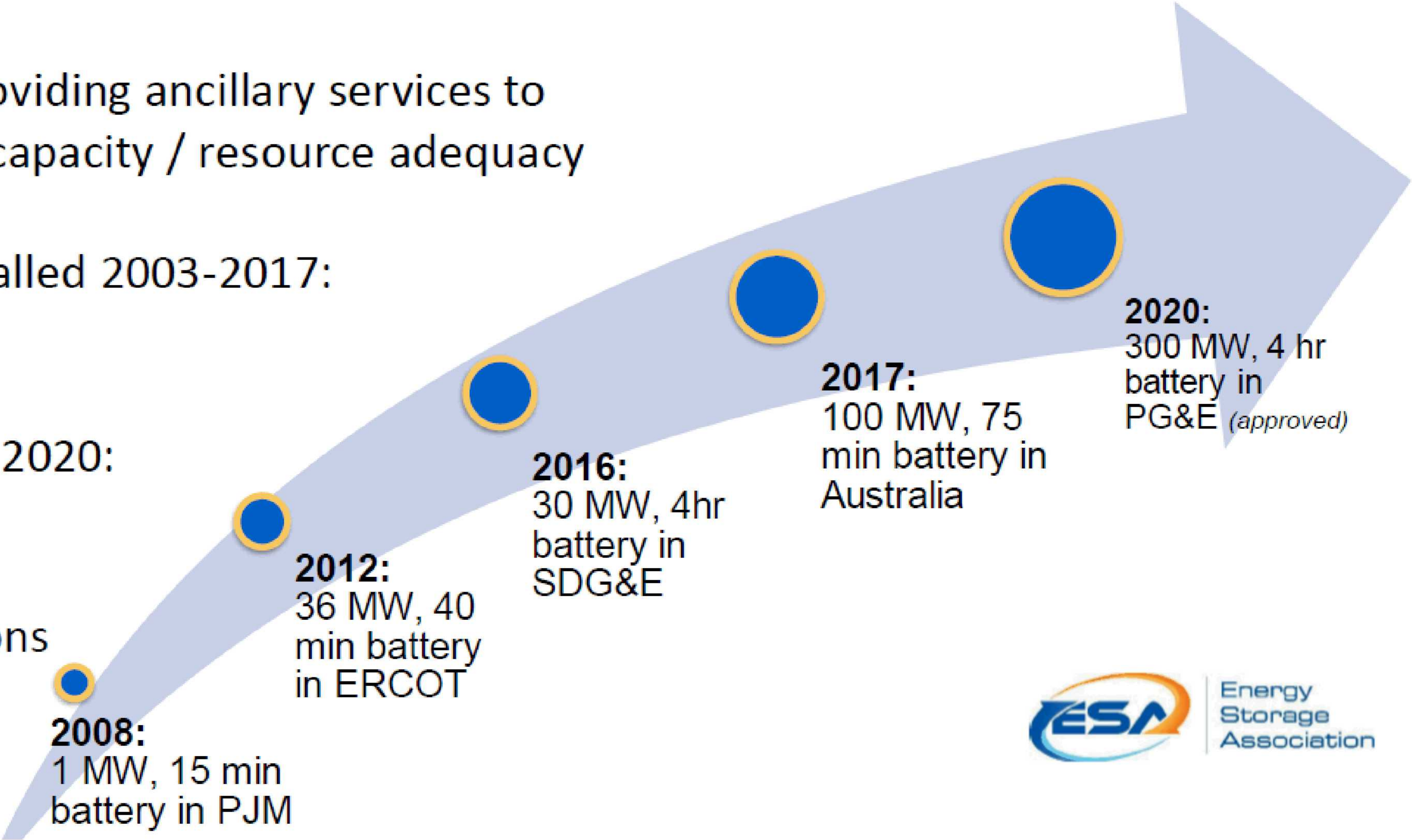
As costs go down, size and duration go up

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)



ESA Energy Storage Association

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 or 0.08%)	5 GW/25 GWh
Solar PV	818 MW[2] (0.818 GW or 8%)	10 GW
Wind	1,953 MW[3] (1.953 GW or 40%)	5 GW

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

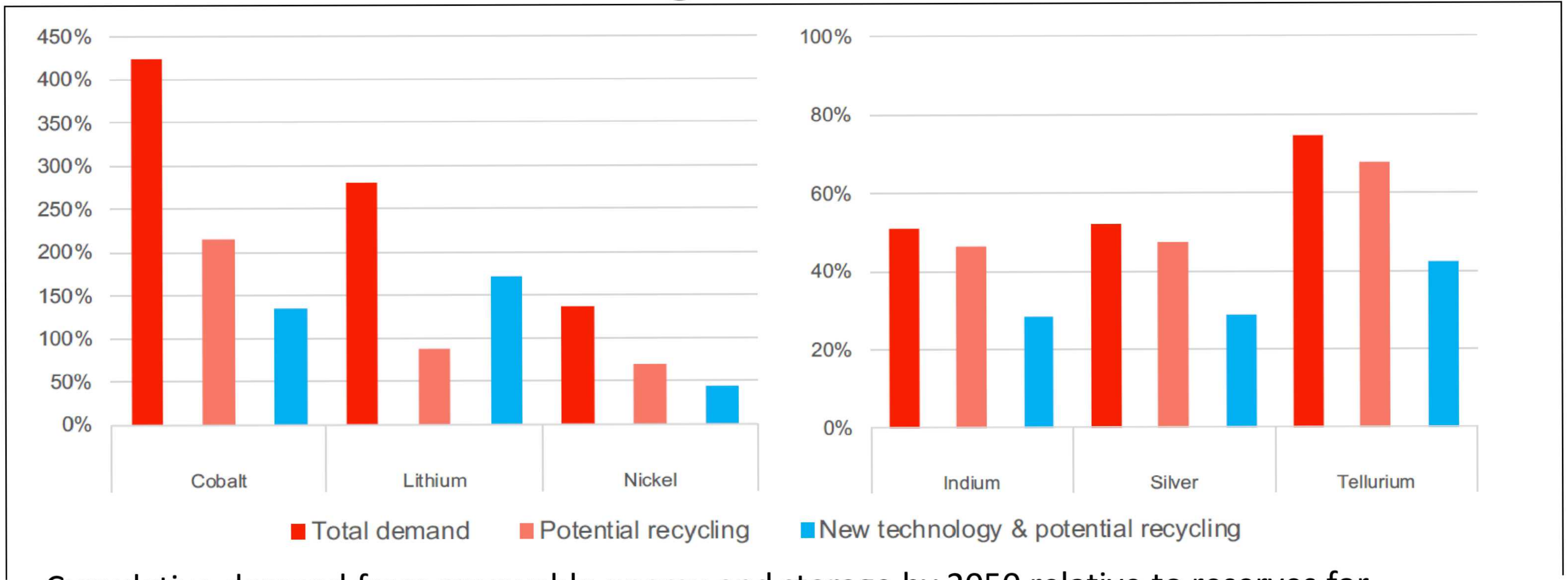
[3] American Wind Energy Assoc. 2019; [4] Copp et al., in press

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*

RE & ES Challenges



Cumulative demand from renewable energy and storage by 2050 relative to reserves for selected battery metals (left) and solar PV metals (right).

Dominish, E., Floin, N., and Teske, S., 2019. Responsible Minerals Sourcing for Renewable Energy. Institute for Sustainable Futures, University of Technology Sydney.

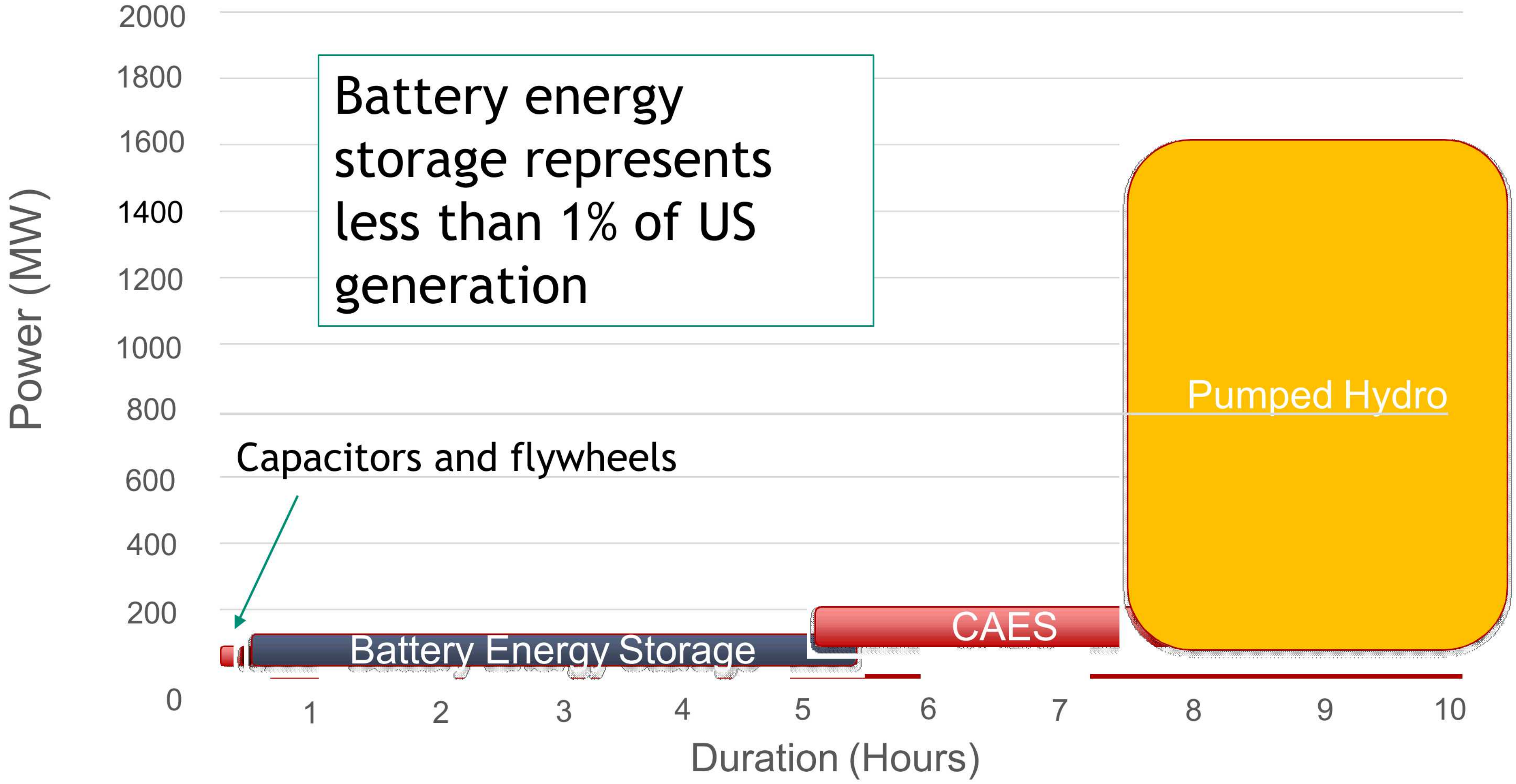
-- Toxic mining
-- Toxic waste
-- Insufficient LCA

-- Child labor
-- Inadequate recycling
-- Inadequate substitutes
-- Short duration

-- Inadequate cradle-to-cradle design (circular economy)

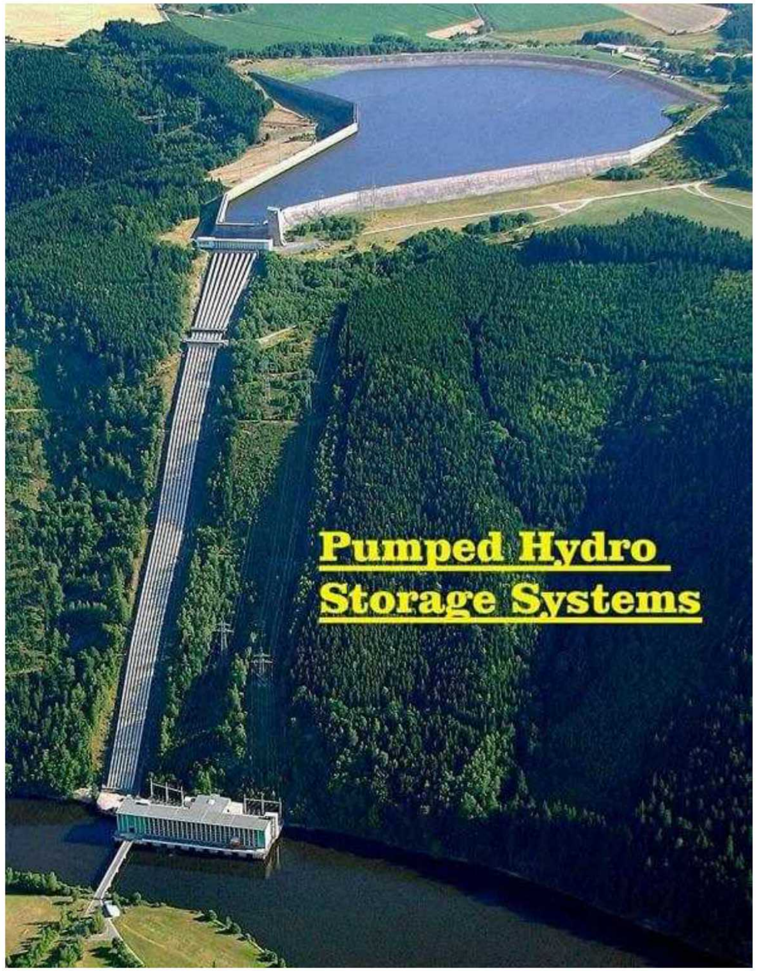
Electromechanical, Capacitor, Thermal, and Gravitational Technologies

Energy Storage Technologies



Pumped Hydro

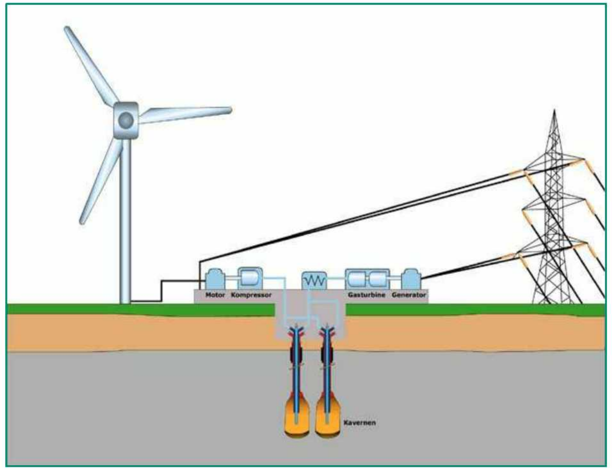
- Largest global and US ES capacity (95%)
- Potentially long duration (6h to 22h)
- High power capacity (GWs)
- Mature technology
- 70-80% round trip efficiency
- Long Life (20+ years)
- Broad applications
- Low energy density
- Slower response (seconds to minutes)
- Net energy consumer
- High initial costs
- Tough to site new projects in the US



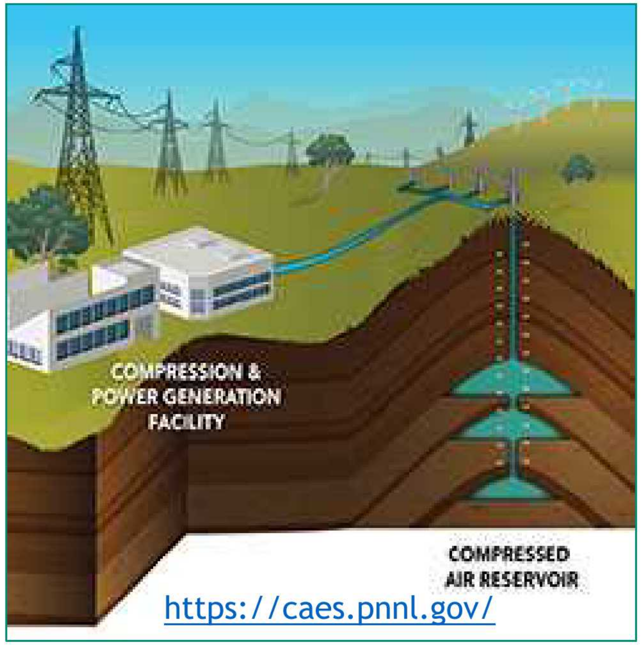
https://www.windpowerengineering.com/pumped-hydro-storage-market-to-surpass-350-billion-by-2024/

Compressed Air (CAES)

- Only 3 large-scale in the world – Germany (1) & U.S. (2)
- Potentially long duration (2h – 30h)
- High power capacity (100s MW)
- Long life (20 - 30 years)
- Many efforts at small scale applications
- Broad applications
- Low roundtrip efficiency (40-50%)
- Low energy density
- Slower response (seconds)
- Must be sited above geological repository (e.g., deep salt caverns)
- Initial costs are high



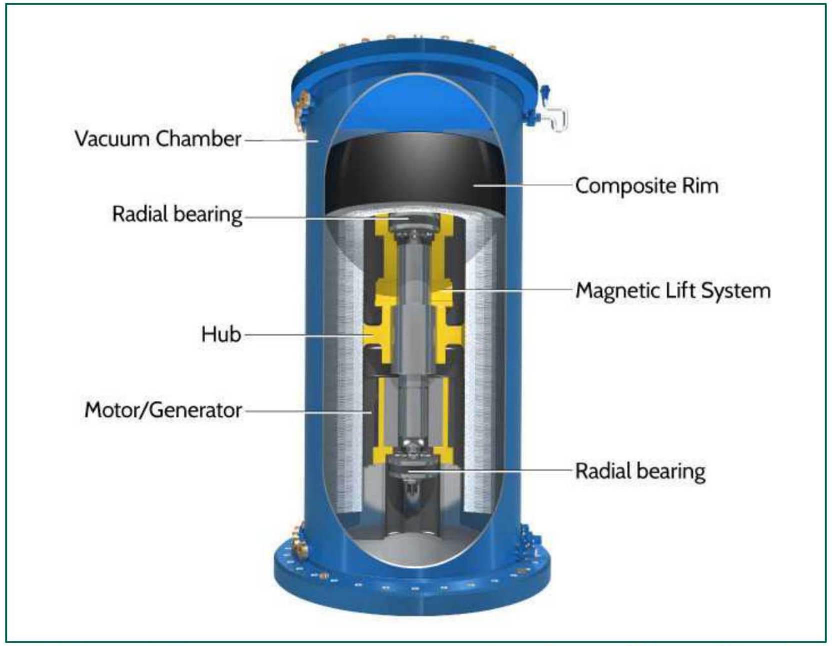
https://www.uigmbh.de/images/referenzen/CAES_animiert.gif



https://caes.pnnl.gov/

Flywheels

- High power capacity (MWs with banks of flywheels)
- High cycle life (millions)
- Very fast response (milliseconds)
- Broadly applied at many scales (potters wheels, steam engines, cars, large scale ES)
- Short term storage with limited grid applications (frequency and voltage regulation, transient stability, stopping and starting electric trains)



https://beaconpower.com/carbon-fiber-flywheels/

20 MW Frequency Regulation Plant, Hazle, PA https://beaconpower.com/hazle-township-pennsylvania/

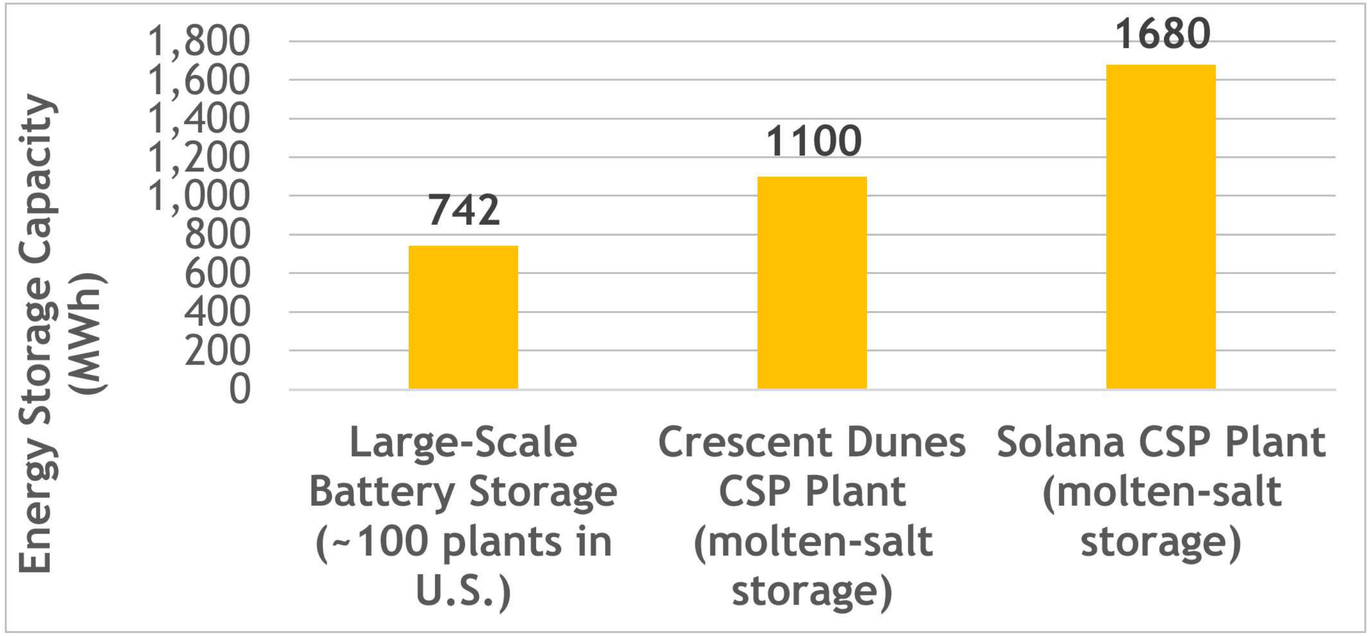
Super Capacitors

- Electrochemical . . .
- Long life (5-10 years)
- High cycle life (thousands to millions)
- Fast discharge (milliseconds)
- High round trip efficiency (95%)
- Broad applications – regenerative braking, laptops, photographic flashes cordless tools, defibrillators . . .
- No heavy metals
- Potential to replace Li-ion
- High cost
- Low energy density
- Limited grid applications (power quality, frequency regulation)

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

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

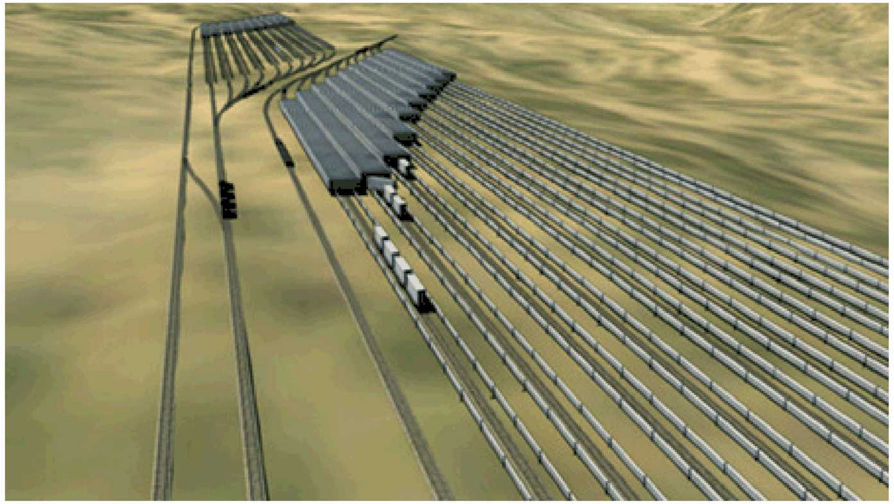
Gravity energy storage

- Long duration storage
- High capital costs
- Long cycle life
  - High maintenance costs

Vault Energy Storage

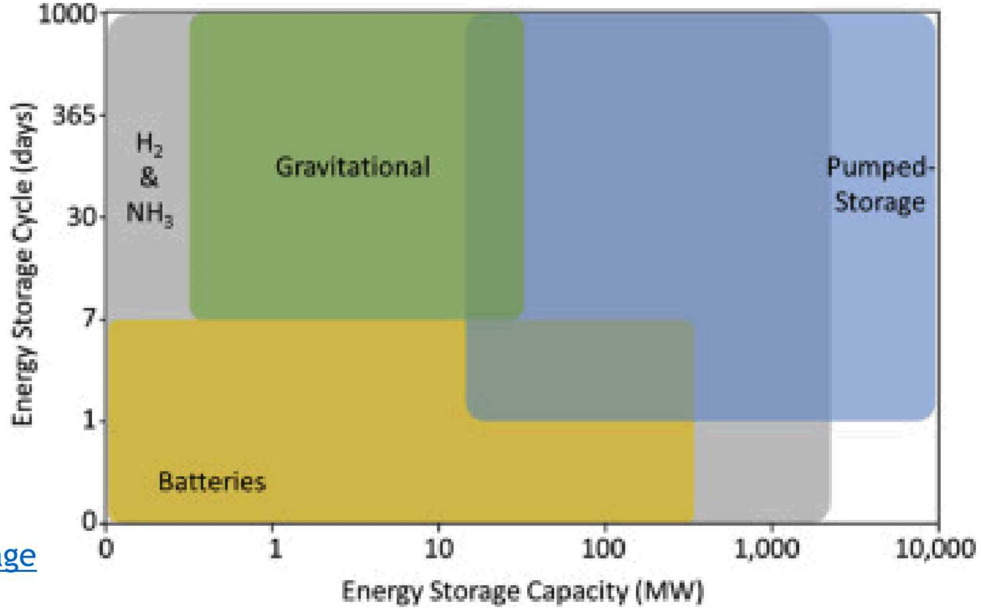
Energy Vault

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

$CH_2O + O_2 \xrightarrow{\text{Enzymes}} CO_2 + H_2O +$ **ENERGY** (Reduced carbon) (Oxidized carbon)

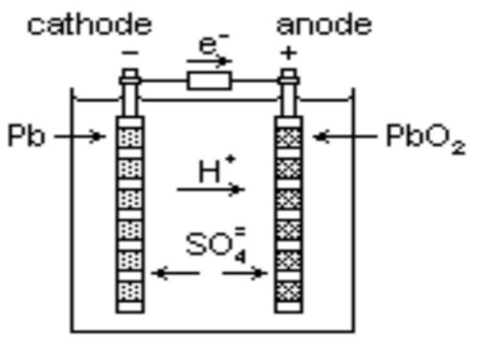
Electrons move from carbon to oxygen

- 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

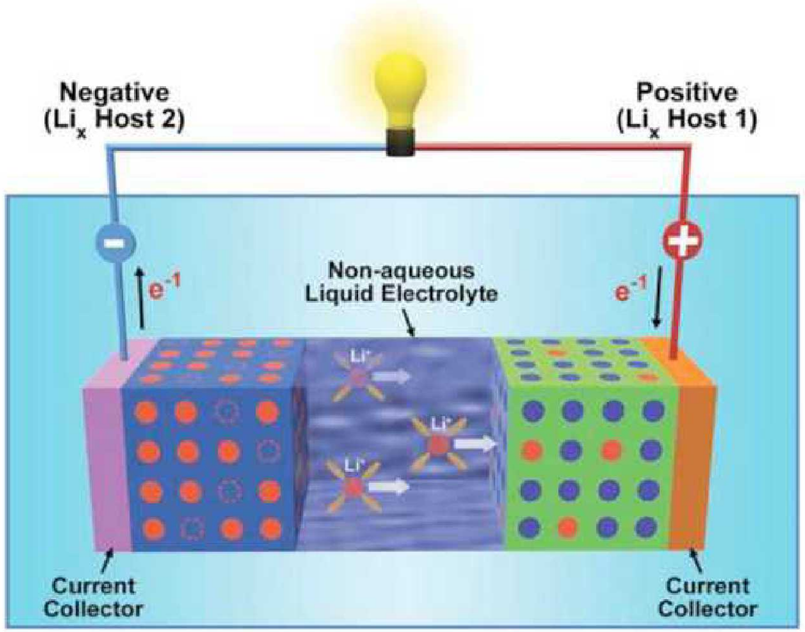
Reduced lead in the presence of oxidized lead, and in a sulfuric acid electrolyte, results in lead sulfate and water, and electrons move with a force of 2 V.

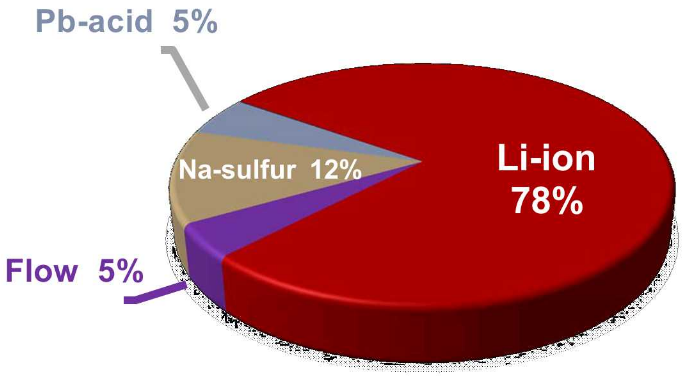
Oxidation is defined as removal of electrons from an atom leading to an increase in its positive charge, and reduction as addition of electrons resulting in a decrease (reduction) in positive charge.



Lead Acid Cell

Li-ion Batteries





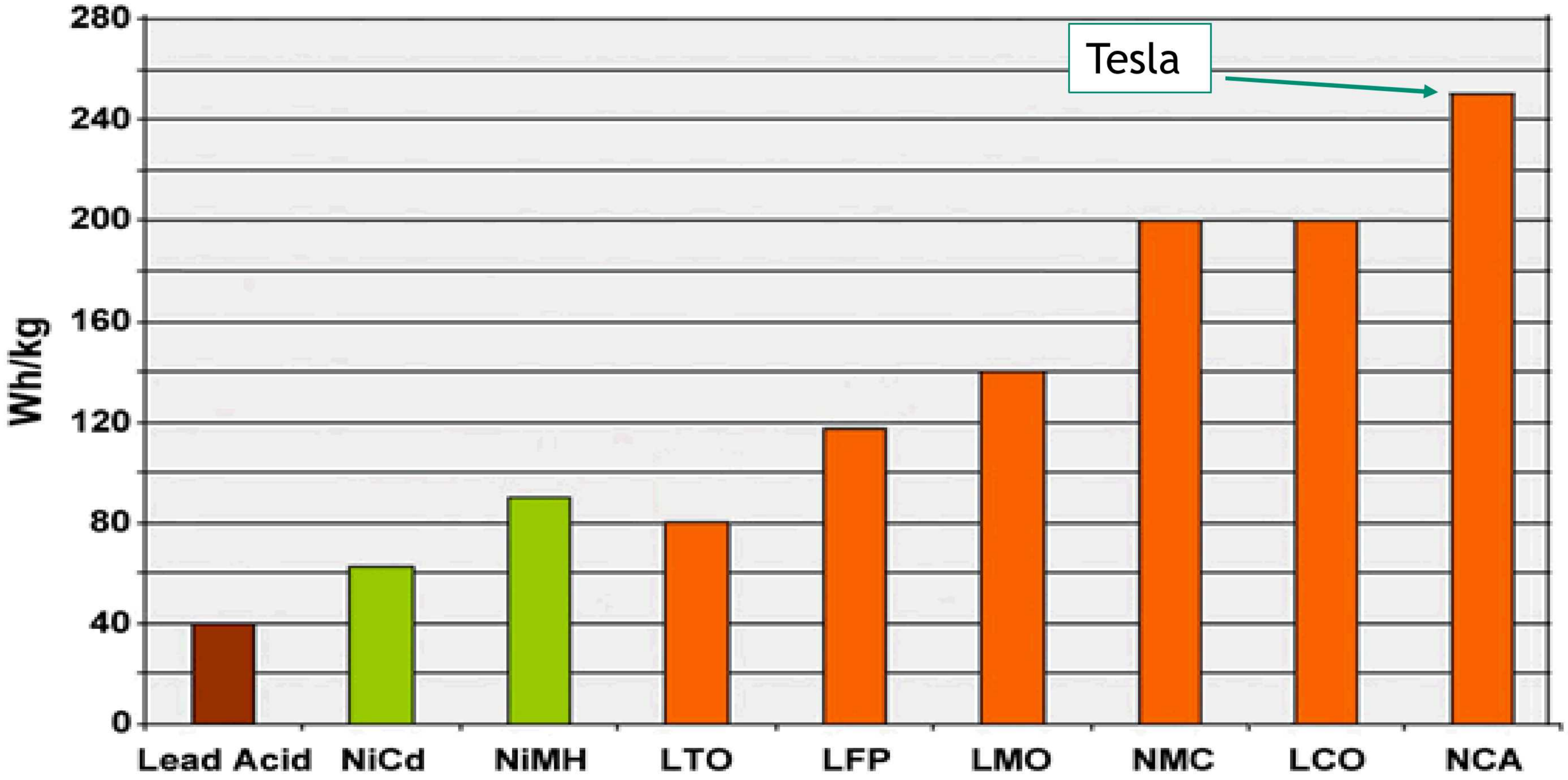
Chemistries	
LiCoO2	iphone
$LiNiO_2$	
$LiNi_xCo_yMn_zO_2$	Volt
$LiNi_xCo_yAl_zO_2$	Tesla
$LiMn_2O_4$	
$LiMn_{1.5}Ni_{0.5}O_4$	
$LiFePO_4$	
$LiMnPO_4$	
$LiNiPO_4$	
$LiCoPO_4$	

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.

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

Tesla and the 18650 Li-ion cell

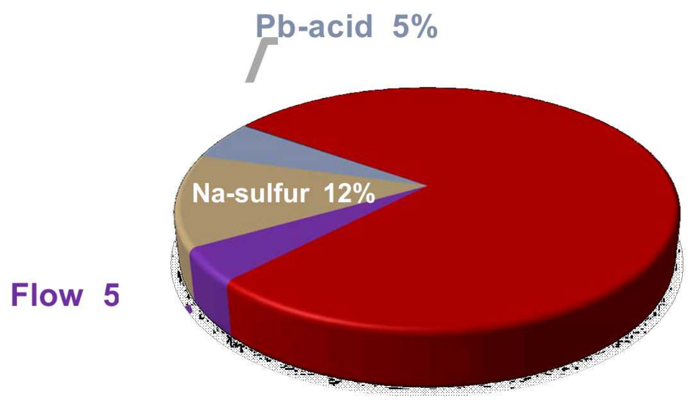
Tesla Model S Battery Pack

7104 cells

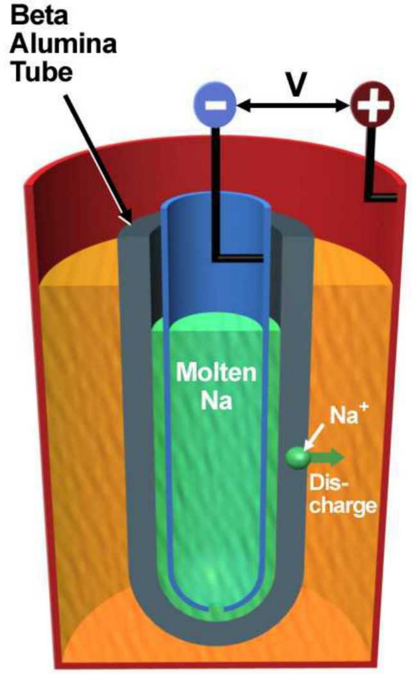
18650 cell format used in 85 kWh Tesla battery

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

Sodium -- Sulfur Batteries

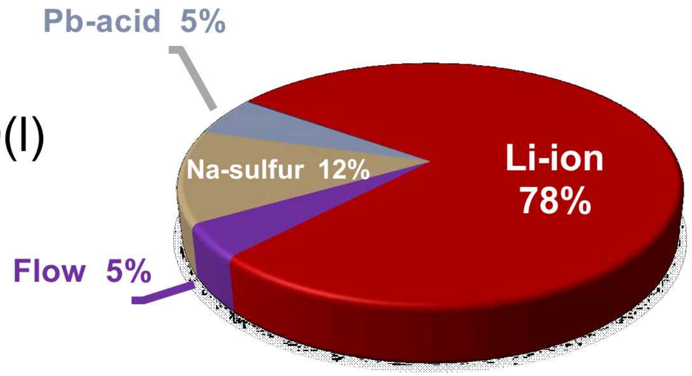


- High energy density
- Life cycles
  - 2500 at 100% DOD
  - 4500 at 80% DOD
- Fast response (milliseconds)
- 85% round trip efficiencies
- Must be kept hot!
  - 300 - 350º C
  - Stand by losses are high, battery has to keep running or be heated up
- Longer term -- 4-6 hours
- Broad applications
- Low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

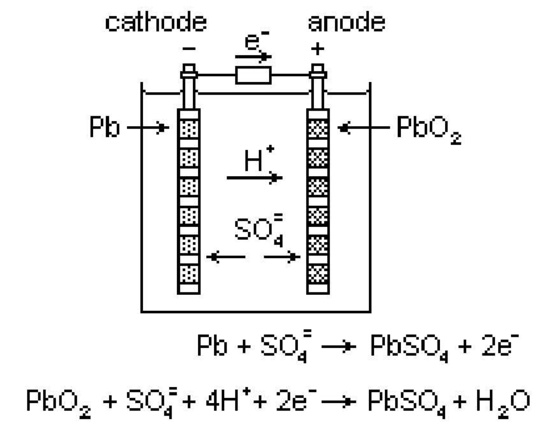


Lead Acid Batteries

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

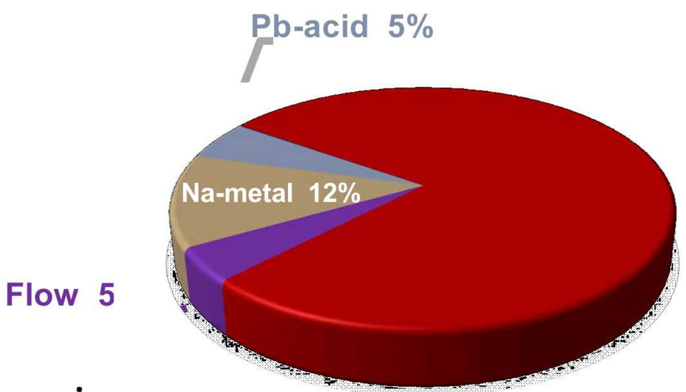


- The most common batteries worldwide
- Limited life time (5~15 yrs)
- Limited cycle life (500~1000 cycles)
- Degradation w/ deep discharge (>50% DOD)
- Low energy density (30-50 Wh/kg)
- Overcharging leads to H_2 evolution
- Sulfation occurs with prolonged storage
- Recyclable
- Less expensive the Li-ion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



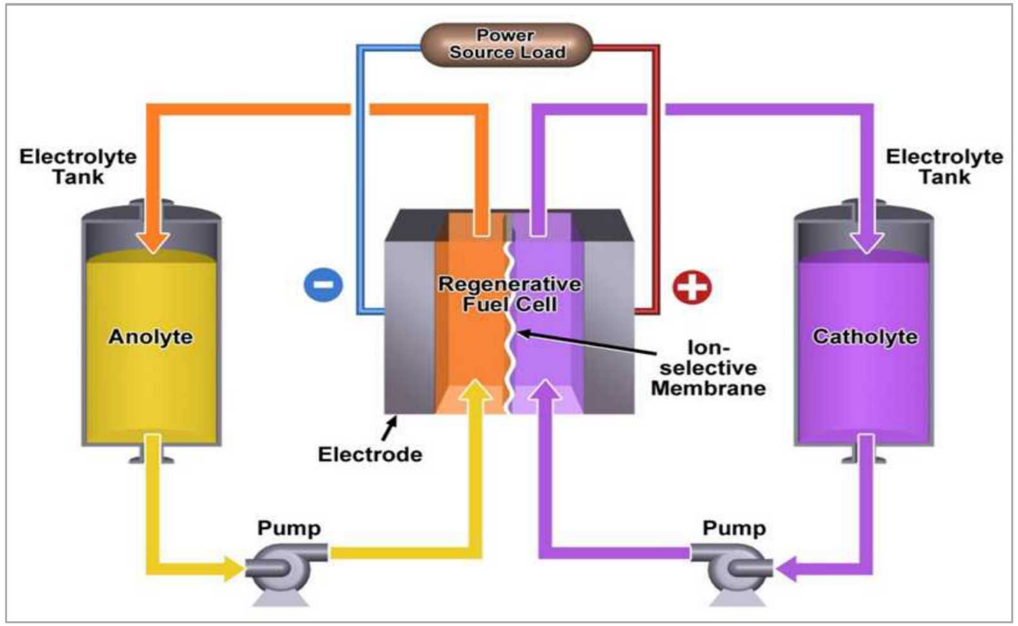
Lead-Acid Storage Cell

Flow Batteries



Two tanks of liquid electrolytes which are pumped past a membrane held between two electrodes to generate electricity through an external circuit

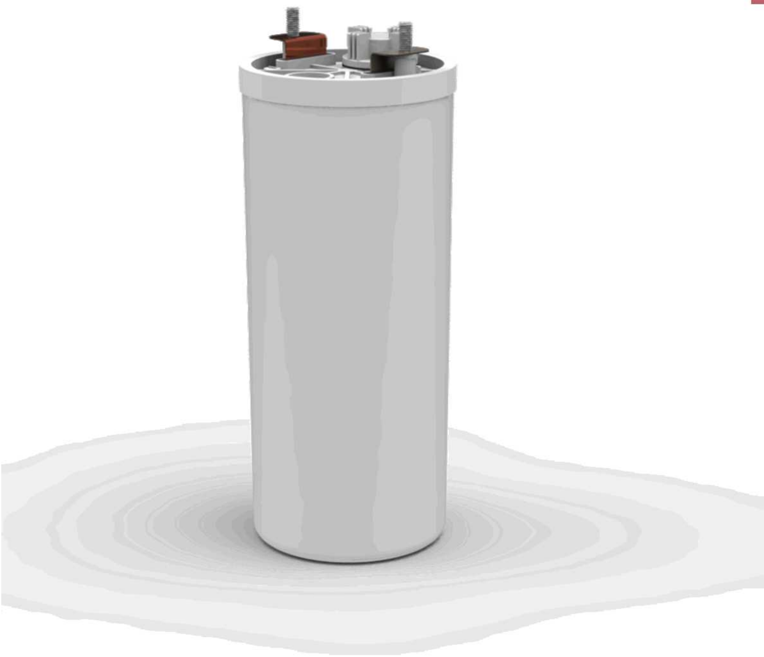
- Wide range of chemistries available -- Vanadium, zinc bromine, iron chromium
- Flexible -- increase volume of tanks to increase energy (no new racks, no new controllers)
- Suitable for wide range of applications, 5 kW to 10s MW
- Tens of thousands of cycles, and high duration (10 hours)*
- Low energy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



*Vionxenergy.com

$Zn\text{-}MnO_2$ 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

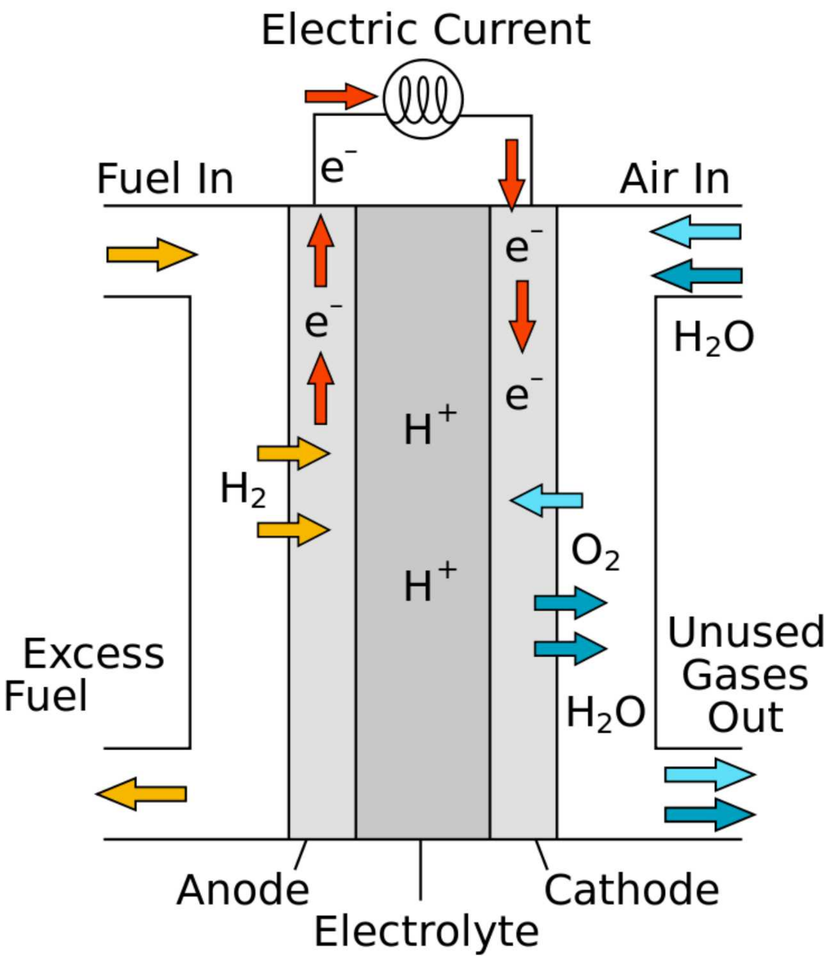


URBAN ELECTRIC POWER

Hydrogen Storage

- Electricity splits H_20 into H_2 and O
- H_2 is stored in above-ground steel tanks, with engines, or in underground caverns
- Fuel cell uses redox chemistry to produce electricity
- Waste product is H_20
- About as efficient as ICE
- Many applications

Hydrogen Fuel Cell

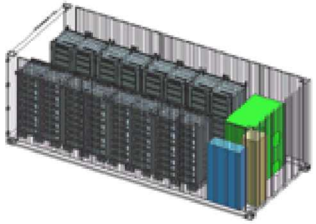


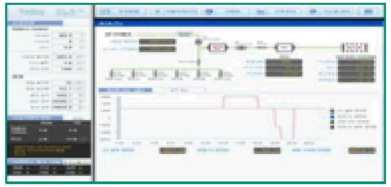
By R.Dervisoglu - Own work, based on http://en.wikipedia.org/wiki/File:Solid_oxide_fuel_cell.svg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=19314043

Battery Energy Storage Systems (BESSs)

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 • Interconnection with grid • Islanding and microgrid control	• Housing • HVAC • Wiring • Climate control • Fire protection • Permits • Personnel

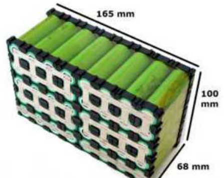




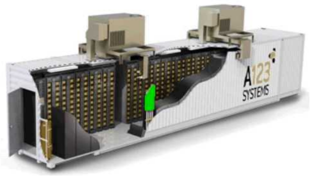
NOTE: Important to have single entity responsible for the ESS integration.

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

And others . . .

- Policy shapes the landscape
  - Procurement targets, incentives, RPSs, interconnection standards, etc.
- Economics
  - Energy storage applications & revenue streams
  - Stacking benefits
  - Modeling
- Design and commissioning
- Safety
- Decommissioning/ end of life

Many resources are available

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 with longer durations is required to meet 100% carbon free goals in NM and across the country
- Toxicity, waste, end of life issues, recycling, cradle to cradle design, all still nascent
- Li-ion overwhelms the market, but many other chemistries are in development
- Batteries can provide important services to the grid, and many of value streams, but some of those values are hard to quantify, and markets don’t exist
- PV + batteries is already outcompeting new and existing gas peaker plants

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