SAND2021-14054C

Sandia National Laboratories

Exceptional service in the national interest

Battery Energy Storage Technologies and Applications

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11/06/2021, PUC-RS, Porto Alegre, Brazil

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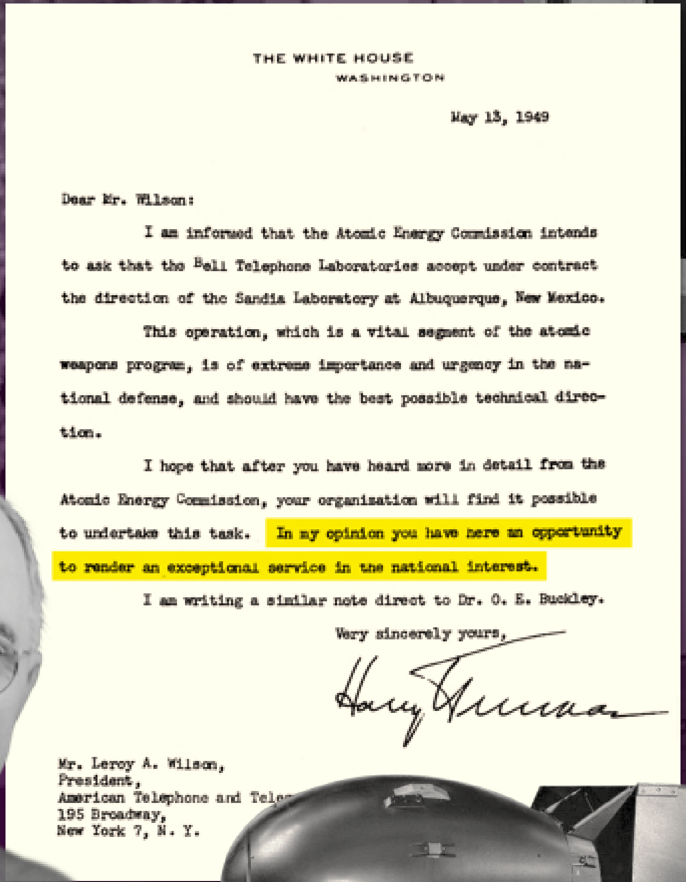
OUTLINE

1. Sandia National Laboratories and Energy Storage Program
2. Background
3. Energy Storage Applications
4. Energy Storage Technologies
5. Challenges
6. Conclusion

SANDIA'S HISTORY IS TRACED TO THE MANHATTAN PROJECT



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Tele
195 Broadway,
New York 7, N. Y.

- July 1945: Los Alamos creates Z Division
- Nonnuclear component engineering
- November 1, 1949: Sandia Laboratory established
- AT&T: 1949–1993
- Martin Marietta: 1993–1995
- Lockheed Martin: 1995–2017
- Honeywell: 2017–present

OUR MULTIMISSION ROLE HAS EXPANDED OVER THE DECADES

- **1950s** — NUCLEAR WEAPONS ENGINEERING AND TESTING — Arms race
- **1960s** — NW STOCKPILE DIVERSITY AND BUILD-UP — Cuban missile crisis & Vietnam War
- **1970s** — NW + ENERGY: MULTIPROGRAM LABORATORY — Energy crisis
- **1980s** — DOE MULTIPROGRAM + MISSILE DEFENSE AND OTHER DoD WORK — End of Cold War
- **1990s** — DOE MULTIPROGRAM + DoD, ECONOMIC COMPETITIVENESS — Stockpile stewardship
- **2000s** — EXPANDED NATIONAL SECURITY ROLE POST 9/11 — Broader national security
- **Today** — MULTIMISSION LAB: LEPs CYBER, BIO, SPACE, TERRORISM — Evolving national security challenges

WE HAVE FACILITIES ACROSS THE NATION

Activity locations

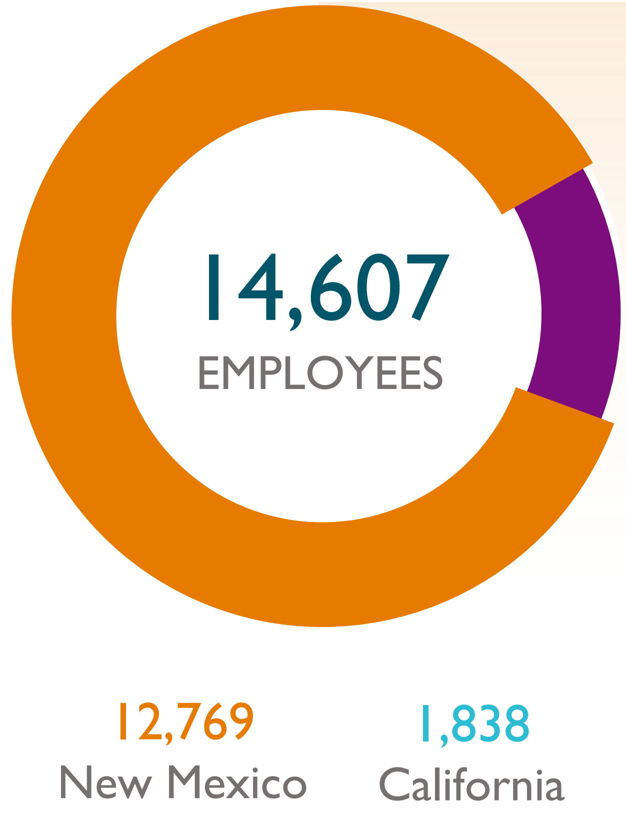
- Kauai, Hawaii
- Waste Isolation Pilot Plant, Carlsbad, New Mexico
- Pantex Plant, Amarillo, Texas
- Tonopah, Nevada

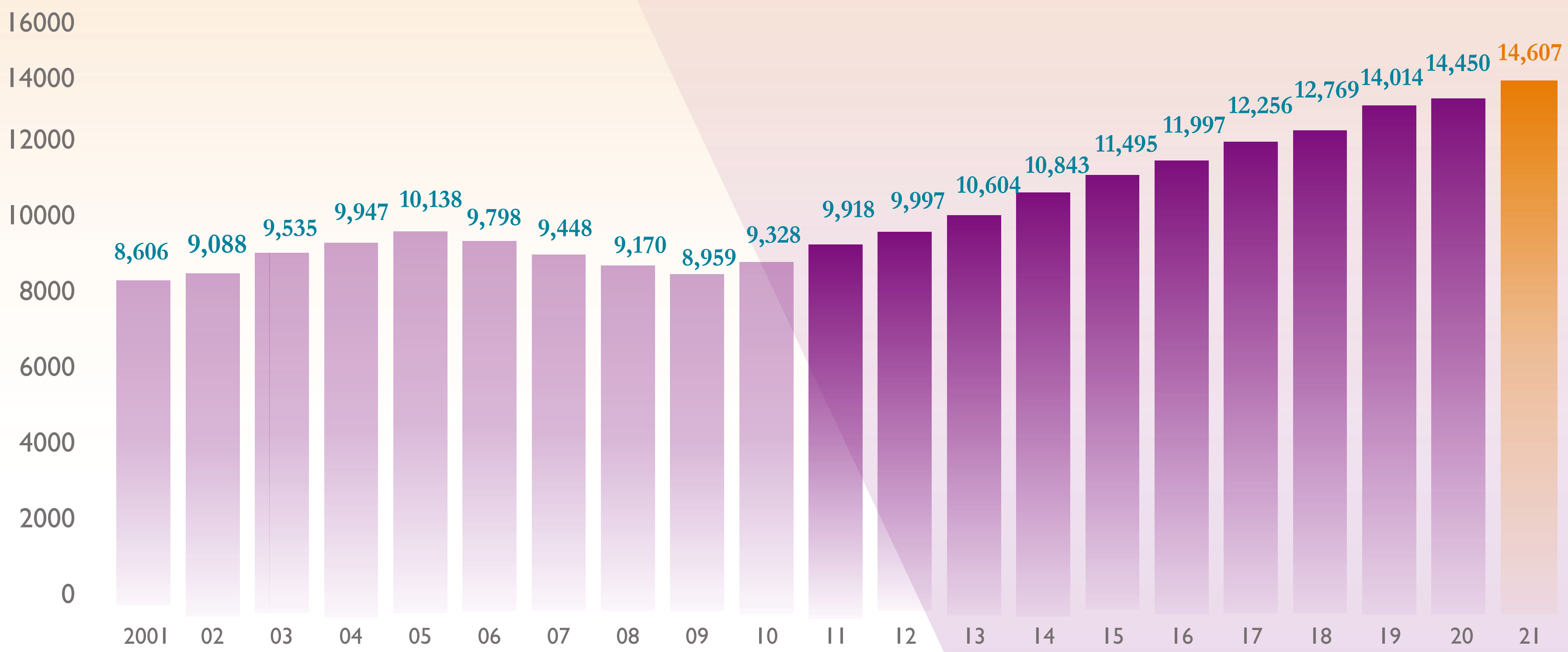
Main sites

- Albuquerque, New Mexico
- Livermore, California

SANDIA'S WORKFORCE IS GROWING

Staff has grown by over 4,600 since 2011 to meet all mission needs



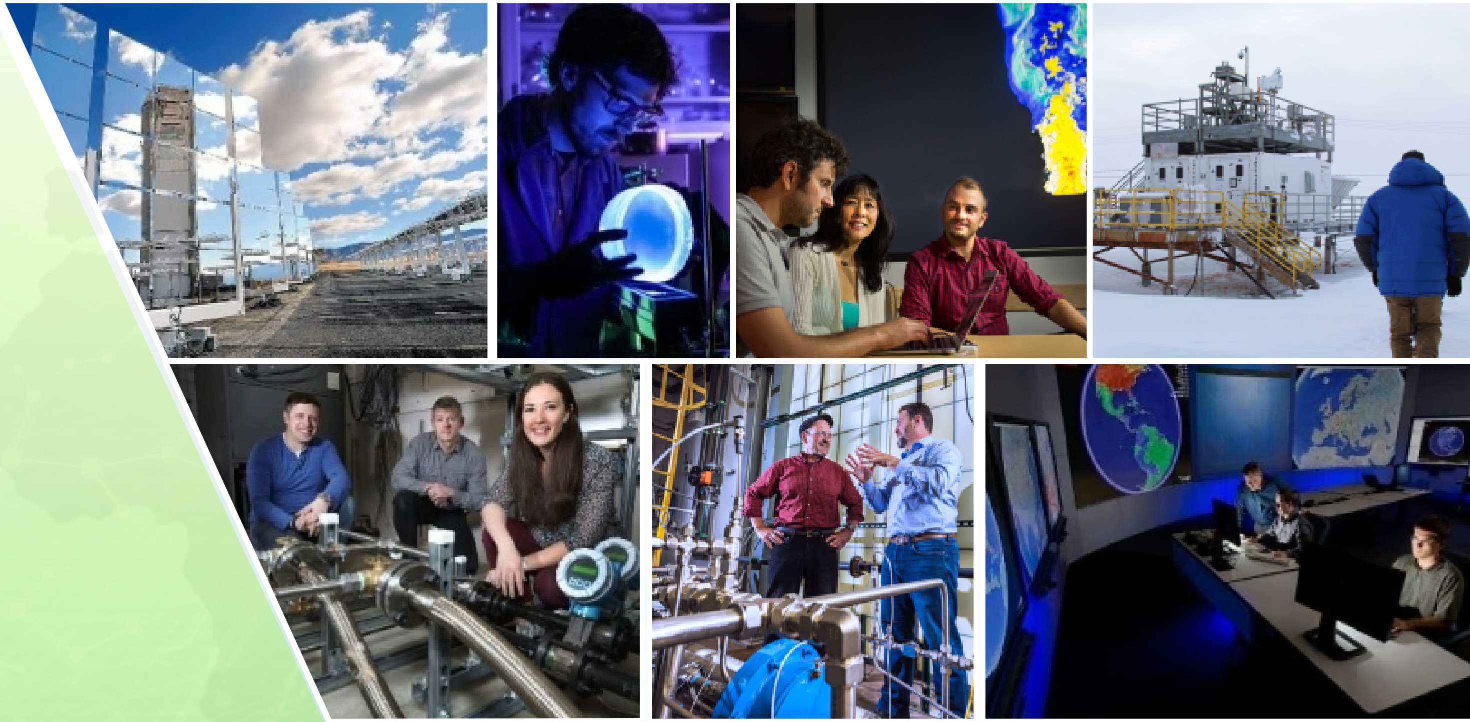


SANDIA HAS FIVE MAJOR PROGRAM PORTFOLIOS

ENERGY & HOMELAND SECURITY

Secures the nation's critical infrastructures and environment against attacks, threats, and climate change by performing world-class research and development.

- Advance energy technologies and solutions to climate change
- Create solutions for a safe, secure, and resilient energy future
- Provide transformative solutions in the transportation sector
- Reduce the nation's vulnerability to chemical, biological, radiological, and nuclear threats
- Provide protection for our nation's digital and physical critical infrastructures

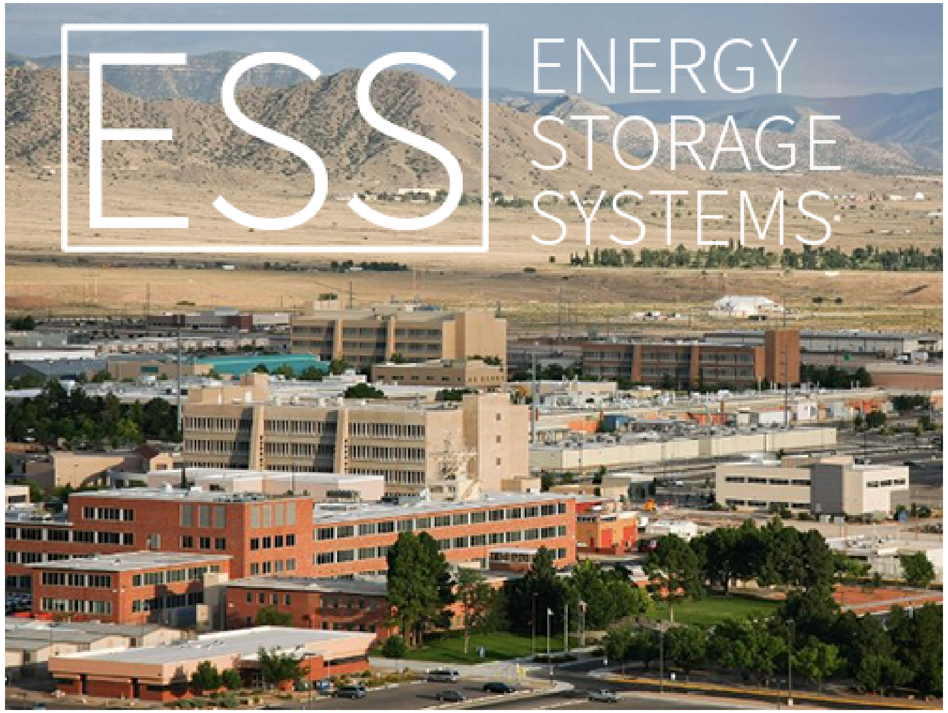


ENERGY STORAGE SYSTEMS PROGRAM

Started in 1950's

- Develop power sources for Nation's nuclear stockpile
- From 1970s on, focus moved to electric power
- Develop advanced energy storage technologies and systems
- Increase the reliability, performance, and competitiveness of electricity generation and transmission
- Electric grid
- Standalone systems

For more information: **energystorage.sandia.gov**



ENERGY STORAGE R&D AT SANDIA

BATTERY MATERIALS

Large portfolio of R&D projects related to advanced materials, new battery chemistries, electrolyte materials, and membranes.

CELL & MODULE LEVEL SAFETY

Evaluate safety and performance of electrical energy storage systems down to the module and cell level.

POWER CONVERSION SYSTEMS

Research and development regarding reliability and performance of power electronics and power conversion systems.

SYSTEMS ANALYSIS

Test laboratories evaluate and optimize performance of megawatt-hour class energy storage systems in grid-tied applications.

DEMONSTRATION PROJECTS

Work with industry to develop, install, commission, and operate electrical energy storage systems.

STRATEGIC OUTREACH

Maintain the ESS website and DOE Global Energy Storage Database, organize the annual Peer Review meeting, and host webinars and conferences.

GRID ANALYTICS

Analytical tools model electric grids and microgrids, perform system optimization, plan efficient utilization and optimization of DER on the grid, and understand ROI of energy storage.

Wide ranging R&D covering energy storage technologies with applications in the grid, transportation, and stationary storage

U.S. ELECTRICITY GENERATION

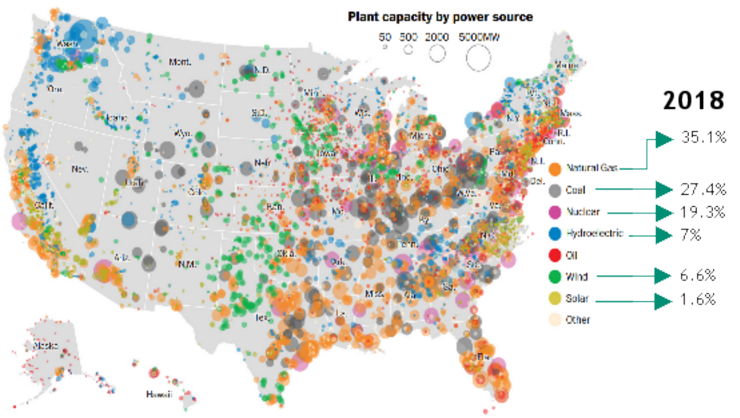
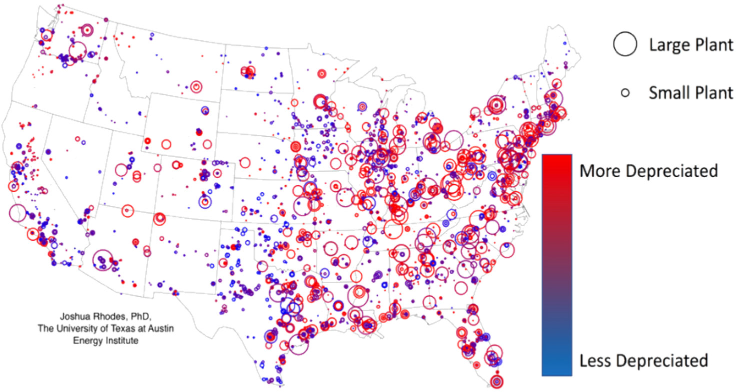
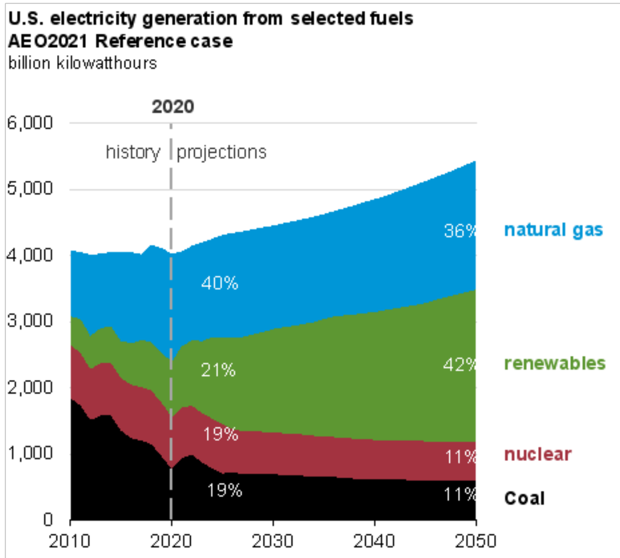
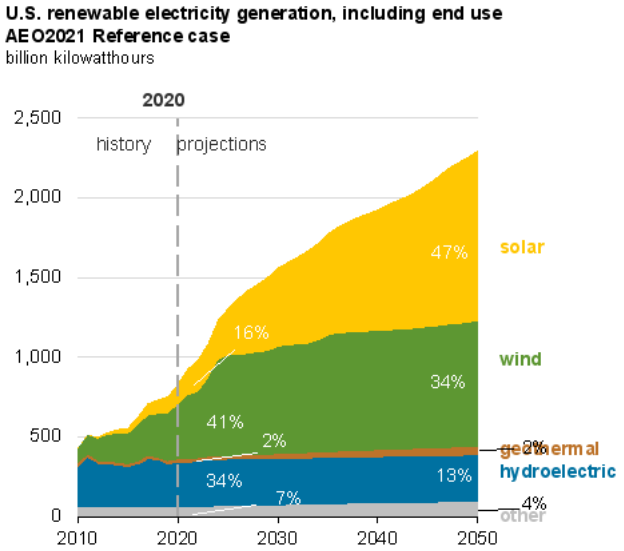
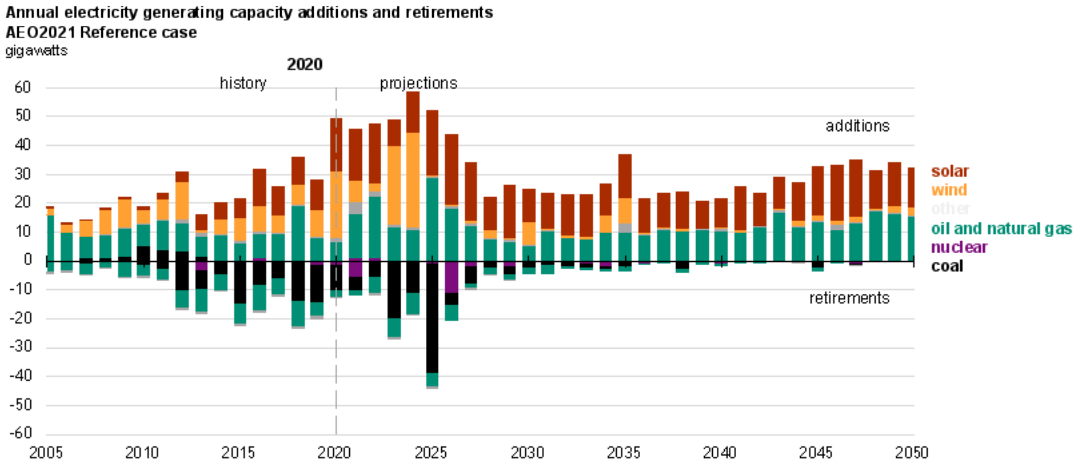


Image credit: Washington Post









- 7000 power plants (name plate capacity of 1 MW or larger)
- Accelerating retirements of coal fired power plants
- EIA projection – RE providing 42% of electricity by 2050
- Amount of storage deployment will significantly impact growth of renewables

Source: Form EIA-860M, *Monthly Update to the Annual Electric Generator Report*, July 2020
U.S. Energy Information Administration, *Annual Energy Outlook 2021 (AEO 2021)*
www.eia.gov/aeo

CLIMATE CHANGE STATES DRIVING MAJOR POLICIES FOR CLEAN ENERGY

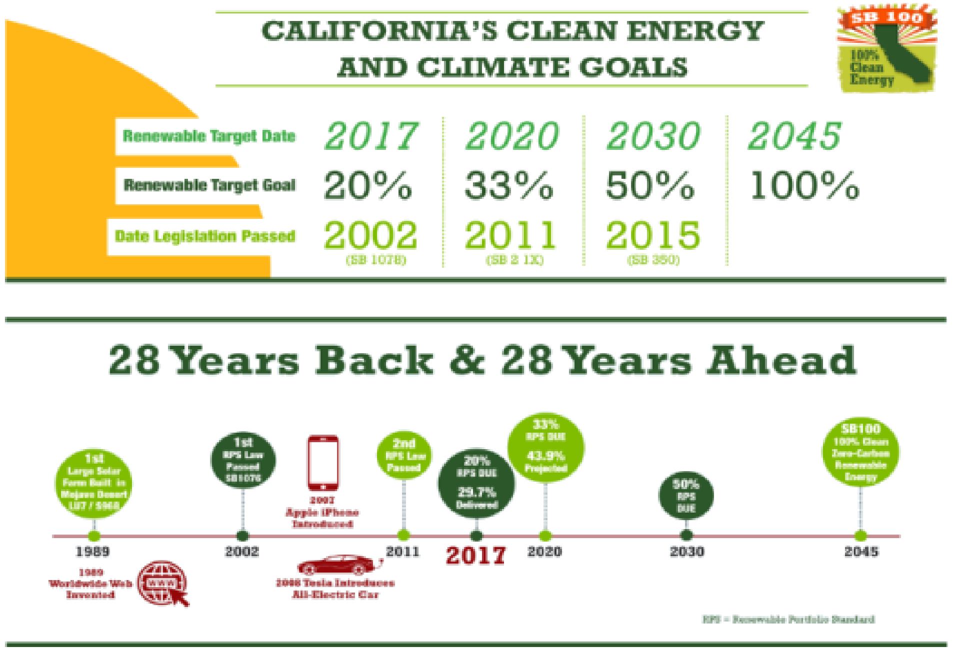
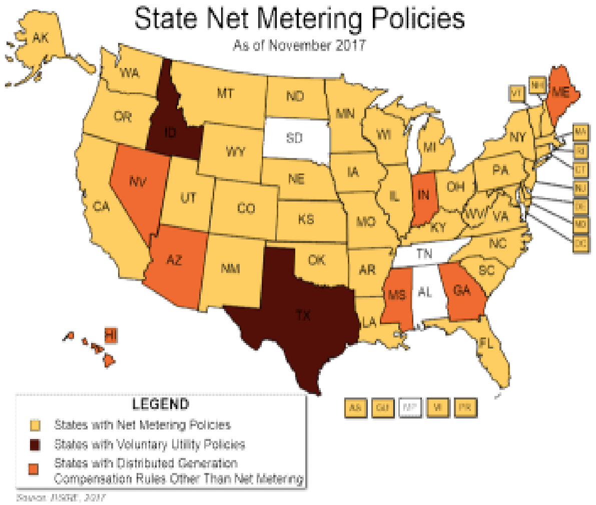
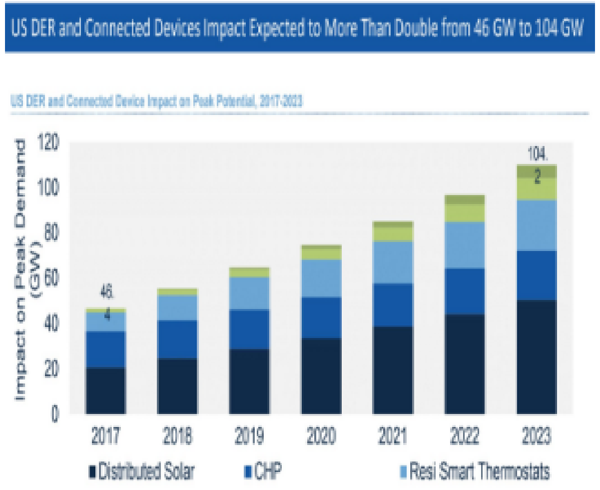


Image Source: California Senate



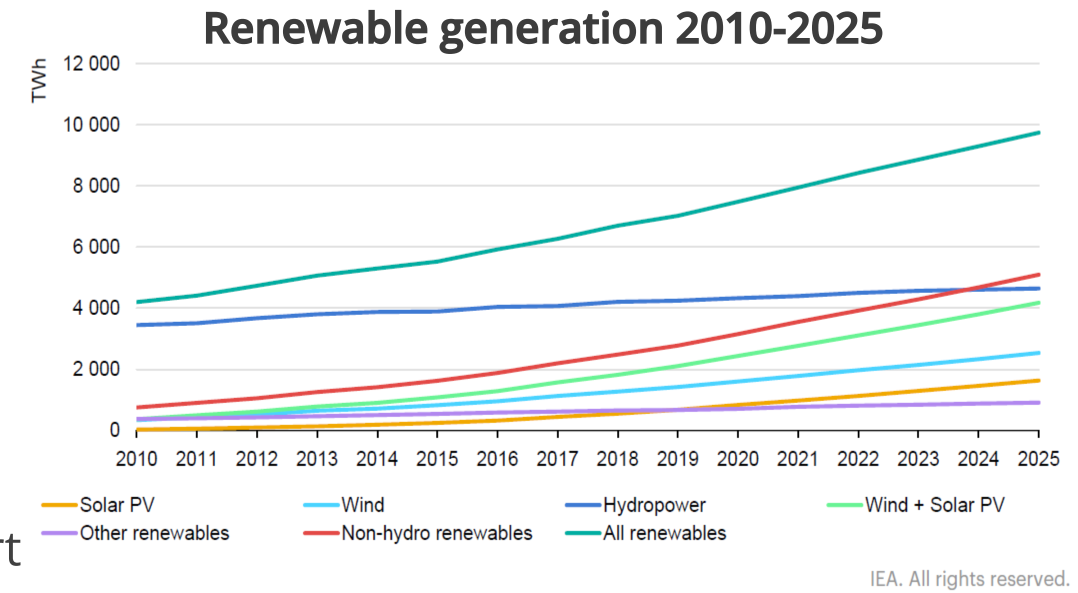


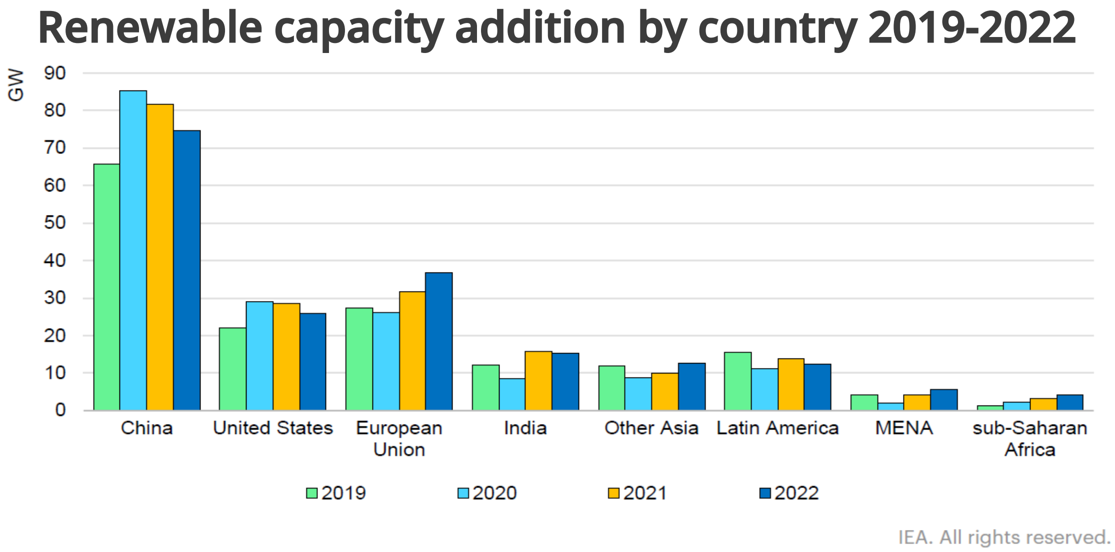
Source: GTM Research and US DOE

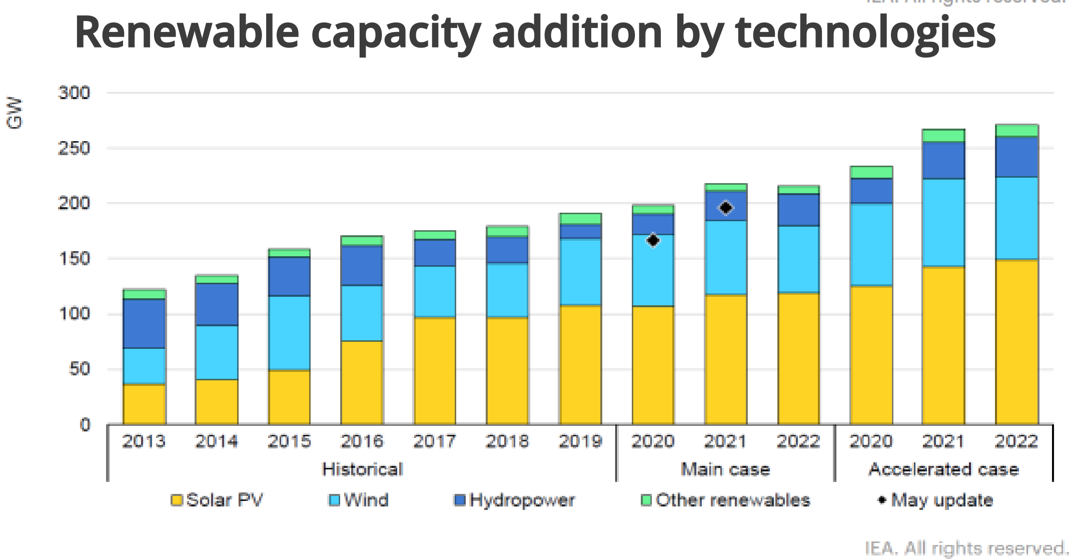
- Generation is becoming distributed
- Almost all states have Net Metering programs
- California, Hawaii, New Mexico, Washington, and Nevada legislating 100% renewable energy in the next 20-30 years.

INCREASING ADOPTION OF RENEWABLE ENERGY RESOURCES

- Current trends:
  - Accelerating retirements of coal fired power plants
  - Stalled replacement/expansion of nuclear generation
- Growth of net renewable electricity capacity, mainly from wind, utility-scale PVs; and hydro in some locales
- Share of renewables in electricity grid sector will take the largest portion, followed by buildings and transport





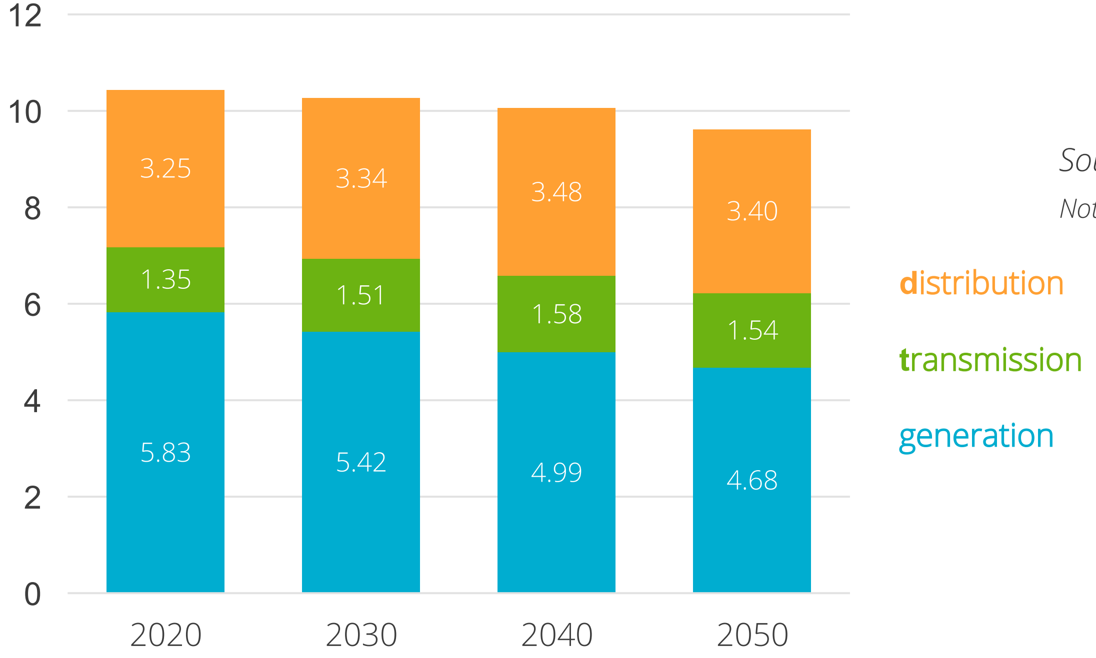


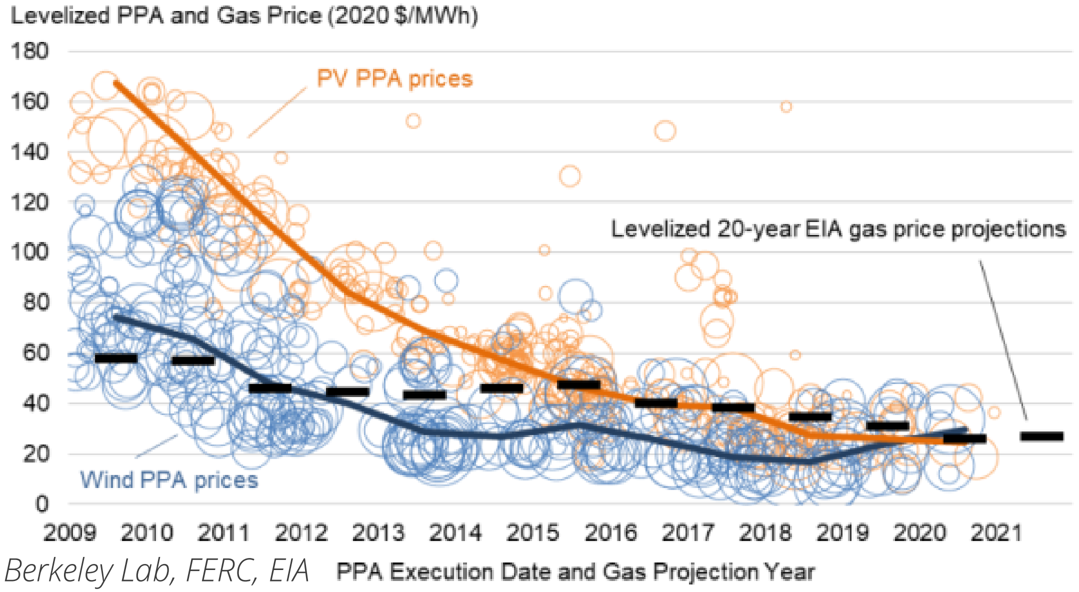
Source: IEA Renewables 2020

DECREASING COST OF RENEWABLE GENERATION

- Becoming cheaper
- At parity with traditional generation

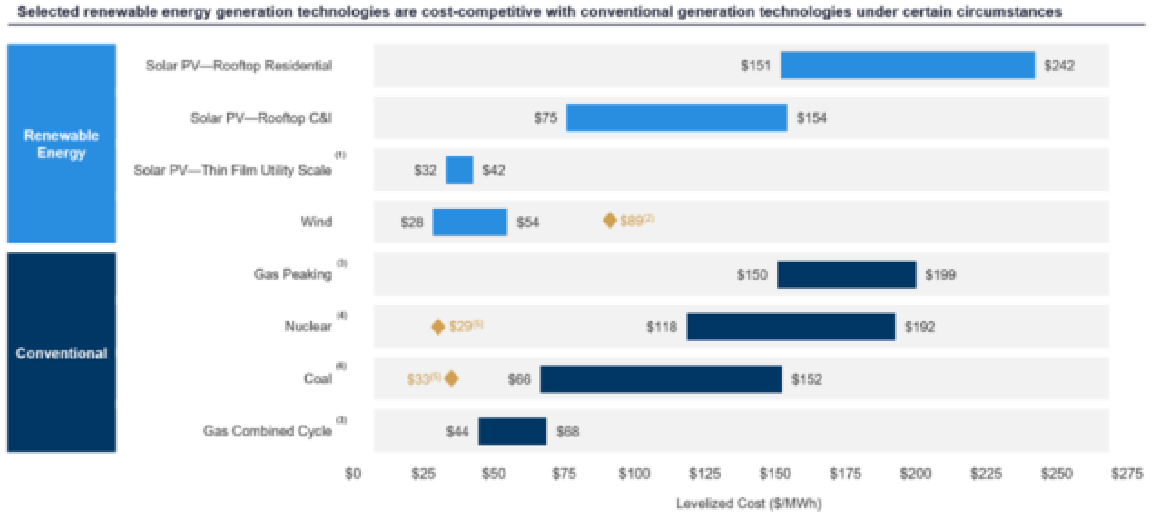
Components of U.S. Electricity Prices AEO2021
2020 c/kWh





Source: Berkeley Lab, FERC, EIA

Note: Smallest bubble sizes reflect smallest-volume PPAs (<5 MW),largest reflect largest-volume PPAs (>500 MW).



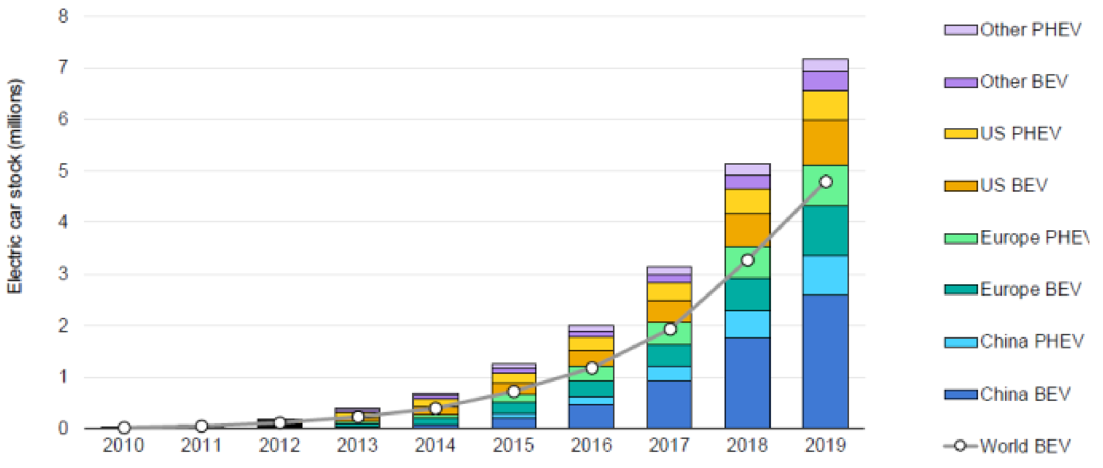
https://www.lazard.com/perspective/lcoe2019

ZERO EMISSIONS AND ELECTRIFICATION

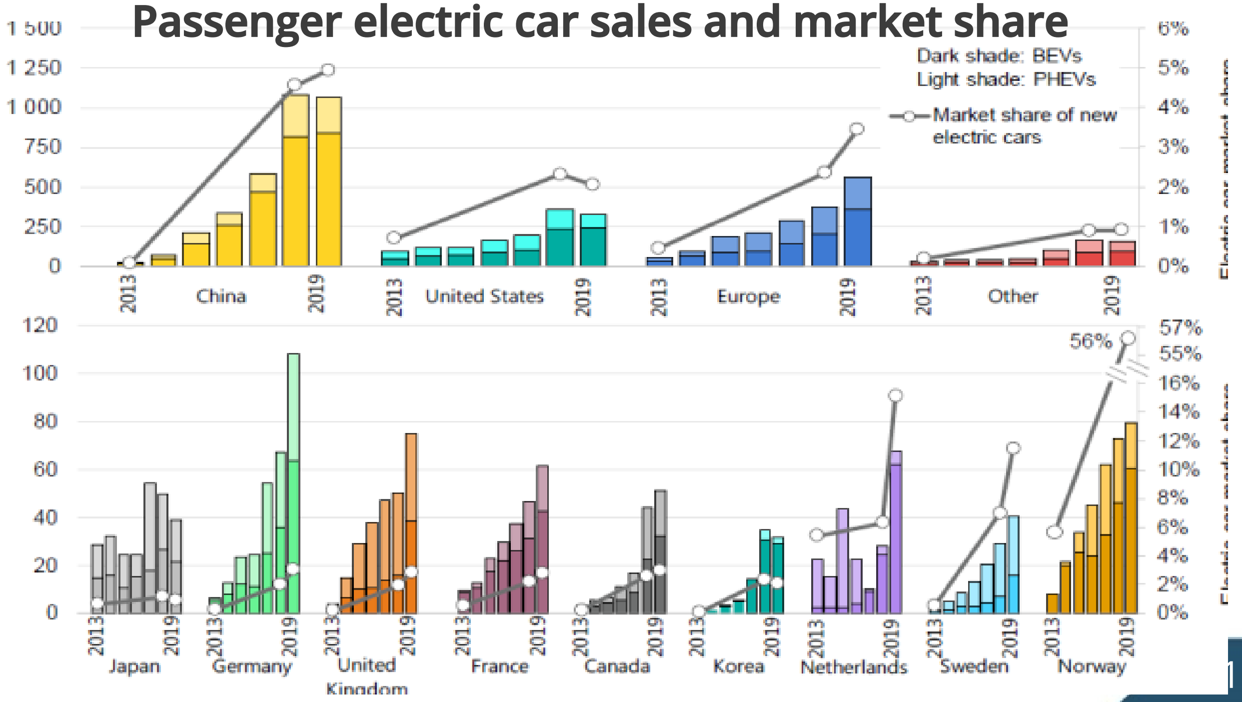
- **Transport Electrification**
  - Transport will undergo electrification to reduce transport emission (e.g., 33% rise in 2050 REmap)
  - Battery storage for electric vehicles will increase significantly, causing major changes in electricity grid due to charging infrastructure
- **Buildings**
  - Despite improved efficiency, electricity demand in the building sector is projected to increase by 70% by 2050, mainly due to electrification of heating systems
- **Industry**
  - Industry sector is second largest CO2 emission source, mostly due to the demand from high temperature processes
  - Use of electricity will increase to promote low-temperature process, causing electricity demand increase

Sources: IEA Global EV Outlook

Global EV car stock

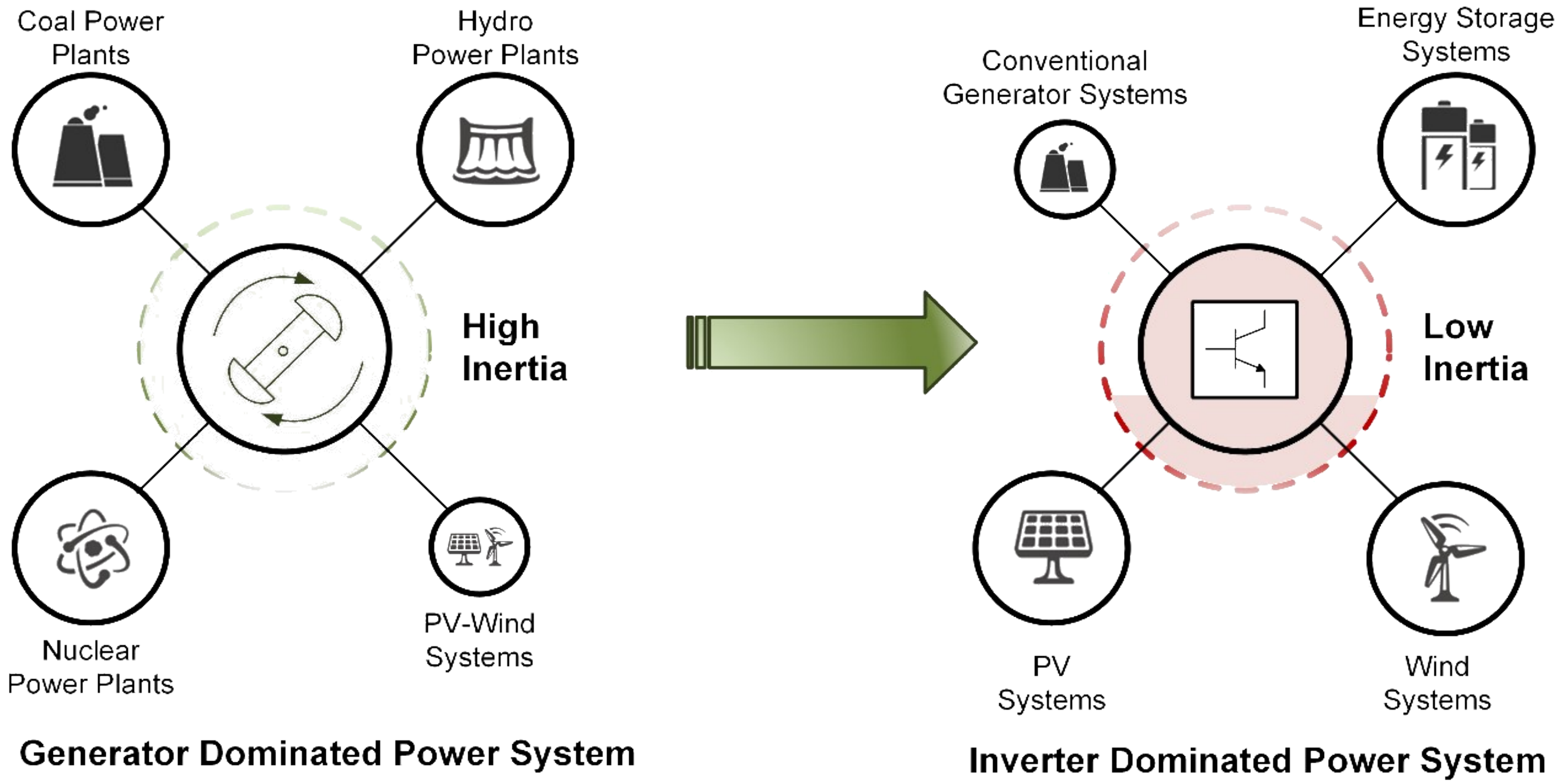


Passenger electric car sales and market share



OPERATING CHALLENGES OF GRID OF THE FUTURE – LOW INERTIA

- The power conversion system is at the center of DER, Energy Storage, and EV infrastructure
- System will operate with much lower inertia



Source: U. Tamrakar, D. Shrestha, M. Maharjan, B. Bhattarai, T. Hansen, and R. Tonkoski, "Virtual Inertia: Current Trends and Future Directions," Applied Sciences, vol. 7, no. 7, p. 654, Jun. 2017.

ENERGY STORAGE IN THE GRID TODAY

- Grid-Scale Energy Storage < 0.1% of U.S. Generation Capacity
- US installed energy storage capacity of 32 GW represents ~15 min ride through
- BESS reached 2GW in installed capacity in 2018, rest is mostly Pumped Hydro.

Compared to the need, the scale of energy storage deployments is insignificant.
With a 1 TW US electric grid, even 1 hourr of energy storage means 1 TWh

1.6 GW Raccoon **Mountain** PHS

100 MWh BESS Plant - Tesla

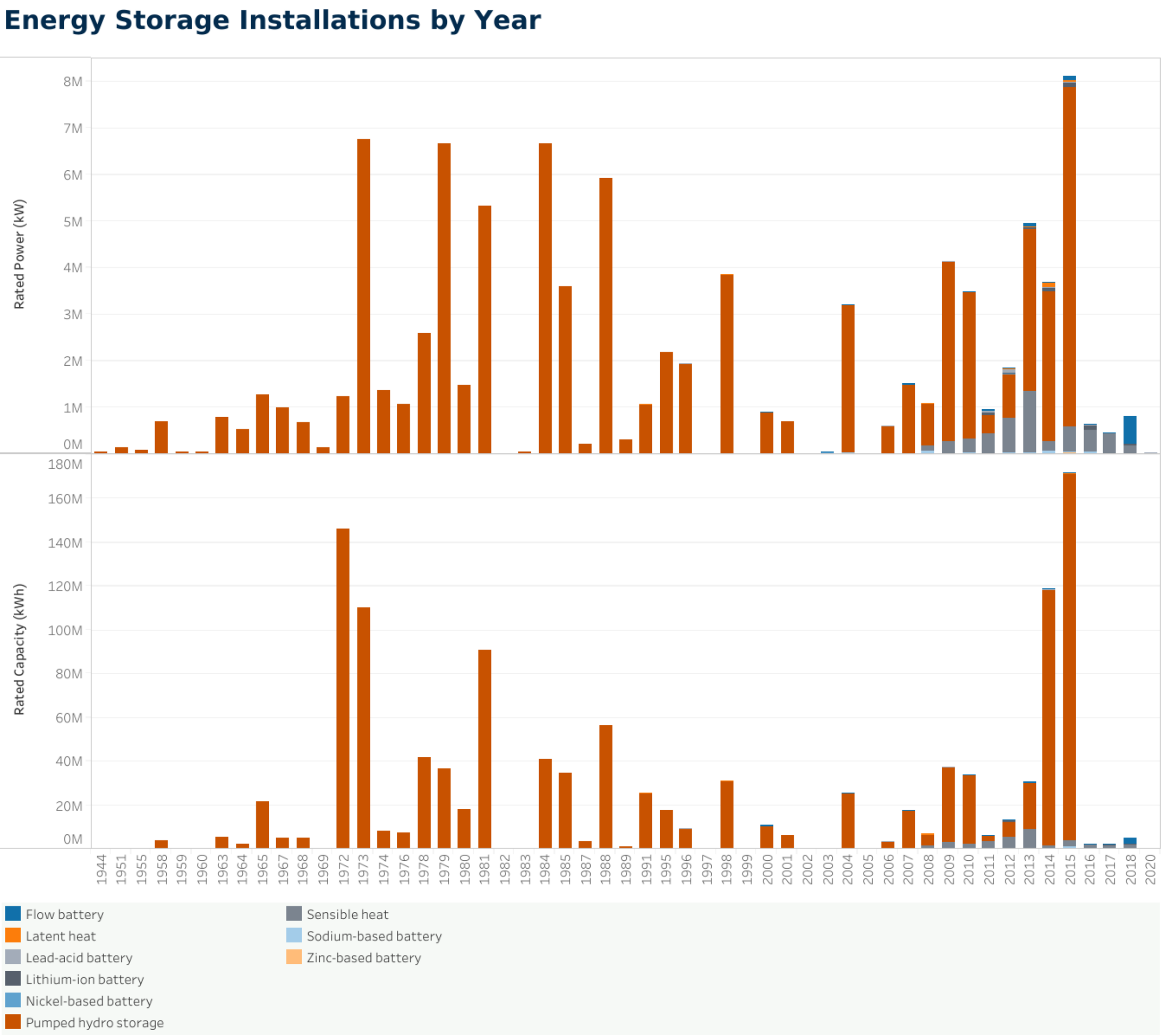
Wood Mackenzie P&R

ESA | U.S. energy storage monitor 2018

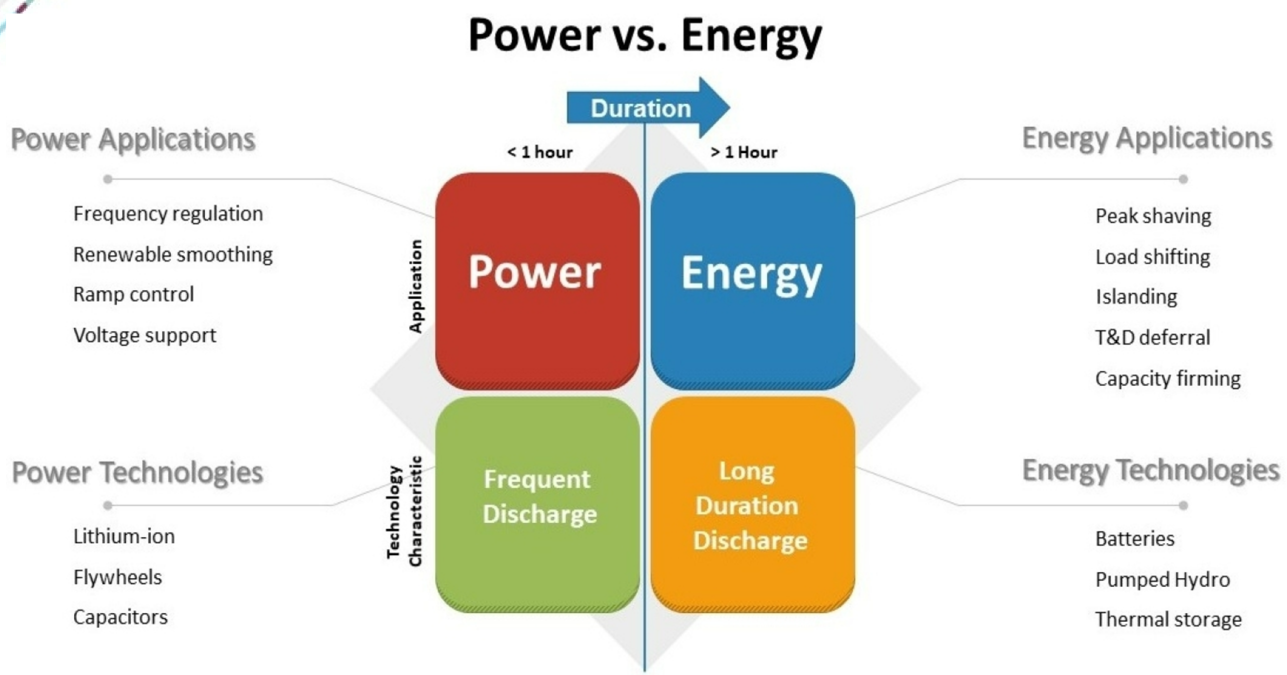
DOE Global Energy Storage Database, 2018

DOE GLOBAL ENERGY STORAGE DATABASE

- Repository of energy storage projects around the world
  - Submission-based
  - Visualization tools
- Energy policy
- For more information:
- **sandia.gov/ess-ssl/gesdb/public/**
- **sandia.gov/ess-ssl/doe-global-energy-storage-database/**



OVERVIEW OF ENERGY STORAGE APPLICATIONS



Source: Energy Storage Primer, IEEE Power and Energy Society, 2020

- Front-of-the-meter x behind-the-meter
- Grid- connected x off-grid

Applications	Power or Energy?	FTM or BTM?	Grid-connected or Off-grid?
General Energy Applications			
Energy Arbitrage in ISO/RTO Markets	Energy	FTM	Grid-connected
Renewable Energy Time-shift (Renewable smoothing and firming)	Energy	FTM and BTM	Grid-connected and Off-grid
Ancillary Services			
Frequency Regulation	Power	FTM	Grid-connected
Operating Reserve (spinning, non-spinning, supplementary)	Energy	FTM	Grid-connected
Frequency Response and Virtual Inertia	Power	FTM	Grid-connected
Voltage support	Power	FTM	Grid-connected
Ramp support	Power	FTM and BTM	Grid-connected
Black Start	Power	FTM	Grid-connected
Transmission Services			
Transmission Upgrade Deferral	Energy	FTM	Grid-connected
Transmission Congestion Relief	Energy	FTM	Grid-connected
Stability Damping Control	Power	FTM	Grid-connected
Distribution Services			
Peak shaving and Upgrade Deferral	Energy	FTM and BTM	Grid-connected
Voltage regulation	Power	FTM and BTM	Grid-connected
Reliability and Resilience	Energy and Power	FTM and BTM	Grid-connected
End-user Services			
Time-of-use, demand charge and net-metering management	Energy	BTM	Grid-connected
Power Quality	Power	BTM	Grid-connected
Resilience (Back-up power)	Energy	BTM	Grid-connected and Off-grid

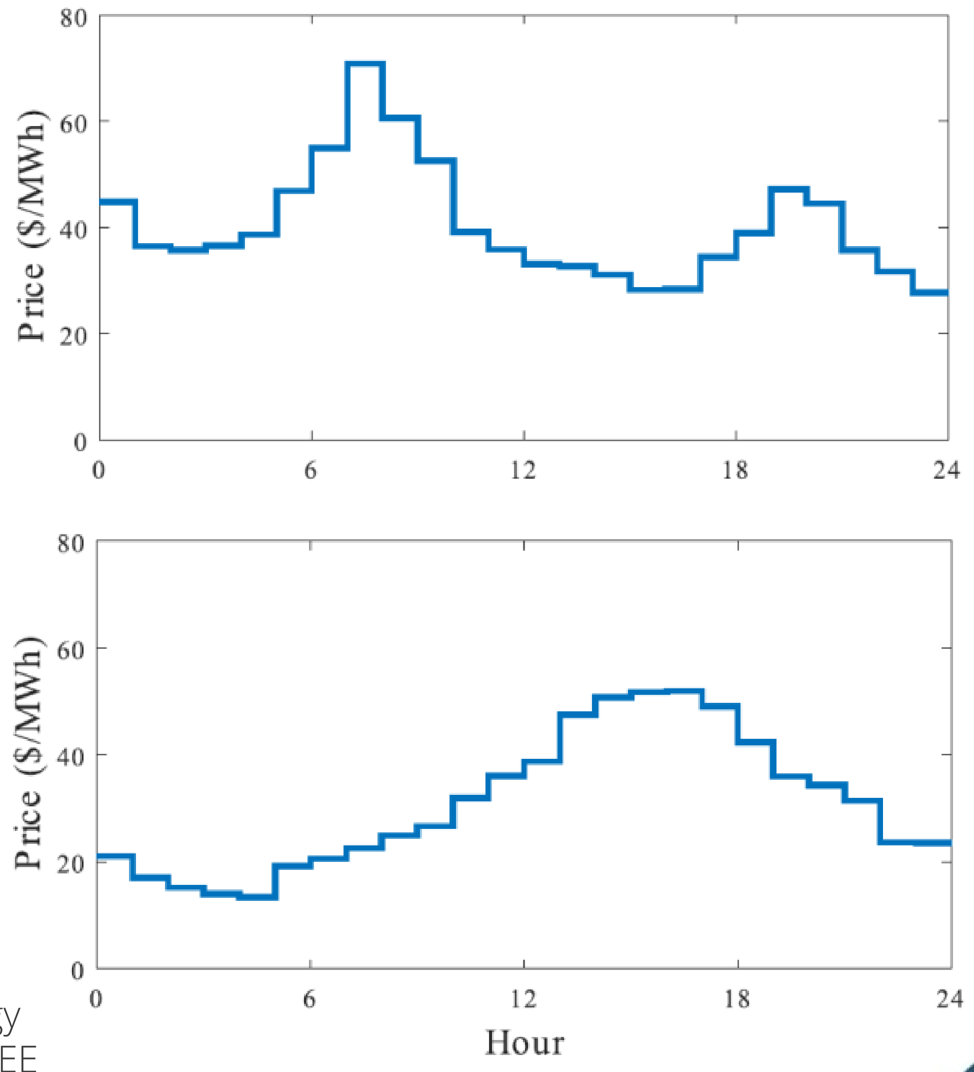
Source: 2020 U.S. DOE Energy Storage Handbook, Chapter 23: Applications and Grid Services - https://www.sandia.gov/ess-ssl/eshb/

ENERGY STORAGE FOR ENERGY ARBITRAGE

- Market energy application
  - Locational marginal prices (LMPs)
  - Day-ahead
  - Real-time (15-minutes)
- Charge – *buy* energy (load)
- Discharge – *sell* energy (generator)
  - Charge q
  - Round-trip efficiency η_c

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

$$\frac{LMP_H}{LMP_L} \geq \frac{1}{\eta_c}$$



Source: R. H. Byrne, T. A. Nguyen, D. A. Copp, B. R. Chalamala and I. Gyuk, "Energy Management and Optimization Methods for Grid Energy Storage Systems," in IEEE Access, vol. 6, pp. 13231-13260, 2018, doi: 10.1109/ACCESS.2017.2741578.

ENERGY STORAGE FOR PEAK SHAVING (NYISO EXAMPLE)

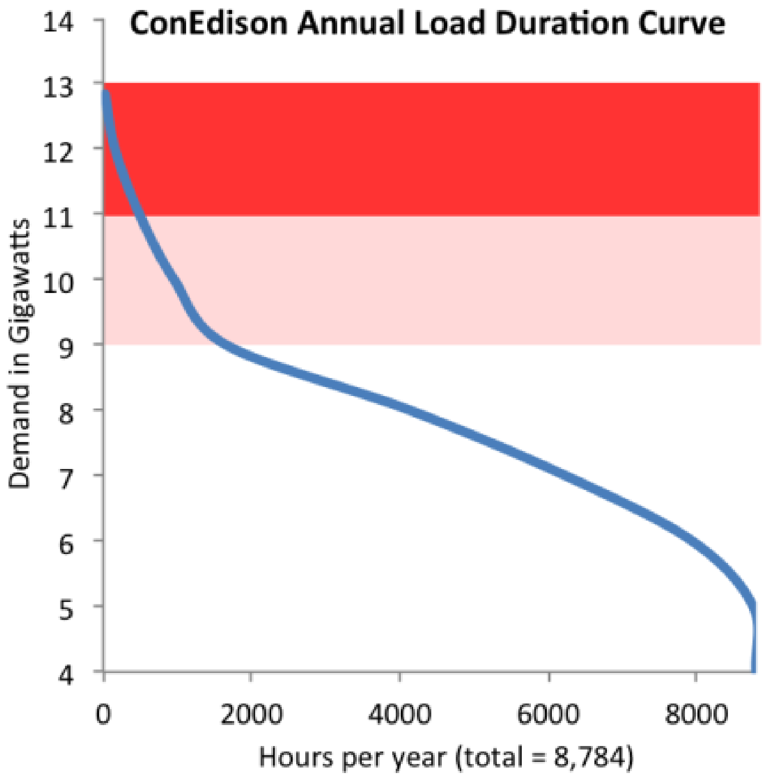


Table I-1: NYCA Energy and Demand Forecasts Net of Energy Saving Impacts

2017 Long Term Forecast[1] - 2017 to 2027

Energy - GWh

Year	Low[3]	Baseline[4]	High[3]
2016		159,169	
2017	156,755	158,632	160,504
2018	156,128	157,996	159,859
2019	155,546	157,405	159,258
2020	154,903	156,752	158,598
2021	154,017	155,855	157,689
2022	153,613	155,444	157,271
2023	153,468	155,298	157,124
2024	153,306	155,135	156,959
2025	153,182	155,009	156,832
2026	153,094	154,920	156,743
2027	153,143	154,971	156,795

Summer Peak Demand - MW

Year	Low[3]	Baseline[4,5]	High[3]
2016		33,225	
2017	29,980	33,178	35,487
2018	29,891	33,078	35,375
2019	29,854	33,035	35,326
2020	29,817	32,993	35,279
2021	29,832	33,009	35,297
2022	29,856	33,034	35,323
2023	29,911	33,096	35,388
2024	29,962	33,152	35,448
2025	30,034	33,232	35,533
2026	30,118	33,324	35,629
2027	30,185	33,398	35,707

Winter Peak Demand - MW

Year	Low[3]	Baseline[4]	High[3]
2016-17		24,416	
2017-18	22,693	24,365	25,989
2018-19	22,628	24,294	25,913
2019-20	22,546	24,207	25,821
2020-21	22,439	24,090	25,696
2021-22	22,394	24,043	25,645
2022-23	22,375	24,023	25,624
2023-24	22,361	24,008	25,607
2024-25	22,362	24,007	25,606
2025-26	22,356	24,001	25,600
2026-27	22,356	24,001	25,599
2027-28	22,356	24,000	25,599

Average Annual Growth - Percent

Energy:

Period	Low	Baseline	High
2017-27	-0.23%	-0.23%	-0.23%
2017-22	-0.40%	-0.41%	-0.41%
2022-27	-0.06%	-0.06%	-0.06%

Summer Peak Demand:

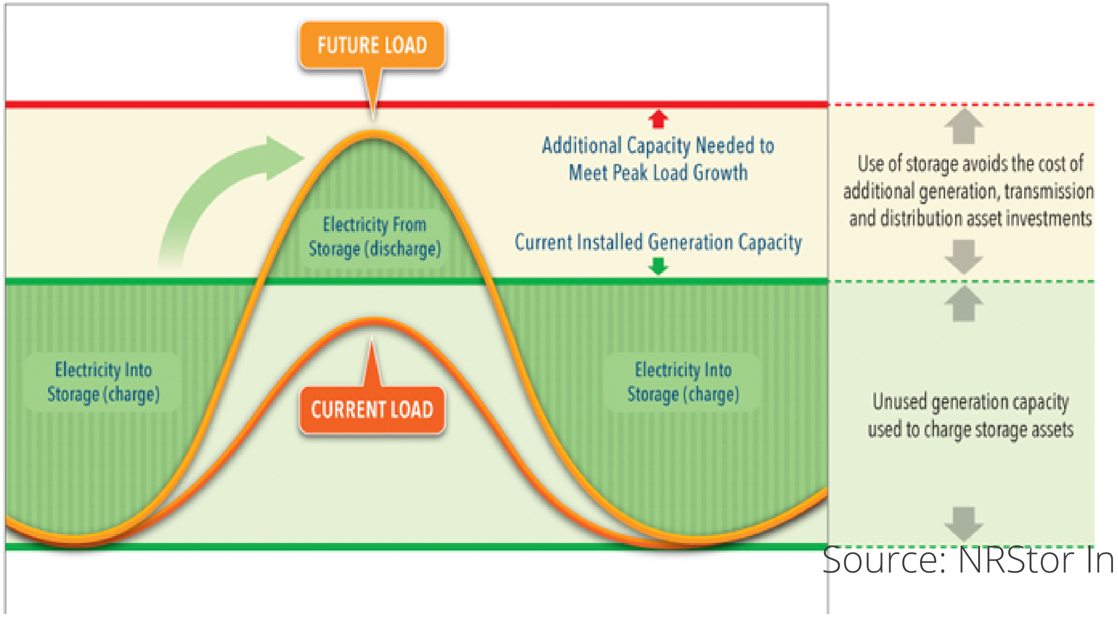
Period	Low	Baseline	High
2017-27	0.07%	0.07%	0.06%
2017-22	-0.08%	-0.09%	-0.09%
2022-27	0.22%	0.22%	0.22%

Winter Peak Demand:

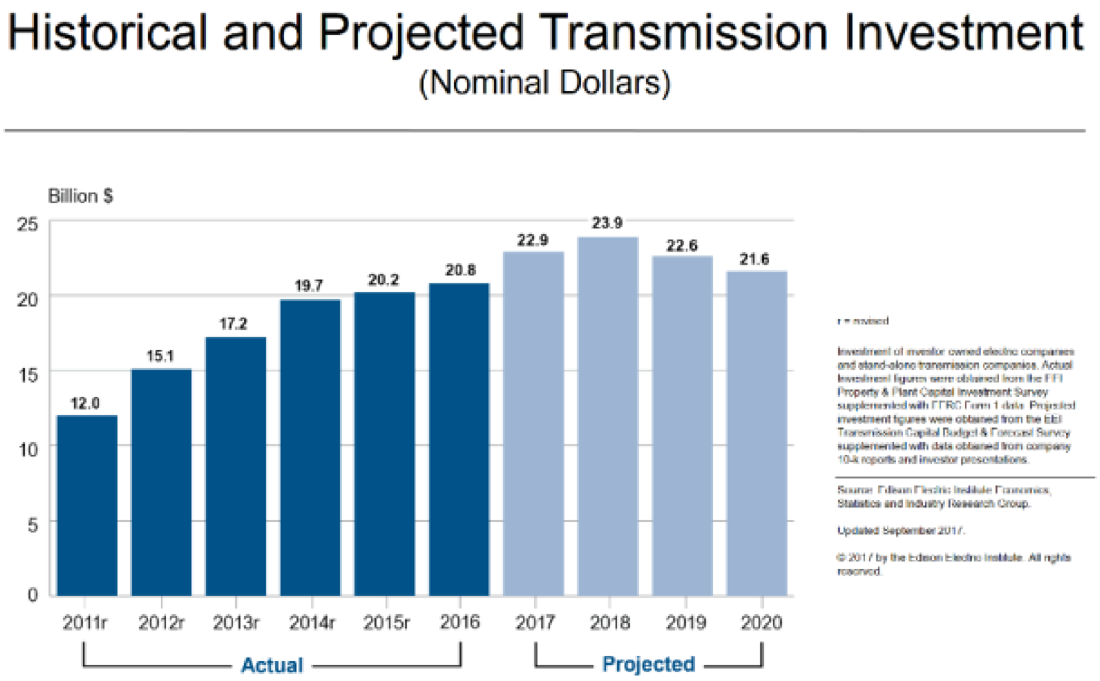
Period	Low	Baseline	High
2017-27	-0.15%	-0.15%	-0.15%
2017-22	-0.28%	-0.28%	-0.28%
2022-27	-0.02%	-0.02%	-0.02%

- Top 15% (~5GW) of total demand runs 7 days/yr, <2% of the time
  - Cutting top 100 hours saves $1.7B
  - Opportunity for energy storage: at least 500 GWh

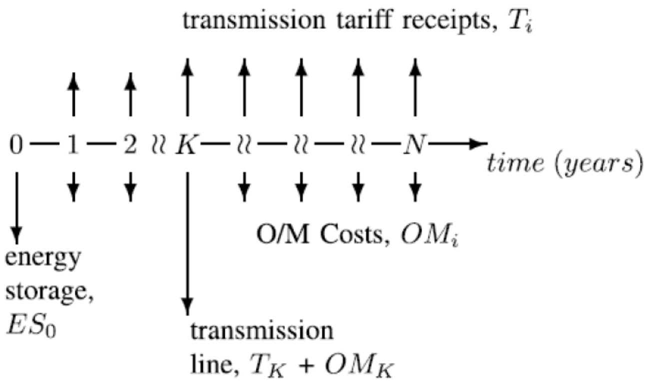
ENERGY STORAGE FOR T&D DEFERRAL



Source: NRStor Inc



Source: Edison Electric Institute

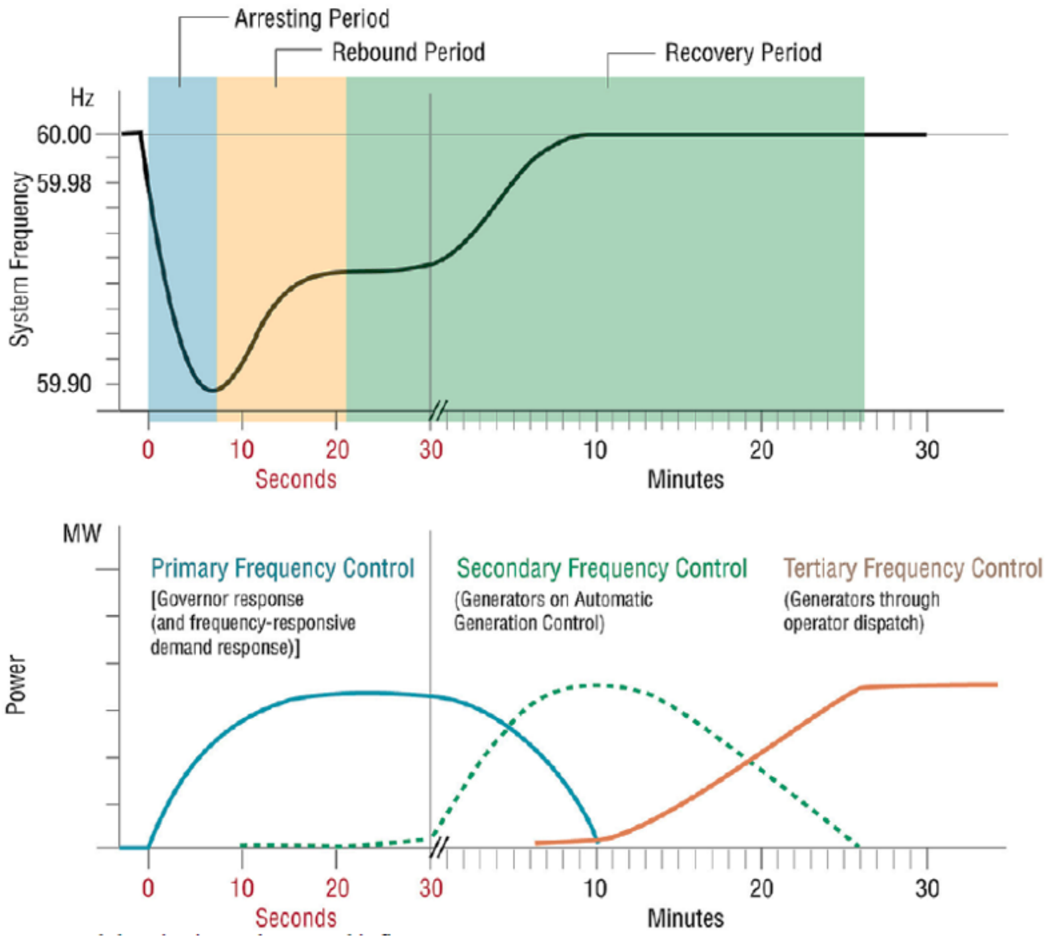


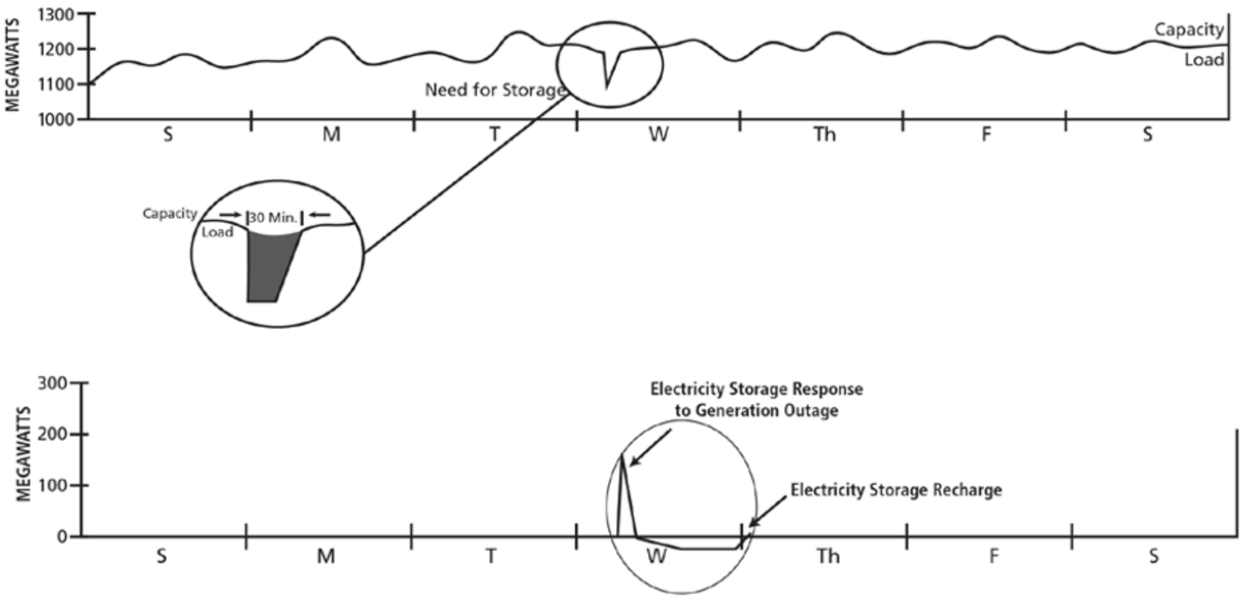
$$NPV_{\text{deferral}} = -ES_0 - T_K e^{-rK} - \sum_{i=1}^{N} OM_i e^{-rt_i} + \sum_{i=1}^{N} T_i e^{-rt_i}$$

How do you differ T&D deferrals? Energy storage is beginning to get traction.

Source: R. H. Byrne, T. A. Nguyen, D. A. Copp, B. R. Chalamala and I. Gyuk, "Energy Management and Optimization Methods for Grid Energy Storage Systems," in IEEE Access, vol. 6, pp. 13231-13260, 2018, doi: 10.1109/ACCESS.2017.2741578.

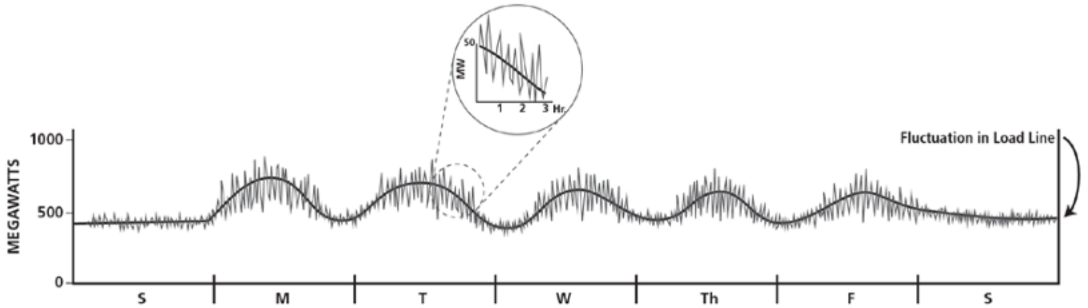
SPINNING RESERVES AND FREQUENCY RESPONSE

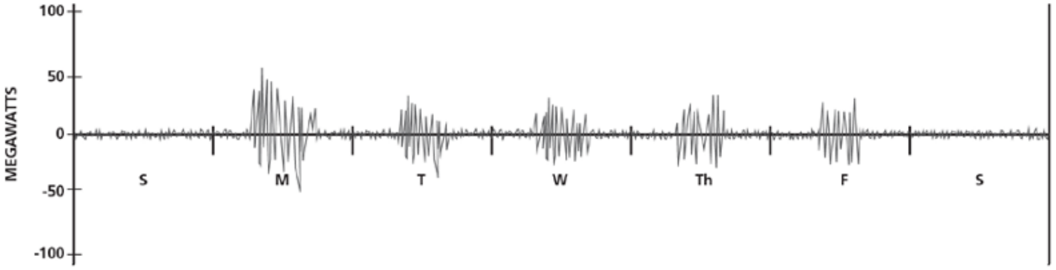


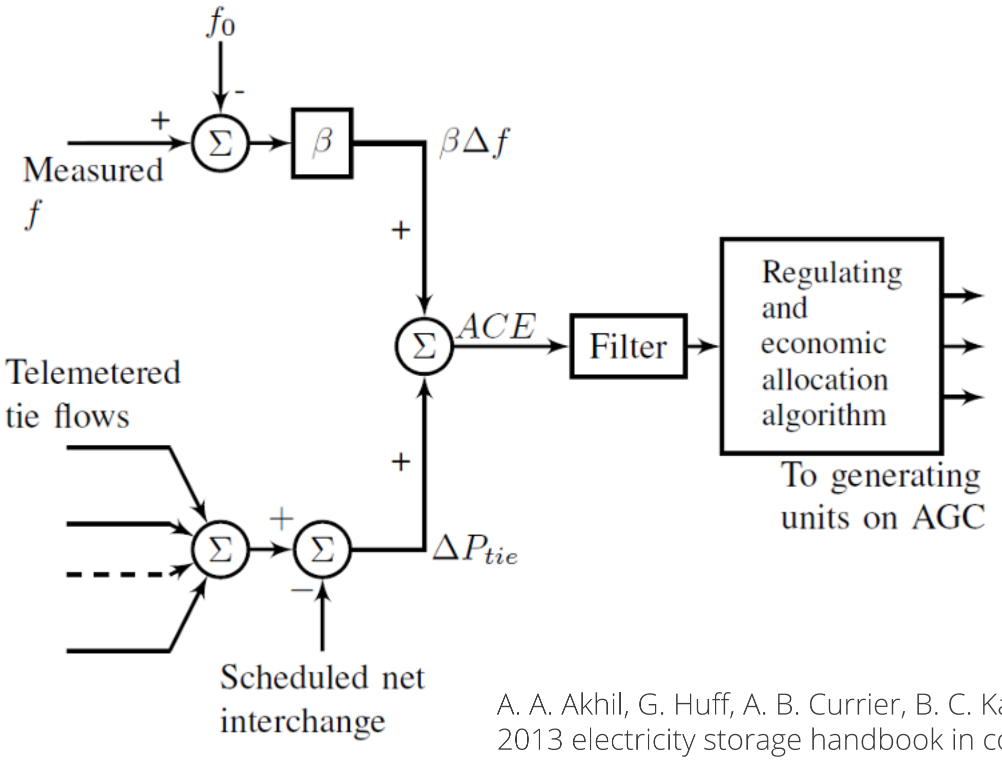


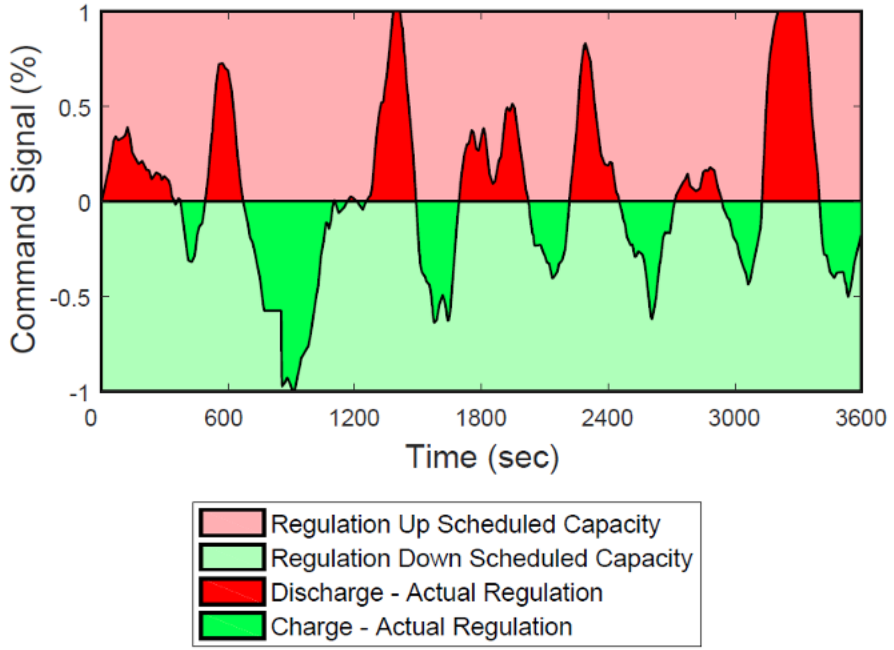
Source: A. A. Akhil, G. Huff, A. B. Currier, B. C. Kaun, D. M. Rastler, S. B. Chen, A. L. Cotter, D. T. Bradshaw, and W. D. Gauntlett, DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA. Sandia National Laboratories Albuquerque, NM, 2013.

ENERGY STORAGE FOR FREQUENCY REGULATION









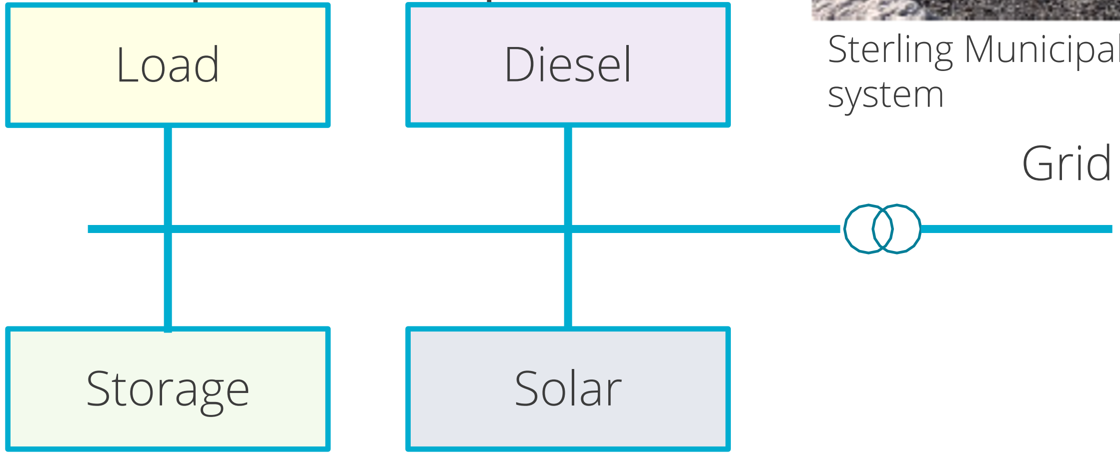
Representative regulation command signal (RegD from PJM)

A. A. Akhil, G. Huff, A. B. Currier, B. C. Kaun, D. M. Rastler, S. B. Chen, A. L. Cotter, D. T. Bradshaw, and W. D. Gauntlett, DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA. Sandia National Laboratories Albuquerque, NM, 2013.

RESILIENCY AND MICROGRIDS

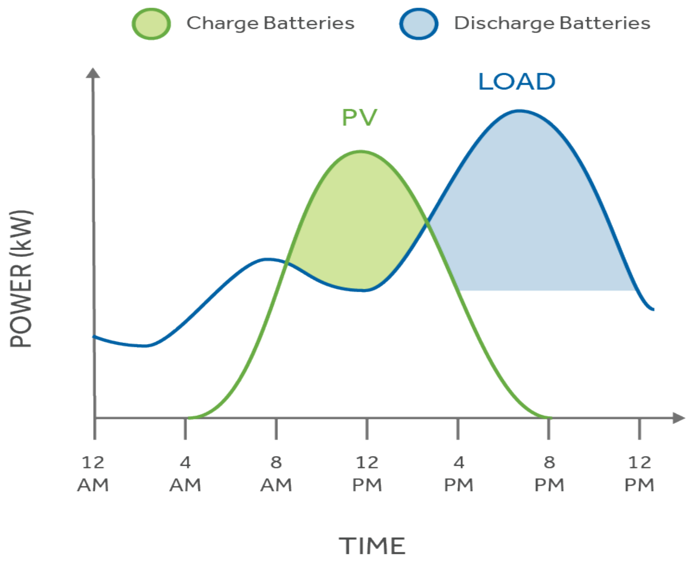
- Natural disasters
- Microgrids
  - Energy storage is a key component
- Often paired with distributed generation:
  - Solar
  - Wind
  - Diesel
  - Natural gas
- Design and operation are optimization problems

Sterling Municipal Light Department 2 MW, 3.9 MWh system

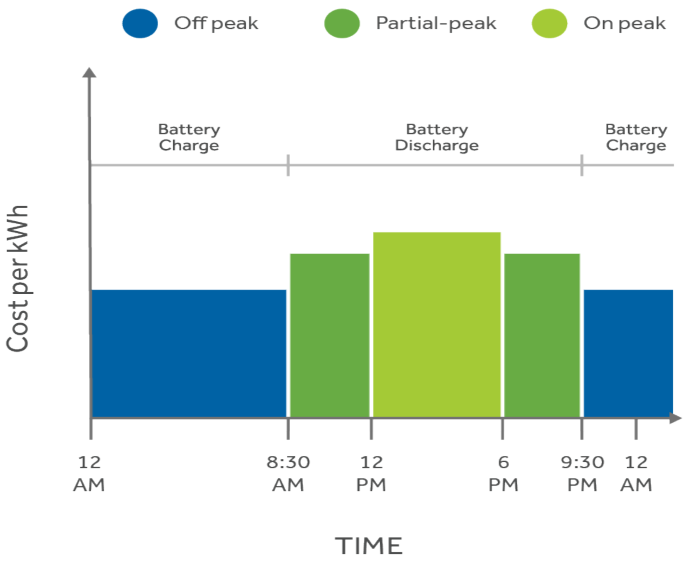


BEHIND-THE-METER APPLICATIONS

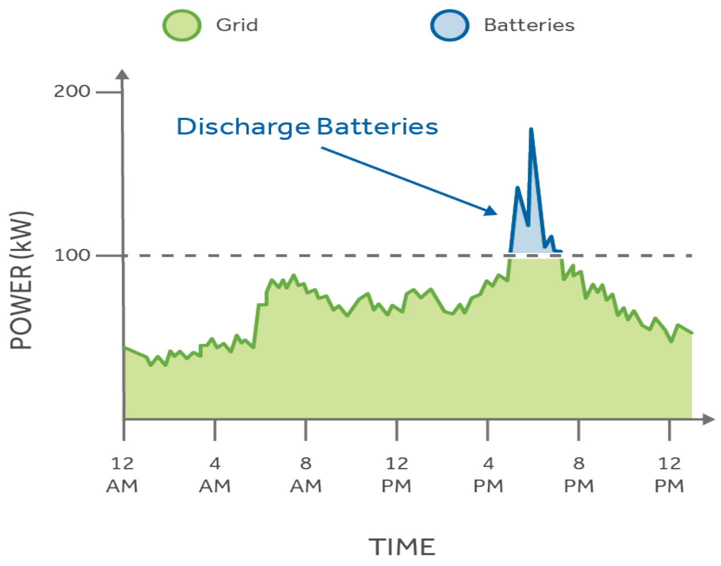
To benefit from dynamic rate structures, the customers must be able to change their loads in a manner that lowers their electricity bills without interrupting their operations (commercial and industrial customers) or sacrificing their conveniences (residential customers).



Renewable Time Shift



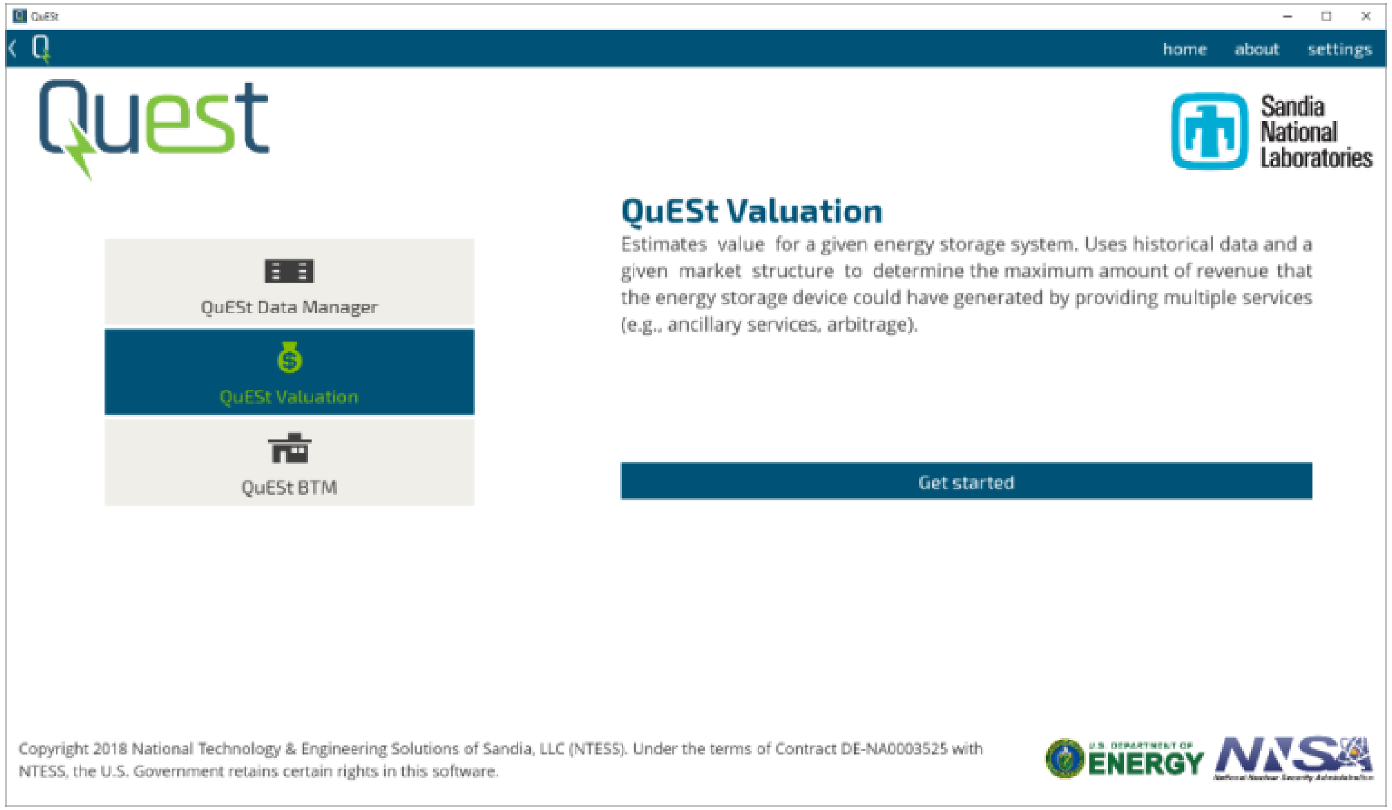
Time-of-use Management



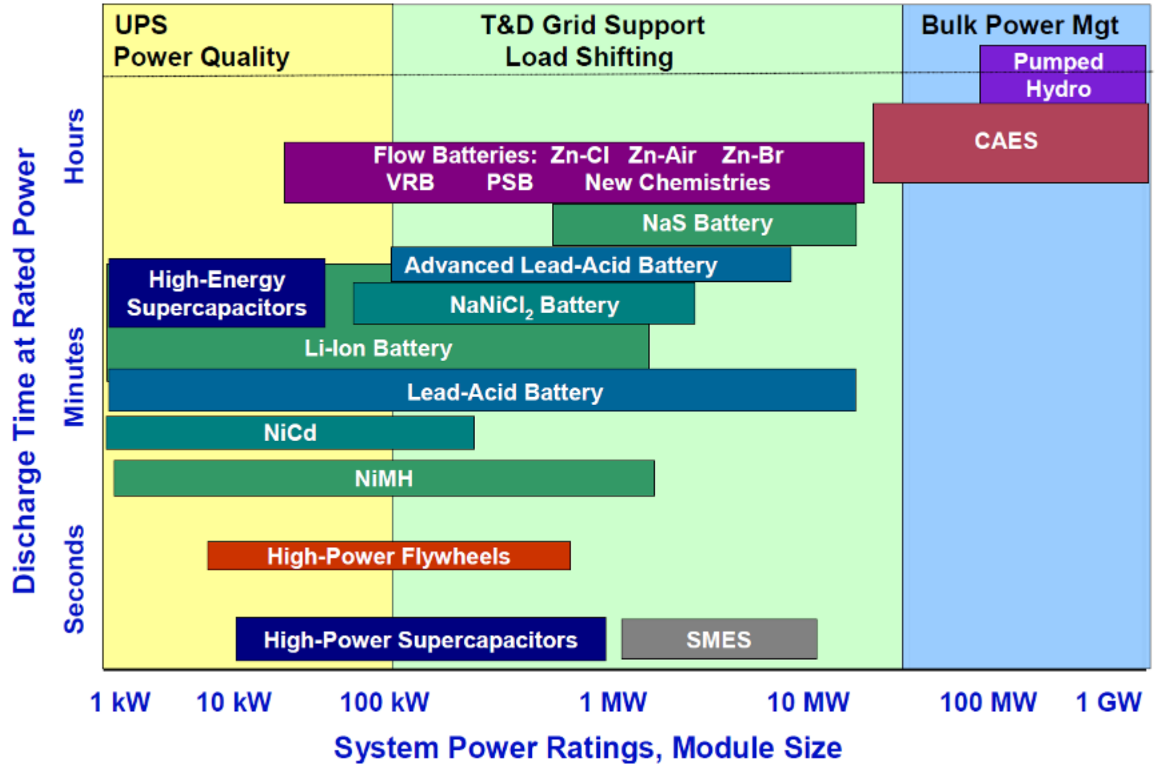
Demand Charge Reduction

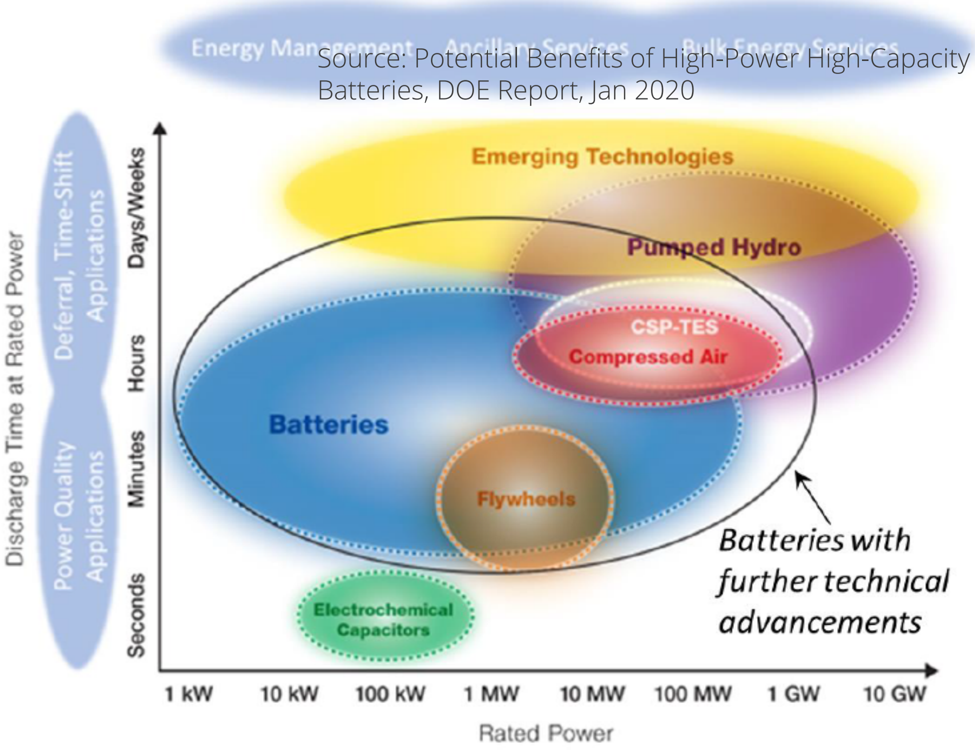
QUEST: ENERGY STORAGE VALUATION

- Energy storage analysis software application suite
- Developed as a graphical user interface for the optimization modeling capabilities of Sandia's energy storage analytics group
- Quest Data Manager
- Quest Valuation
- Quest BTM
- Version 1.0 publicly released in September 2018
- Version 1.2 available on GitHub
- **github.com/snl-quest/snl-quest** or **sandia.gov/ess** (tools)



RANGE OF TECHNOLOGIES AND APPLICATIONS





Source: Potential Benefits of High-Power High-Capacity Batteries, DOE Report, Jan 2020

Type	Voltage[a]	Voltage range	Temperature range	Energy density	Efficiency[b]	Cycle life
LFP	3.3 V	2.5 - 3.6 V	-30 - 60 °C	60-110 Wh/kg	95%	>1000
NMC	3.7 V	2.5 - 4.2 V	-20 - 60 °C	100-240 Wh/kg	95%	>500
Lead Acid	2.0 V	1.75 - 2.1 V	-45 - 50 °C	10-40 Wh/kg	70-75%	200 - 1500
Zinc-Mn	1.5 V	0.9 - 1.5 V	-20 - 40 °C	100 Wh/kg	55-65%	20 - 5000[c]
Redox flow	1.4 V	1 - 1.6 V	0 - 40 °C	10-50 Wh/kg	85%	>10,000
NaS	2.076 V	1.78 - 2.1 V	270 - 350 °C	117 Wh/kg	86%	4,500

Sources: DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA. Sandia National Laboratories Albuquerque, NM, 2013.
T. Reddy, Linden's handbook of batteries 4th edition. McGraw-Hill, New York, 2010.
P. Alotto, M. Guarnieri, and F. Moro, "Redox flow batteries for the storage of renewable energy: A review," Renewable and Sustainable Energy Reviews, vol. 29, pp. 325–335, 2014.
U. Koehler, "General overview of non-lithium battery systems and their safety issues," Electrochemical Power Sources: Fundamentals, Systems, and Applications, pp. 21–46, 2019.
M. B. Lim, T. N. Lambert, and B. R. Chalamala, "Rechargeable alkaline zinc–manganese oxide batteries for grid storage: Mechanisms, challenges and developments," Materials Science and Engineering: R: Reports, vol. 143, p. 1005

BATTERY ENERGY STORAGE TECHNOLOGIES

- Market drivers
  - Consumer electronics, mobile devices and EVs – primarily Li-ion batteries
  - Grid energy storage – growing market, currently modest size. Range of technologies

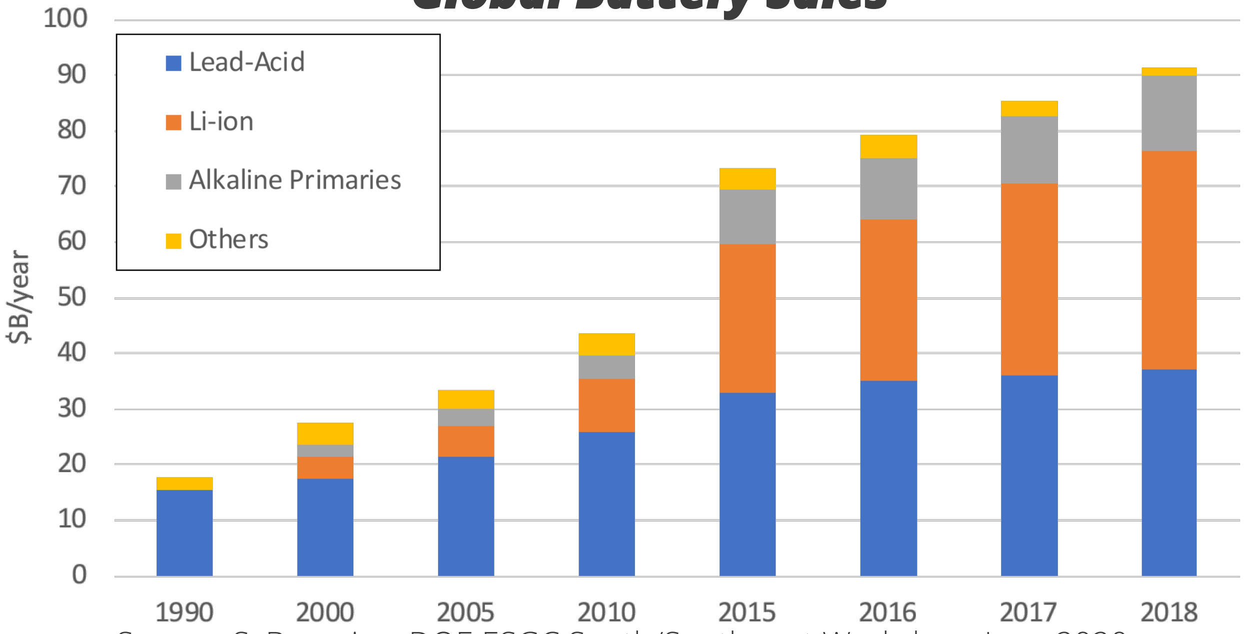
Traditional Batteries
e.g. Lead-acid, Ni-Cd, Ni-MH, Zn-MnO$_2$

Lithium Batteries
e.g. Li-ion, Li-polymer, Li-metal, Li-S

High-temperature Batteries
e.g. Na-S, Na-NiCl$_2$

Flow Batteries
e.g. Vanadium redox, Zn-Br

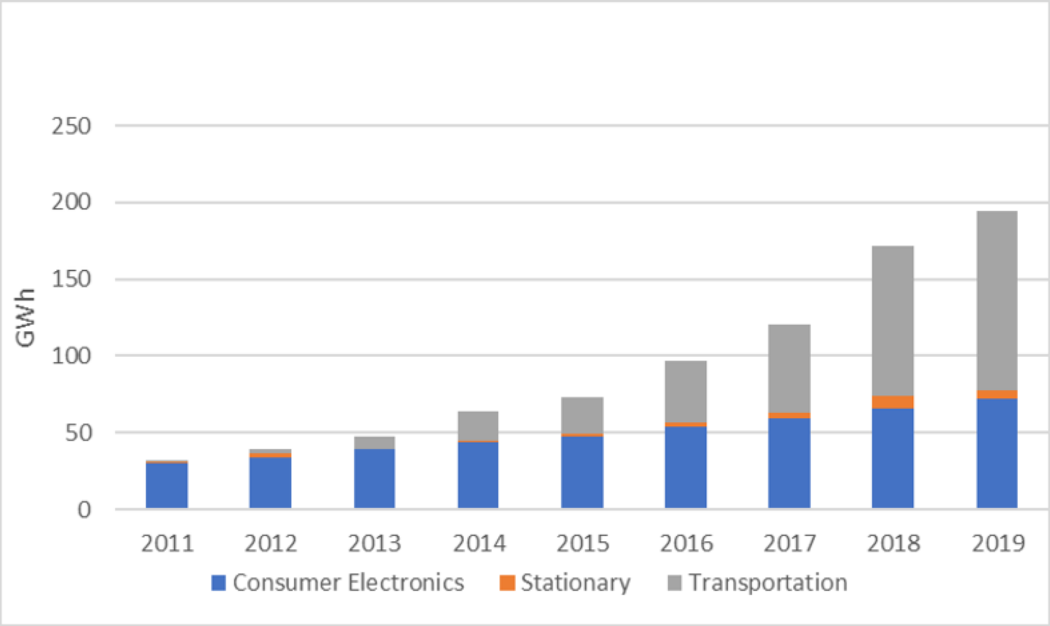
Global Battery Sales

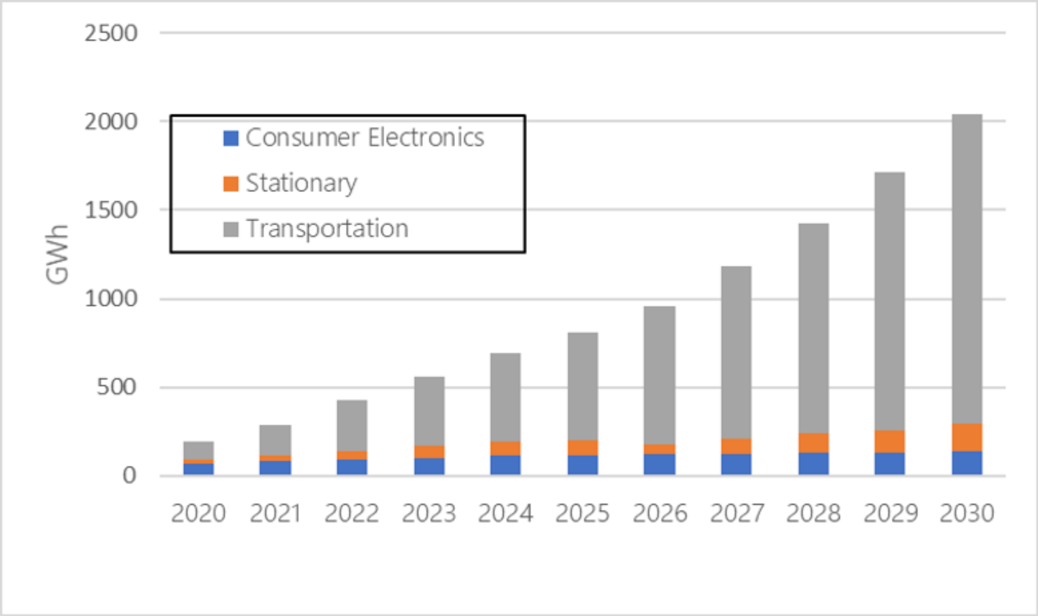


Source: S. Banerjee, DOE ESGC South/Southwest Workshop, June 2020

- Lead-Acid: 350 GWh production capacity, $38B/yr
- Li-ion: over 300 GWh and growing capacity, $40B/yr
- Primary cells: $13B/yr

LI-ION BATTERIES: MARKET

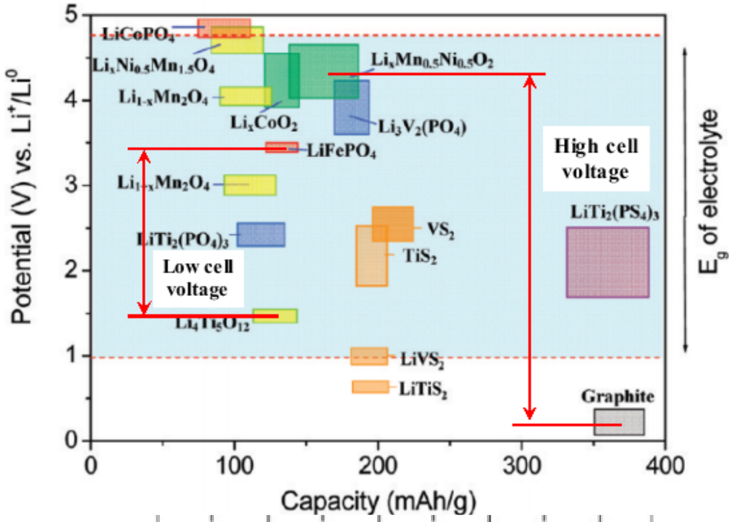


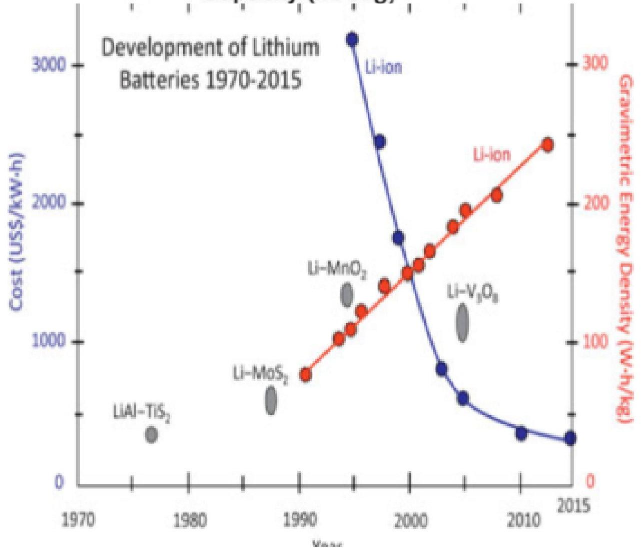


Source: Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/.

LI-ION BATTERIES

- Family of electrochemical systems
- Positive electrode
  - Metal-oxides (e.g. LCO, NMC, NCA)
  - Phosphates (e.g. LFP)
- Negative electrode
  - Graphite and other carbons
  - Lithium titanate
- SOA EV batteries - Specific energies near 250 Wh/kg
- 330-350 Wh/kg possible near term with composite anodes (Si-based anodes)
- 500 Wh/kg as a longer term goal based on significant improvements in electrode design and composition (e.g., lithium anodes), electrolyte formulations, and separator innovations.
- Safety continue to be a significant concern

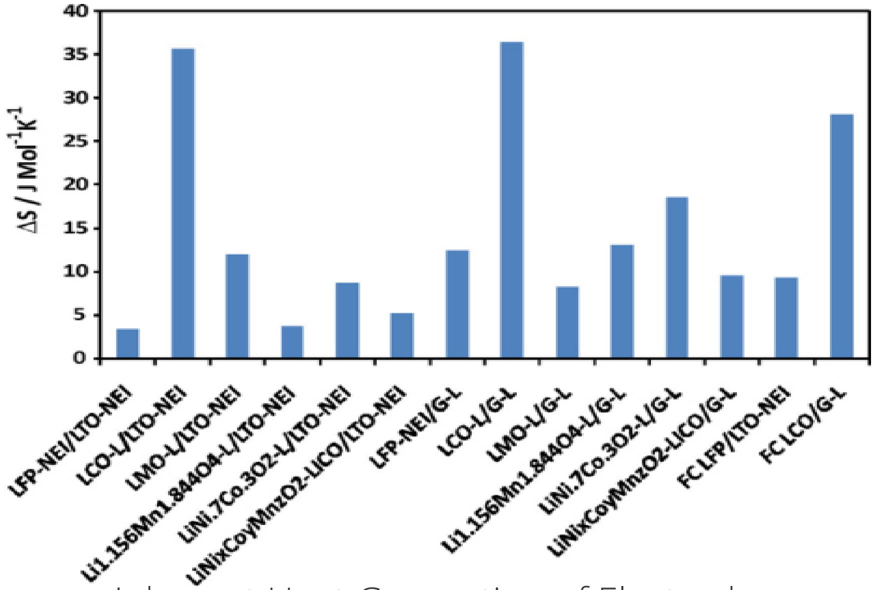




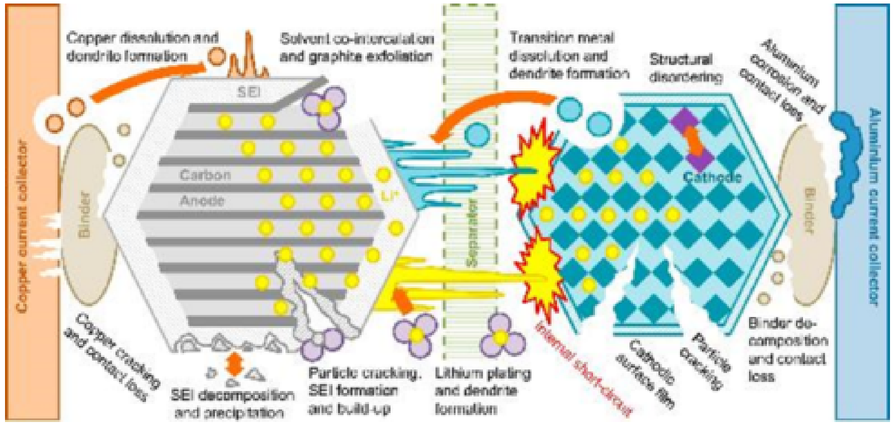
Source: Crabtree, Kocs, Trahey, MRS Bulletin, Dec 2015

LI-ION BATTERIES – CHALLENGES

- Battery safety is very important for applications where high power is required.
  - Heat generation during high power usage must be managed
  - Dictates smaller form factor
  - Higher production costs
- High Temperature
  - Typical operating window 0-50°C
  - Operation above this temperature can lead to organic electrolyte decomposition and flammable gas, rapid internal pressure build-up
- Overcharging
  - Overcharging can lead to Li metal plating on anode, potential for short
  - Need better understanding of the degradation pathways and engineering to control thermal runaway



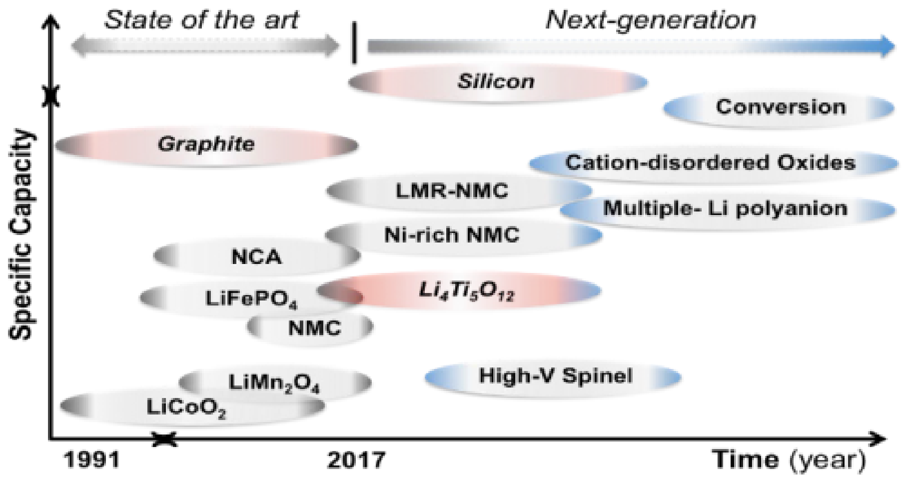
Inherent Heat Generation of Electrodes



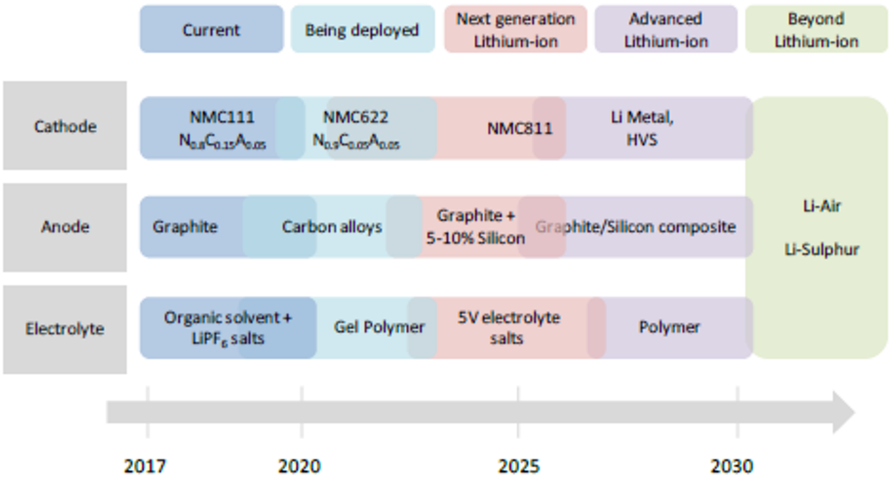
J. Power Sources, **2017**, 341, 373

FUTURE DEVELOPMENTS IN LI-BASED BATTERIES

- Higher-voltage positive (cathode) materials
  - Lithium manganese phosphate
  - Lithium cobalt phosphate
- Higher-capacity negative (anode) materials
  - Silicon-based
- Safer electrolytes
  - Inorganic
  - Solid-state electrolytes
- Other Li chemistries
  - Lithium-sulfur



DOE Basic Research Needs Report on Energy Storage DOE Office of Science, 2017



Global EV Outlook Report, IEA 2018 Based on DOE-VTO and NEDO Projections

HIGH ENERGY DENSITY LI-S AND METAL AIR BATTERIES

Li-S: high theoretical energy density (>2700 Wh/kg), prototype cells ~ 400Wh/kg

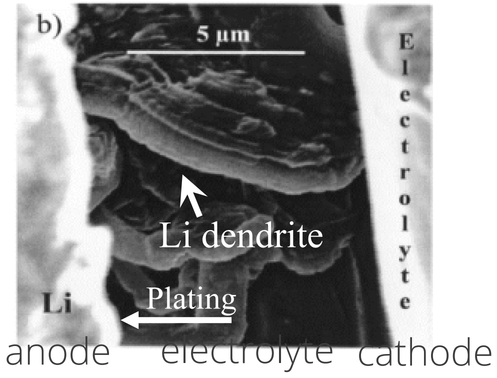
- Suffers from self discharge and poor life
- Breakthroughs needed with Li electrodes
- Managing the Sulphur shuttle reactions

Metal air batteries (Li-air, Zn-air)

- Potential to deliver high energy densities at low cost. Challenges with recharging have so far precluded commercialization of the technology.
- Not mature, many years away
- Potential fundamental problems

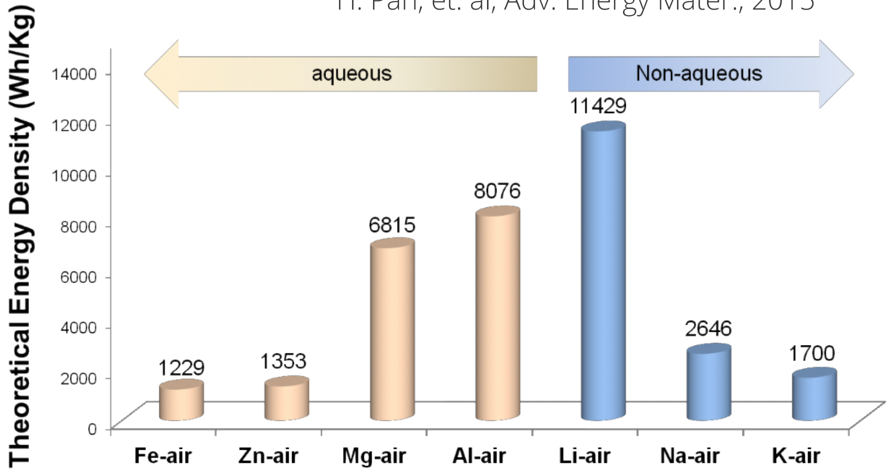
Li-Air combines difficulties of air and lithium electrodes

- Breakthroughs needed in cheap catalysts, more stable and conductive ceramic separators
- Developing a robust air electrode is a challenge, need major breakthroughs



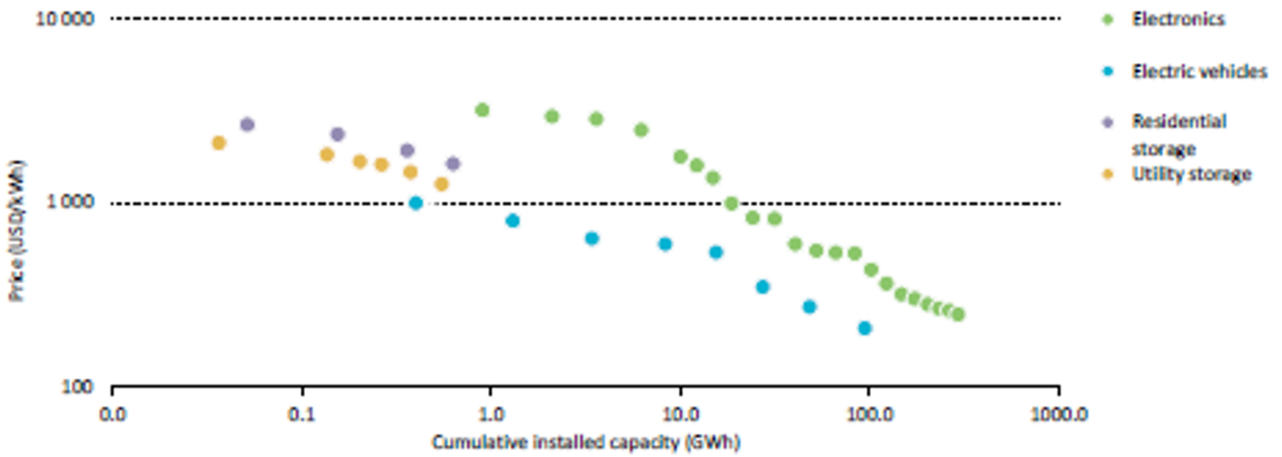
Li dendrite growth

H. Pan, et. al, Adv. Energy Mater., 2015



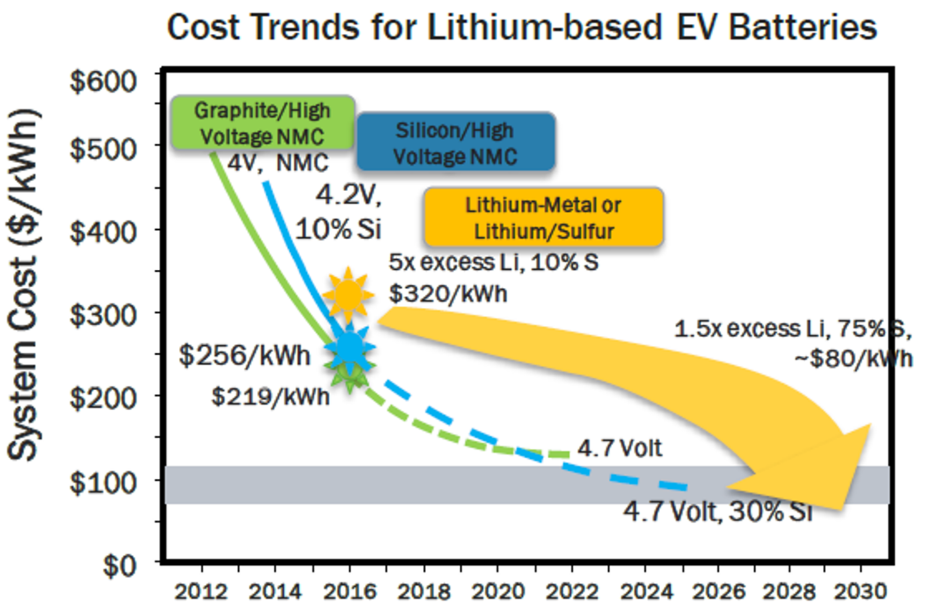
Y. Li and J. Lu, "Metal-Air Batteries: Future Electrochemical Energy Storage of Choice?," PNNL, 2017

MANUFACTURING SCALE AND CELL/SYSTEM COSTS



Li-ion storage technology price with manufacturing volume. Source: IEA, 2018

Future cost projections predicated on stable commodity prices, significant improvements in energy density and cell performance



Cost trends for Li-based EV Batteries (pack level)
Source: David Howell, DOE VTO, 2018

LEAD-ACID BATTERIES

Flooded lead-acid

- Requires continuous maintenance

Sealed lead-acid

- Gel and Absorbed Glass Mat (AGM)

Advanced Lead Acid Energy Storage

- Carbon plates significantly improve performance

Mature technology

High recycled content

Low cost/Ubiquitous

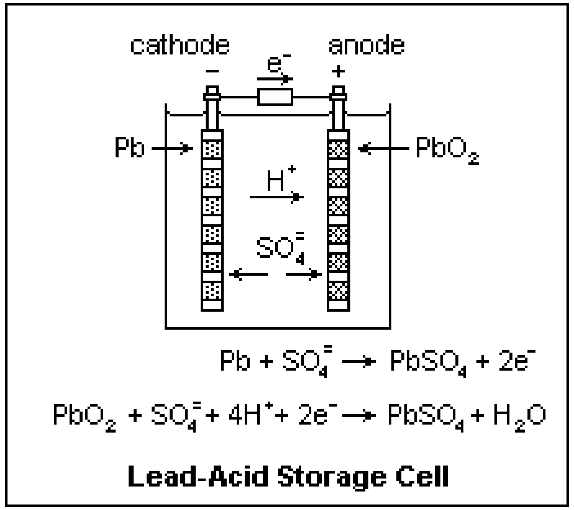
Good battery life

- Limited life time (5~15 yrs)/cycle life (500~1000 cycles) and degradation w/ deep discharge (>50% DoD), new Pb/C systems > 5,000 cycles.

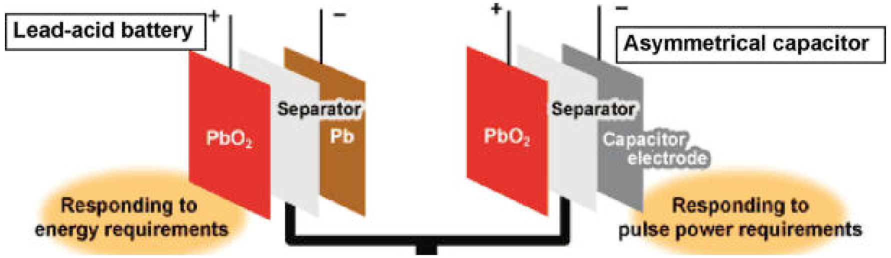
Low specific energy (30-50 Wh/kg)

Overcharging leads to H2 evolution.

Sulfation from prolonged storage



OCV ~ 2.0 V



http://www.ultrabattery.com/

LEAD-ACID BATTERIES – DEPLOYMENT FOR GRID SERVICES

3 MW/3 MWh advanced lead acid battery system for utility applications (Source: EastPenn, East Lyons, PA)

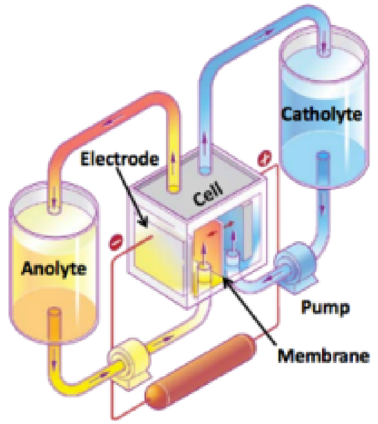
Solar plus ultrabattery storage (Source: PNM Albuquerque, NM

1.3MW/1.9 MWh advanced lead acid battery system providing support for a 68MW solar farm in Alt Daber, Germany (Source: BAE Batteries, 2018)

REDOX FLOW BATTERIES

Energy storage technology utilizing redox states of various species for charge/discharge purposes

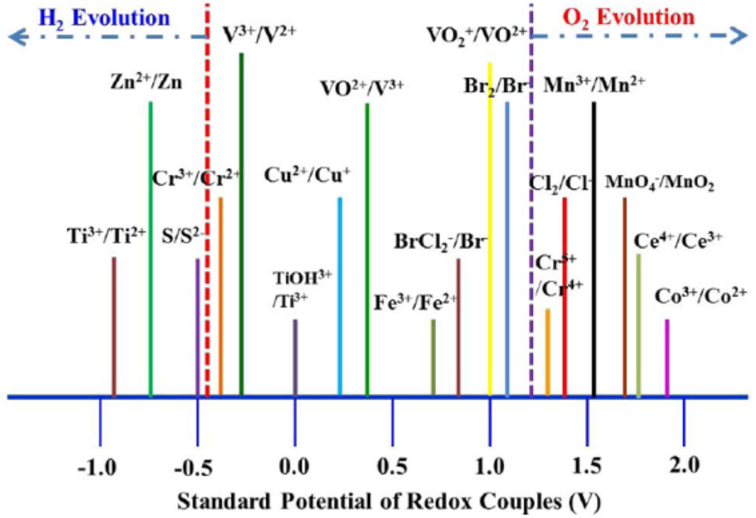
- Key Aspects
  - Power (kW) and energy (kWh) separation
  - Greater flexibility and safety
  - Modular and scalable across a wide range of power and energy
  - Long cycle life
  - Low energy density ~ 30 Wh/L



Source: Travis Anderson, Sandia National Laboratories, 2013

Range of redox chemistries

- Fe-Cr, Zn-Br, V-V are most studied and large systems demonstrated
- Most large commercial flow batteries are based on V-V chemistry, and Zn-Br



B.R. Chalamala, et.al., Proc IEEE, vol. 102, pp. 976-999, June 2014

REDOX FLOW BATTERIES – TECHNICAL CHALLENGES

Low energy density

- Limited voltage window of aqueous electrolyte solutions (< 1.5 V)
- Large form factor/footprint

Limited electrolyte stability

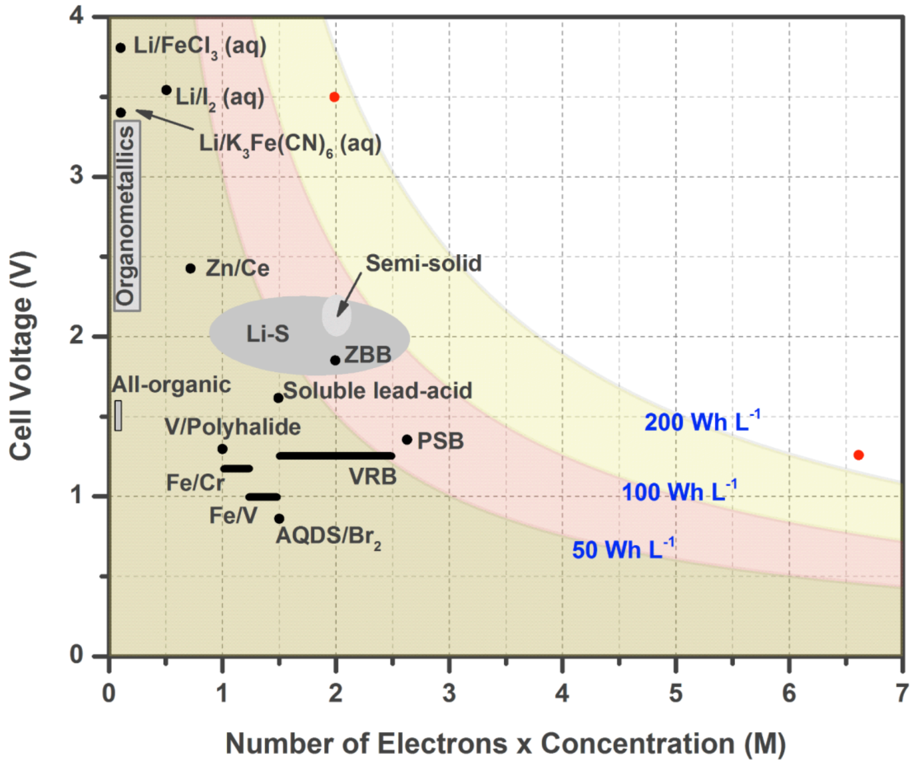
- Low solubility of redox species in aqueous electrolytes
- Capacity decay during cycling
- Narrow temperature range

Corrosion of membranes and electrode materials by acidic electrolyte solutions

- Long-term reliability

Opportunities to Reduce Materials Cost

- New redox chemistries, new electrolytes under development
- Lower cost of membranes
- Increased current



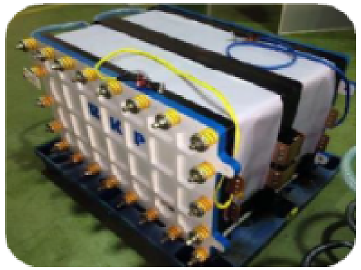
Wei Wang, et. al., Adv. Funct. Mater., , 23, 970, 2013

RFB DEPLOYMENTS

- Rapid progress in the development of large utility class redox flow battery systems
- Rapid development of new electrolytes to replace Vanadium species
- Further potential to reduce the size of the stacks and to increase energy density

Containerized Systems

UniEnergyTechnologies, 1MW/4MWh



32 KW Stack Rongke Power/UET 120 mA/cm2 Meter size stack

Flow battery power plants

Sumitomo Electric, 15MW/60MWh

Stack room

SODIUM BATTERIES (NaS & $NaNiCl_2$)

Abundant low cost materials (Na, S, …)

Offer potential for safe, versatile, cost-effective energy storage

Molten sodium batteries - Two primary chemistries

- NaS, mature technology, deployed in grid applications
- NaNiCl2, mature, more stable than NaS
- Neither NaS nor NaNiCl2 are at high production volumes and the economies of scale needed

Early Stage Technologies

- Sodium Ion Batteries (NaIBs)
- Solid State Sodium Batteries (SSSBs)
- Sodium Air Batteries (Na-O2)

NaS BATTERIES

Batteries consisting of molten sodium anode and β"-Al_2O_3 solid electrolyte (BASE)

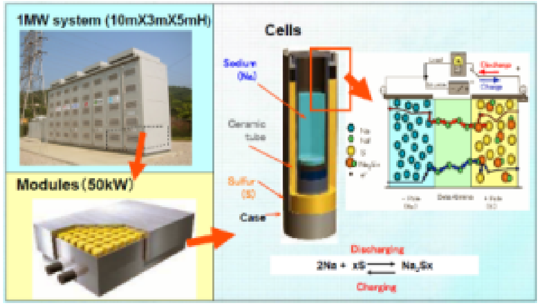
- High specific energy density (120~240 Wh/kg)
- Good specific power (150-230 W/kg)
- Long duration batteries, with 4-6 hr discharge
- Operated at relatively high temperature (300~350°C)

Originally developed at Ford Motors, later commercialized by NGK Insulators in Japan

NGK has deployed ~ 580 MW/4 GWh of storage, primarily in Japan

Challenges

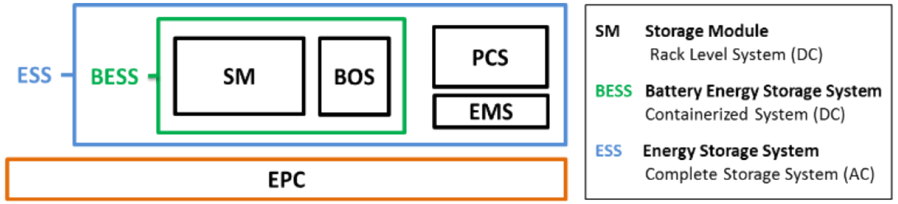
- Battery is assembled fully charged, presents a major safety/handling issue
- System needs to be maintained at temperature
- High temperature operation, safety and containment challenges
- Relatively expensive



50 MW system at a solar farm Fukuoka, Kyushu, Japan (NGK)

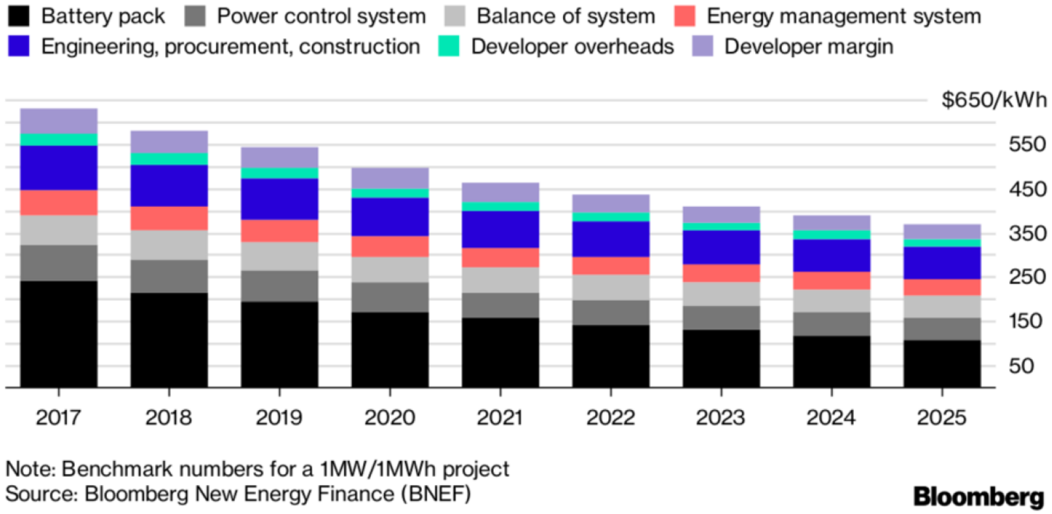
Source: NGK Insulators

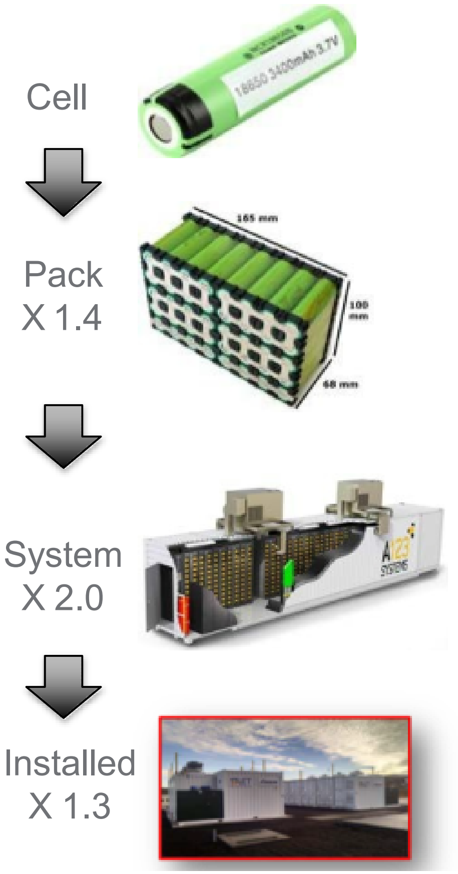
BATTERY ENERGY STORAGE IS NOT JUST ABOUT BATTERIES …



Storage Module (SM)	Balance of System (BOS)	Power Conversion System (PCS)	Energy Management System (EMS)	Engineering Procurement & Construction (EPC)
Racking Frame / Cabinet	Container	Bi-directional Inverter	Application Library	Project Management
Local Protection (Breakers)	Electrical Distribution & Control	Electrical Protection	Economic Optimization	Engineering Studies / Permitting
Rack Management System	Fire Suppression	Connection to Transformer	Distributed Asset Integration	Site Preparation / Construction
Battery Management System	HVAC / Thermal Management		Data Logging	Foundation / Mounting
Battery Module			Communication	Commissioning

Source: R. Baxter, I. Gyuk, R.H. Byrne, B.R. Chalamala, IEEE Electrification, Aug 2018





Cell to Battery to a Storage System
> Doubling in cost, $250/kWh battery leads to $500-$700/kWh at the System level

Integration costs are significant

Big savings now are not in the cells, but in the systems and integration

$NaNiCl_2$ BATTERIES

NaNiCl2 battery

- $2Na + NiCl_2 \rightarrow 2NaCl + Ni$
- E = 2.58V at 300°C

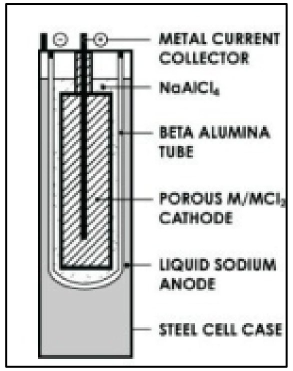
Large cells and stable chemistry

- Lower temperature than NaS
- Cells loaded in discharge mode
- Improved safety compared to NaS. Addition of catholyte $NaAlCl_4$ leads to a closed circuit on failure

High efficiency, low discharge

Long warm up time (16 hr)

Supply chain concerns. Only one major manufacturer (FIAMM). Limited deployments



FIAMM 222-kWh System Duke Energy Rankin Substation

620 V 1.4 MWh (400 kW)

SODIUM ION BATTERIES ON THE HORIZON

While not yet commercially mature, several types of NaIBs are in development or early production

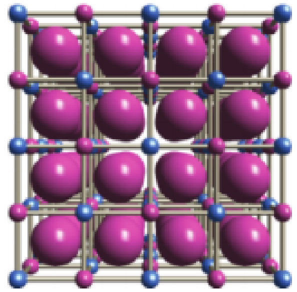
Prussian blue analogs (PBAs)

- Utilize ferric ferrocyanide salts as electroactive materials (mostly cathodes)
- Natron Energy is developing NaIBs with PBAs aimed at 8kW units for data server backup power.

Li-Ion "Analogs" – possibly manufacturable on Li-ion production lines?

"Salt-water batteries"

- Carbon-titanium phosphate composite Anode, sodium perchlorate aqueous electrolyte, manganese oxide cathode.



Y. Moritomo, *Adv. Cond. Matt. Phys*. (2013) 539620.

https://www.bluesky-energy.eu/en/greenrock-home-2/

RECHARGEABLE ALKALINE BATTERIES

Range of alkaline battery chemistries

- NiMH, Ni-Fe, Ni-Cd, Zn-Ni, Zn-MnO2

Zn-MnO_2 shows most promise for grid storage

Cost

- Traditional primary batteries, low cost ($18-20/kWh primaries)
- Low-cost materials and manufacturing
- Established supply chain

Safety

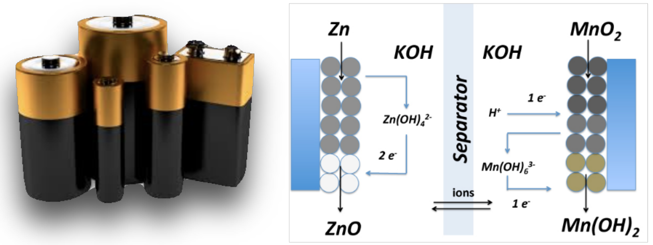
- Aqueous chemistry
- Non-flammable
- EPA certified for landfill disposal

Reliability

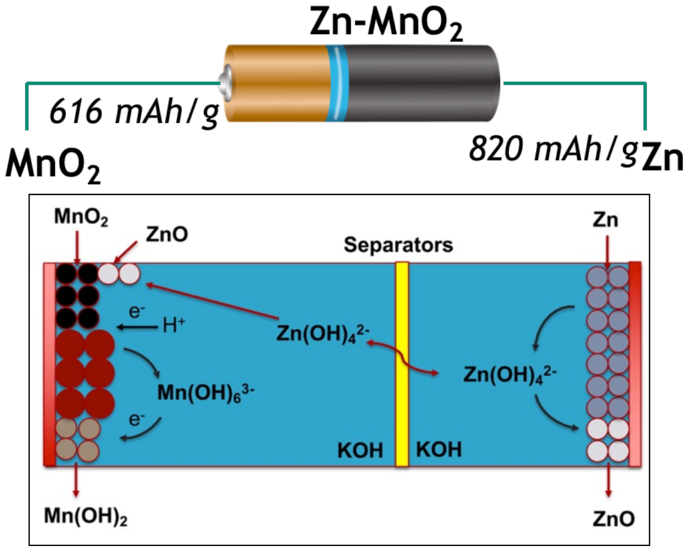
- Long shelf-life
- Limited thermal management required

Reversibility and cycle life have been the primary technical challenges

Recent breakthroughs, promising potential for <$50/kWh



Single-use Alkaline Battery $25/kWh



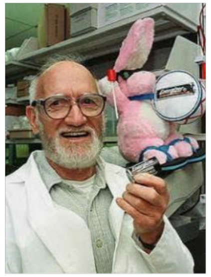
Source: S. Banerjee, CUNY Energy Institute

HISTORY OF RECHARGEABLE ZN-MNO$_2$ BATTERIES

- Early commercial products based on cylindrical formats (Union Carbide, Rayovac, BTI, …)
- Focused on consumer markets, rapid development of Li-ion batteries made small cell business not competitive
- Resurgence in the field for stationary storage

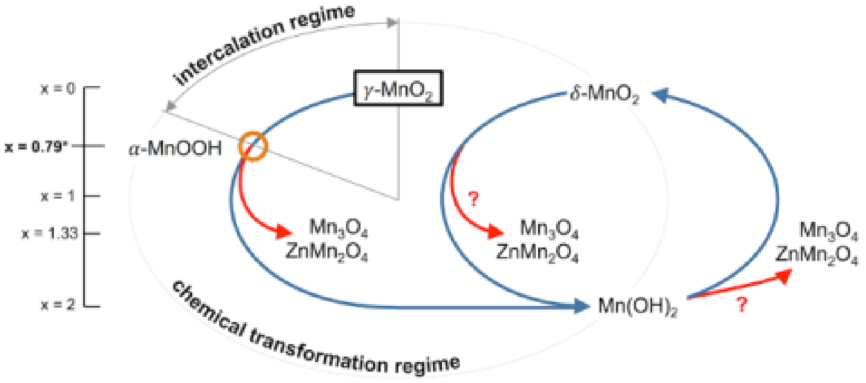
J. Daniel-Ivad and K. Kordesch, "Rechargeable Alkaline Manganese Technology: Past-Present-Future," ECS Annual Meeting, May 12-17, 2002

1866	1950	1970	1980	2010-2016
Primary Low Power	Primary	Limited Capacity Poor Energy Density	Potentiodynamic Poor Cycle Life	Stabilized full-cycling MnO2
1st Zn-MnO$_2$ battery	Alkaline Zn-MnO$_2$ battery	5% Rechargeable Capacity	60-80% Rechargeable Capacity	**2010-2014**: CUNY Energy Institute shallow-cycle MnO$_2$ **2014-2016** Stabilized full-cycling MnO$_2$



Halina Wroblowa

S. Banerjee, Symposium on Grid Energy Storage, MRS Spring Meeting, 2015
G. Yadav, CUNY Energy Institute, 2018



Failure Mechanisms of Cathode

Instability of Mn(III) resulting in formation of irreversible Mn_3O_4
Zn poisoning forming irreversible $ZnMn_2O_4$

GRID ENERGY STORAGE - GAPS?

- Technology - Need further improvements in cost and performance
  - Lower cost, longer duration energy storage is a major gap
  - Technologies that can scale from microgrids to large transmission applications
  - Further improvements in safety and reliability
- Energy storage is new for the electric utility industry
  - Markets and Operations – Business Models and Operational Tools
  - Analytics – Economics and Planning tools
  - Appropriate Regulatory Policy – Business Models, Asset Classification
- Industry needs cycles of learning - manufacturing scale through deployments
  - Project finance - bankable, warrantees, Performance guarantees, risk management
  - Standardization- equipment, permitting, construction processes

REDUCING THE COST OF BATTERY ENERGY STORAGE

Li-ion batteries
- Increase reliability and cycle life
- Improve safety

Sodium batteries
- Lower temperature Na batteries
- Sodium ion batteries

Alkaline Zn-MnO_2 Batteries
- Make alkaline batteries fully chargeable

Energy Storage Grand Challenge goals
- \$0.05/kWh LCOS for long-duration by 2030
- 90% reduction from 2020 costs
- \$80/kWh manufactured cost for a battery pack by 2030 for a 300-mile range electric vehicle
    - 44% reduction from the current cost of \$143/kWh.
    - Achieving this cost target would lead to cost-competitive electric vehicles.

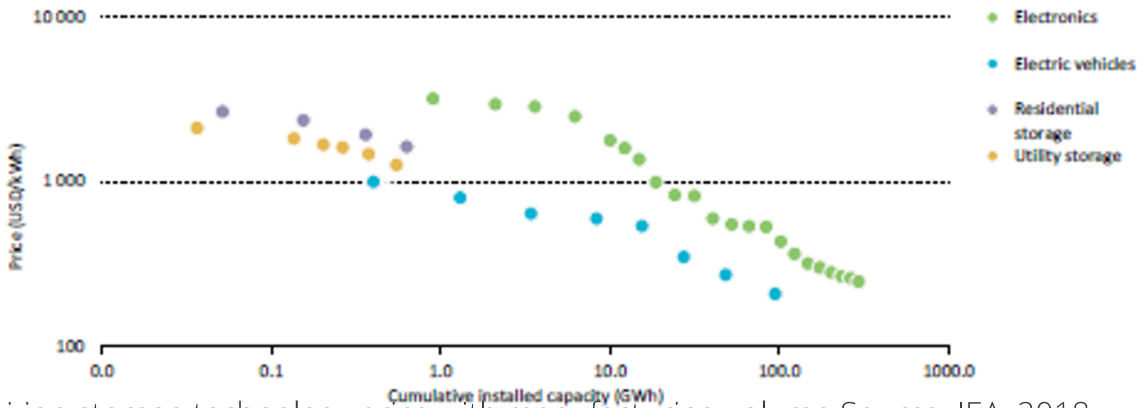
Levelized Cost of Storage (LCOS):

$$LCOS = \frac{present\ value\ of\ all\ costs}{present\ value\ of\ all\ energy\ injected}$$

Costs:
- Capital (investment)
- Operation and Maintenance
- Charging cost

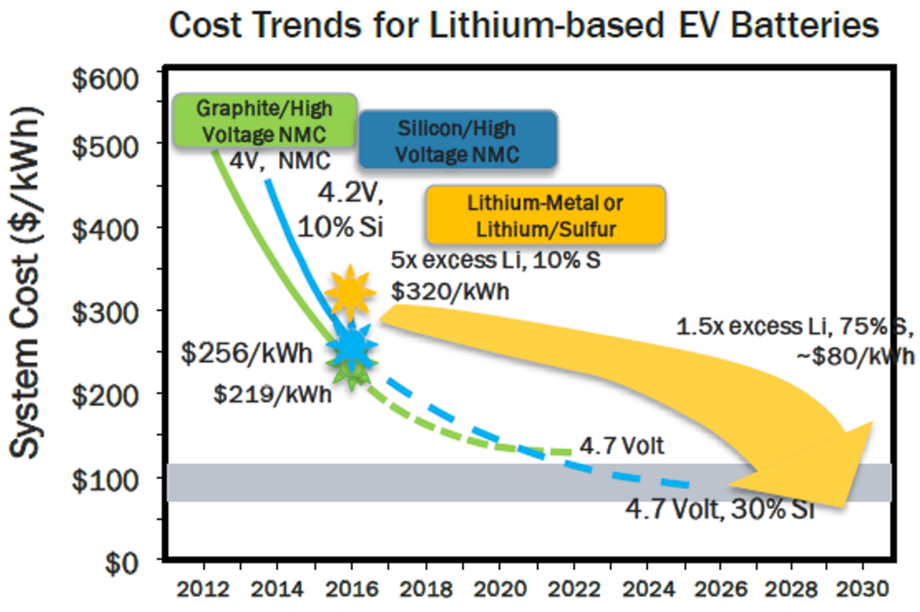
ENERGY STORAGE GRAND CHALLENGE
U.S. DEPARTMENT OF ENERGY

MANUFACTURING SCALE AND CELL/SYSTEM COSTS



Li-ion storage technology price with manufacturing volume Source: IEA, 2018

Future cost projections predicated on stable commodity prices, significant improvements in energy density and cell performance

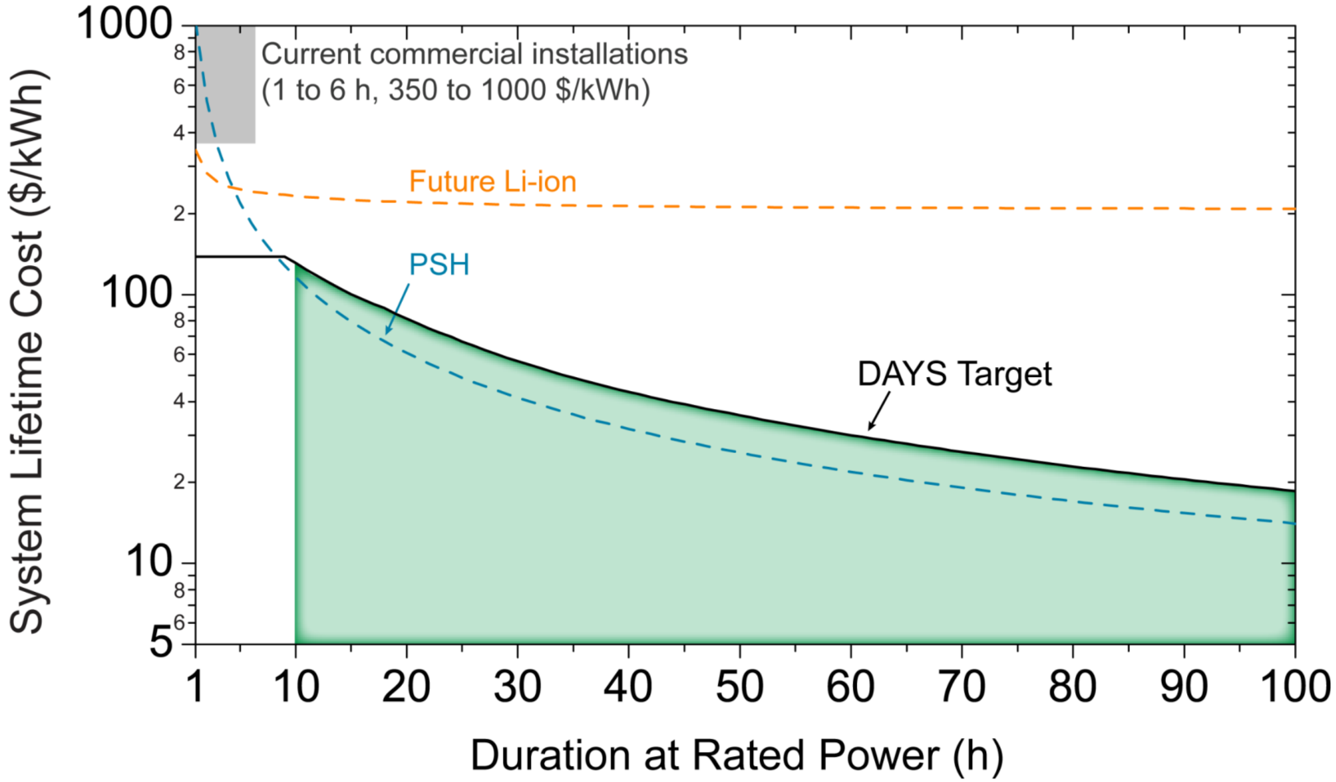


Cost trends for Li-based EV Batteries (pack level)
Source: David Howell, DOE VTO, 2018

LONG DURATION ENERGY STORAGE

- Majority of current battery energy storage today are for applications that require ~ 4 hours at rated power. Requirement for 10 hours coming up quickly.
- No ready solutions for longer duration storage, days to seasonal.

- Longer duration energy storage economic requirements are significantly different from battery storage. Projects have to be larger to justify lower system costs



Reference: Albertus et al., Joule *4*, 21-32, January 15, 2020.

LI-ION BATTERY FIRE SAFETY IN THE NEWS


2006 Sony/Dell battery recall 4.1 million batteries


2008 Navy, $400M Advanced Seal Delivery Sub, Honolulu


2010 FedEx Cargo Plane Fire, Dubai


2011 NGK Na/S Battery Explosion, Japan (two weeks to extinguish blaze)


2011 Chevy Volt Latent Battery Fire at DOT/NHTSA Test Facility


2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm


2013 Storage Battery Fire, The Landing Mall, Port Angeles, (reignited one week after being “extinguished”)


2018-2019 A string of 21 energy storage system fires in South Korea leads to suspension of new projects


2013 Boeing Dreamliner Battery Fires, FAA Grounds Fleet

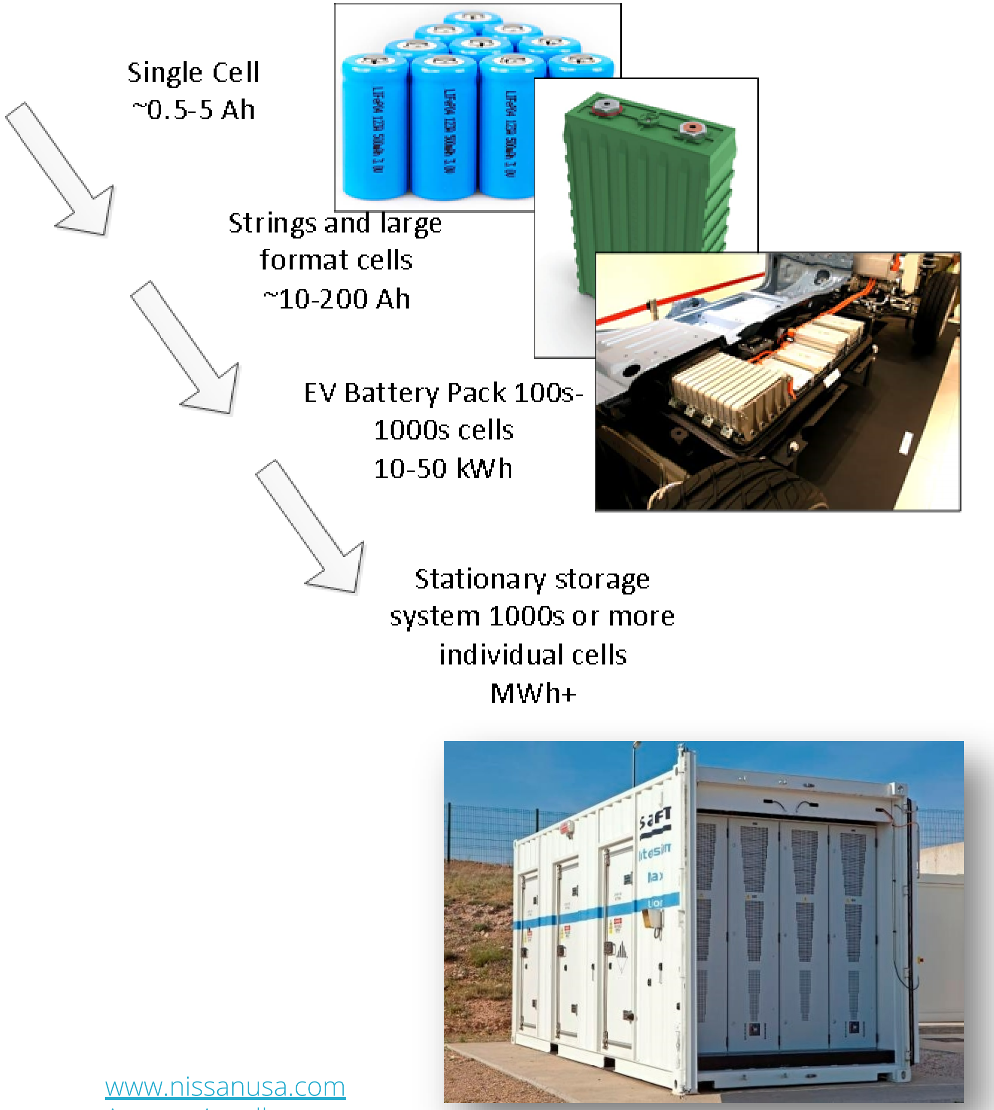

2018 Tesla Model S catches on fire during normal traffic/no accident

2019 A fire in an ESS in Surprise, AZ leads to an explosion injuring first responders

WHAT HAPPENS WHEN BATTERIES FAIL?

- How do cells fail? Manufacturing defects, improper cycling, accidents, end of life…
- Most cells fail quietly
- The failure probability is low (on the order of 1 in several million)
- But for a large installation (~1000s of cells), this probability is not insignificant

- How do we improve safety?



www.nissanusa.com
www.internationalbattery.com
www.samsung.com
www.saft.com

SAFETY OF BATTERY STORAGE SYSTEMS

Development of Inherently Safe Cells

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

Safety Devices and Systems

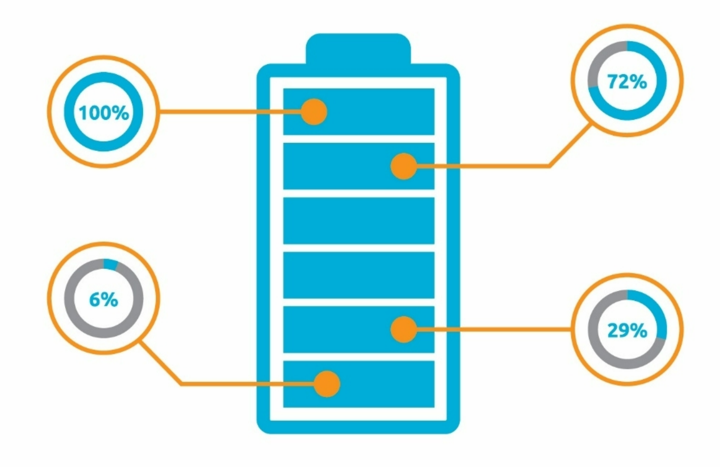
- Cell-based safety devices
  - current interrupt devices
  - positive T coefficient
  - Protection circuit module
- Battery management system
- Charging systems designed

Effective Response to Off-Normal Events

- Suppressants
- Containment
- Advanced monitoring and controls

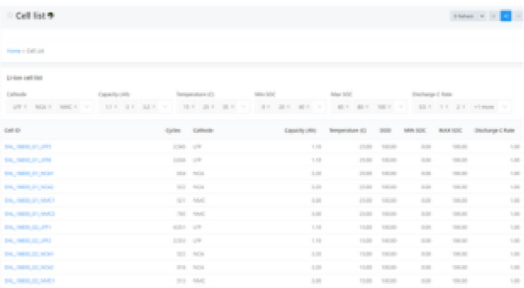
BATTERY ARCHIVE.ORG

- A user friendly platform to make battery performance data and analysis from a variety of institutions accessible
- Manage/Visualize data
- Open source software
- Collaborative interface
- For more information: **batteryarchive.org/**



1

Filter battery data



Query and filter for specific experimental conditions.

2

Visualize and compare data

Display battery data, including voltage curves and capacity fade.

3

Compare data with models

Apply performance and degradation models to battery data.

ACKNOWLEDGMENT

The Energy Storage program at Sandia is supported by
DOE Office of Electricity Energy Storage Program

U.S. DEPARTMENT OF ENERGY

energystorage.sandia.gov

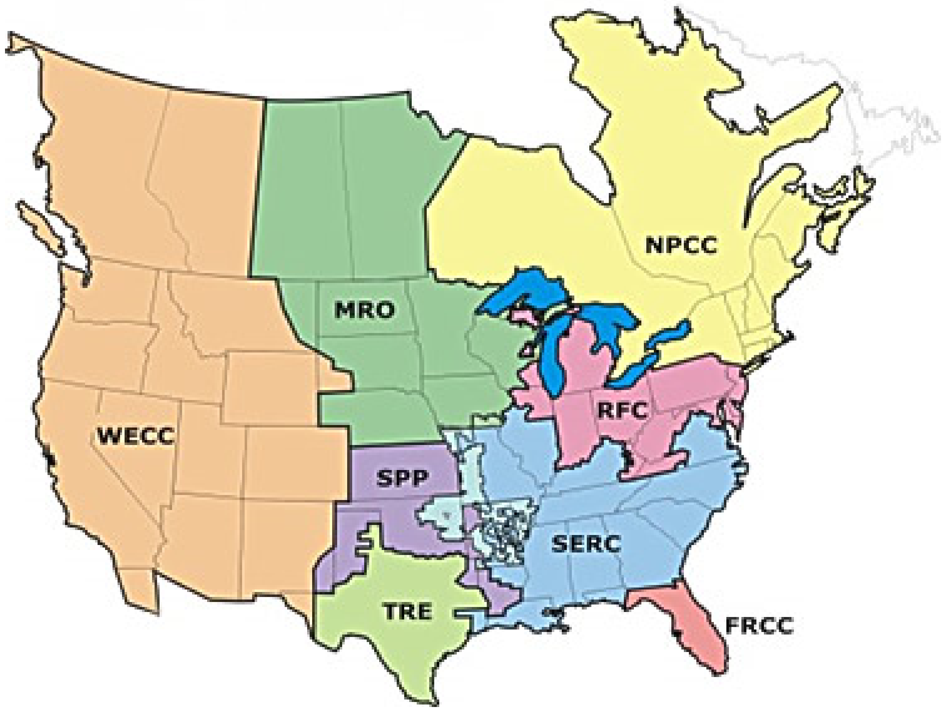
NERC and Regional Entities

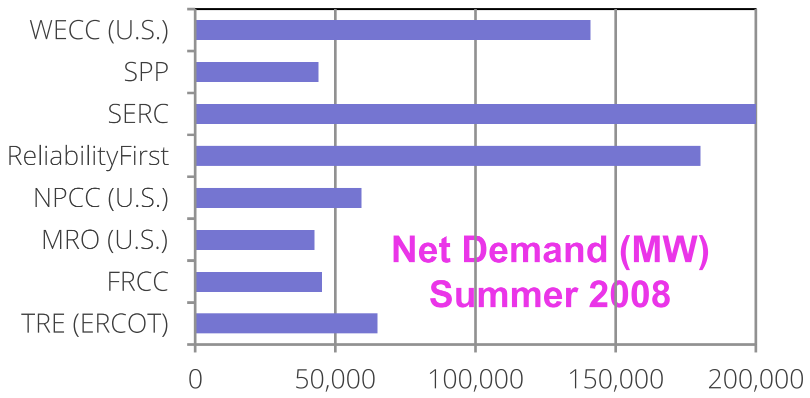
NERC: North American Electricity Reliability Corporation

"Ensure the reliability of the NA bulk power system…"

Regional Entities:

- FRCC: Florida Reliability Coordinating Council
- MRO: Midwest Reliability Organization
- NPCC: Northeast Power Coordinating Council
- RFC: Reliability First Corporation
- SERC: SERC Reliability Corporation
- SPP: Southwest Power Pool, RE
- TRE: Texas Reliability Entity
- WECC: Western Electricity Coordinating Council





Contiguous US: 780,068 MW
Capacity Resources: 929,338 MW
Capacity Margin: 16.1
Source: NERC

NERC NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

http://www.nerc.com

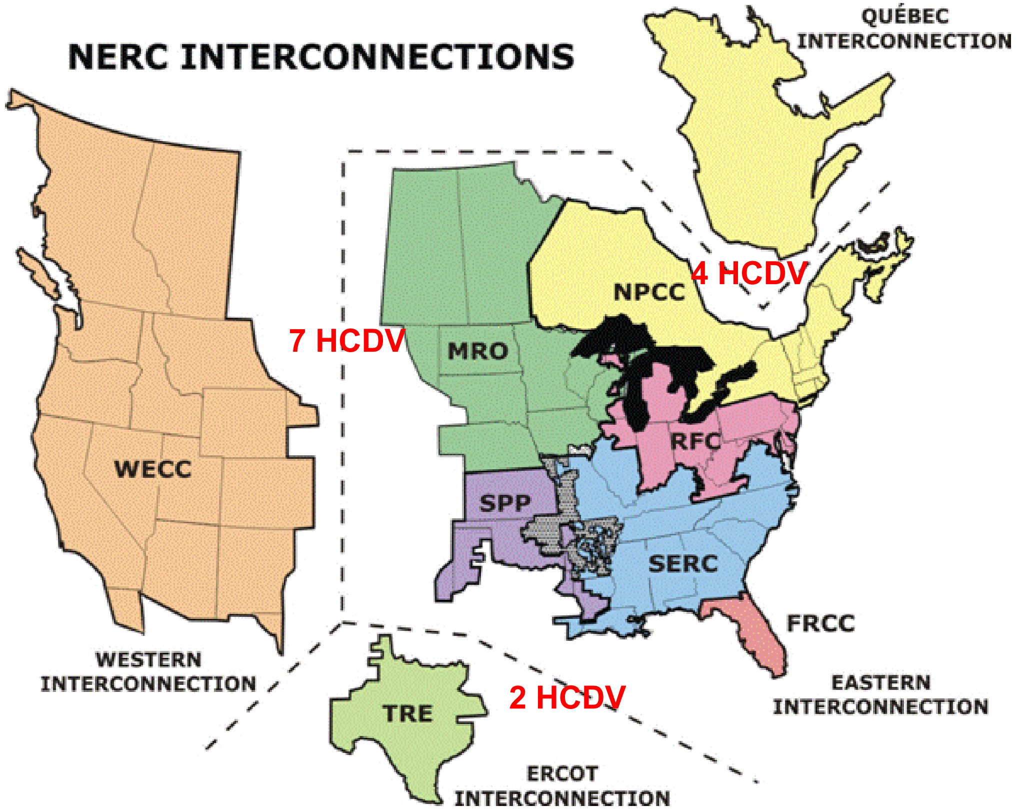
"Interconnections" in North America

An interconnection…
- Has a common frequency
- Shared assets (gens, etc.)

The NA Grid is really four interconnected systems, limited ties between!

DC lines or back-to-back HVDC can be used to tie interconnections

An electrical disturbance in one interconnection does not propagate to other interconnections



Source: NERC

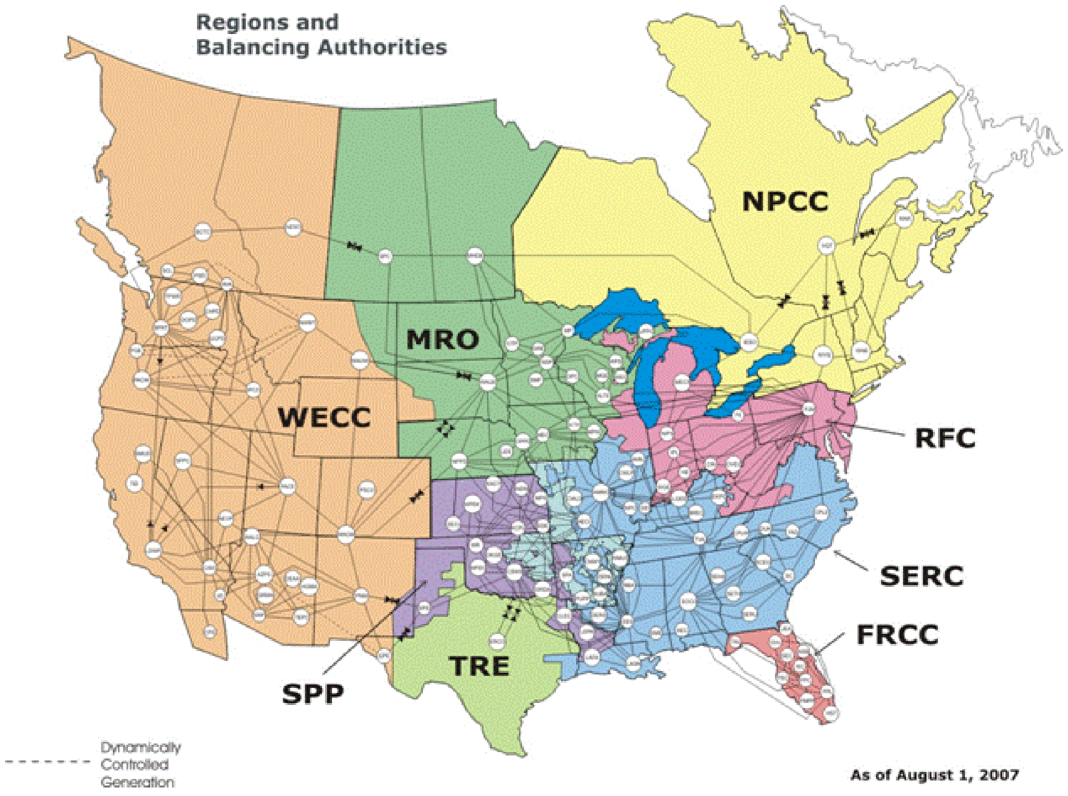
NERC Balancing Authorities

BA functions

- Balance demand (load) & supply (generation)
- Support interconnection frequency
- Maintain desired level of interchange with other BAs

Larger BAs tend to be more efficient (lower cost of electricity)

- Access to more assets, more flexibility
- There are 37 BAs in WECC! Why don't we consolidate?



Source: NERC

Pumped Hydro – 2013 DOE ESHB

Technology Type For Bulk Storage Application	Pumped Hydro		Pumped Hydro		Pumped Hydro		Pumped Hydro	
Survey Year	2010		2010		2010		2010	
DESIGN BASIS - General								
Unit Capacity - Net kW	280,000		1,300,000		900,000		1,200,000	
Hours of Energy storage at rated Capacity - hrs	8		9		16		8	
Depth of Discharge (DOD) per cycle	1		1		1		1	
Energy Capacity - kWh @ rated DOD	2,240,000		11,700,000		14,400,000		9,600,000	
Energy Capacity - kWh @ 100% DOD	2,240,000		11,700,000		14,400,000		9,600,000	
Auxiliaries - kW	na							
Unit Size - Net kW	variable		variable		variable		variable	
Number of Units - #	1 - 4		1 - 4		1 - 4		1 - 4	
Physical Size - Unit / SF	< 10 Acres		250 Acres		40 Acres		250 Acres	
Foot Print - SF	40 Acres		250 Acres		40 Acres		250 Acres	
Unit Weight - lbs	NA		NA		NA		NA	
Round Trip AC / AC Efficiency - %	81%		81%		81%		81%	
Number of cycles / year	365		365		365		365	
DESIGN BASIS - Site								
Design Summer Ambient T - °F	NA		NA		NA		NA	
Design Winter Ambient T - °F	NA		NA		NA		NA	
GENERAL - Timing								
Plant Life, yrs	60		60		60		60	
TOTAL PLANT COST								
$/kW	$2,500		$1,850		$2,200		$2,700	
$/kWh @ rated DOD	$312.50		$206		$138		$338	
$/kWh @ 100% DOD	NA		NA		NA		NA	
$/kWh Delivered @ rated DOD								
PLANT COST	fixed speed	variable speed	fixed speed	variable speed	fixed speed	variable speed	fixed speed	variable speed
Power - $/kW (all elect/mech equipment including prime mover and balance of plant systems to support unit ops)	$550	$750	$550	$750	$550	$750	$500	$650
Storage - $/kWh @ 6 hours	$156		$103		$69		$169	
Storage - $/kW (construct the physical facility to hold the storage and this cost includes all civil works and water conveyance	900 - 2000		900 - 2000		900 - 2000		900 - 2000	
SYSTEM COSTS - Equipment & Install	$/kW	Actual Cost	$/kW	Actual Cost	$/kW	Actual Cost	$/kW	Actual Cost
Pumped Hydro System								
Pumped Hydro Equipment - included in row 56 above								
Pumped Hydro Installation - included in row 56 above								
Enclosures								
Utility Interconnection								
Equipment								
Installation								
Site BOP Installation (Civil Only) - all site civil and water conveyance costs incl in row 57 above.								
Total Cost Equipment								
Total Cost Installation								
General Contractor Facilities at 15% install								
Engineering Fees @ 5% Install								
Project Contingency Application @ 5% install								
Process Contingency Application @ 5% of battery								
Total Plant Cost (TPC)	$2,500	$700,000,000	$1,850	$2,405,000,000	$2,200	$1,980,000,000	$2,700	$3,240,000,000
OPERATING EXPENSES								
Fixed O&M - $/kW-yr	$8.21		$5.60		$6.13		$6.00	
Periodic Major Maintenance - $/kW	$112		$112		$112		$112	
Period between Major Maintenance - yrs	20		20		20		20	
Variable O&M - $/kWh (Charging or Discharging)	$0.00029		$0.0003		$0.0003		$0.0003	

Compressed Air – 2013 DOE ESHB

Technology Type For Bulk Storage Application	CT-CAES (Below Ground)	CT-CAES (Above Ground)	CT-CAES (Above Ground)	CT-CAES (Above Ground)	BRAYTON-CAES (Below Ground)	BRAYTON-CAES (Below Ground)
Survey Year	2011	2011	2010	2011	2011	2011
System Size	50 MW	50 MW	50 MW	50 MW	103 MW	103 MW
Storage Capacity (Hours)	8-26	5	5	5	8-20	8-20
Supplier	**S12**	**S12 - 2**	**S0**	**S12 - 1**	**S9 - 1**	**S9 - 2**
DESIGN BASIS - General						
Minimum storage pressure for full generation capability - psia @ surface	~ 400-800	~ 400-800		~ 400-800	315	315
Maximum compression discharge pressure - psia @ surface	~ 1500-2000	~ 1500-2000		~ 1500-2000	515	515
Storage type - above or below ground	Salt Dome, Aquifer or Hard Rock	Above Ground		Above Ground	Shallow aquifer	Shallow aquifer
Unit Net Capacity - MW @ 95F ambient	50.0	50.0	50	50.0	103	103
Combustion Turbine Capacity - MW, if applicable	19.2	19.2	24	19.5	103	103
Air Expander(s) Total Net Capacity - MW	30.8	30.8	26	30.5		
CAES Energy Stored/Released/Generated based on 8 hrs generation (or 2 hours for above ground air storage) - MWH	304 / 400	124 / 250 (5 hours	250, for a 5 hour storage plant	190 / 250 (5 hours	823.8 MWh	826.5 MWh
More Storage – CAES Energy Stored/ Released/ Generated based on 20 hrs generation (or 4 hours for above ground air storage) - MWH	988 / 1300	N/A		N/A	2,059 MWh	2,066.2 MWh
Round Trip AC / AC Efficiency - %						
Energy Charge Ratio - kWh in/kWh out @ Full Load	0.70	0.45	0.8	0.70	0.74	0.74
Number of cycles / year	365	365	365	365	365	365
CAES Plant unit Net Heat Rate @ Full Load - Btu/kwh (LHV)	3,900	5,880	4,091	3,900	3,916	3,901
Total Compressors Power - MW. Compressors number are optimized to meet "smart" grid requirements.	19.0	Jan-00	23	Jan-00	76470 kW (based on 415 psia mean	76150 kW (based on 415 psia mean
Hours of Energy storage at Rated Capacity shown - hrs	8.0	5.0	5	5.0	8.0	8
More Storage – CAES Energy Stored/Released - kWH based on 20 hrs storage for underground	1,300,000	N/A		N/A	2,059,400	2,066,500
Storage Efficiency (Energy Generated/Energy Stored); Inverse of Energy Ratio - %	>90%	>90%	See Heat Rate and Energy Ratio	>90%	1.346	1.357
DESIGN BASIS - Site						
Design Summer Ambient T - °F	95F	95F		95F	60	60
Design Winter Ambient T - °F	Not Limited	Not Limited		Not Limited		
GENERAL - Timing						
Month $ for Input Data	9	9	9	9		
Plant Life - yrs	40	40	35	40	40	40
Pre-construction Time - yrs						
TOTAL PLANT COST						
$/kW	$1,210	$1,762	$1,950	$1,958	$1,040	$1,053
$/kWh @ rated DOD	$151	$352	$390	$392	$130	$132
$/kWh @ 100% DOD	$151	$352	$390	$392	$130	$132
TOTAL PLANT COST (More Storage)						
$/Kw (20 or 26 hours underground storage)	$1,359				$1,129	$1,142
$/kWh @ rated DOD	N/A				N/A	N/A
$/kWh @ 100% DOD	$52				$56	$57
PLANT COST						
Power - $/kW	$1,078	$1,188	$1,131	$1,078	$921	$934
Storage - $/kWh @ 8 hours underground, varies above ground	$17	$115	$164	$176	$15	$15
Storage - $/kWh @ 20 or 26 hours	$11	N/A	N/A	N/A	$10	$10
Incremental Cost for each hour of storage - $/kW-hour						
SYSTEM COSTS - Equipment & Install						
CAES Capital Costs						
Power Plant Cost Excluding Storage	$49,000,000	$54,000,000	$56,550,000	$49,000,000	$56,118,650	$57,655,350
BOP equipment and installation	included	included	included	included	$35,215,740	$35,337,150
Compressed Air Storage Cost	$6,000,000	$26,105,300	$40,950,000	$40,000,000	$11,120,760	$11,159,100
Total CAES Plant Cost	55,000,000	80,105,300	$88,636,364	89,000,000	102,455,150	104,151,600
Total CAES Plant Cost w/ 10% Contingency of BOP and Storage	$60,500,000	$88,115,830	$97,500,000	$97,900,000	$107,088,800	$108,801,225
CAES TPC ($/KW) (8 hours underground storage)	$1,210	$1,762	$1,950	$1,958	$1,040	$1,053
Capital Costs (More Storage)						
Power Plant Cost Excluding Storage	$49,000,000				$91,334,390	$92,992,500
Compressed Air Storage Cost	$12,750,000				$19,461,330	$19,528,425
Total CAES Plant Cost w/ 10% Contingency	$67,925,000				$116,263,427	$118,007,483
CAES TPC ($/KW) (20 or 26 hours underground storage)	$1,359				$1,129	$1,142
Total Plant Cost (TPC)	$60,500,000	$88,115,830	$97,500,000	$97,900,000	$107,088,800	$108,801,225
OPERATING EXPENSES						
Fixed O&M - $/kW-yr	$3	$3	$4	$3	$5	$5
Periodic Major Maintenance - $/kW	$90	$90	$90	$90	$90	$90
Period between Major Maintenance - yrs	4	7	7	7	4	4
Variable O&M - $/kWh (Charging or Discharging)	$0.0030	$0.0030	$0.0040	$0.0030	$0.0035	$0.0035

Advanced Lead Acid (Bulk)– 2013 DOE ESHB

Application	Bulk Storage	Bulk Storage	Bulk Storage	Bulk Storage	Bulk Storage	Bulk Storage	Bulk Storage
Technology Type	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid
Supplier	**S15**	**S15**	**S11**	**S11**	**S13**	**S44**	**S44**
Survey Year	2010	2010	2011	2011	2011	2010	2010
DESIGN BASIS - General							
System Capacity - Net kW	20,000	50,000	50,000	100,000	50,000	50,000	100,000
Hours of Energy storage at rated Capacity - hrs	6	5	5	4	5	4.8	4.8
Depth of Discharge (DOD) per cycle - %	33%	33%	60%	60%	80%	75%	75%
Energy Capacity - kWh @ rated DOD	120,000	250,000	250,000	400,000	250,000	240,000	480,000
Energy Capacity - kWh @ 100% DOD	363,636	757,576	416,667	666,667	312,500	320,000	640,000
Auxiliaries - kW			n/a	n/a			
Unit Size - Net kW	20,000	50,000	n/a	n/a		100	100
Number of Units - #	685	1713	Building Concept	Building Concept	Chino x 5		
Physical Size - SF/Unit			Not used	Not used			
System Foot Print - SF	101169	252923	95,000	110,000	103200	120,000	240,000
System Weight - lbs			n/a	n/a	5 x 627,800 lbs		
Round Trip AC / AC Efficiency - %	90%	90%	90%	90%	85%	85%	85%
Number of cycles / year	365	365	365	365	365	365	365
GENERAL - Timing							
Commercial Order Date			2012	2012		6 to 9 Months	
Plant Life, yrs	15	15	15	15	15	15	15
TOTAL PLANT COST							
$/kW	$5,876	$4,897	$4,809	$4,326	$1,743	$2,287	$2,254
$/kWh @ rated DOD	$979	$979	$962	$1,082	$349	$476	$470
$/kWh @ 100% DOD	$323	$323	$577	$649	$279	$357	$352
PLANT CAPITAL COST							
Power - $/kW	$796	$663	$634	$546	$507	$527	$494
Storage - $/kWh @ rated DOD	$847	$847	$835	$945	$247	$367	$367
SYSTEM COSTS - Equipment & Install	Actual Cost	Actual Cost	Projected Cost	Projected Cost	Projected Cost	Projected Cost	Projected Cost
ES System							
ES Equipment	$92,363,636	$192,424,242	$175,000,000	$320,000,000	$56,200,000	$80,000,000	$160,000,000
ES Installation	$4,618,182	$9,621,212	$25,000,000	$42,000,000	$2,810,000	$4,000,000	$8,000,000
Enclosures	$3,644,084	$9,107,228	$3,422,000	$3,962,000	$3,717,200	$4,322,000	$8,642,000
Owner Interconnection							
Equipment	$5,154,500	$9,981,500	$9,981,500	$18,893,500	$9,981,500	$9,981,500	$18,893,500
Installation	$644,500	$1,247,500	$1,247,500	$2,361,500	$1,247,500	$1,247,500	$2,361,500
Enclosures	included	included	Included	Included	Included	Included	included
System Packing	$0	$0	$0	$0	$0	included	included
System Shipping to US Port	$0	$0	$0	$0	$0	$0	$0
Utility Interconnection							
Equipment	$2,012,500	$3,875,000	$3,875,000	$6,875,000	$3,875,000	$3,875,000	$6,875,000
Installation	$2,012,500	$3,875,000	$3,875,000	$6,875,000	$3,875,000	$3,875,000	$6,875,000
Site BOP Installation (Civil Only)	$202,338	$505,846	$190,000	$220,000	$206,400	$240,000	$480,000
Total Cost Equipment	$103,174,720	$215,387,970	$192,278,500	$349,730,500	$73,773,700	$98,178,500	$194,410,500
Total Cost Installation	$7,477,520	$15,249,558	$30,312,500	$51,456,500	$8,138,900	$9,362,500	$17,716,500
General Contractor Facilities at 15% install	$1,121,628	$2,287,434	$4,546,875	$7,718,475	$1,220,835	$1,404,375	$2,657,475
Engineering Fees @ 5% Install	$373,876	$762,478	$1,515,625	$2,572,825	$406,945	$468,125	$885,825
Project Contingency Application @ 0-15% install	$747,752	$1,524,956	$3,031,250	$5,145,650	$813,890	$936,250	$1,771,650
Process Contingency Application @ 0-15% of battery	$4,618,182	$9,621,212	$8,750,000	$16,000,000	$2,810,000	$4,000,000	$8,000,000
Total Plant Cost (TPC)	$117,513,678	$244,833,608	$240,434,750	$432,623,950	$87,164,270	$114,349,750	$225,441,950
OPERATING EXPENSES							
FIXED O&M - $/kW-yr	$5.8	$4.5	$4.5	$4.3	$4.5	$4.5	$4.3
Replacement Battery Costs - $/kW	$1,385	$1,155	$1,050	$960	$337	$480	$480
Battery replacement - yrs	8	8	8	8	8	8	8
Variable O&M - $/kWh (Charging or Discharging)	0.0005	0.0005	0.0005	0.0007	0.0005	0.0006	0.0006