HDR

Energy Storage

Industry Snapshot

Topics

- Definition of Energy Storage
- U.S. Grid Energy Storage Portfolio
- Value of Energy Storage
- Definitions
- Energy Storage Technology Characterization
- Comparison of Technologies

What is Energy Storage

Breaking down the Mystery

Wikipedia Definition:

Energy storage is the capture of energy produced at one time for use at a later time.

Energy comes in multiple forms including radiation, chemical, gravitational potential, electrical potential, elevated temperature, latent heat and kinetic.

ENERGY STORAGE TECHNOLOGIES

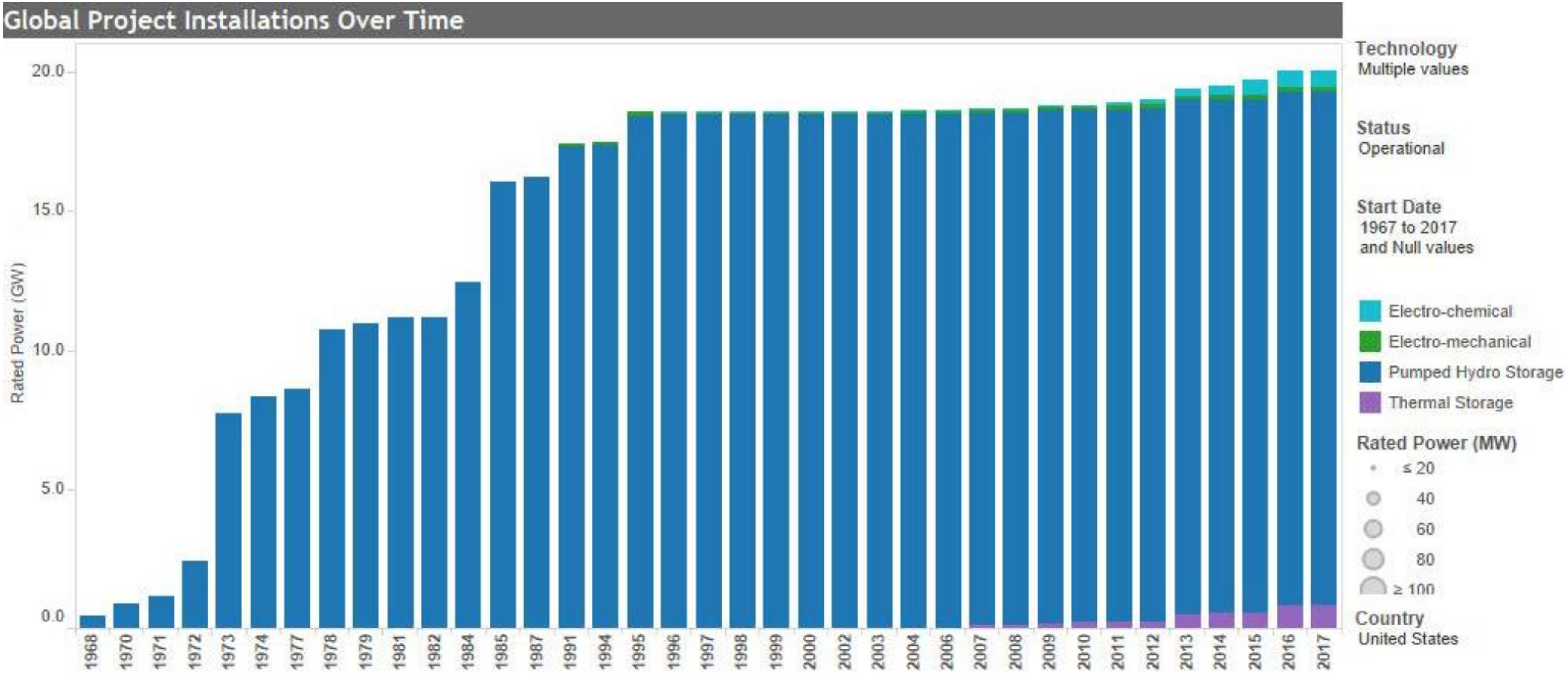
- Battery
- Flywheel
- Pumped Hydro
- Compressed Air Energy Storage
- Liquid Air Energy Storage
- SuperCapacitors
- Superconducting Magnet Energy Storage
- Electric Vehicles

Overview

Installed Grid System Energy Storage

Installed Storage 1967 to 2017

Source: DOE Global Energy Storage Database

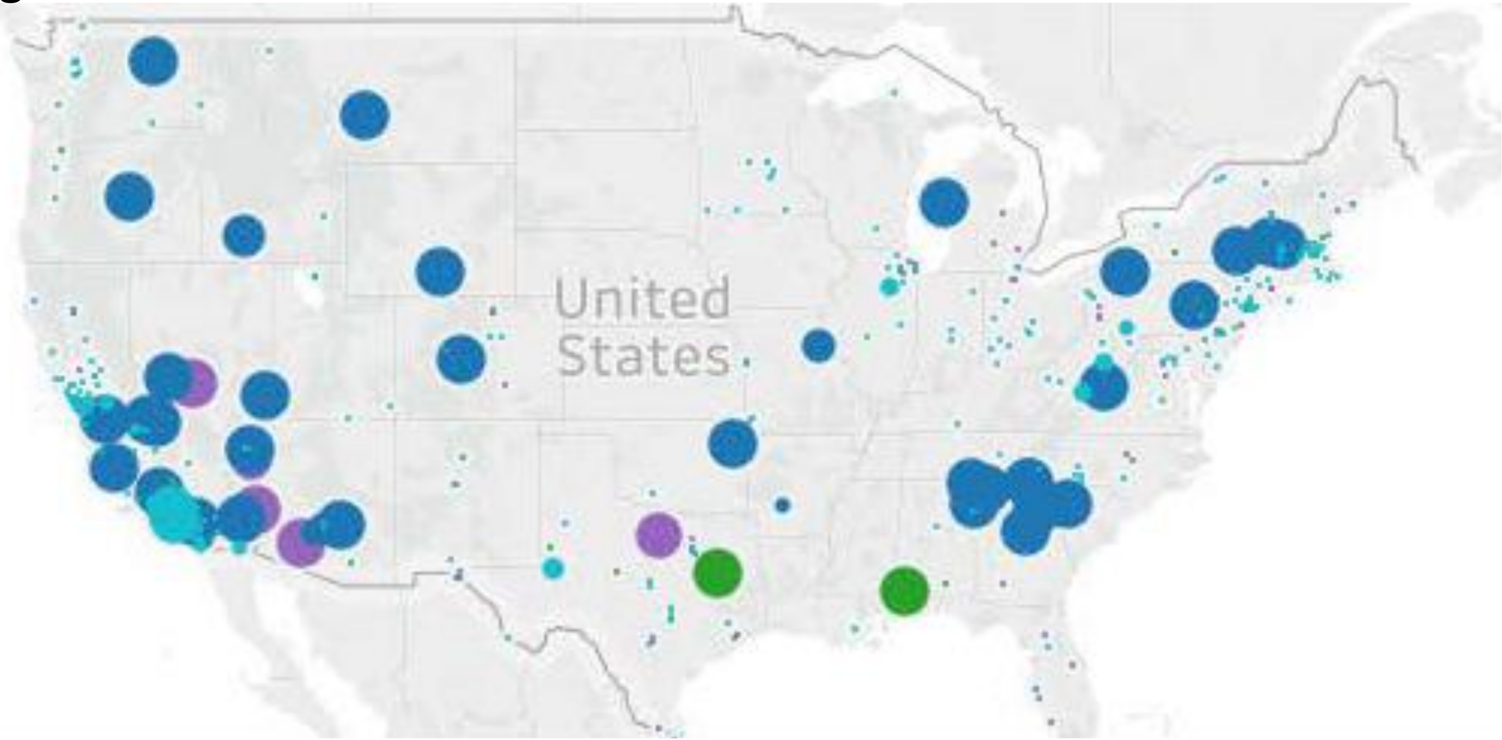


Installed Storage 1967 to 2017

27.14 GW

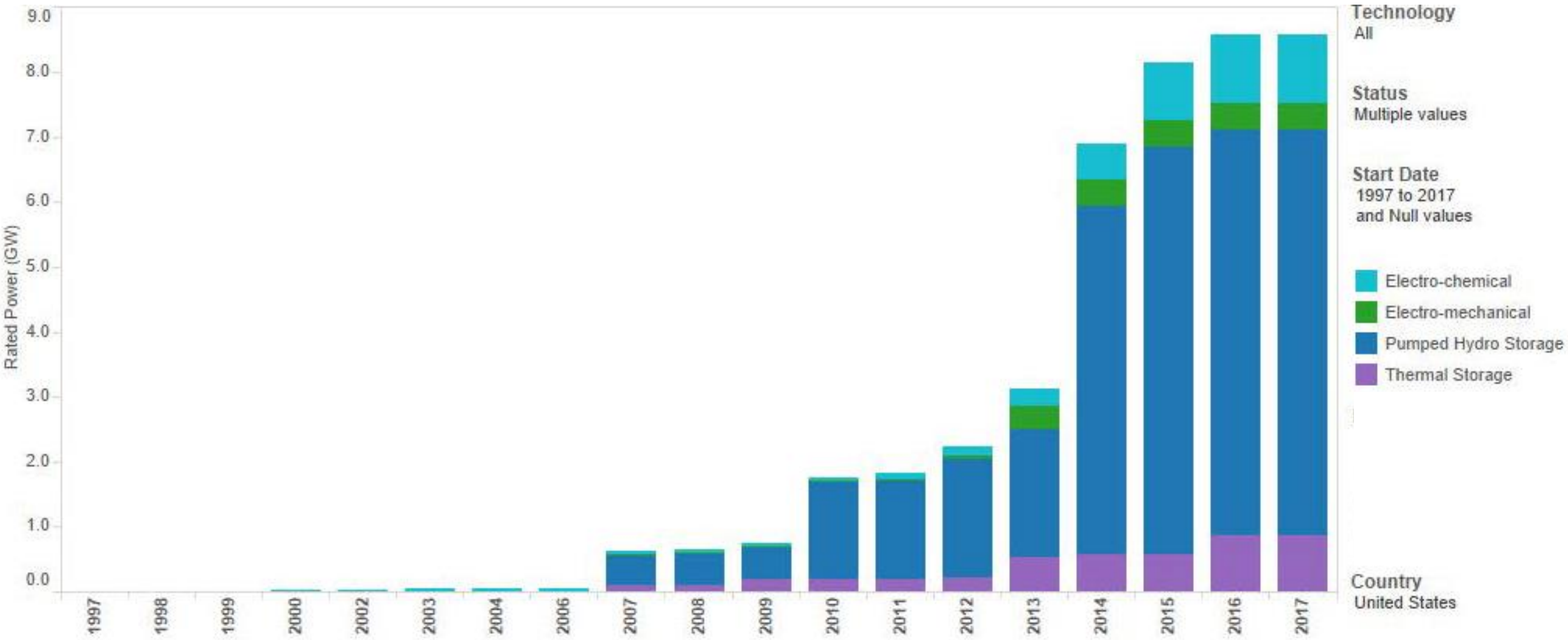
636 Projects

Source: DOE Global Energy Storage Database



Installed Storage 1997 to 2017

Source: DOE Global Energy Storage Database



Installed Storage 1997 to 2017

8.58 GW

603 Projects

Source: DOE Global Energy Storage Database

Applications of energy storage in a utility grid

Application

- Energy Arbitrage
- Capacity (Resource Adequacy)
- Demand Response/Demand Charge Reduction (Peak Shaving)
- Frequency Regulation and Response
- Resilience
- Renewables Integration / Firming
- Generation, Transmission, and Distribution System Upgrade Deferral
- Ancillary Services
    - Voltage Support;
    - Spinning Reserve.

Arbitrage

Energy arbitrage is buying energy when the price is low, and selling that energy, and discharge when the price of energy is high.

For example, a storage device can charge during a period of excess renewable generation when the cost of power is low, and discharge during the day.

Resource Adequacy

Resource adequacy is the degree to which electric supply resources are capable of delivering needed energy and power, typically over a specified period of time.

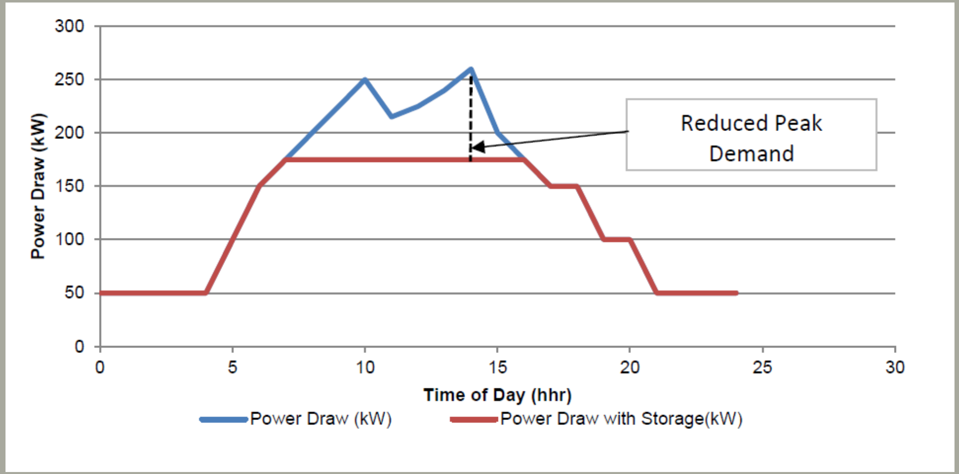
California resource adequacy qualification is achieved by the level of generation produced in a few hour period over three consecutive days. Load serving entities (LSE) procure capacity so that it is available to the balancing authority during these periods.

Demand Response

Demand Charge Reduction

Demand response provides an opportunity for consumers to reduce or shift their electricity usage during peak periods to capitalize on time-based rates or other financial incentives.

Demand response programs can be used by electric system planners and operators to balance supply and demand. Such programs can lower the cost of electricity in wholesale markets, and in turn, lead to lower retail rates.



Frequency Regulation and Response

Frequency regulation is the ability of a balancing authority to help an interconnection maintain a scheduled frequency, 60 Hz in the United States.

The regulation can be provided by turbine governor response, automatic generation control, or energy storage devices

Grid Asset Optimization and Resilience

Grid resilience is the ability of our nation’s electrical grid to maintain service and resist failure and allow rapidly recover, especially during heavy weather event.

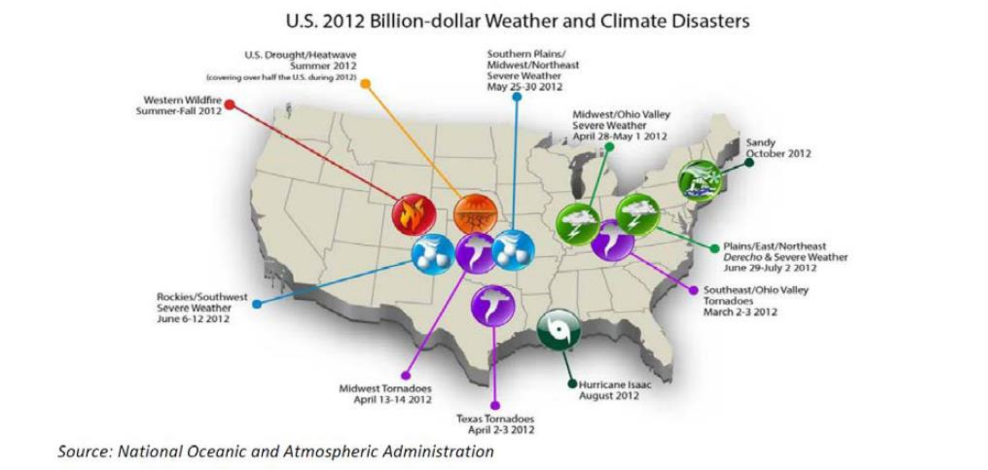


Figure 1. Areas Prone to Extreme Weather Outages

Renewables Integration

Renewable integration refers to a combination of specific applications to mitigate the impacts of intermittent generation on the power grid.

Intermittent generators such as wind turbines and photovoltaic (solar) panels have a predictable but uncontrollable output.

Generation or T&D System Upgrade Deferral

System upgrade deferral uses a relatively small amount of modular storage to defer the need to replace or to upgrade existing equipment and to increase the equipment's existing service life.

Ancillary Services

Voltage Regulation

Electric power delivered to the end user is generally allowed to vary within the narrow band of +/-5% of rated voltage. Off-nominal voltage can increase losses and potentially damage equipment both at the utility and at the end user and impact the overall stability of the electric power grid. Voltage support (or voltage regulation) is accomplished through a mix of generators, capacitors, reactors, static VAR compensators, static synchronous compensators (STATCOM), DVARs, HVDC converters, voltage regulators, and transformer load-tap changers.

Ancillary Services

Spinning Reserve

Spinning reserve refers to generation capacity that is online but unloaded, and can respond within 10 minutes to compensate for generation or transmission outages (ESA).

Storage Terms

When we describe energy storage we typically use terminology such as Megawatts and Megawatt-hour.

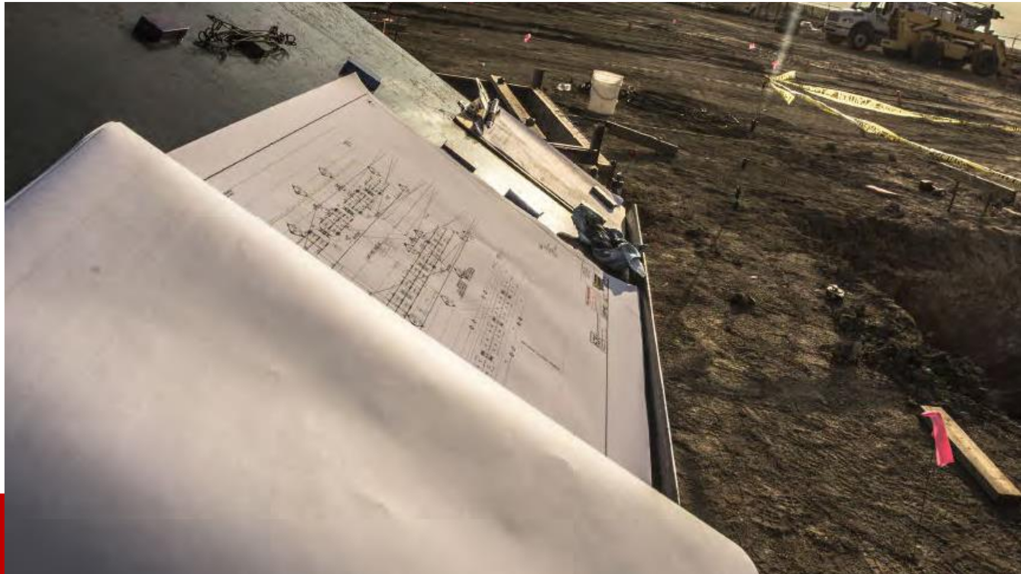
Megawatts of a system is comparable to the horsepower of your car's engine. The larger the engine, the more power it can deliver to the wheels to get you moving.

Megawatt-hours (MWh) of a system is comparable to your car's fuel tank. The more MWh's a system has, the larger the fuel tank it has to and the longer you can drive.

Storage Terms

Inverter: is an electronic device that changes direct current to alternating current. The inverter does not produce any power; the power is provided by the DC source.

Balance of Plant: is a term generally used in the context of power engineering to refer to all the supporting components and auxiliary systems of a power **plant** needed to deliver the energy, other than the generating unit itself.



Storage Terms

C-Rate: The rate of charge and discharge current of a battery. A charge or discharge equivalent to the batteries' capacity over one hour would be 1C. For example, A 1C discharge from a 100 Ah battery is 100 amperes for one hour.

Depth of Discharge (DOD): A way to quantify the capacity discharged from a battery during any status of the cycle. It can be written as amp-hours used or percentage used. For example, a 100 Ah battery that has discharged 20 Ah would be at a 20% depth of discharge.

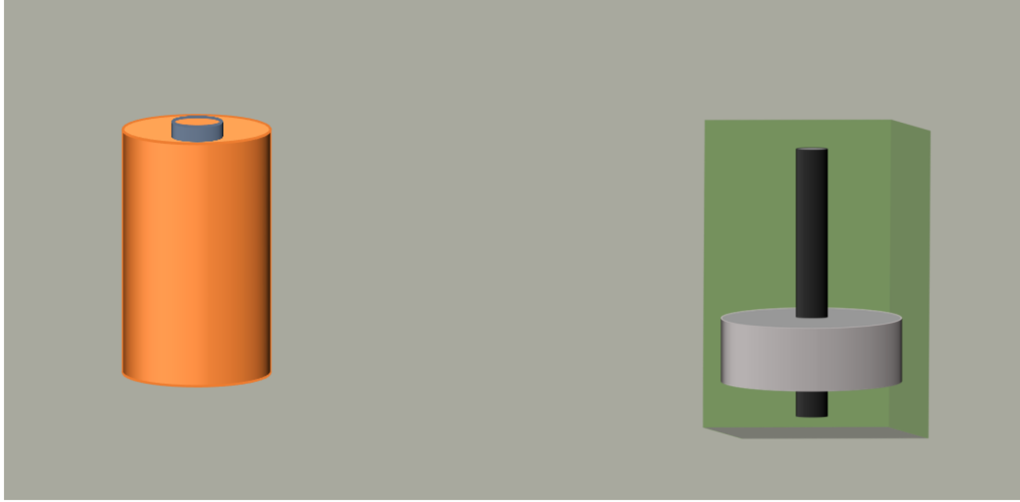
Storage Terms

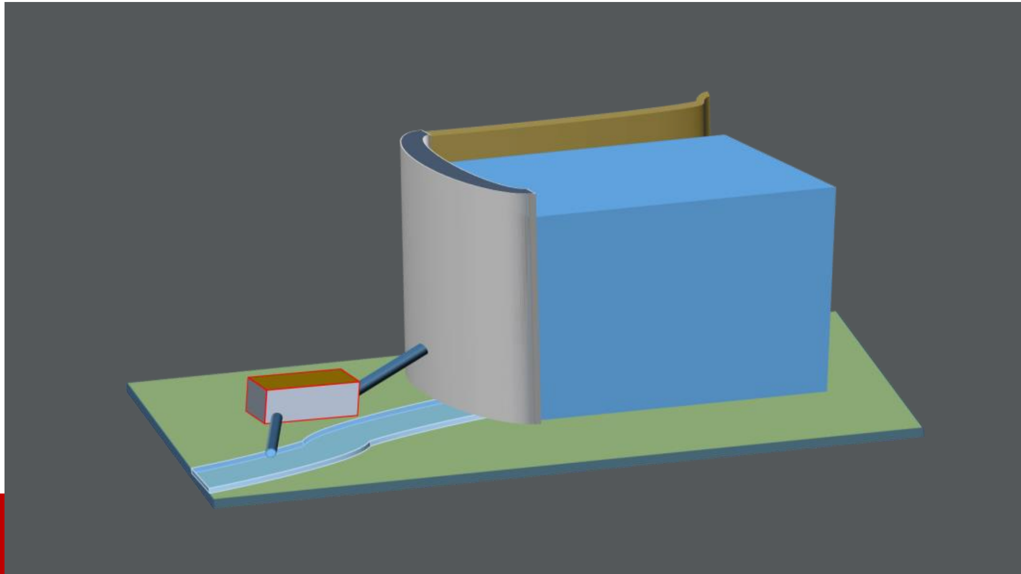
Round trip efficiency: Ratio of energy available to be discharged from a battery relative to the amount of energy required to charge to that state of charge. Example, if it takes 100kWh to charge and the available energy to discharge is 80kWh, the battery has a Round trip efficiency of 80%.

Interconnection: In Power, interconnection is the physical connection of a transmission and distribution network to generation equipment or facilities. The term may also refer to a connection between a utility's facilities and equipment belonging to its customer, or to a connection between two (or more) utilities.

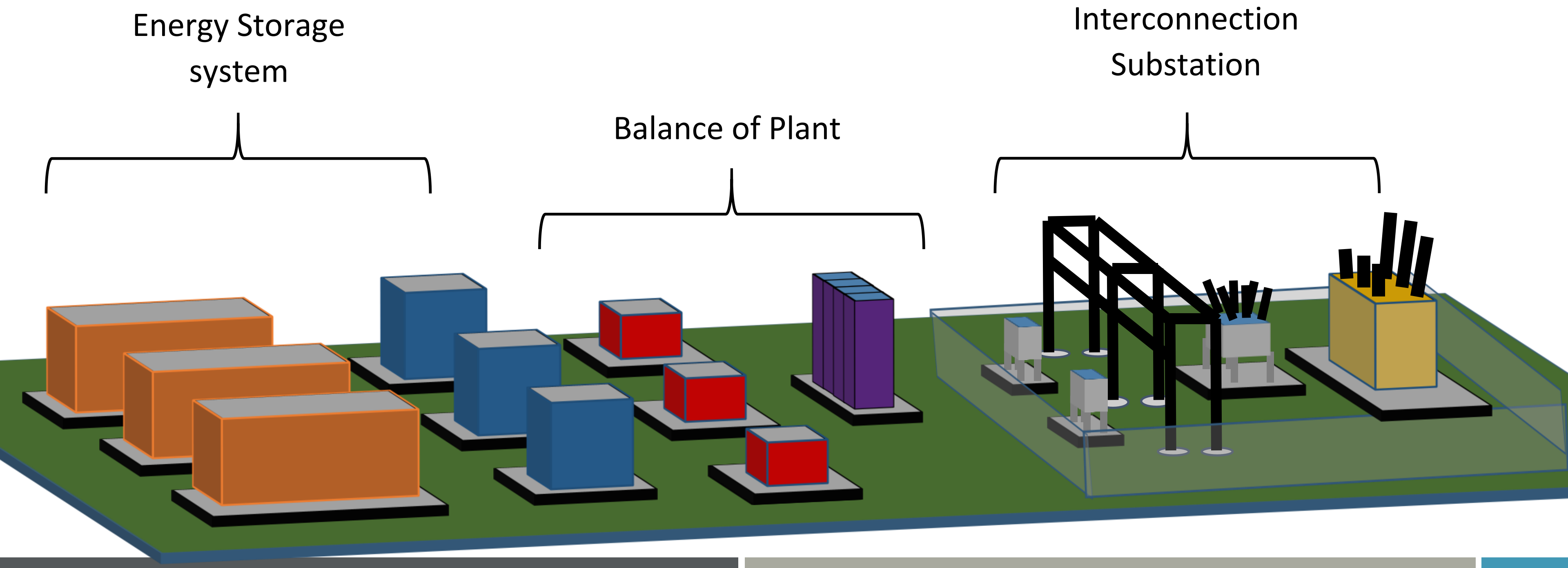
What Makes Up a Storage System

1. **Storage Medium**
   1. Dam and reservoir
   2. Chemical battery
   3. Compressed air
   4. Mechanical motion
2. **Power conversion System**
   1. Mechanical generator
   2. Power electronic inverter
3. **Balance Of Plant**
4. **Interconnection Substation**





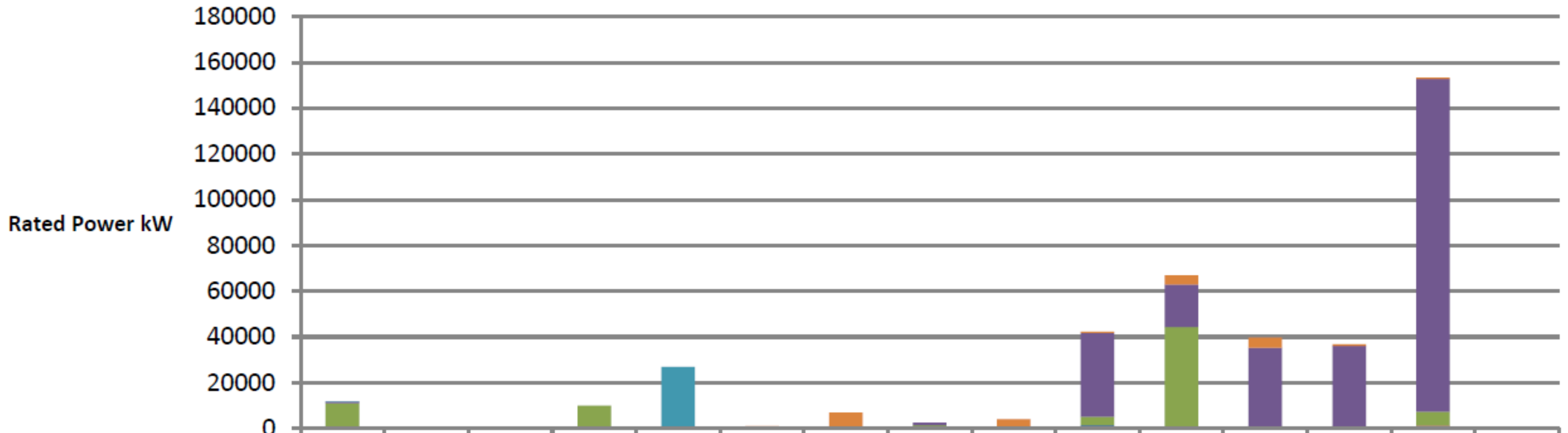
Example Configuration



Battery and Flywheel Technologies

ENERGY STORAGE TECHNOLOGIES

Operational battery projects (4-6-2016) including projects being verified



	0	1996	1997	2001	2003	2006	2008	2009	2010	2011	2012	2013	2014	2015	2016
Sodium based Battery						1200	7000		4000	402	4025	4365	600	470	25
Nickel based Battery	85				27000										
Lithium-ion Battery	790							1000	100	36800	18665	34131	35016	145470	430
Lead-acid Batter	11008	250	1000	10000				1500	100	3625	43641	1044	1100	6100	
Flow Battery	25										660	100	100	1270	
Electro-chemical										1500				48	

Source: Deployment of Grid-Scale Batteries in the United States, U.S. DOE, June 2016

Li-ion

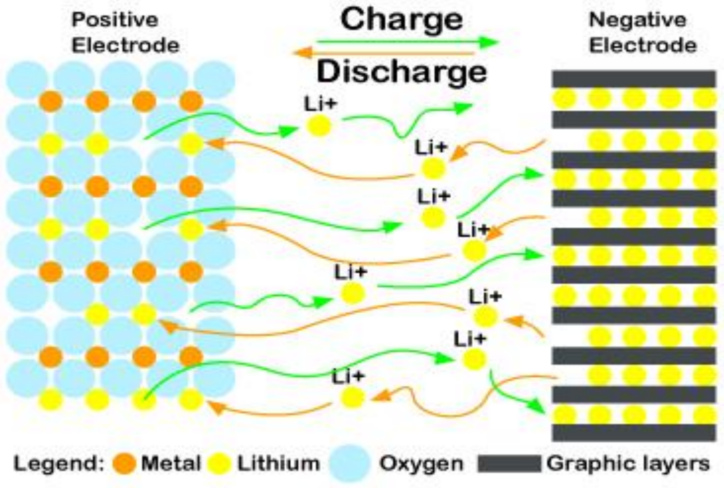
Li-Ion batteries consist of a range of technologies varying in size, shape, and chemistry. The primary chemistries in use today are lithium nickel manganese cobalt oxide (NMC), lithium manganese oxide (LMO), lithium iron phosphate (LFP), and lithium titanate (LTO).

The battery cells are typically a graphite anode, metal-oxide cathode, and a lithium salt electrolyte gel. For stationary applications these are typically packaged in a flat pouch (prismatic) or rolled up like a jelly-roll.

General Characteristics:

High energy density

High efficiency



Source: University of Tokyo (Japanese)

Li-ion

Typical Use Case

- Frequency Regulation, Resource Adequacy, Demand Response, Upgrade Deferral, Spinning Reserve, Grid Resiliency

Technical Characteristics

Maturity: Mature

Cycle Life: >4500@ 80% DOD

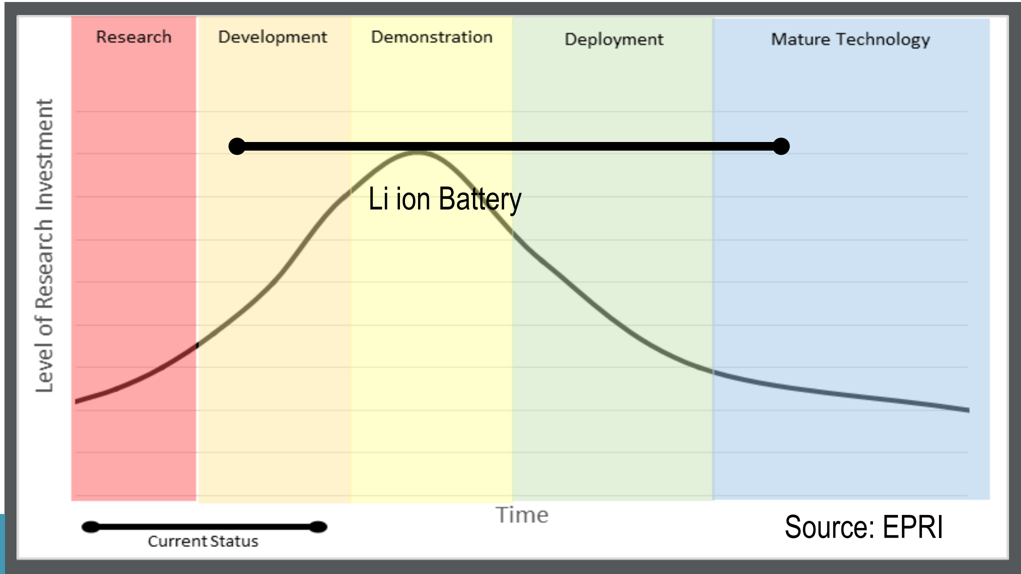
Efficiency: 80-94%

Replacement

Frequency: 10 years

Sizing: <1 MW to 20MW

Duration: 15 min to 4 hr

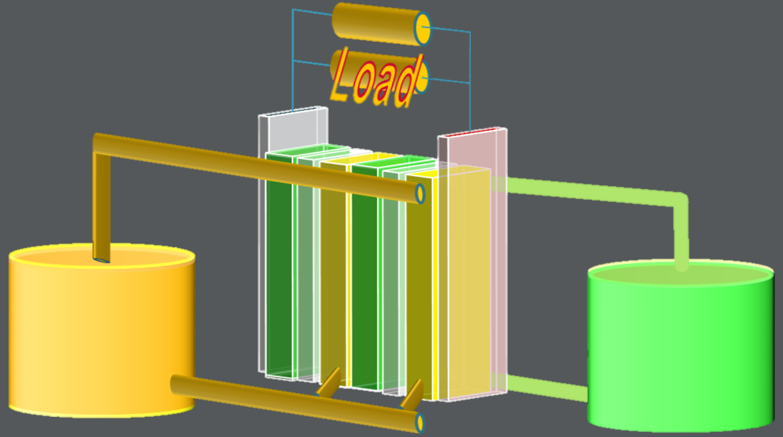


Flow Batteries

A **flow battery** is a electrochemical cell where two electrolyte chemical components are separated by a Ion exchange membrane. Electric current occurs through the membrane when both liquids are circulate in their respective loops..

General Characteristics:

Cost effective for longer duration storage
Scalable by increasing storage tank size
Lower efficiency
Long service life



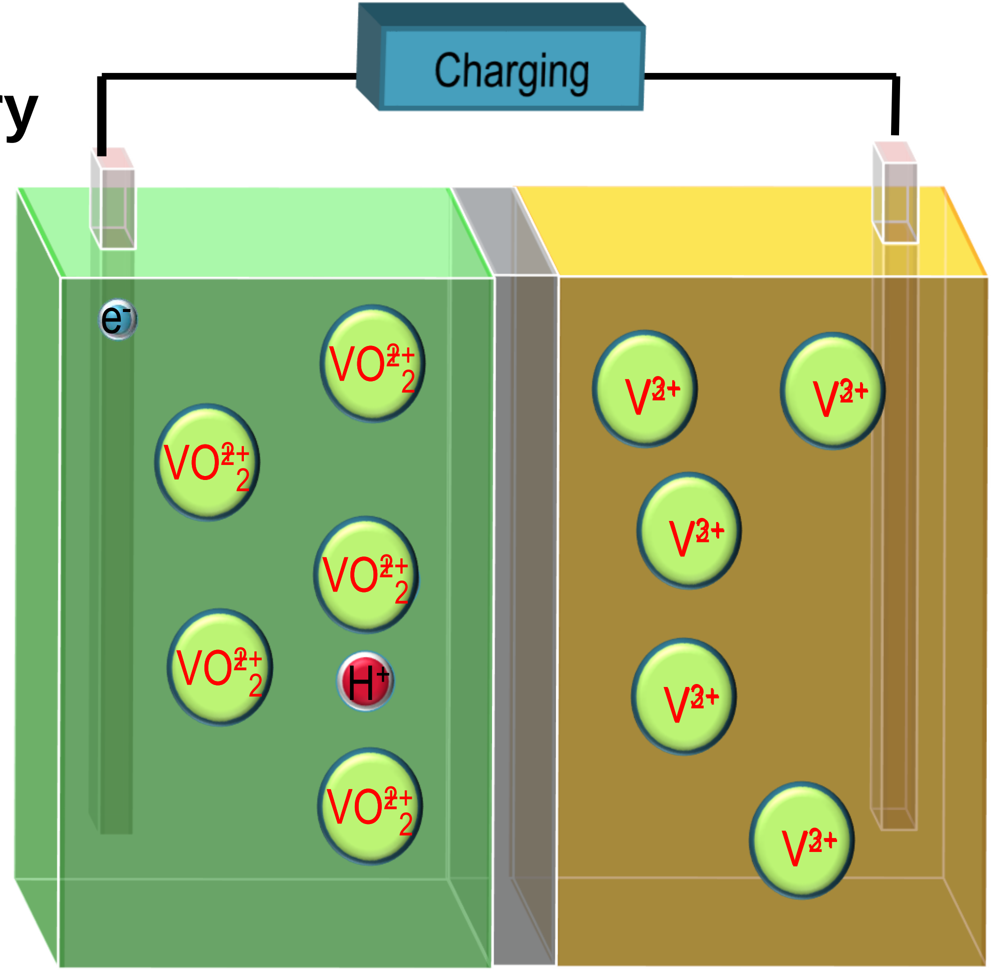
Vanadium Redox Battery

In a vanadium redox battery both electrolytes are vanadium-based, the electrolyte in the positive half-cells contains VO_2^+ and VO^{2+} ions, the electrolyte in the negative half-cells, V3+ and V2+ ions.

When the vanadium battery is being charged, the VO^{2+} ions in the positive half-cell are converted to VO_2^+ ions when electrons are removed from the positive terminal of the battery. Similarly in the negative half-cell, electrons are introduced converting the V^{3+} ions into V^{2+} . During discharge this process is reversed.

Source: Prudent Corporation

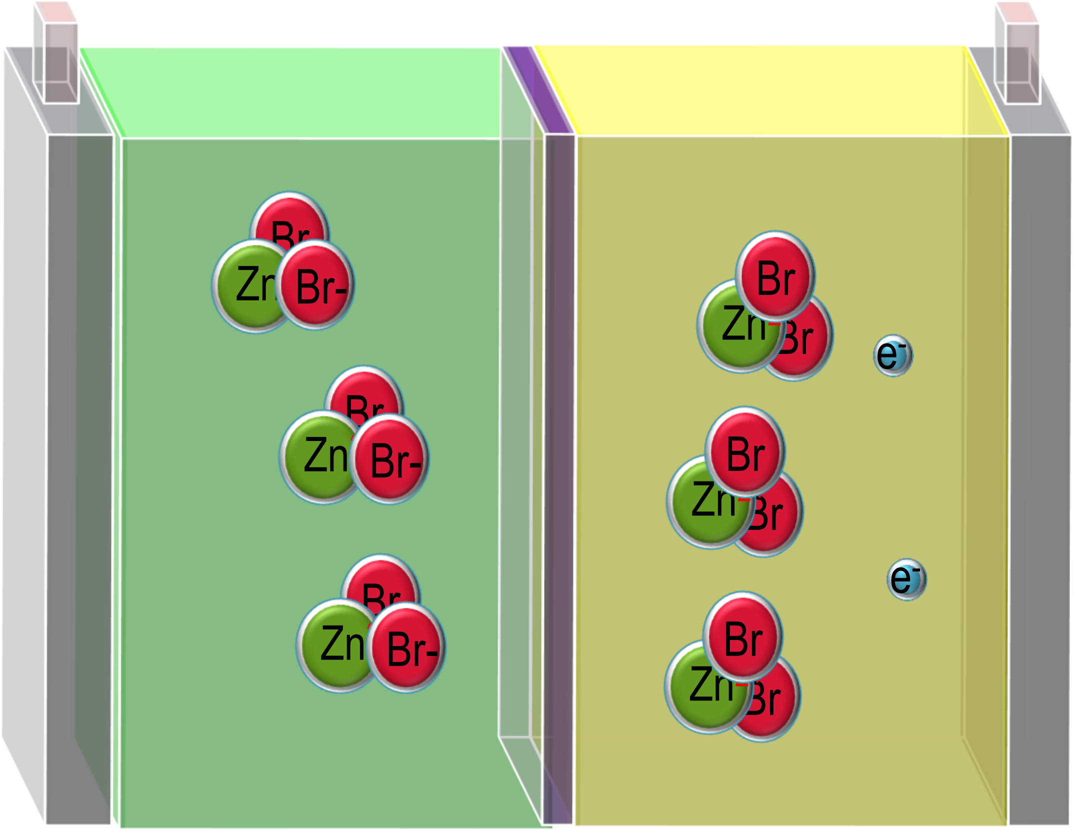
Vanadium Redox Battery



Zinc-Bromine Flow Battery

The zinc-bromine battery is a hybrid redox flow battery, energy is stored by plating zinc metal as a solid onto the anode plates in the electrochemical stack during charging. Energy storage capacity of the system is directly dependent on electrode area and the size of the electrolyte storage reservoirs. The system is made up of a zinc anode and a bromine cathode separated by a ion exchange (micro-porous) membrane with circulating aqueous $ZnBr_2$ Solution on each side.

Zinc Bromine Battery



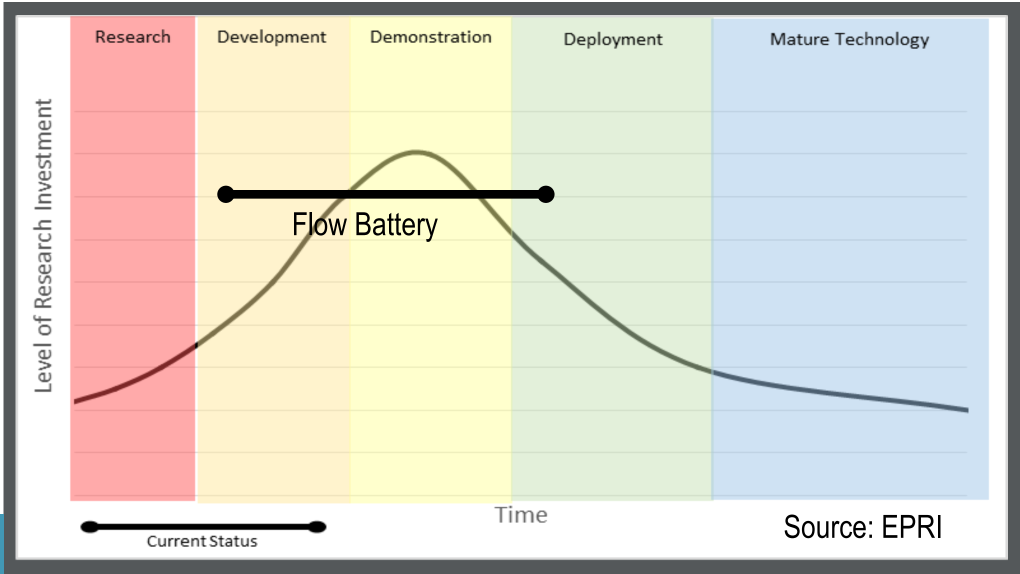
Flow Battery

Typical Use Case

- Frequency Regulation, Resource Adequacy, Demand Response, Upgrade Deferral, Spinning Reserve, Grid Resiliency

Technical Characteristics

Maturity:	Early Deployment
Cycle Life:	>5,000 @ 100% DOD
Efficiency:	60-78%
Replacement Frequency:	15 - 25 years
Size:	<1MW to 20MW
Duration:	4 to > 16 hours

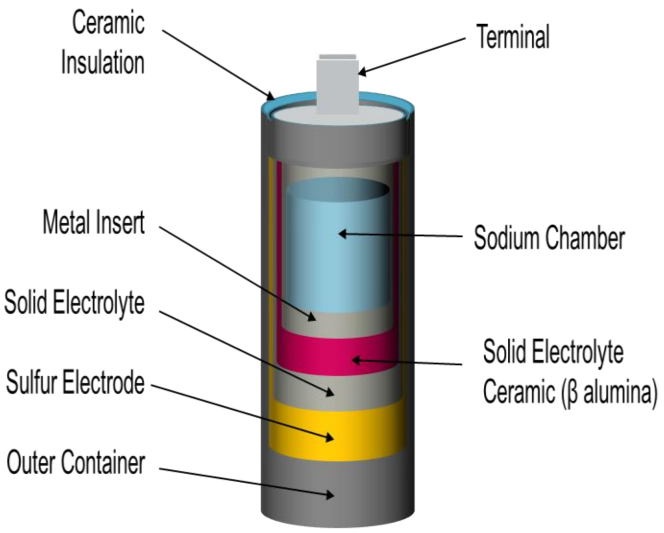


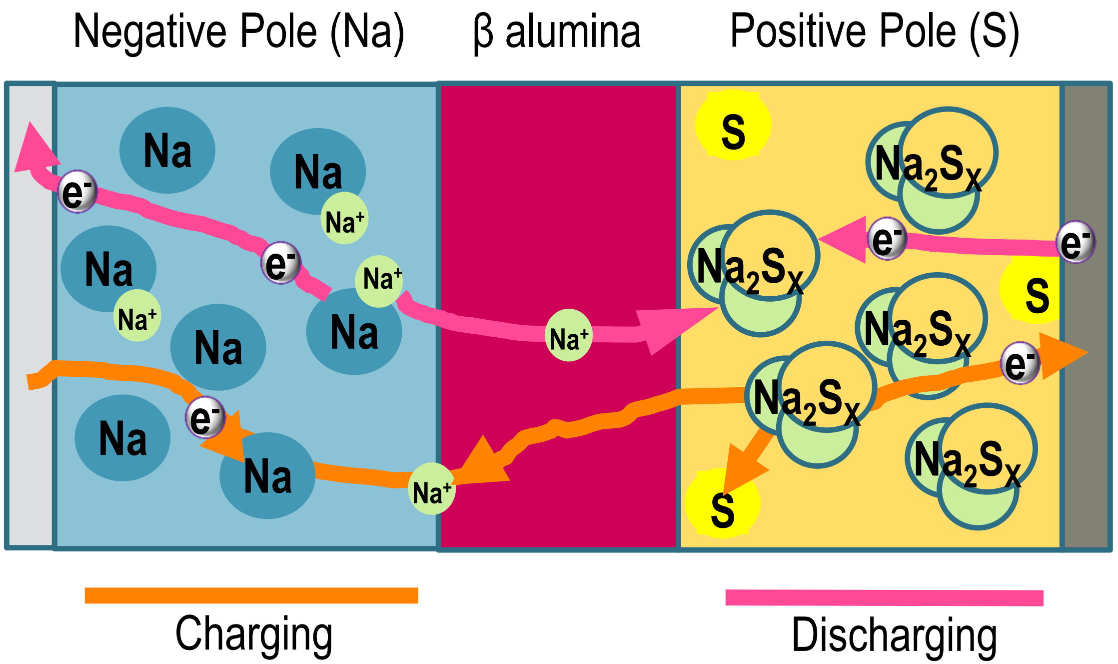
NaS Battery

A sodium–sulfur battery is a type of molten salt battery constructed from liquid sodium (Na) and sulfur (S). During Discharge Na (negative electrode) sends electrons through the circuit, Na^+ pass through the electrolyte, Na^+ reacts with S to form sodium polysulfides at the positive electrode The operating temperatures are from 300 to 350 °C.

<u>General Characteristics</u>:
High proven cycle life
High energy density (just below Li-ion)
100% DOD capable with long discharge times
Over 10 years of deployment

Sodium Sulfur Battery





NaS

Typical Use Case

- Frequency Regulation, Resource Adequacy, Demand Response, Upgrade Deferral, Spinning Reserve, Grid Resiliency

Technical Characteristics

Maturity: Limited Deployment

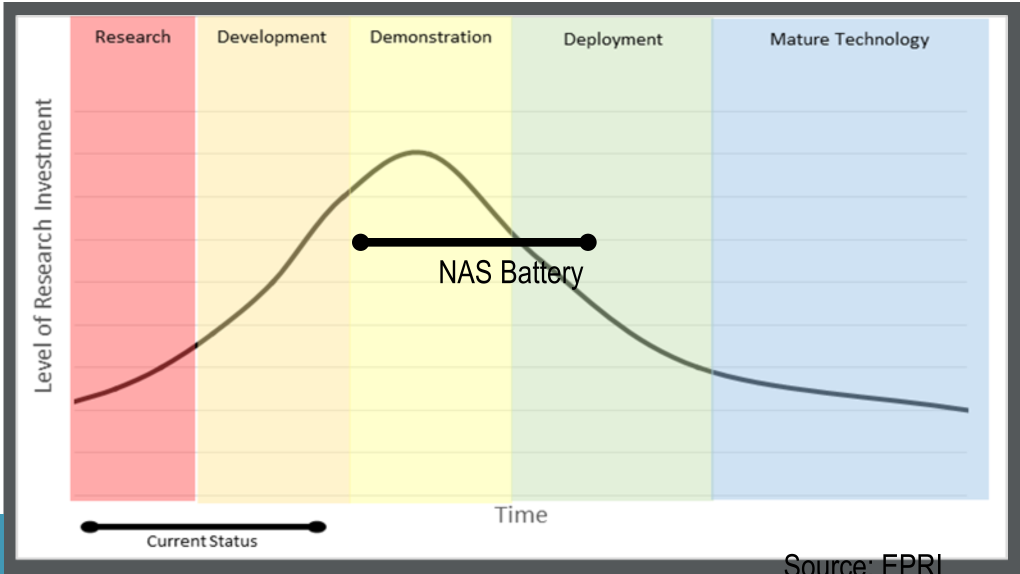
Cycle Life: >4500 @ 100% DOD

Efficiency: 77-83%

Replacement Frequency: 10 - 15 years

Size: 1 - 50MW

Duration: 1 - 6hr

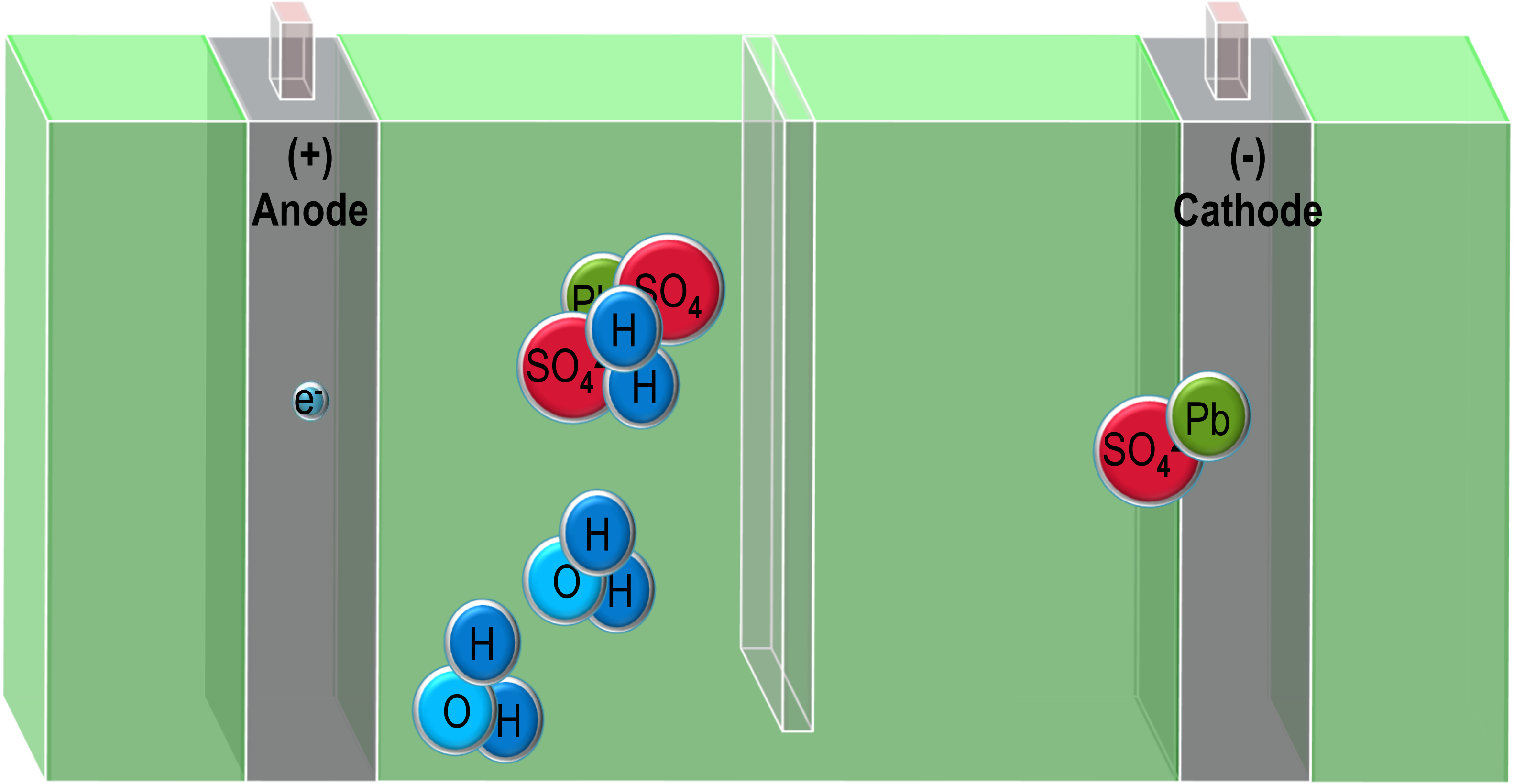


Lead Acid Battery

Lead acid batteries vary by use and are typically composed of connected cells made up of electrodes, separators, electrolyte, vessel with lid, and ventilation. A cell consists of a positive lead plate covered with a paste of lead dioxide (PbO) and a negative made of sponge lead (Pb), with an insulating separator in between and suspended in a aqueous electrolyte solution of sulfuric acid (H2SO4).

General Characteristics:
Mature technology (oldest available)
Lower costs
Low energy density, heavy weight, short life

Lead Acid Battery (charging)



Lead Acid

Typical Use Case

- Frequency Regulation, Resource Adequacy, Demand Response, Upgrade Deferral, Spinning Reserve, Grid Resiliency

Technical Characteristics

Maturity: Mature

Cycle Life: >2200 to 3500 @ 50% DOD

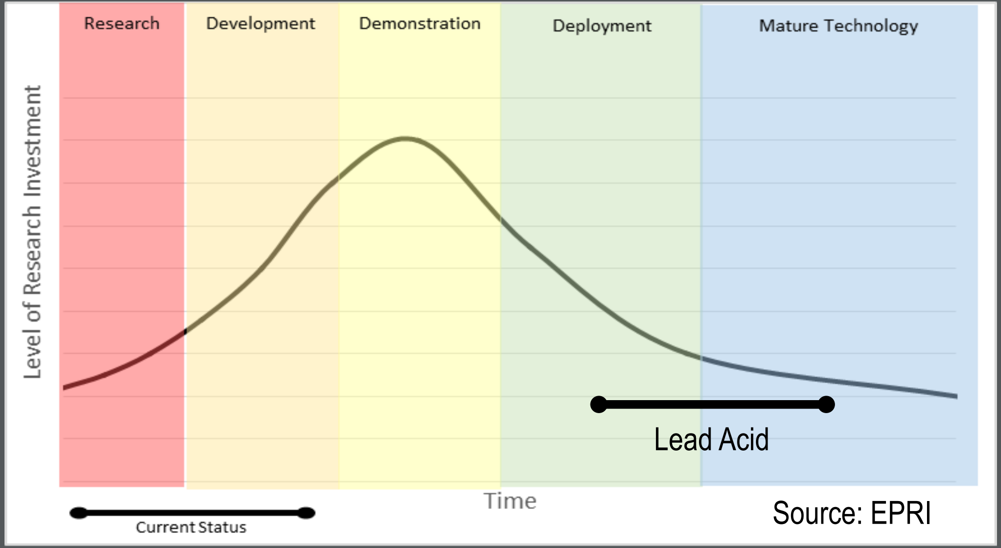
Efficiency: 75-90%

Replacement

Frequency: 3-10 years

Size: <1MW to 36MW4

Duration: .25 to > 1 hour



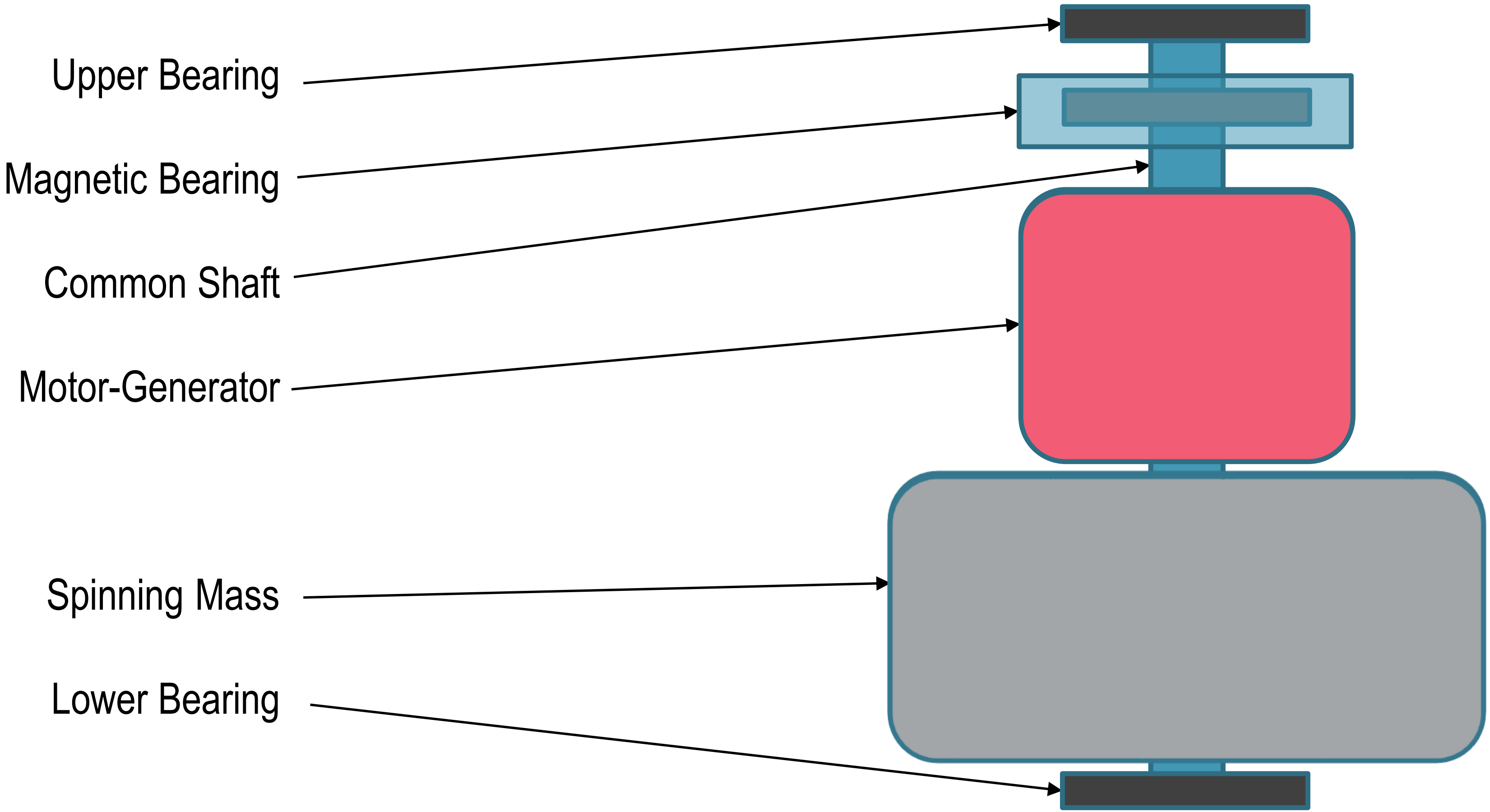
Flywheel

Flywheel energy storage systems are typically housed with within a reinforced enclosure and contain a cylindrical mass and motor - generator on a common shaft spinning at high RPM's. Most designs use magnets to lift and levitate shaft limiting friction-related losses and wear on the systems bearings. Electric energy is converted by the motor/generator to kinetic energy. That kinetic energy is stored by increasing the flywheel's rotational speed.

General Advantages:

Fast acting instantaneous output response

Flywheels


Upper Bearing
Magnetic Bearing
Common Shaft
Motor-Generator
Spinning Mass
Lower Bearing

Flywheel

Typical Use Case

- Frequency Regulation, Resource Adequacy, Demand Response, Upgrade Deferral, Spinning Reserve, Grid Resiliency

Technical Characteristics

Maturity: Mature

Cycle Life: >100,000 @ 100% DOD

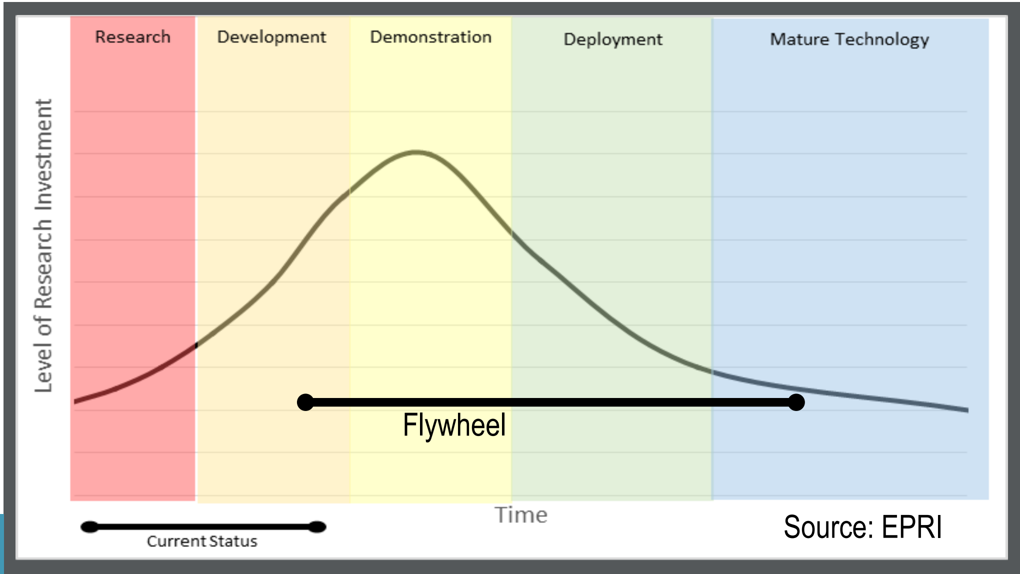
Efficiency: 87%

Replacement

Frequency: 20 years

Size: 100kW to 1MW

Duration: 15 Seconds to 15 minutes



Characteristics Comparison

Characteristics Data Comparison									
Storage Type	Energy		Charge Rate	Round Trip Efficiency	Availability	Capacity Degradation		Life	
	SOC High Limit	SOC Low Limit				Energy	Power	Years	Cycles
Li-Ion NCM	90%	10%	1C	77 - 85%	97%	30-40%	10-20%	10	3,500
Li-Ion LiFePO4	85%	15%	2C-1C	78 - 94%	97%	20-40%	15-25%	10	2,000
Li-Ion LTO	98%	10%	3C-1C	77 - 85%	96%	15-25%	5-15%	10	15,000
NaS	90%	10%	1C-0.5C	77 - 83%	95%	15-30%	5-15%	15	4,500
VRB	95%	5%	1C-0.25C	65 - 78%	95%	5-10%	5-10%	15	5,000
ZnBr	98%	5%	1C-0.25C	65 - 80%	95%	5-10%	5-10%	15	3,000
Lead Acid	98%	50%	.3C-.2C	75 - 90%	96%	25-45%	15-30%	3 to 10	5,000
Flywheel	100%	0%	Varies	70 - 87%	94%	0%	0%	20	unlimited

Bulk Storage Technologies

Compressed Air Energy Storage

Typical Use Case

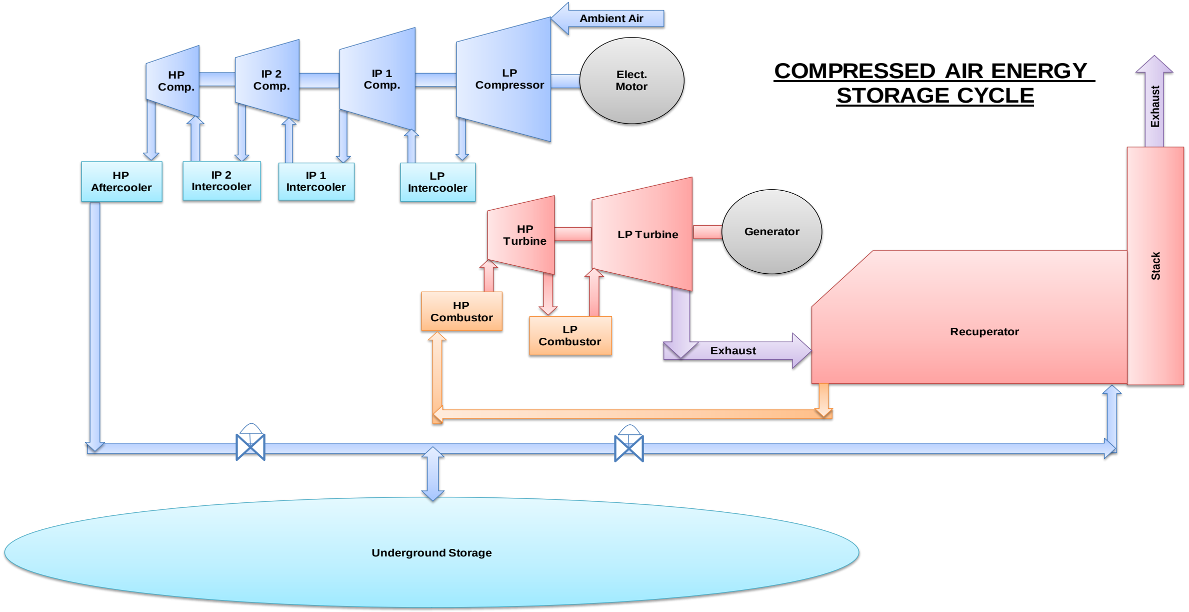
- Arbitrage, Resource Adequacy, Demand Response, Grid Resiliency

Example Providers

- Dresser Rand
- Alstom

Notes

- Few grid scale installations
- Limited deployment
- 5 min to 8 hour competitive system costs
- Underground infrastructure (salt domes, etc)
- Long development timeline (5 to 10 years)



COMPRESSED AIR ENERGY STORAGE (CAES)

- CAES
  - Storage of compressed air in caverns at pressures of up to 1,500 psig, reducing to 600 psig
  - Low cost, off-peak power used to drive compressor
  - Two Primary Technologies
    - Diabatic - Compressed air expanded through combustion turbine with fuel combustion
    - Adiabatic – Heat from combustion is stored and utilized to preheat released air
  - Two plants in service
    - Alabama Electric Coop MacIntosh (1991-110 MW) (1998 upgraded to 226 MW)
    - Huntorf, Germany (1978, 290 MW for 2 hours, 8 hour charging time)
  - ADELE plant in Germany also reported to be in service as of 2016 (90 MW, 360 MWh)
  - Proposed projects include Western Energy Hub (Magnum Energy), Norton Energy Storage, PG&E Kern County
  - Dresser-Rand and Alstom have operating equipment
  - Efficiencies – McIntosh (54%), Huntorf (42%), ADELE (70% proposed)
  - Startup times of 9 to 12 minutes

LIQUID AIR ENERGY STORAGE (LAES)

- **Uses off-peak electricity to cool air to minus 195^{o}C** at which air liquefies and is at 1/1000 of the volume of the gas
- **25% efficient, can be increased to approximately 50% if use low-grade cold store,** such as a large gravel bed, to capture the cold generated by evaporating the cryogen.
- Liquid air stored in large vacuum flask at atmospheric pressure
- When power is required, the liquid air is heated with ambient air or low grade waste heat
- The massive increase in volume and pressure is used to drive a turbine to generate electricity

Typical Use Case

- Arbitrage, Resource Adequacy, Demand Response, Grid Resiliency

Example Providers

- Highview Power Storage

Notes

- One pilot scale (350 kW) installation in service in the UK since 2010 - developmental technology
- 5 min to 4 hour competitive system costs

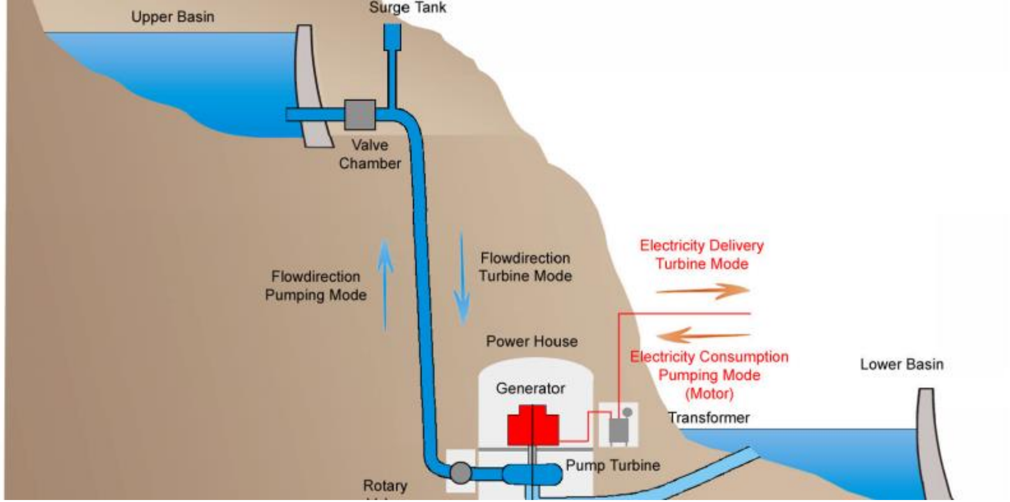
Pumped Hydro Storage

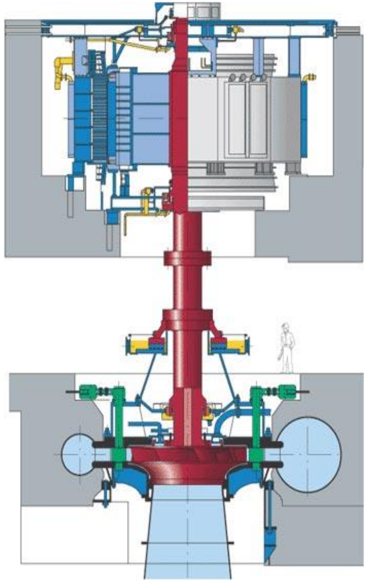
Typical Use Case

- VAR support, Arbitrage, Frequency Regulation, Resource Adequacy, Demand Response, Grid Resiliency
- Best suited for large scale capacity installations

Characteristics

- Turnaround efficiency of nearly 82%
- 6 to 20 hour storage durations
- Key is hydraulic head between reservoirs
- Approximately 40 projects operating in the U.S.
- Over 20 GW (nearly 2%) of generating capacity
- Most mature energy storage technology
- No new capacity added in over a decade
- Long development timeline (5 to 10 years)





ENERGY STORAGE TECHNOLOGIES

Application	Description	CAES	Pumped Hydro	Flywheels	Lead-Acid	NaS	Li-ion	Flow Batteries
Off-to-on peak intermittent shifting and firming	Charge at the site of off peak renewable and/ or intermittent energy sources; discharge energy into the grid during on peak periods	◑	◑	○	●	●	●	●
On-peak intermittent energy smoothing and shaping	Charge/discharge seconds to minutes to smooth intermittent generation and/or charge/discharge minutes to hours to shape energy profile	○	◑	◑	●	●	●	●
Ancillary service provision	Provide ancillary service capacity in day ahead markets and respond to ISO signaling in real time	◑	◑	◑	◑	◑	◑	◑
Black start provision	Unit sits fully charged, discharging when black start capability is required	◑	◑	○	●	●	●	●
Transmission infrastructure	Use an energy storage device to defer upgrades in transmission	○	○	○	●	●	●	●
Distribution infrastructure	Use an energy storage device to defer upgrades in distribution	○	○	○	●	●	●	●
Transportable distribution-level outage mitigation	Use a transportable storage unit to provide supplemental power to end users during outages due to short term distribution overload situations	○	○	○	◑	●	●	●
Peak load shifting downstream of distribution system	Charge device during off peak downstream of the distribution system (below secondary transformer); discharge during 2-4 hour daily peek	○	○	○	●	●	●	●
Intermittent distributed generation integration	Charge/Discharge device to balance local energy use with generation. Sited between the distributed and generation and distribution grid to defer otherwise necessary distribution infrastructure upgrades	○	○	○	●	◑	◑	◑
End-user time-of-use rate optimization	Charge device when retail TOU prices are low and discharge when prices are high	◑	◑	○	◑	◑	◑	◑
Uninterruptible power supply	End user deploys energy storage to improve power quality and /or provide back up power during outages	○	○	◑	●	●	●	●
Micro grid formation	Energy storage is deployed in conjunction with local generation to separate from the grid, creating an islanded micro-grid	○	○	○	●	●	●	●

Definite suitability for application ● ; Possible use for application ◑ ; Unsuitable for application ○

Source: Grid Energy Storage, U.S. DOE, December 2013

Installation Requirements

30MW/30MWh

Containerized System

Dimension: 400'x135'

Property: 1.23 Acers

Fences: 1.16 Acers

PCS: 2MW

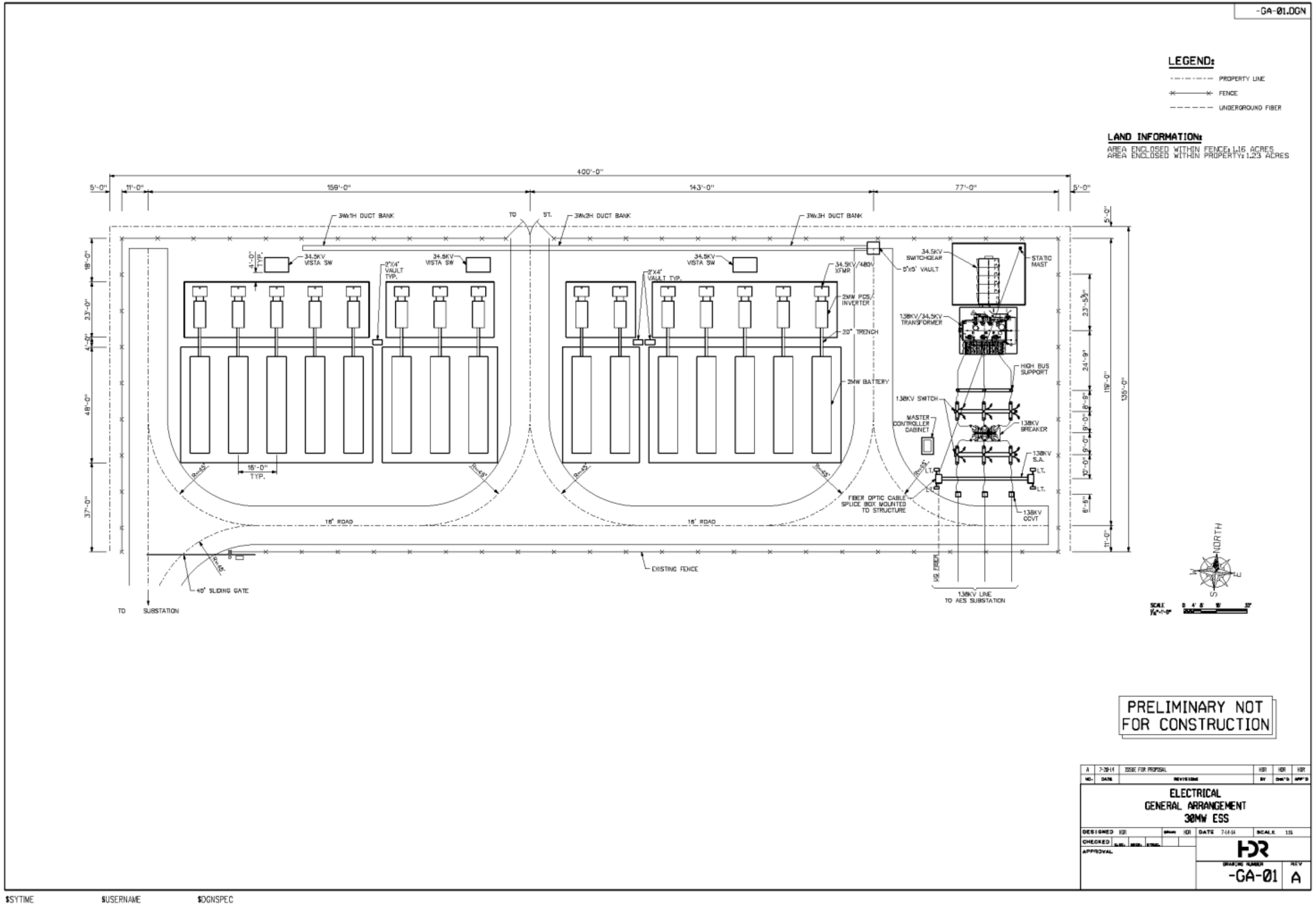
Containers: 40 Foot

Battery: 2MW

Battery VDC: 1000V

Collection VAC: 34.5kV

Interconnection: 138kV



20MW/80MWh

Building Housed System

Dimension:	514’x324’
Property:	3.82 Acers
Building:	1.68 Acers
PCS:	1MW
Containers:	40 Foot
Battery:	250KW/4hr (Block)
Battery VDC:	1000V
Collection VAC:	15kV
Interconnection:	115kV

90MW/90MWh

Containerized System

Dimension: 514’x324’

Property: 3.81 Acers

Fences : 3.58 Acers

PCS: 2MW

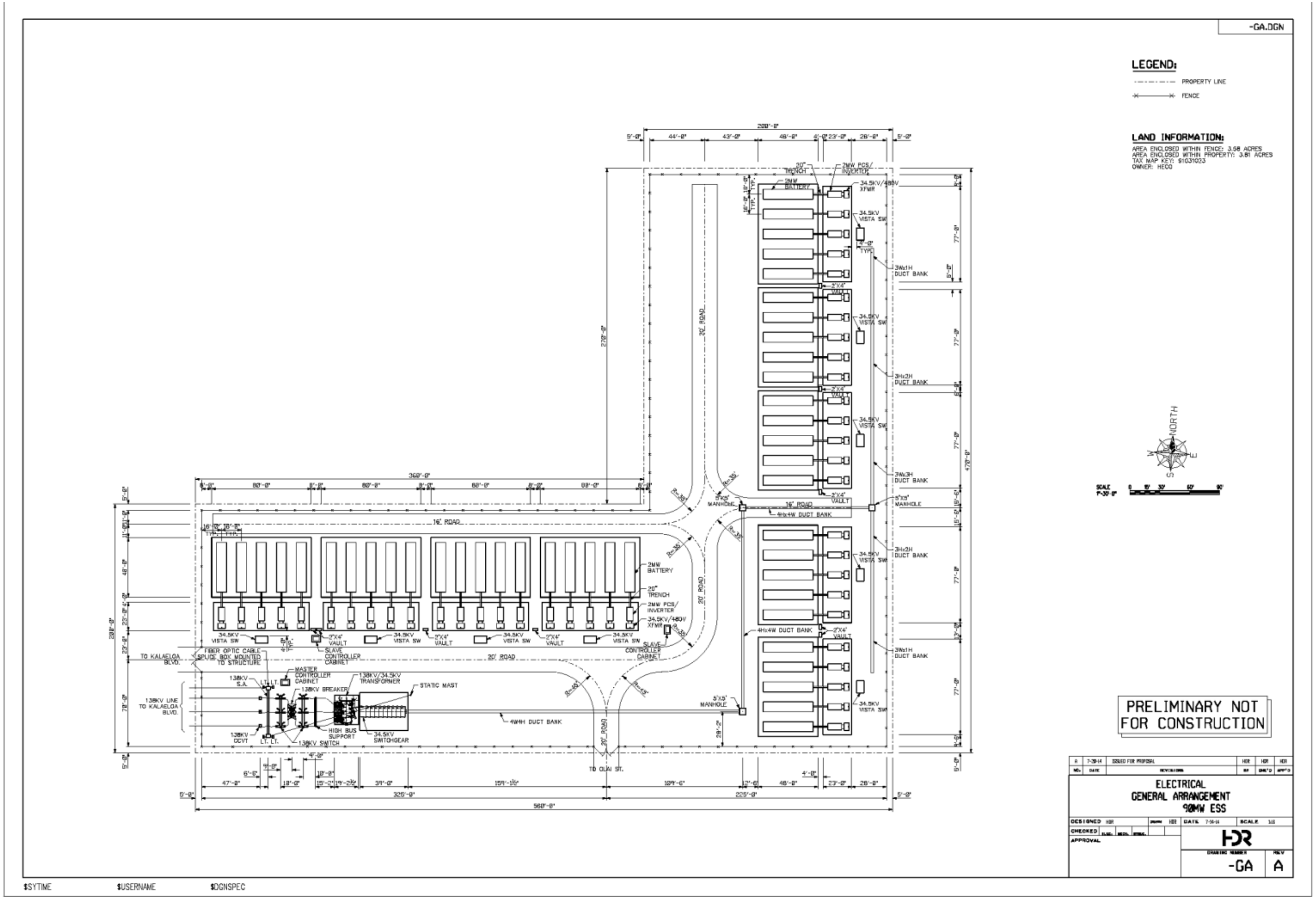
Containers: 40 Foot

Battery: 2MW

Battery VDC: 1000V

Collection VAC: 34.5kV

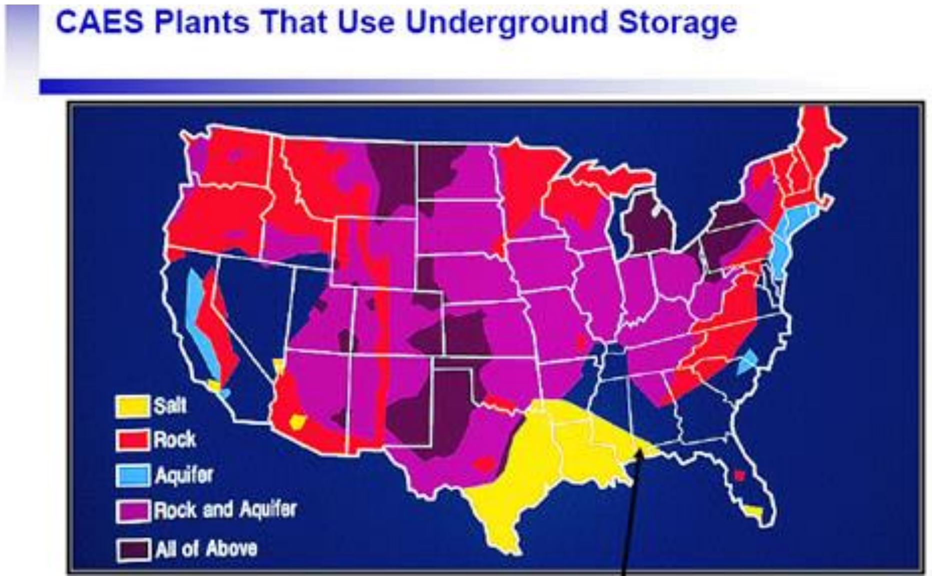
Interconnection: 138kV



Compressed Air Energy Storage

Installation Requirements

- Salt domes, aquifers, and rock caverns
- Constant volume or pressure caverns
- Aquifers and depleted gas reservoirs are the least expensive storage formations
- Salt caverns are the most expensive storage formations since solution mining is necessary



The following references were cited in the preparation of this presentation.

Federal Energy Regulatory Commission, “Market Oversight Glossary”, http://www.ferc.gov/market-oversight/guide/glossary.asp.

ERCOT “Nodal Protocols”.

ERCOT Concept Paper, “Future Ancillary Services In ERCOT”, Draft Version 1.1, 2013.

IESO Website.

Midcontinent ISO, “Business Practices Manual 002” and “Business Practices Manual 015”.

FERC Docket No. ER12-1664-000, Issued September 20, 2012.

SBC Energy Institute, “Electricity Storage Factbook”, September, 2013.

NYISO, “Market Administration and Control Area Services Tariff, 15.3 MST Rate Schedule 3”.

NYISO, “Ancillary Services Manual”, V.4, 2014.

PJM, “State of the Market Report”, 2014.

PJM, “Manual 11, Energy & Ancillary Services Market Operations”, Revision 73, April, 2015.

Department of Energy, “Grid-Scale Energy Storage Demonstration using Ultrabattery Technology”, October, 2012.

Ecoult Website.

Beacon Power Website.

Uni Energy Technologies Website.

Rocky Mountain Institute, HOMER Energy, and global X, "The Economics of Load Deflection", April, 2015.

NERC, "Ancillary Services Summary Across North American RTOs and ISOs".

U.S. DOE, NETL, "Seneca Compressed Air Energy Storage (CAES) Project", September, 2012.

GTM Research, "U.S. Energy Storage Monitor: 2014 Year in Review: Executive Summary"

The Brattle Group, "The Value of Distributed Electricity Storage in Texas", Prepared for ONCOR, November, 2014.

Sandia National Laboratories, "Performance Assessment of the PNM Prosperity Electricity Storage Project", Report SAND2014-2883, May, 2014.

Sandia National Laboratories, "Market and Policy Barriers to Energy Storage Deployment: A Study for the Energy Storage Systems Program", Report SAND2013-7606, September, 2013.

Sandia National Laboratories, "Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems", Report SAND2013-7084, August, 2013.

International Energy Agency, "Technology Roadmap: Energy Storage", 2014.

U.S. Department of Energy (DOE), "Grid Energy Storage", December, 2013.

U.S. Department of Energy (DOE), "Energy Storage Safety Strategic Plan", December, 2014.

CAISO, "Advancing and Maximizing the Value of Energy Storage Technology: A California Roadmap", December, 2014.

CAISO, "Draft Energy Storage Roadmap for California", October, 2014.

DOE, “DOE/EPRI 2013 Electricity Storage Handbook”, in Collaboration with NRECA, July, 2013.

Executive Office of the President (White House) and DOE, “Economic Benefits of Increasing Grid Resilience to Weather Outages”, August, 2013.

PNNL and DOE, “National Assessment of Energy Storage for Grid Balancing and Arbitrage”, Phases 1 (WECC) and 2 (Cost and Performance Characterization), Volumes 1 and 2, June, 2012 and September, 2013.

EPRI, “Cost-Effectiveness of Energy Storage in California”, June 2013

Lux Research “Grid Storage under the Microscope:” April, 2012

Sandia Report, “Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation,” Dec. 2012

Sandia Report, “Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation,” Dec. 2012

Energy Information Admin, “Annual Energy Outlook 2007” Feb. 2007