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Grid Energy Storage Technologies and the Future Electric Grid

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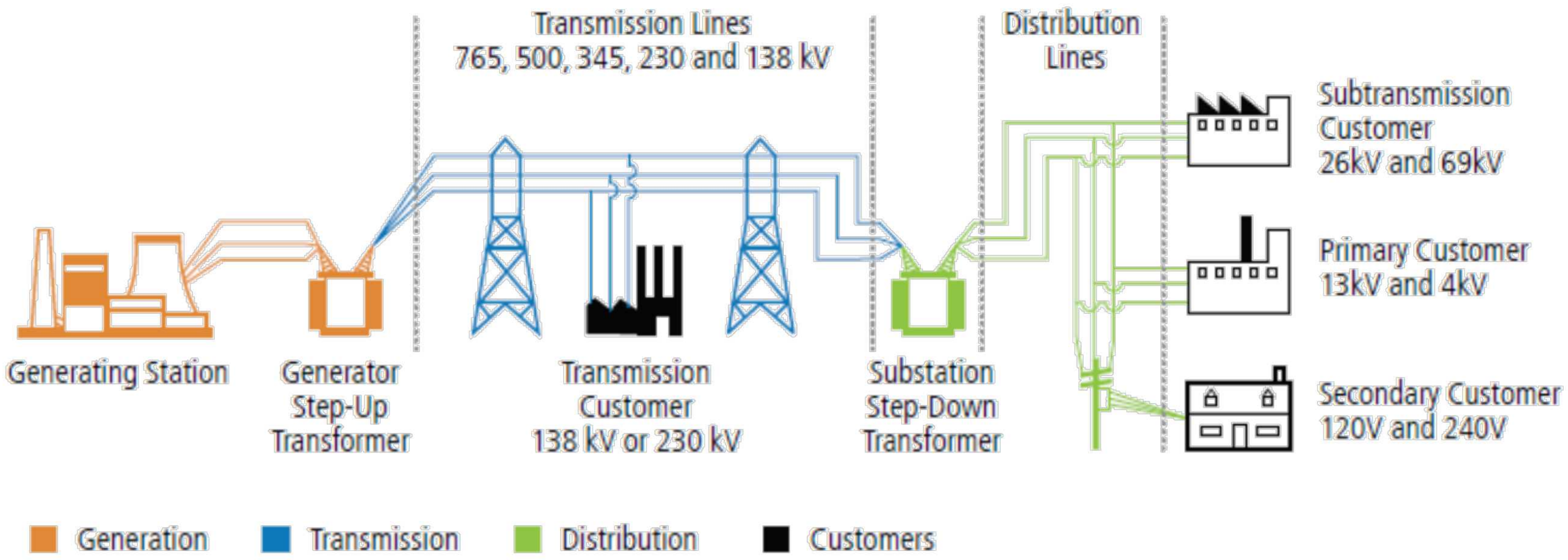
The Success of the Electric Grid



NERC

- A one way delivery system with very little flexibility, with generation and load always balanced
- Utilities deliver reliable power at prices set by regulators in most markers, and variable market driven pricing in a few markets

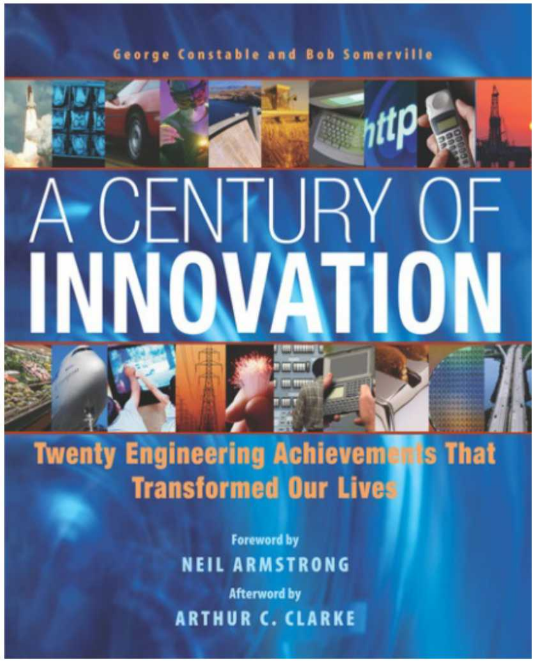
The Success of the Grid

Remarkably reliable and efficient

- Large interconnected network
- Just-in-time production and consumption
- Highly reliable 99.999%

Success rests on two important principles

- Diversity of aggregated loads
  - Aggregated loads change is predictable
  - Control over generation, throttled to provide power as needed



Electrification ranks as the most important engineering achievement of the 20th century
National Academy of Engineering, 2003

U.S. Electric Grid

850GW baseload, 1250 GW summer peak, 7,000 operational power plants

3,200 utilities, 60k substations, 642k miles of HV transmission lines, 6.2 million miles of distribution circuit, 159 million customers.

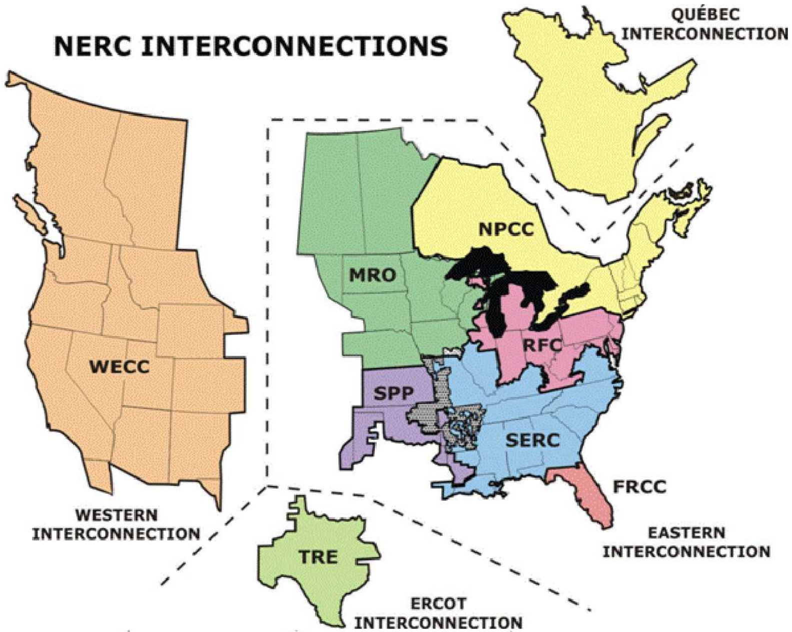
In 2015, total U.S. electricity generation was 4,087,381 GWh

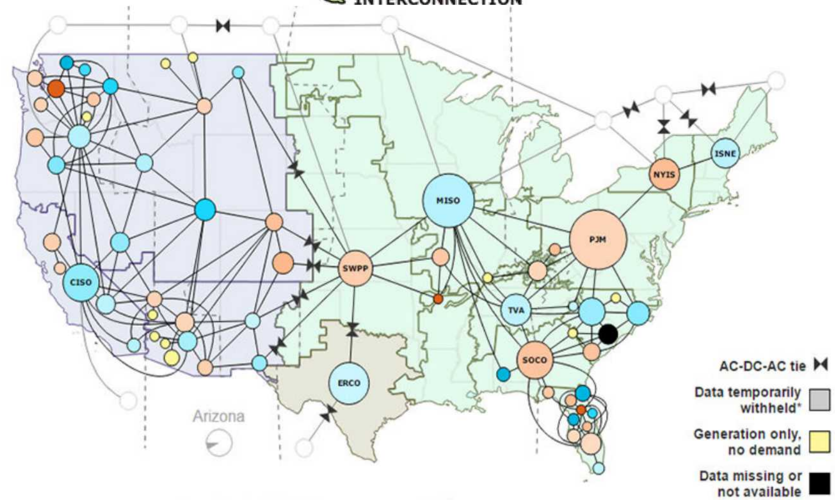
- Increasing NG and renewable generation (6.1% hydropower and 7.3% from wind and solar)

Revenues reaching $400 B, 10.42 c/kWh avg

Four interconnect regions and a number of balancing authorities:

- Eastern Interconnection (31 US, 5 Canada)
- Western Interconnection (34 US, 2 Canada,1 Mexico)
- ERCOT, Hydro-Quebec

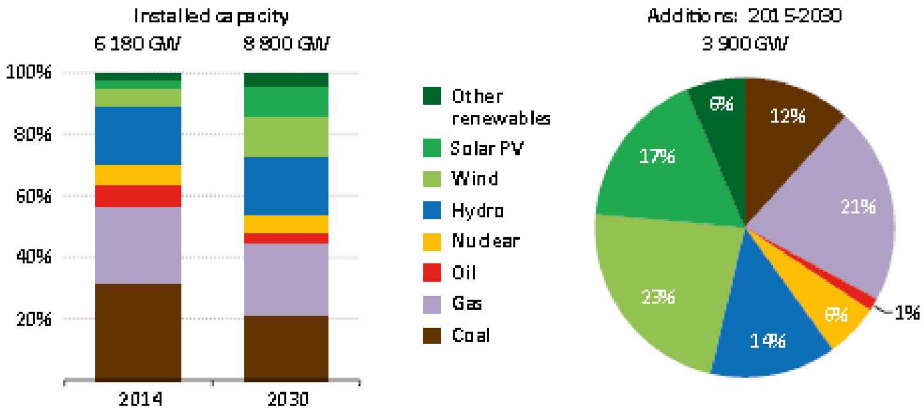


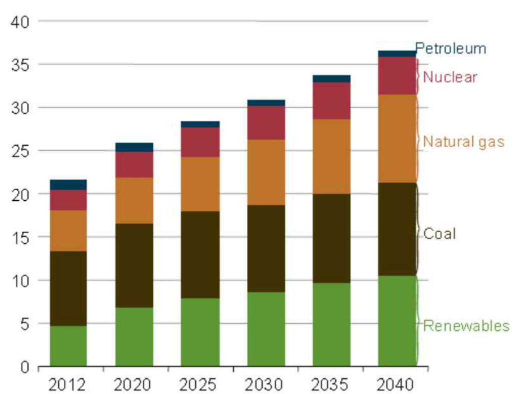


Sources: EIA, EEI

http://www.nerc.com

Electric Grid: Are we at the cusp of a major transformation?





Source: International Energy Outlook, EIA, 2016

Of the 6 TW of worldwide generation capacity, renewables are reaching the 20% range in many markets.

- Installed solar and wind capacity reached 1 TW in 2018, penetration levels approaching 30-40% in some markets.

US Grid: 850 GW baseload, 1250 GW summer capacity.

- Installed solar and wind capacity reached 150GW in 2018

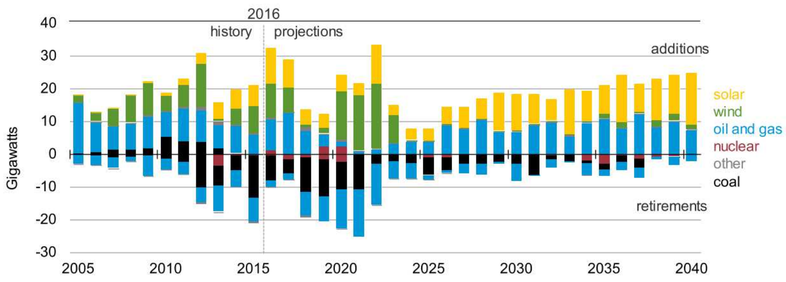
Handling intermittency is becoming a challenge in many markets

- High level integration of energy storage and hybrids, on a grand scale.

In 2000, the IEA forecast that by 2030, renewable energy would be 4.4% of the total mix
In 2018, installed wind and solar capacity reached 1 TW, new generation is more renewable

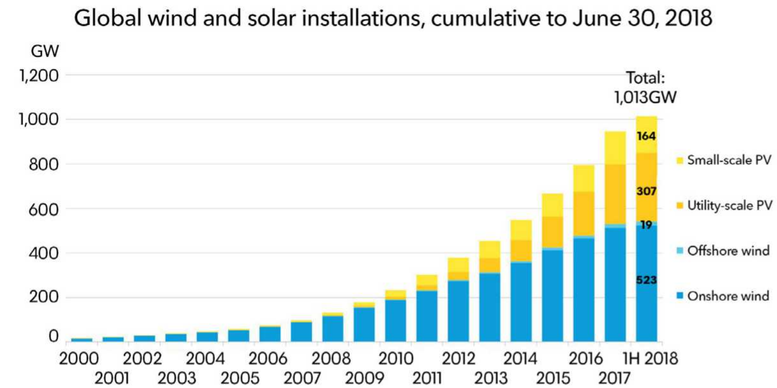
Major Trends in Electricity Markets

Capacity Additions and Retirements



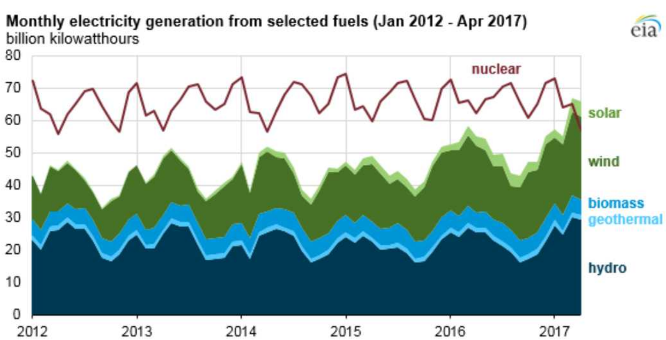
Source: EIA, Annual Energy Outlook 2017

Coal-fired unit retirements driven by low NG prices (EIA, 2017)
In California by 2021, solar, storage and wind capacity additions will exceed natural gas (GTM Research)

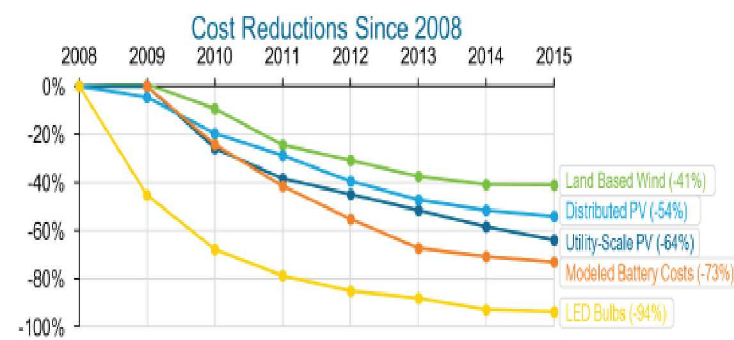


Source: Bloomberg NEF. Note: 1H 2018 figures for onshore wind are based on a conservative estimate; the true figure will be higher. BNEF typically does not publish mid-year installation numbers.

Utility-scale Renewables Generation surpassed Nuclear Generation – April 2017



Cost reductions primarily due to high volume manufacturing and large scale deployments



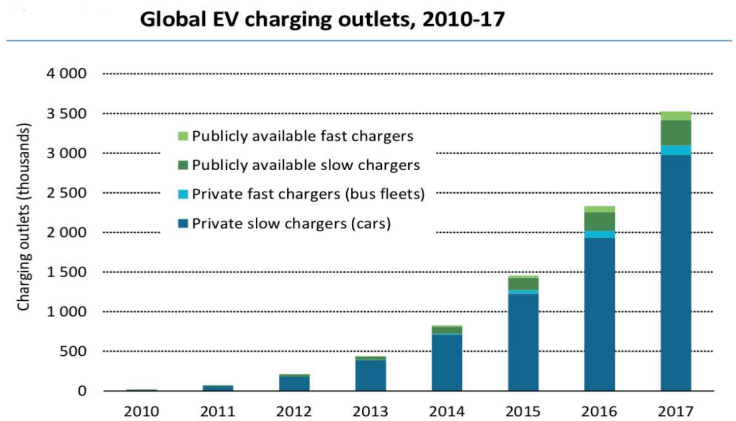
http://energy.gov/eere/downloads/revolutionnow-2016-update

Transformation of the Grid Edge

Electrification, Decentralization, Digitalization

Electrification of the Transportation Sector

- EV charging infrastructure and fast charging
  - Ensure stability of the power grid
  - Accommodate large loads
  - Provide grid services,. Infrastructure for transactive energy



Advanced Batteries for longer EV range

- Increased energy density and materials use
- Recycling and repurposing
- Improved battery management systems

Behind-the-meter technologies with bi-directional communication

- Smart meters, smart loads, rooftop solar, electric vehicles, battery storage

Computation challenges associated with distributed sensing, control, and big data

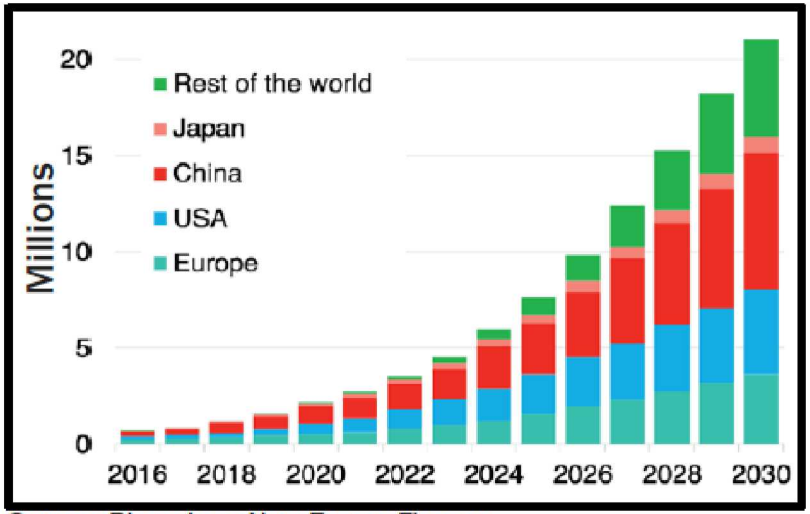
Increasing Role of Power Electronics

Rapid evolution of off-grid and micro-grids

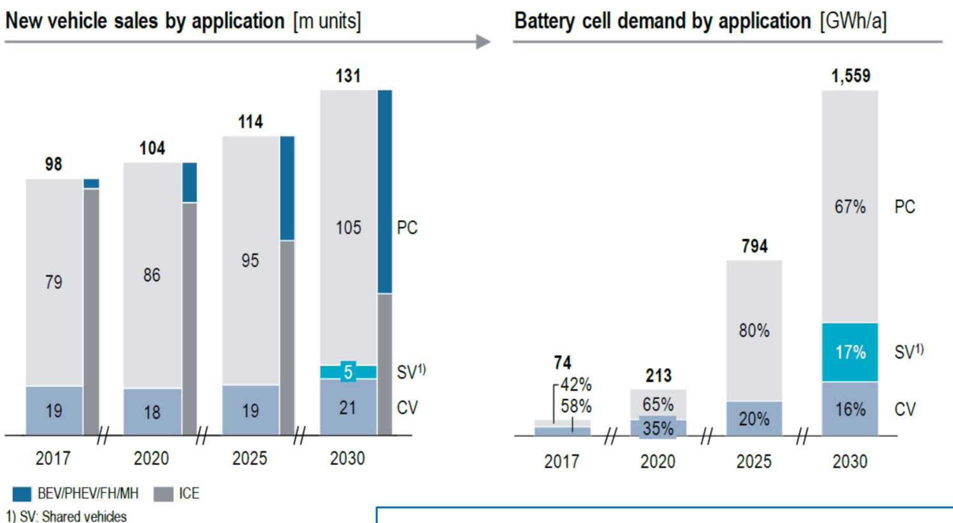
Electrification of Transportation

IEA, IHS, Bloomberg projections for annual production of electric vehicles reaching 20 Million by 2030 and a fleet of 130 Million vehicles (mostly passenger vehicles) on road as base case, 230M vehicles optimistic case'

- Typical battery pack: 100 kWh/80kW, 500 mile



Source: Bloomberg New Energy Finance



Source: IHS; Roland Berger

Projected battery capacity needs for EVs in 2030

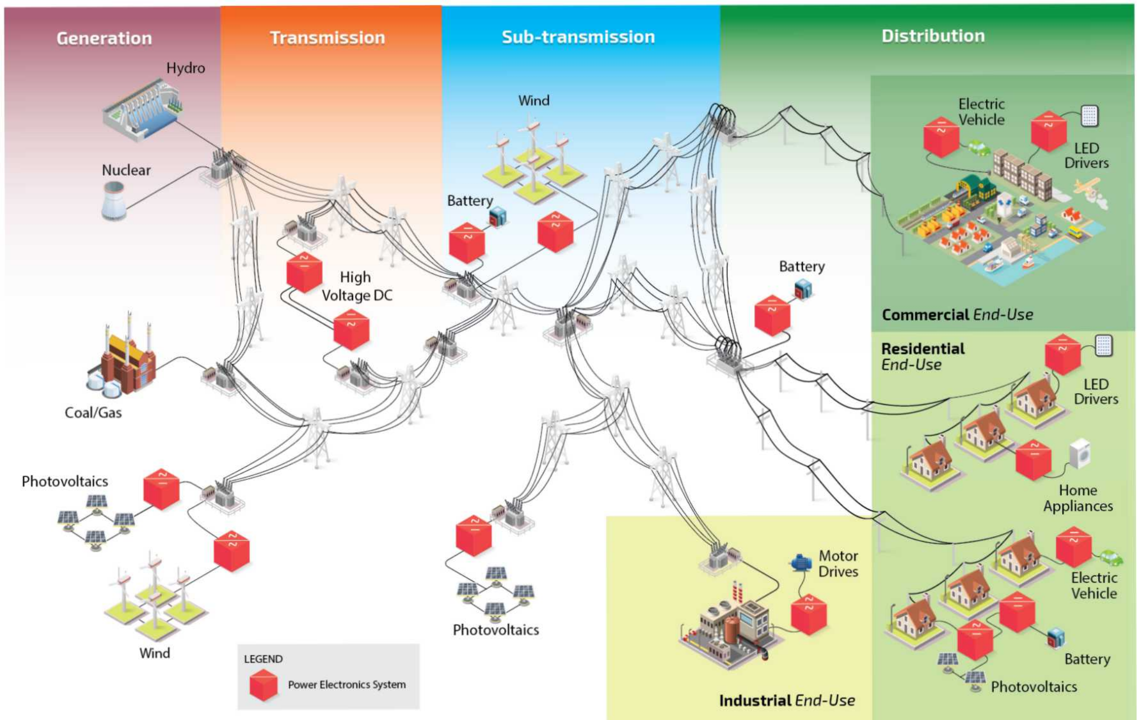
- 1.5 - 2.5 TWh of manufacturing capacity

International Energy Agency projects at least 125 million EVs worldwide by 2030.

Infrastructure updates required:

- prevalent charging stations
- accommodation of increased loads (potentially at ends of distribution feeders)

Increasing Role of Power Electronics in Electricity Infrastructure



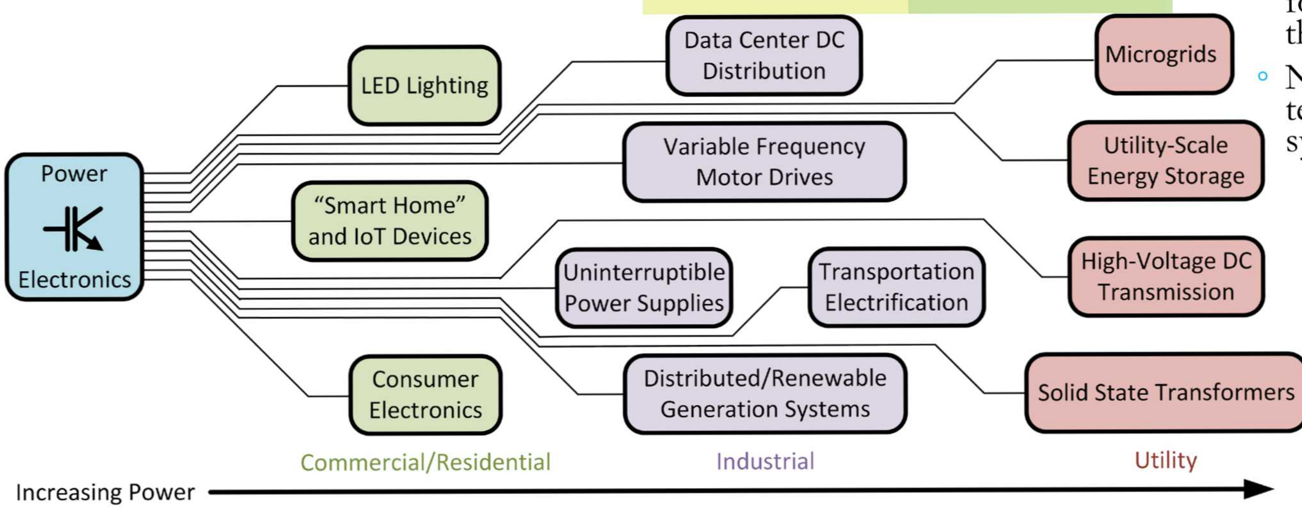
Continued increase in the role power electronics through out the grid

Approximately 30% of all electric power currently generated uses PE somewhere between the point of generation and distribution.

By 2030, it is expected that 80% of all electric power will flow through PE converters.

Cost reductions in power electronics and power conversion systems has been slow to come.

- Bringing in WBG devices can make format factor smaller, reduces thermal management issues
- New magnetics and high temperature capacitors can make the systems more compact and robust



Policy Changes for a Greater Role for Clean Energy Technologies

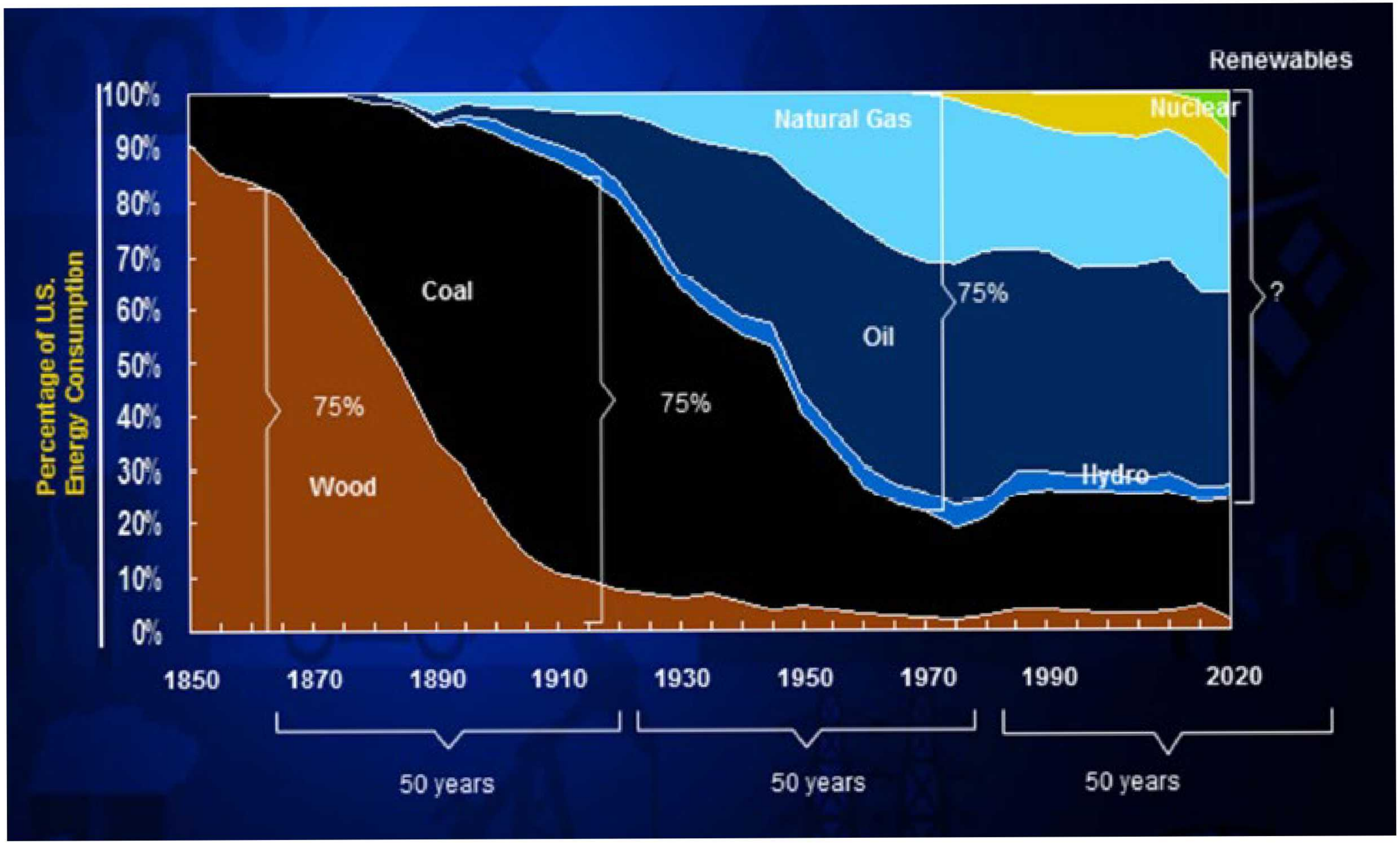
7 countries are already at 100% renewable including Albania, Bhutan, Ethiopia, Iceland, Lesotho, Nepal and Paraguay.

Many others are close to this mark such as Norway (98.5%), New Zealand (80.8%) and Brazil (75%).

California and Hawaii are aiming for 100% renewable energy by 2045; many U.S cities and counties have made public commitments to reach 100% clean energy in the next ten to twenty years.

100% fossil free generation is no longer an idea

But, Energy Transition Cycles are Long (50 Year Cycles)



EIA Annual Energy Review 2008

Immediate Needs to for Grid Modernization

Economic

- Aging electric power system exacts substantial costs due to outages and inefficient energy technologies.

Environmental and Policy

- Increasing frequency and severity of extreme weather (drought, storms, etc.) affects the ability to generate power and stress the resiliency of electric power grid.

Security

- Physical: damage to infrastructure by malicious actors or natural hazards increasing risk to critical assets
- Cyber: disruption of energy production/energy flow and damage to equipment caused by cyber threats/attacks.

Competitiveness

- Increasing competition worldwide in energy sector as countries are moving toward clean energy technologies
- Competitive energy markets needed for economic competitiveness

How is the Grid Evolving?

We are beginning to see existing business models breaking down

Flat to declining electricity sales in OECD markets

- Investors struggling with poor returns due to long adoption cycles. $2 Tn Asset Base in the US alone

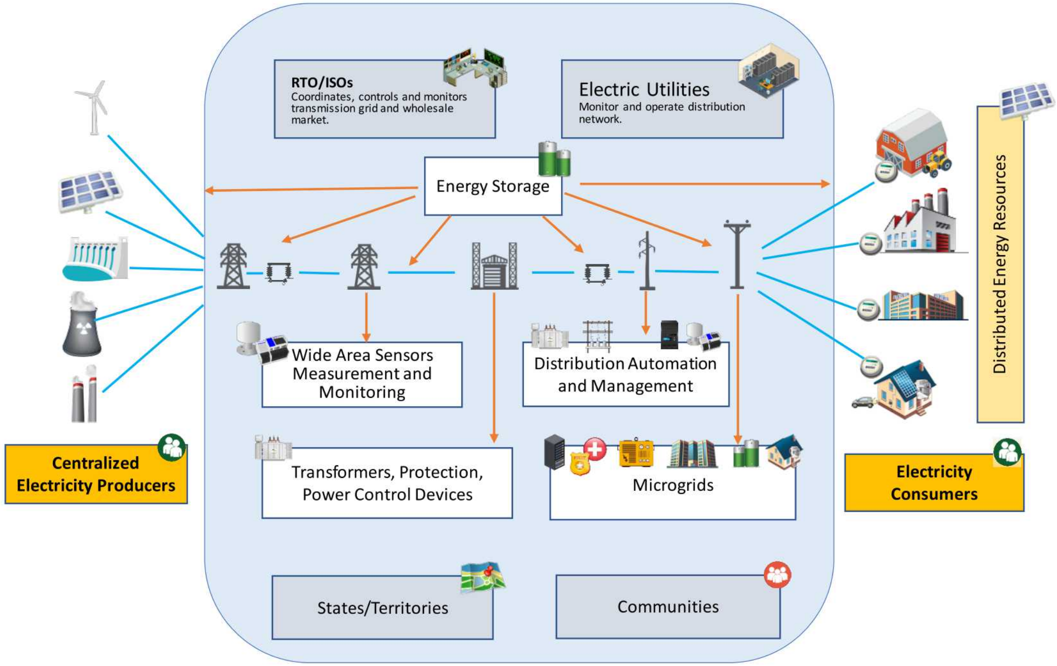
Conservative regulated utility industry

- Not open or reluctant to change business models
- IOUs and PUCs struggling to adapt to rapid change

Rapid change is bottom-up, with major transformation at the grid edge

- EVs, DER, Smart metering, microgrids, demand response, energy efficiency

Changes cuts across technology, economics, policy, and markets



Source: US DOE Office of Electricity

Centralized to a Decentralized Power Delivery Model?

Will we have a hybrid model?

Energy Storage is needed

Role of Energy Storage in the Grid

Grid resiliency and reliability

Improving power quality

Improving the efficiency of existing generation fleet

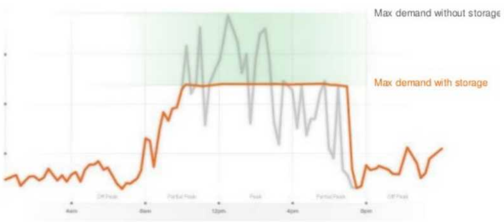
Demand management

Renewable integration

Transmission & Distribution upgrade deferral

Off-grid applications

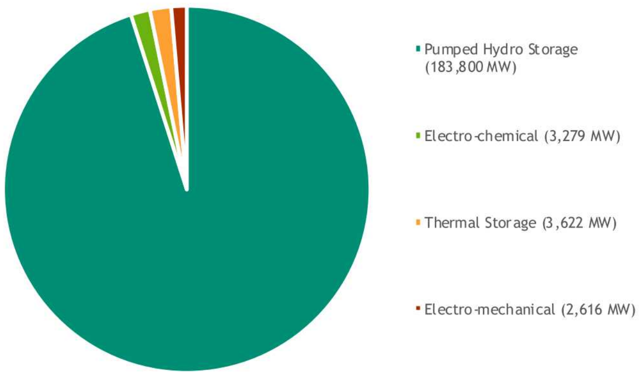
Mitigate $79B/yr in commercial losses from outages



Reduce commercial and industrial electrical bills through demand charge management. 7.5 million U.S. customers are enrolled in dynamic pricing (EIA 2015)

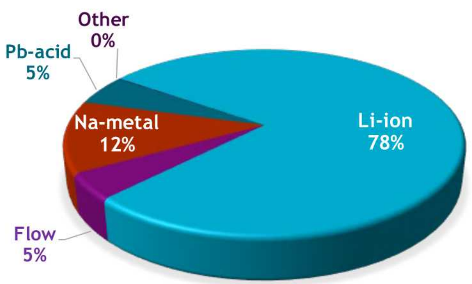
Balance the variability of 825 GW of new renewable generation while improving grid reliability and efficiency.

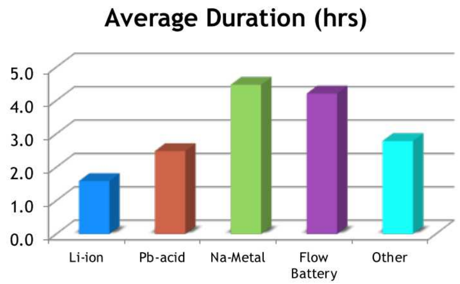
Energy Storage in the Grid Today



Global Installed Storage Capacity

Technology Type	Projects	Rated Power (MW)
Electro-chemical	993	3,279
Pumped Hydro Storage	352	183,800
Thermal Storage	206	3,622
Electro-mechanical	70	2,616





US Battery Energy Storage Deployed Reaching 2 GW in 2018

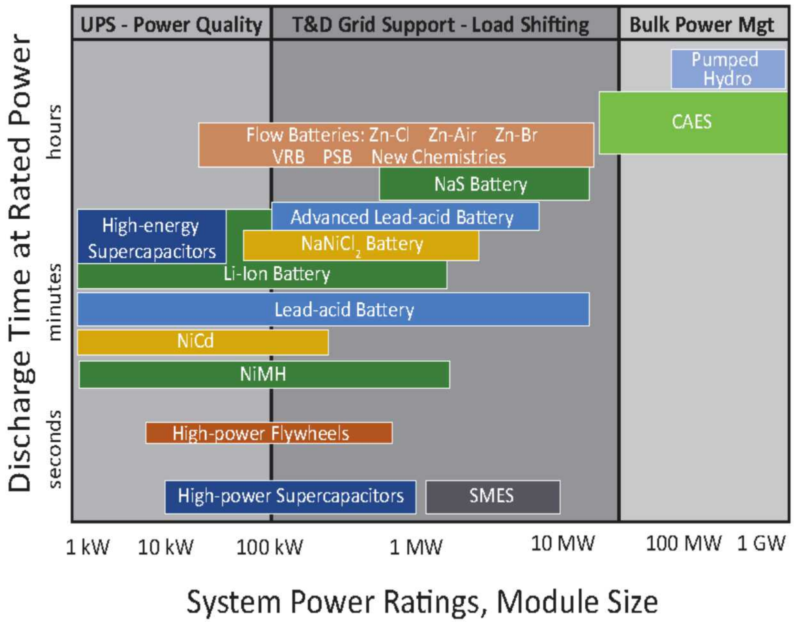
US installed energy storage capacity of 32 GW represents 15 min ride through

Compared to the need, scale of energy storage deployments are insignificant.

DOE Global Energy Storage Database
www.energystorageexchange.org

Numbers reflect projects reported to the DOE Global Energy Storage Database as of Nov 2017

Energy Storage System Needs and Applications



Range of applications and storage system needs [Source: DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, 2013]

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

Energy storage application time scale

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

The grid needs energy storage – right now there are several barriers

- Expensive, especially in energy markets
- Electricity markets/utilities do not properly allocate payments/costs for services provided

The future ….

- Higher energy prices – storage starts looking better
- Lower technology costs – storage starts looking better
- Efficient market design – helps pay for storage costs

Grid Energy Storage Technoloiges

Range of battery technologies for short duration energy storage, seconds to days

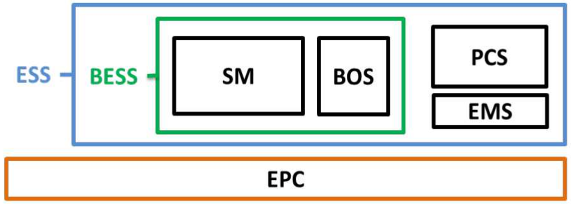
- Li-ion, advanced lead acid, Sodium and Zinc-based battery for power and some energy applications
- Flow batteries – energy applications

Pumped hydro and CAES for hours to day long energy storage

No ready solutions for real long duration and seasonal storage needs

- Range of options including liquid fuels, hydrogen, thermal storage technologies

Energy Storage is Not Just Batteries



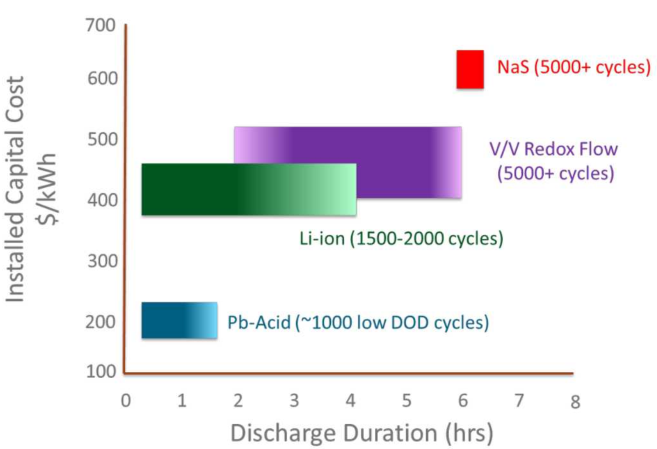
SM	Storage Module	Rack Level System (DC)
BESS	Battery Energy Storage System	Containerized System (DC)
ESS	Energy Storage System	Complete Storage System (AC)

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

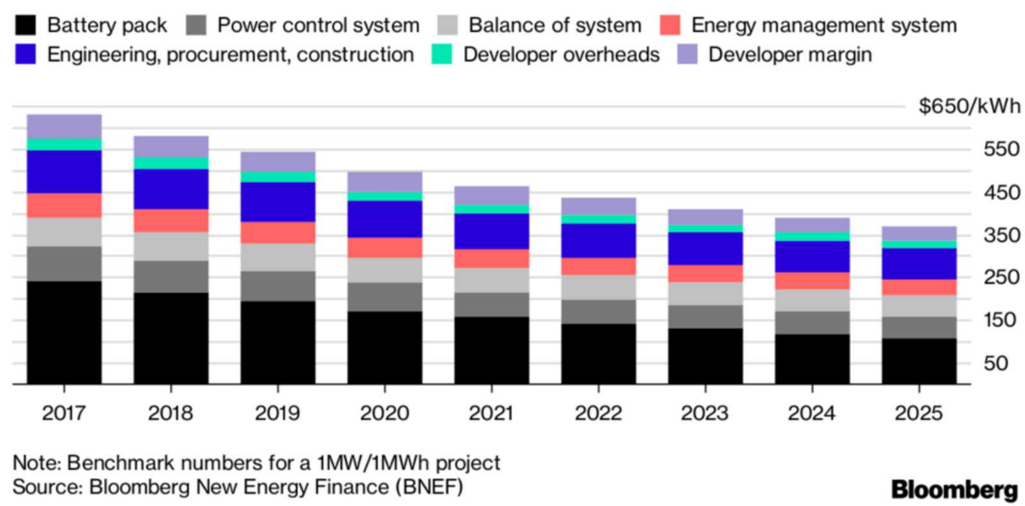
Source: R. Baxter, I. Gyuk, R.H. Byrne, B.R. Chalamala, IEEE Electrification, Aug 2018

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

- Energy Storage is competitive in power markets such as regulation
- Expensive in most energy markets



Source: V. Sprenkle, PNNL, 2017



Energy Storage Installed Costs (BNEF, 2018)

Major Battery Technologies for EVs and Grid Storage

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

	World Wide Production Capacity	Cost and Performance Improvements
Lead Acid Batteries	350 GWh	2%/year (30 year data). \$80-150/kWh
Li-ion Batteries	100 GWh	5%/year (20 year data). Cell level price reaching \$150/kWh
NaS and NaNiCl	300 MWh	Mature, but no economies of scale
Flow Batteries	<200 MWh	Potential for lower cost. \$400/kWh. Reach \$270/kWh
Alkaline chemistries (Zn-MnO2, Zn-air)	<100 MWh	Not fully mature. Lowest cost BOM

Data Sources: Avicenne, 2017; Enersys, 2018

Energy Storage - Design and Application Aspects

Cell Architecture
- Cell format
  - Cylindrical, Prismatic
  - Bipolar
  - Flow Cell

Cell Chemistry
- Aqueous
- Non-aqueous

Thermal management
- Heating
- Cooling

Safety
- Abuse resistance
- Flammability
- Toxicity
- Containment

Plant Models
- Modular
- Centralized

Power vs. Energy
- High-power, short-duration discharge
- High-energy, long-duration discharge
- Fast Charging

Modularity and Scalability
- kW to MW (Power Scaling)
- kWh to MWh (Energy Scaling)
- Module stacking and Containerization

Cycle Life
- Electrical
- Thermal

Operational Aspects
- Round-trip efficiency
- Auxiliary power consumption
- O&M Costs

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

High energy density

Better cycle life than Lead - Acid

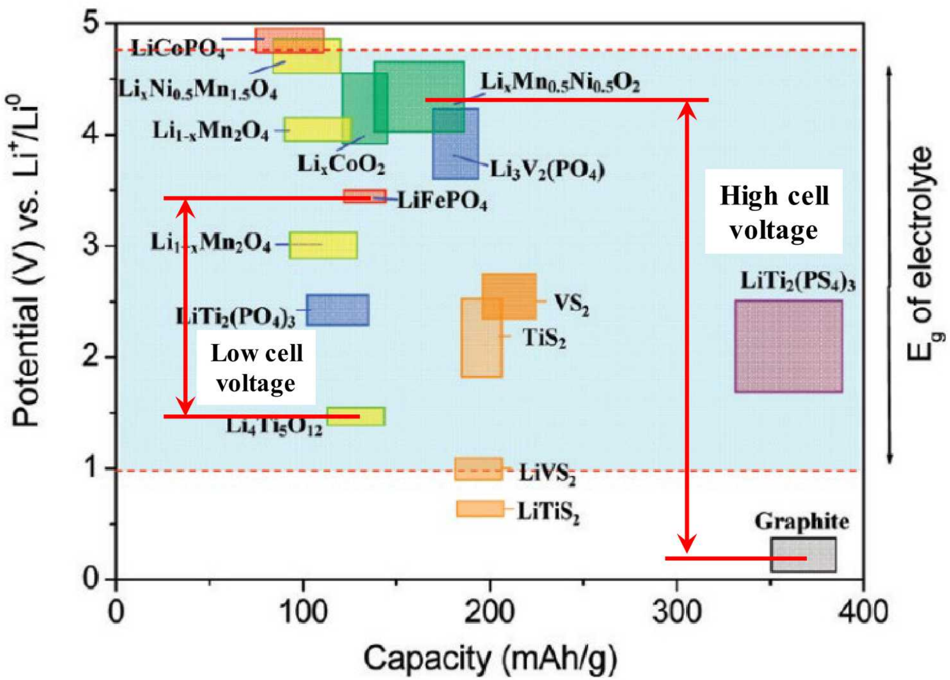
Decreasing costs

Ubiquitous – Multiple vendors

Fast response

Higher efficiency

No single type is best for all applications



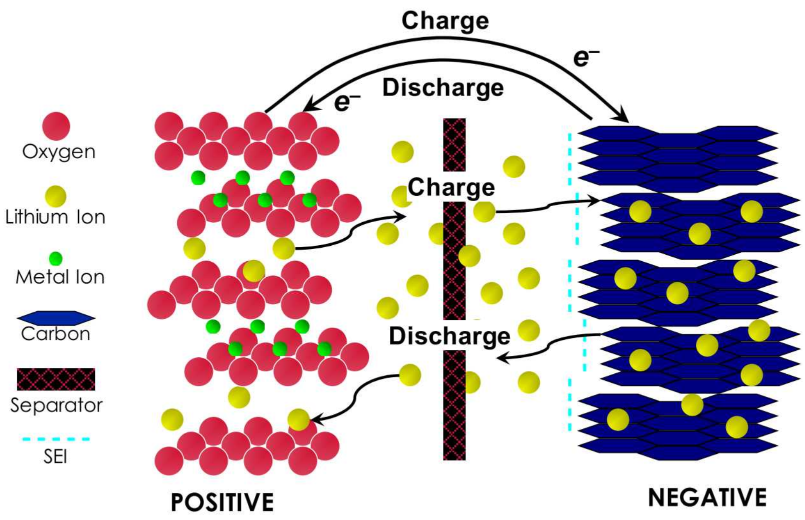
Li-ion: Basic Chemistries

Anodes

Chemistry	Specific Capacity	Potential vs. Li⁺/Li
Soft Carbon	< 700	< 1
Hard Carbon	600	< 1
$Li_4Ti_5O_{12}$	175 / 170	1.55
TiO_2	168 / 168	1.85
SnO_2	782 / 780	< 0.5
Sn	993 / 990	< 0.5
Si	4198 / < 3500	0.5 ~ 1

Cathodes

Chemistry	Specific Capacity	Potential vs. Li⁺/Li	
$LiCoO_2$	273 / 160	3.9	*Consumer Electronics*
$LiNiO_2$	274 / 180	3.6	
$LiNi_xCo_yMn_zO_2$	~ 270 / 150~180	3.8	*NMC - LG/Volt*
$LiNi_xCo_yAl_zO_2$	~ 250 / 180	3.7	*NCA - Tesla*
$LiMn_2O_4$	148 / 130	4.1	
$LiMn_{1.5}Ni_{0.5}O_4$	146 / 130	4.7	
$LiFePO_4$	170 / 160	3.45	*LFP*
$LiMnPO_4$	171 / 80~150	4.1	
$LiNiPO_4$	166 / -	5.1	
$LiCoPO_4$	166 / 60~130	4.8	



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

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

Li-ion Batteries - SOA

First two generations driven by consumer electronics, newer chemistries geared for automotive applications

- $LiCoO_2$ continues be the dominant technology for consumer electronics
- 2nd Generation Li-Ion Chemistries offering better performance, wider temp range, improved safety and lower cost. NMC, NCA preferred for EVs

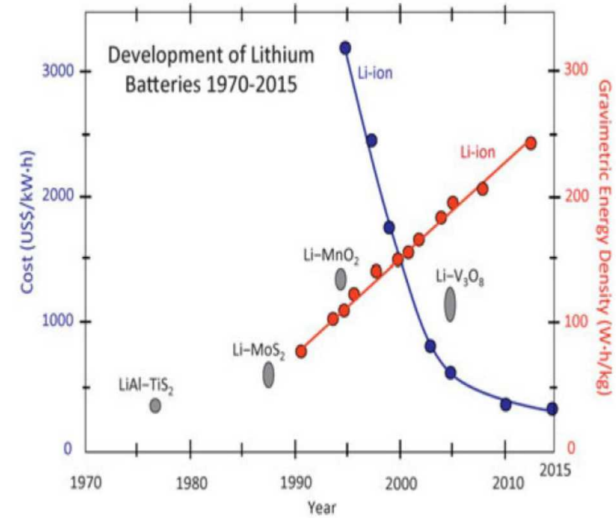
Rapid growth of application beyond frequency regulation and power quality to energy applications. Large plants in the 100 MW are being built.

Capacity improvements are becoming incremental

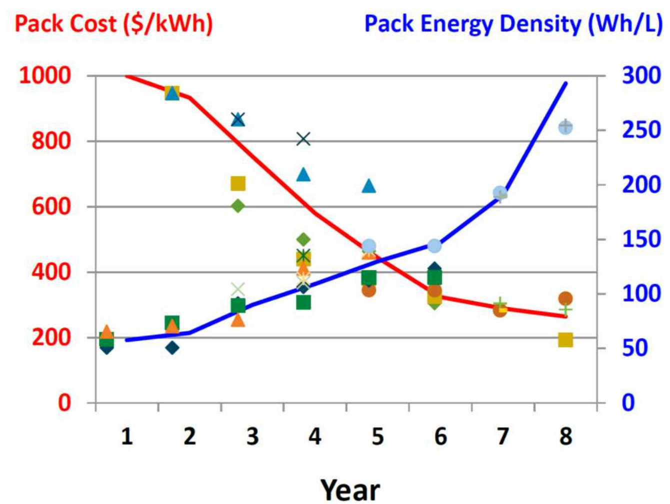
- 8% for LIB (1992-2007); BOM is 80-85% of cell costs, Scaling down materials cost proving difficult
- Engineering larger cells (>100 Ah) is not still economical

Safety and reliability continue to be significant concerns

Deep discharge cycle life issues for energy applications (1000 cycles for automotive)

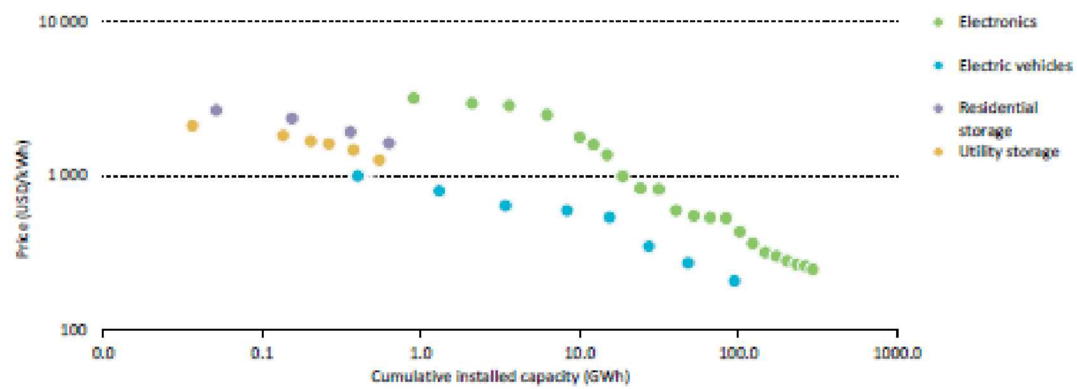


Source: Crabtree, Kocs, Trahey, MRS Bulletin, Dec 2015



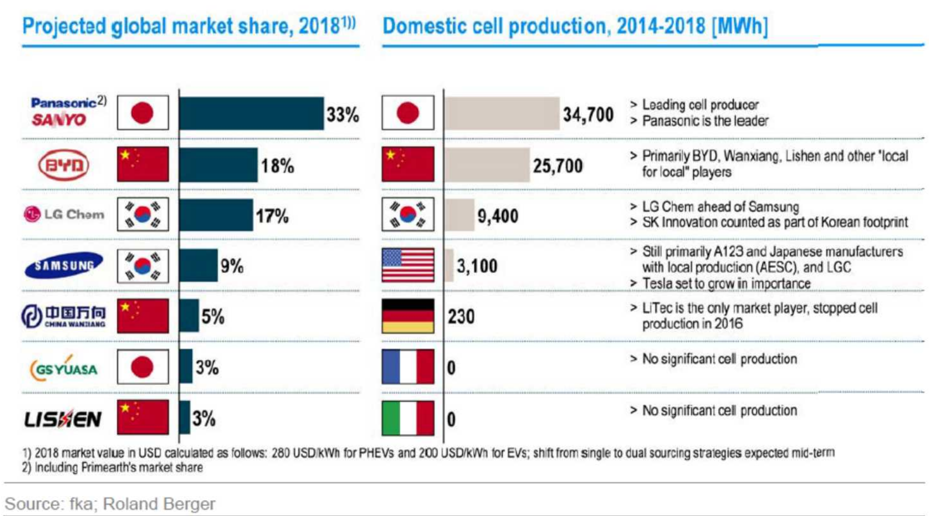
Source: David Howell, DOE VTO, 2017

Manufacturing Scale and Cell/System Costs

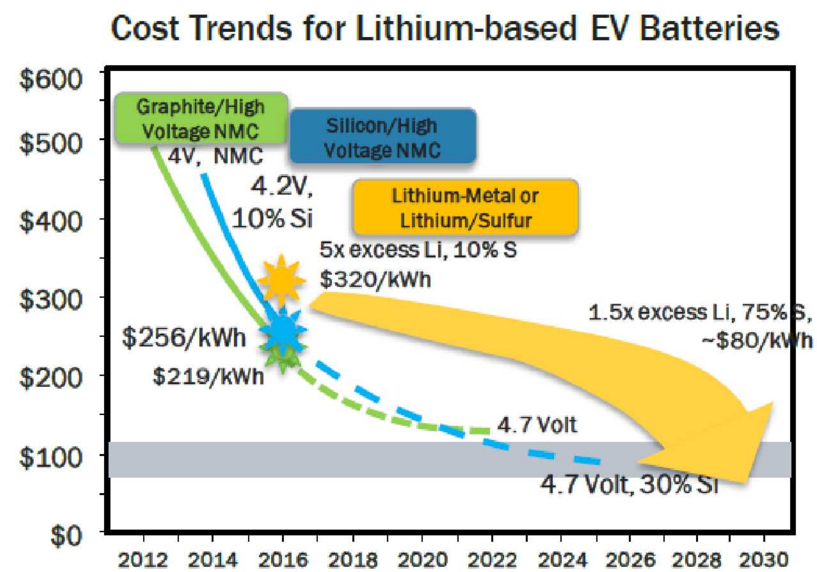


Li-ion storage technology price with manufacturing volume
Source: IEA, 2018

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



Most new capacity coming online is primarily for EVs



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

Li-ion Batteries – Challenges for Power and Energy Applications

Heat Generation

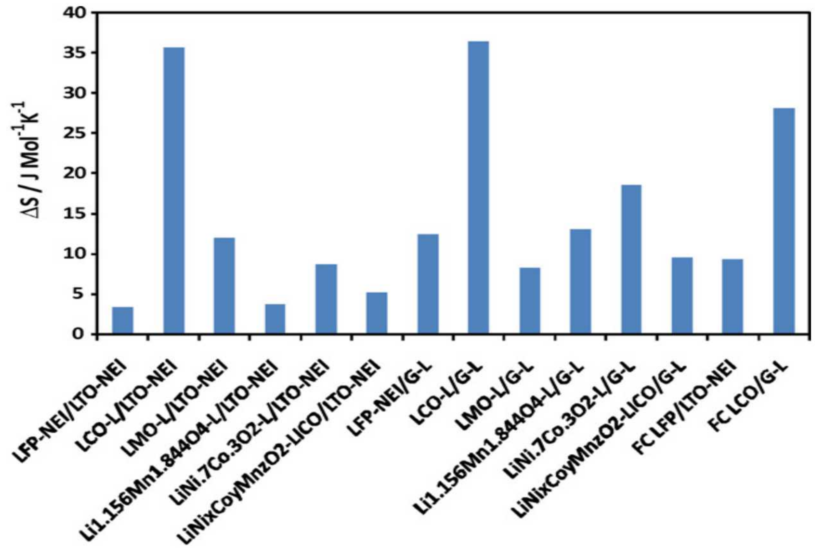
- Dictates smaller form factor
- Higher production costs

High Temperature

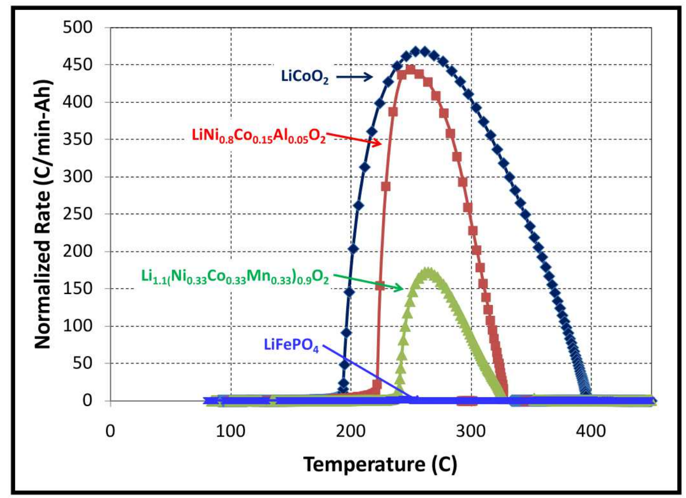
- Typical operating window 0-50°C
- Operation above this temperature can lead to organic electrolyte decomposition and flammable gas, rapid internal pressure build-up

Overcharging

- Max voltage depends on materials, overcharging can lead to Li metal plating on anode, potential for short



Inherent Heat Generation of Electrodes



Calorimetric measurements of Li-ion chemistries
Source: Josh Lamb, Sandia,2018

Li-ion Batteries for Grid Applications

Technology – wider range than EV needs, lower costs, longer cycle life and simpler packaging

Already a dominant technology for Power Applications in the grid

Expanding range of deployments

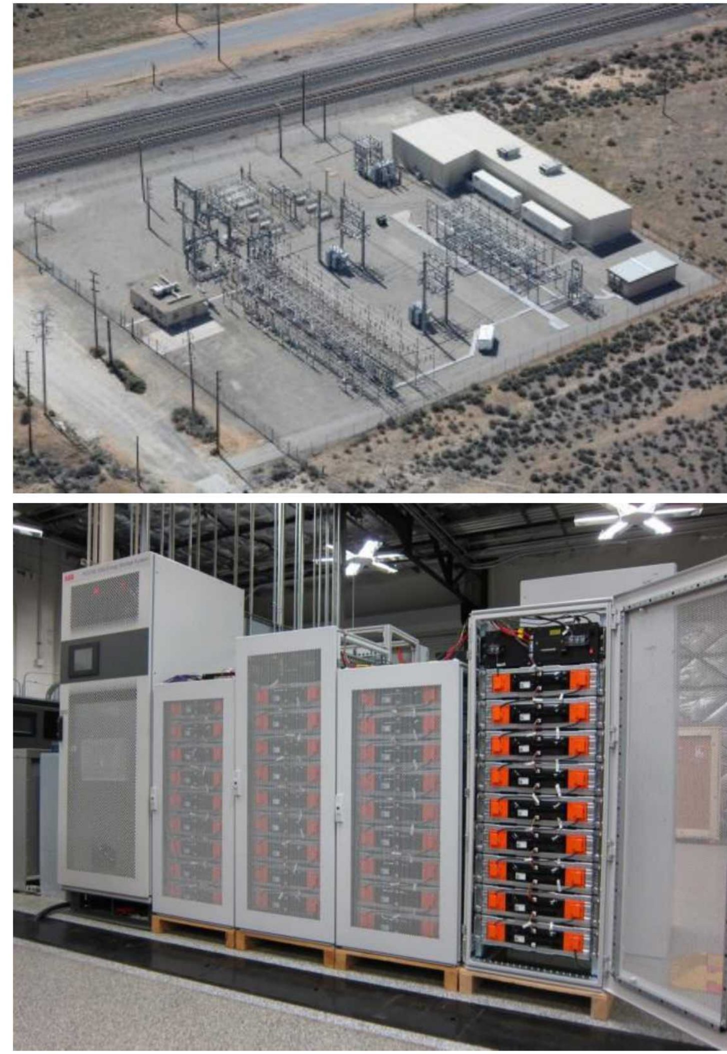
- Behind the meter, regulation, ramping products

Advantages

- High energy density
- Better cycle life than Lead - Acid
- Decreasing costs – Stationary on coattails of increasing EV
- Ubiquitous – Range of vendors
- Fast response
- Higher efficiency

Challenges

- Intolerance to deep discharge
- Cycle life for energy applications
- Sensitive to:
    - Over temperature
    - Overcharge
    - Internal pressure buildup



SCE Tehachapi plant, 8MW, 32MWh

Large Commercial Li-ion Deployments

AES 30 MW / 120 MWh ESS, Escondido, CA
Peaker replacement

Tesla 100 MW / 129 MWh ESS
Australia - Grid stability

Saft 6 MW / 4.2 MWh ESS
Kauai - Grid Stability

Future Developments in Li-based Batteries

Higher-voltage positive (cathode) materials

- Lithium manganese phosphate
- Lithium cobalt phosphate

Higher-capacity negative (anode) materials

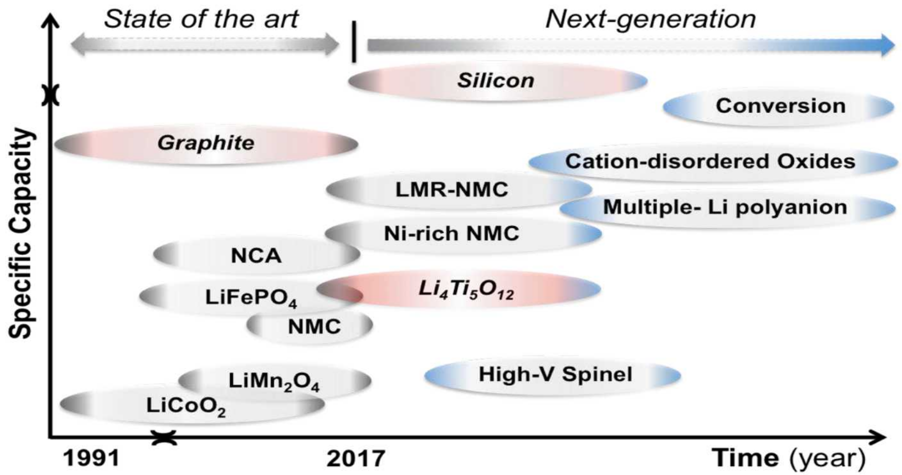
- Silicon-based

Safer electrolytes

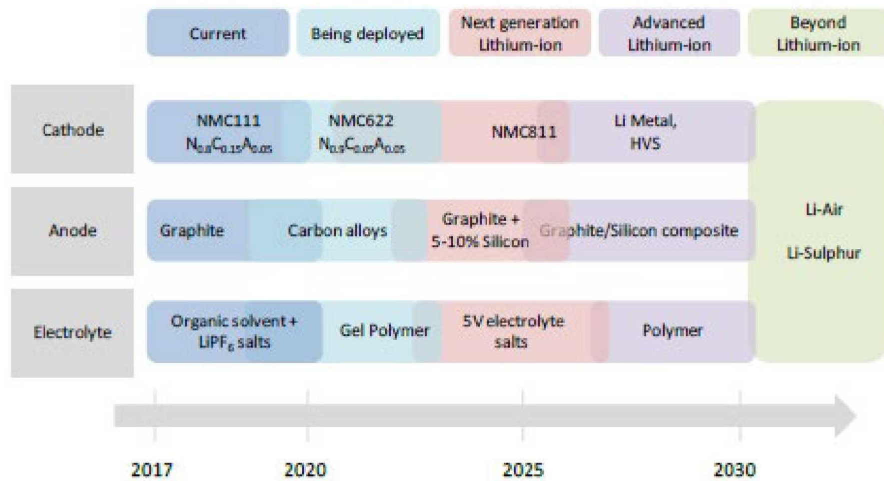
- Inorganic
- Solid-state electrolytes

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 and Metal Air Batteries

All metal air batteries (Li-air, Zn-air) have the potential to deliver high energy densities at low cost

Challenges with recharging have so far precluded commercialization of the technology

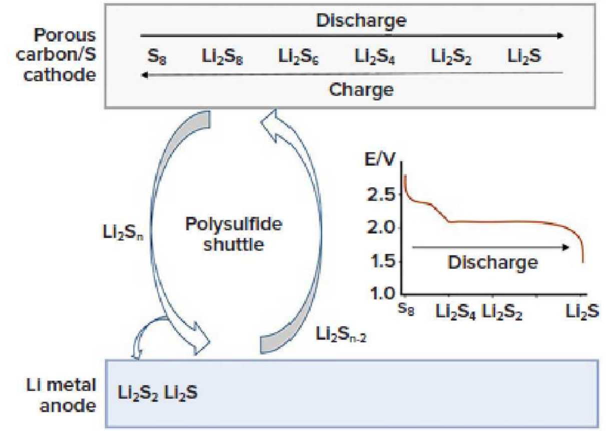
- Lot of startup activity in Metal-Air batteries
- Technology not mature, decade or more away
- Potential fundamental problems

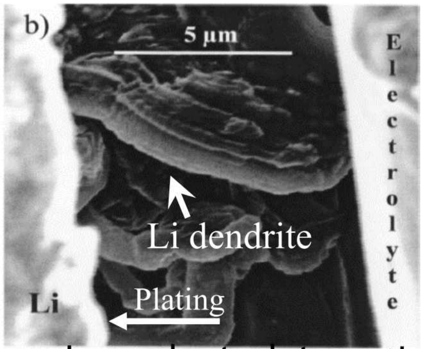
Li-Air combines difficulties of air and lithium electrodes

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

Li-S suffers from major problems of self discharge and poor life

- Breakthroughs needed for life of Li electrode, low cost separator





anode electrolyte cathode

Li dendrite growth

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

Lead-Acid Batteries

Overall Reaction
- Pb(s) + PbO2(s) + 2H2SO4(aq) → 2PbSO4(s) + 2H2O(l)
- OCV ~ 2.0 V

Flooded lead-acid
- Requires continuous maintenance
- Most common

Sealed lead-acid
- Gel and Absorbed Glass Mat (AGM)
- More temperature dependent

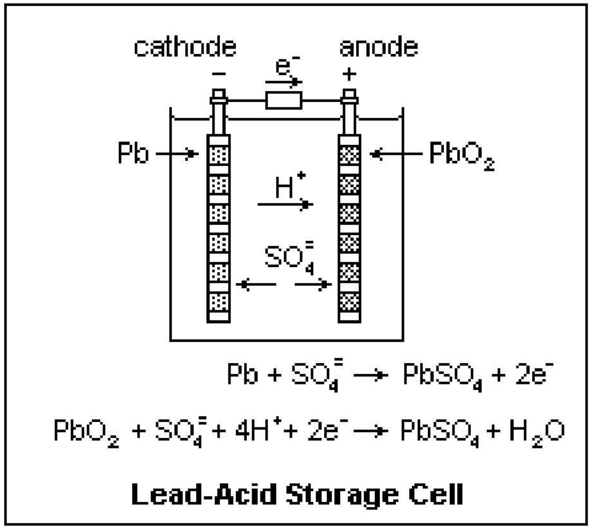
Advanced Lead Acid Energy Storage
- Carbon plates significantly improve performance

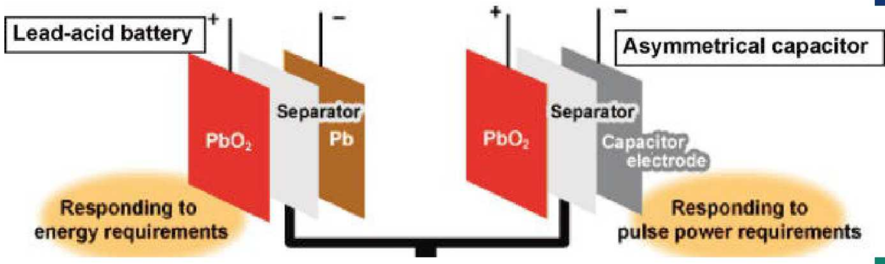
Mature technology

High recycled content

Good battery life

Advantages/Drawbacks
- Low cost/Ubiquitous
- 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





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)

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)

Solar plus Ultrabattery Storage (Source: PNM Albuquerque, NM

Redox Flow Batteries

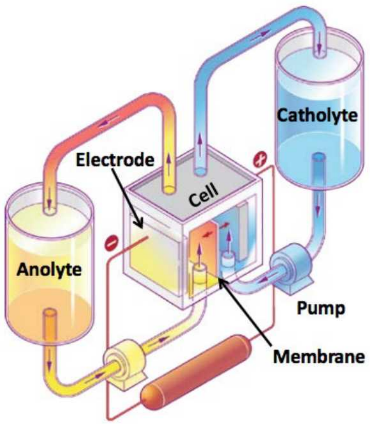
Energy storage technology utilizing redox states of various species for charge/discharge purposes

Key Aspects

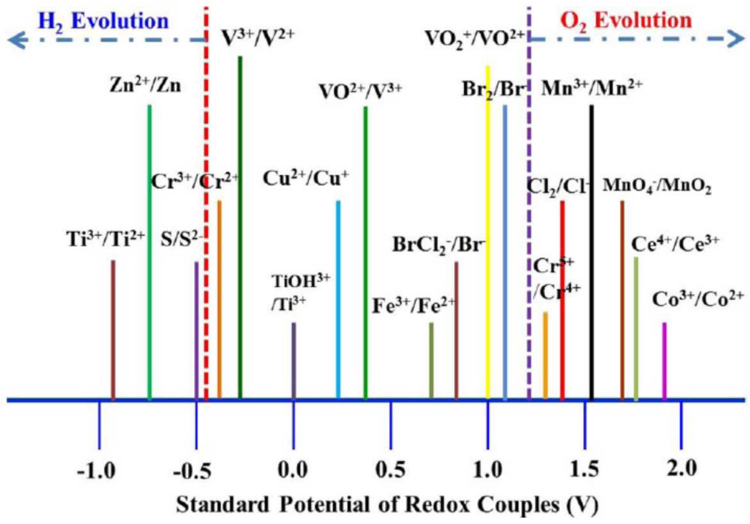
- Power (kW) and energy (kWh) separation
- Greater flexibility and safety
- Modular and scalable across a wide range of power and energy
- Long cycle life
- Low energy density ~ 30 Wh/L

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



Source: Travis Anderson, Sandia National Laboratories, 2013



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

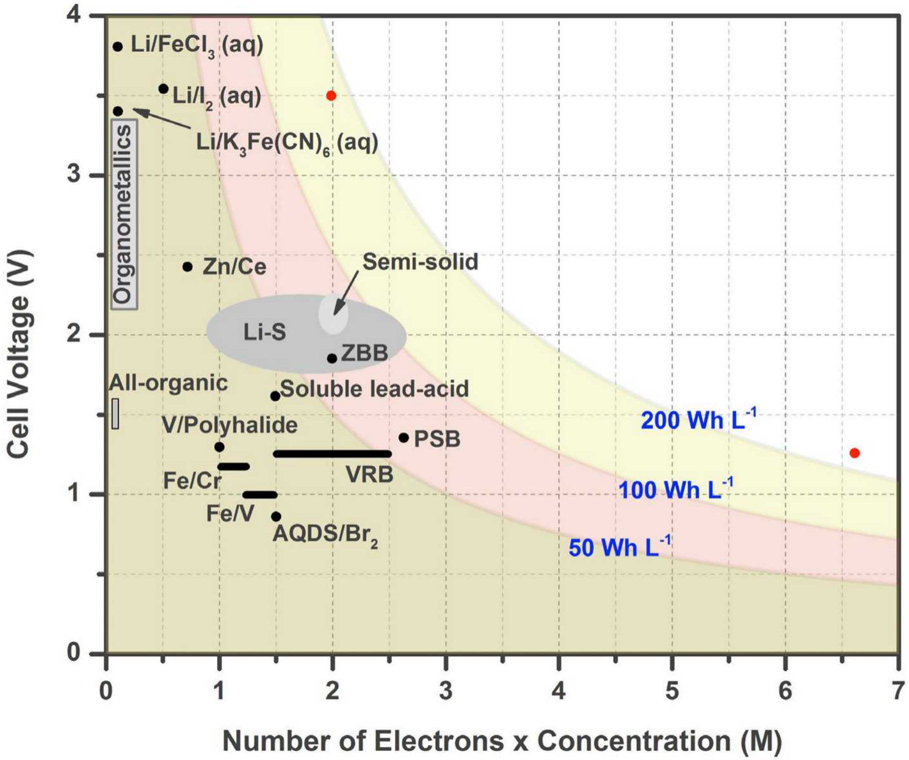
- Low solubility of redox species in aqueous electrolytes
- Capacity decay during cycling
- Narrow temperature range

Corrosion of membranes and electrode materials by acidic electrolyte solutions

- Long-term reliability

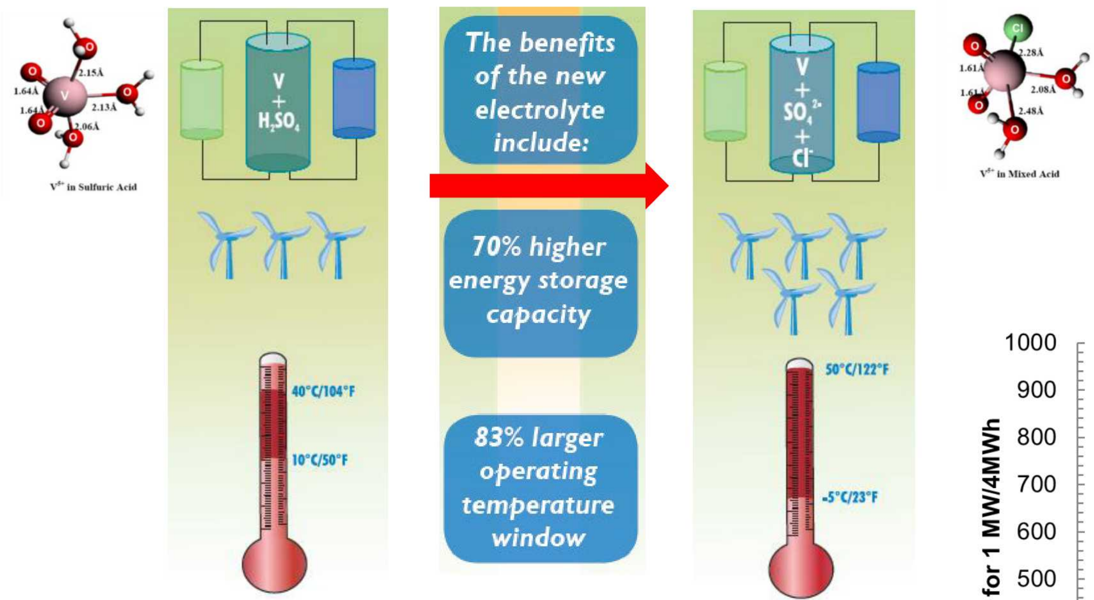
Opportunities to Reduce Materials Cost

- New redox chemistries, new electrolytes under development
- Lower cost of membranes
- Increased current density and lower cost stack design



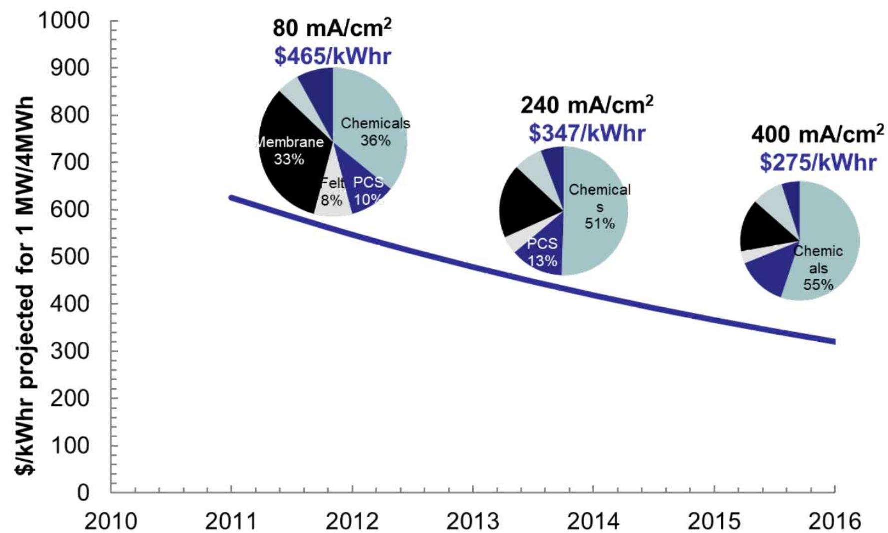
Wei Wang, et. al., Adv. Funct. Mater., , **23**, 970, 2013

Vanadium Mixed Acid Electrolyte



Conventional Sulfate VRB

Mixed Acid VRB



Source: V. Sprenkle, PNNL, DOE OE ESS Peer Review 2017

Increased energy density and larger temperature window

Continued cost reductions in materials and system costs

RFB Stack Sizes Continue to Grow – Large Plants being built

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

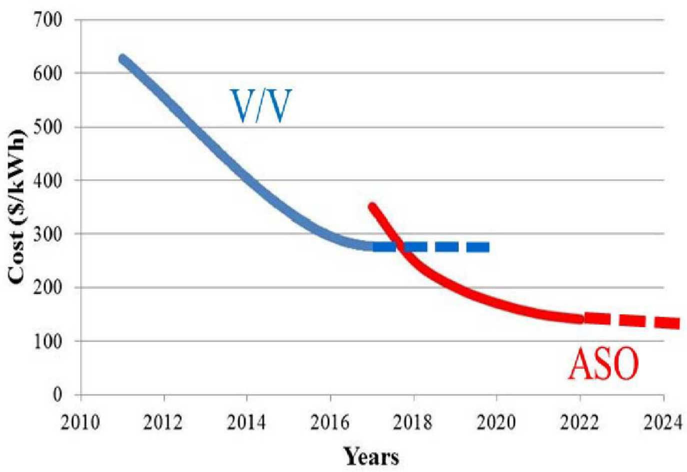
Next Generation Flow Batteries

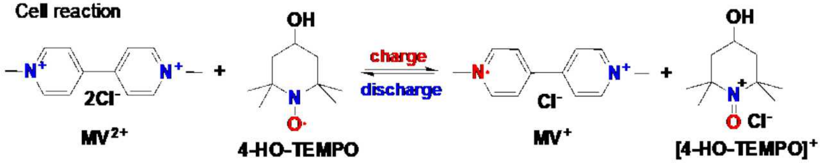
Aqueous Organic Electrolytes

Aqueous soluble organic electrolytes showing promise as drop-in replacement to current V/V systems

Potential for ½ cost reduction if performance and stability targets can be obtained

No resource constraints





Advanced Energ

Non-Aqueous Organic Electrolytes

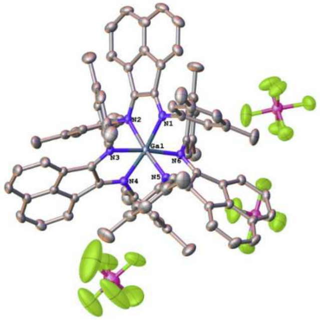
Wider voltage window, Potentially higher energy density

Decreased temperature sensitivity

Potentially favorable cost projections

Metal coordinated redox couple

- Metal coordination complexes (UMich)
- Metal-based ionic liquids (Sandia)
- Semi-solid lithium flow battery (MIT)
- Li-redox flow battery (UTexas/JAIST)
- Li-S flow battery (Stanford/MIT/PNNL)
- Metal-organic hybrid RFB (PNNL)



Mitch Anstey, 2016
DOE Energy Storage Peer Review

Sodium Batteries (NaS and NaNiCl2)

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)

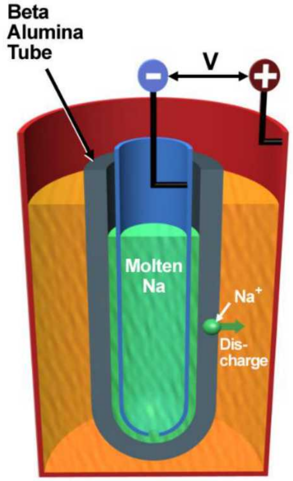
Two primary chemistries

- NaS, mature technology, deployed in grid applications
- $NaNiCl_2$, mature, more stable than NaS

NaNiCl2 (Zebra) developed in the 1980s

- FIAMM in limited production, GE no longer in manufacturing

Neither NaS nor NaNiCl2 are at high production volumes and the economies of scale needed



NaS Batteries

Most widely deployed of long duration batteries

NaS first developed by Ford Motor Co. in 1960s

- Commercialized by NGK in Japan
- 530 MW/3700 MWh of installed capacity, primarily in Japan

NaS battery

- $2Na + xS \rightarrow Na2Sx$ (x = 3~5)
  - E = 2.08~1.78 V at 350°C

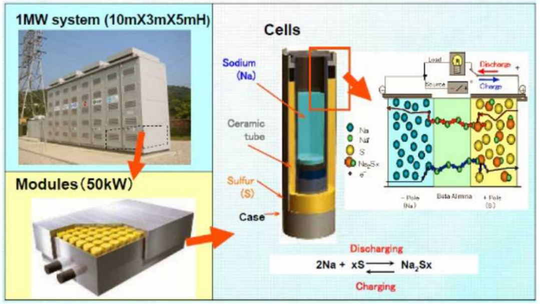
Applications

- Power quality, Congestion relief
- Renewable integration

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

NGK is the only committed manufacturer



Source: NGK

34MW /245 MWh NAS at a wind farm
Rokkasho, Aomori, Japan (Source: NGK, 2017)

Los Alamos, NM. 1 MW, 6MWh

$NaNiCl_2$ Batteries

NaNiCl2 battery

- 2Na + NiCl2 → 2NaCl + Ni
  - E = 2.58V at 300°C

Large cells and stable chemistry

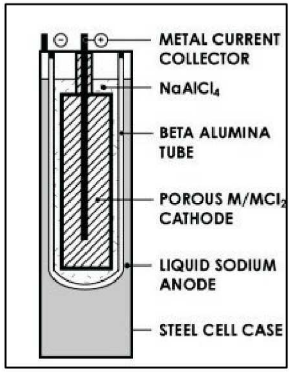
- Lower temperature than NaS
- Cells loaded in discharge mode
- Improved safety compared to NaS. Addition of catholyte $NaAlCl_4$ leads to a closed circuit on failure

High efficiency, low discharge

Long warm up time (16 hr)

Supply chain concerns. Only one manufacturer FIAMM. GE no longer in this business

- Limited deployments



FIAMM 222-kWh System
Duke Energy Rankin Substation

Molten Na Batteries - Engineering Challenges

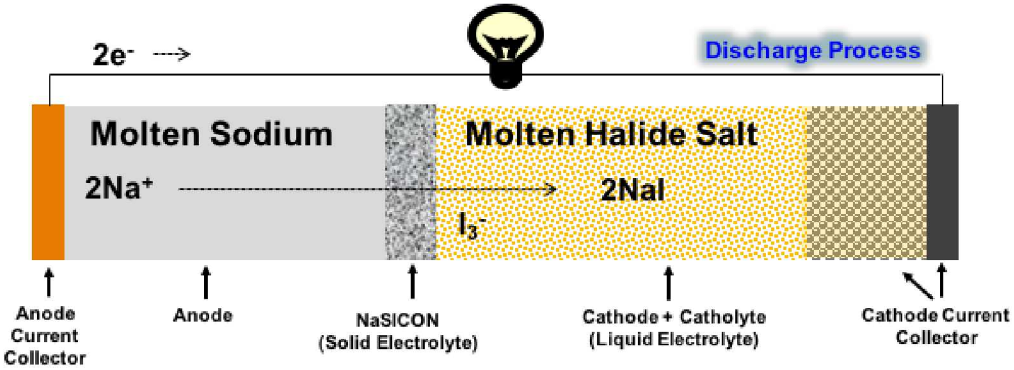
Low cost active materials, but challenging systems engineering

- Need for high temperature operation, kinetics driven by the solid ceramic electrolyte
- Typical operating window 250-350°C. Need for continuous thermal management even when not in use. At lower T, Na metal freezes out, degree of distortion to cell dictated by SOC of battery
- Safety concerns related to membrane rupture. In NaS, failure can lead to exothermic reaction
- Need hermetic seals
- Charging/discharging limitations

Engineering cells that operate at lower T (150°C or lower) remains a challenge. Low temperature operation of a molten Na battery is tremendously enabling

- Improved Lifetime
  - Reduced material degradation, Decreased reagent volatility, Fewer side reactions
- Lower material cost and processing
  - Seals, Separators, Cell body
  - Polymer components become realistic!
- Reduced operating costs
- Simplified heat management costs

Lower Temperature Sodium Halide Batteries

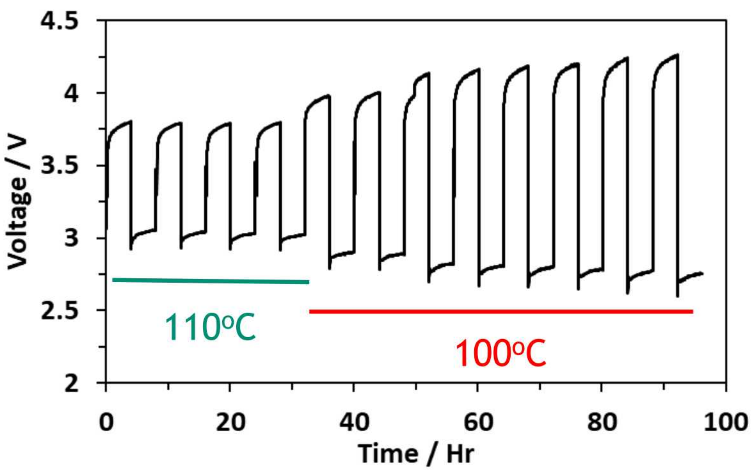


Na-NaI battery:

$Na \rightarrow Na^+ + e^-$ $E^0 = 0V$

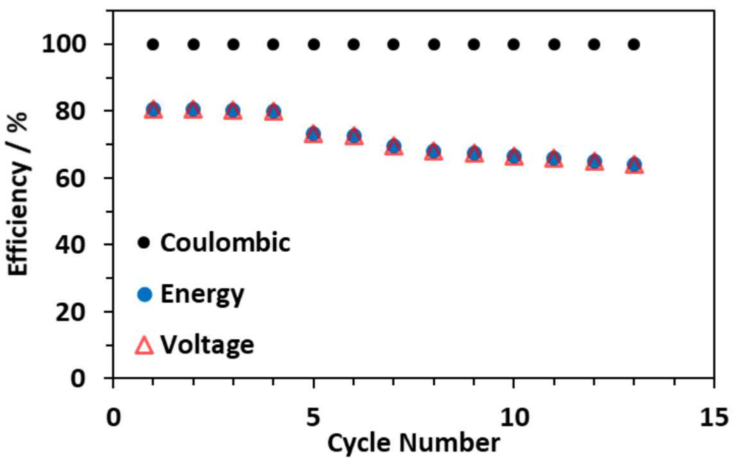
$I_3^- + 2e^- \rightarrow 3I^-$ $E^0 = 3.24$

$2Na + I_3^- \rightarrow 2Na^+ + 3I^-$ $E^0_{cell} = 3.24V$



Battery cycling at **100ºC**!

25 mol% NaI-$AlBr_3$ with NaSICON separator.



Source: E. Spoerke, Sandia National Labs
2018 DOE Energy Storage Program review

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

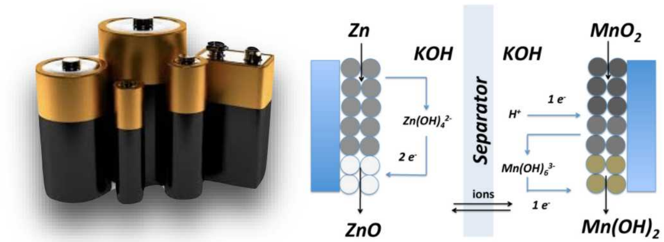
Safety

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

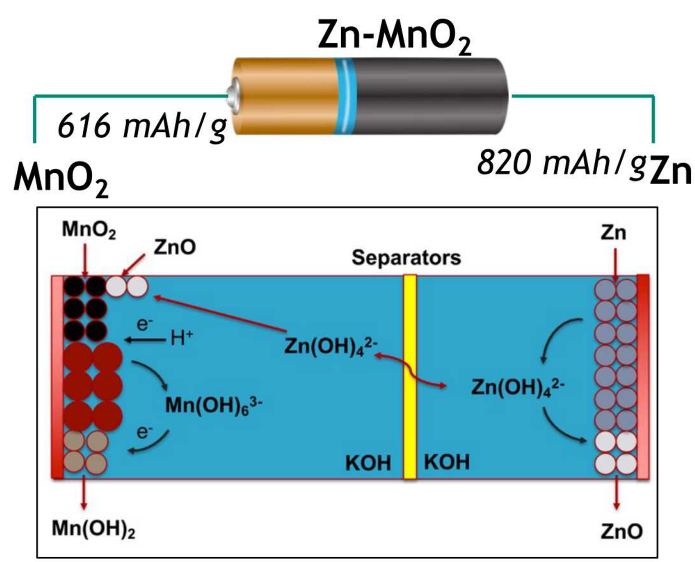
Reliability

- Long shelf-life
- Limited thermal management required

Reversibility and cycle life have been the primary technical challenges



Single-use Alkaline Battery $25/kWh



Source: S. Banerjee, CUNY Energy Institute

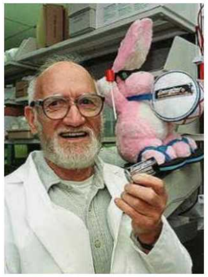
History of Rechargeable Zn-MnO_2 Batteries

- 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 — Primary, Low Power — 1st Zn-MnO_2 battery

1950 — Primary — Alkaline Zn-MnO_2 battery



1970 — Limited Capacity, Poor Energy Density — 5% Rechargeable Capacity

1980 — Potentiodynamic, Poor Cycle Life — 60-80% Rechargeable Capacity

Halina Wroblowa

2010-2016 — Stabilized full-cycling MnO2

<u>2010-2014</u>: CUNY Energy Institute shallow-cycle MnO_2

<u>2014-2016</u> Stabilized full-cycling MnO_2

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

Full Utilization of 2e

On the MnO_2 Cathode

- Regeneration of cathode structure on solution/dissolution/precipitation cycle
- Formation of Inactive phases
- Reducing susceptibility to Zinc poisoning

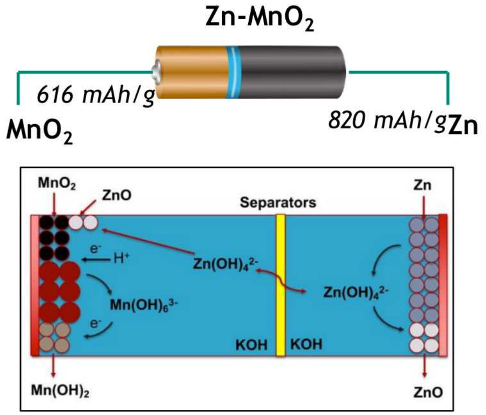
Separator

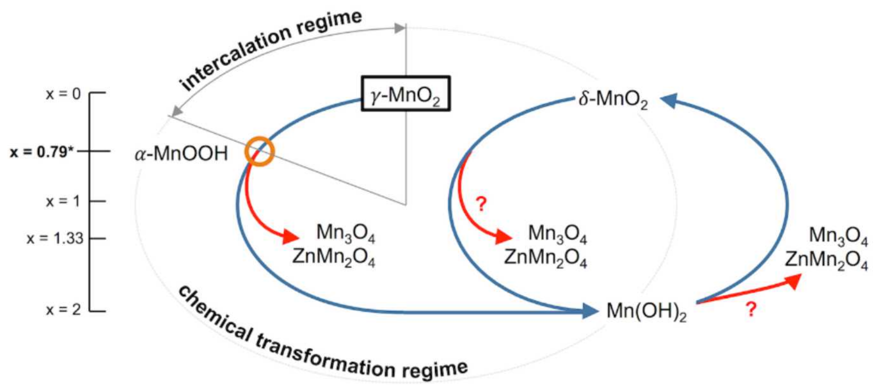
- Reduce Zincate crossover

On the Zn Anode

- Control shape change
- Passivation
- Reduce dendrite formation

Need improvements in materials utilization, process optimization and engineering of large format cells

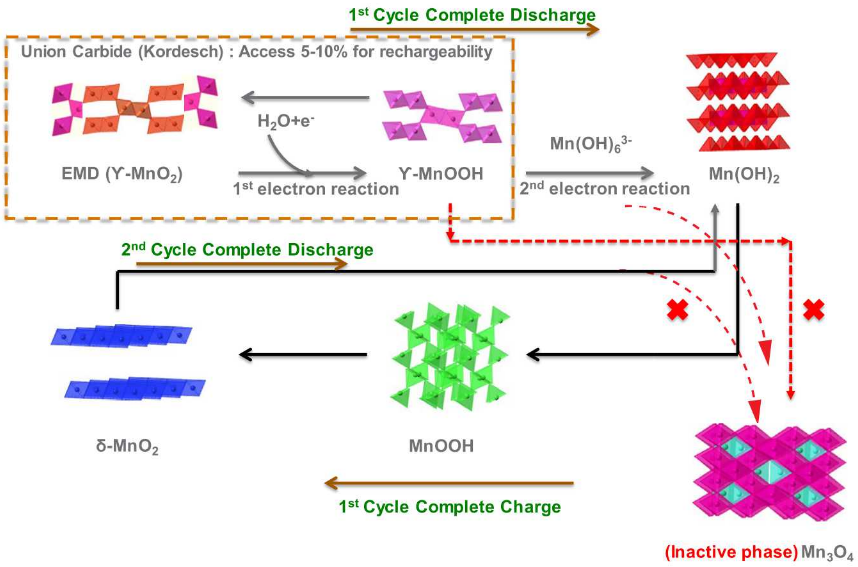


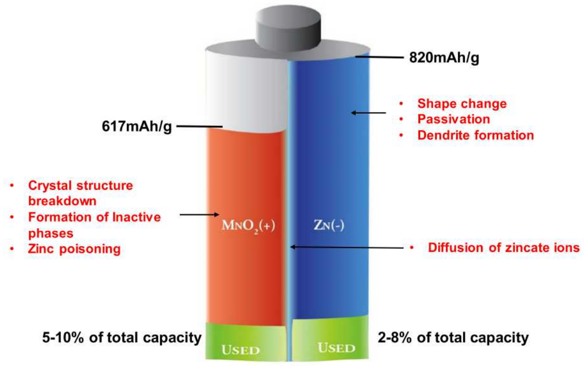


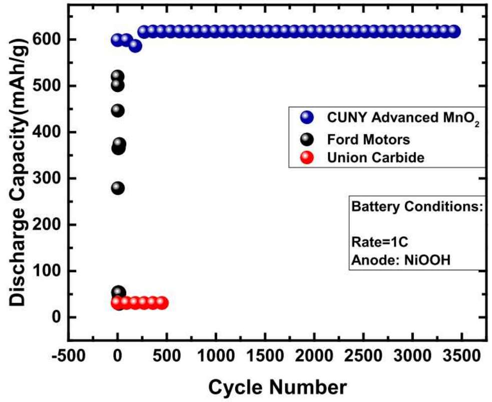
Failure Mechanisms of Cathode

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

Making MnO_2 Fully Rechargeable







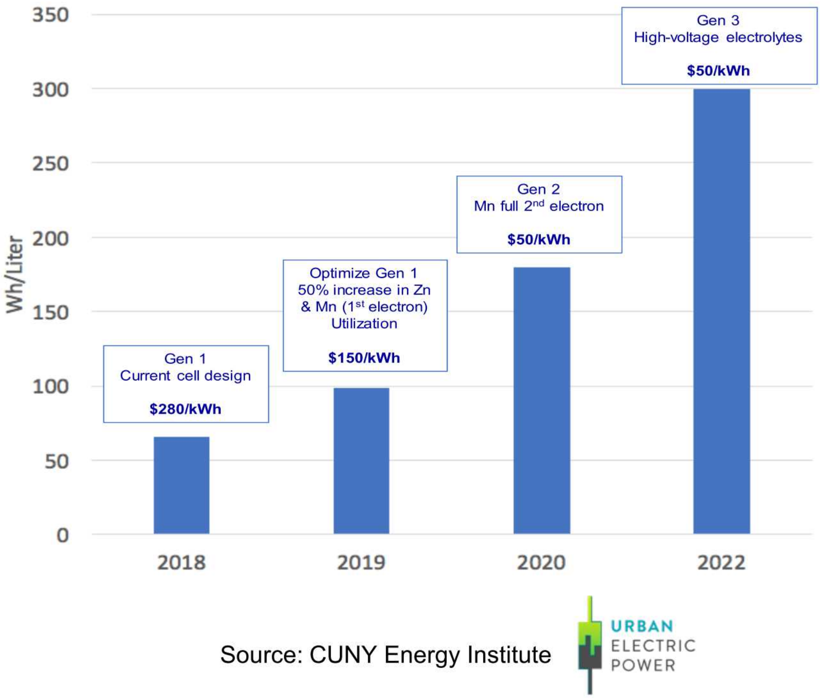
- Chemistry relies on formation of a layered birnessite MnO2 structure and stabilizing this structure for thousands of cycles
- MnO2 goes through a complete regeneration process during each cycle

G.G. Yadav, J.W. Gallaway, D.E. Turney, M. Nyce, J. Huang, X. Wei and S. Banerjee, Nature Communications, vol. 8, 14424 (2017). doi:10.1038/ncomms14424

MnO_2 cycling data against reference anode

Potential for Zn-MnO_2 Cells at \$50/kWh

- Recent breakthroughs in making MnO_2 fully rechargeable. Based on the formation of a layered birnessite MnO_2 structure and stabilizing this structure for thousands of cycles.
- Improvement in energy density and cost by improvement in zinc utilization
- Cathode degradation mitigation by improvements controlling Zn migration across separator
- Potential for \$50/Wh cells with high cycle-rechargeability of Zn-MnO_2



Source: S. Banerjee, CUNY Energy Institute
DOE OE Energy Storage Program Peer Review 2018

Grid Storage needs Large Format Cells

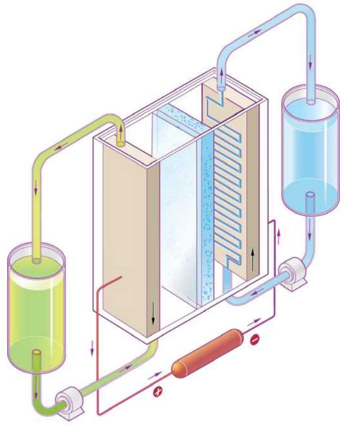
Engineering costs are significant for small format cells. Large format cells are needed to reduce overall system costs.

Large format cells also allow for tighter integration of power electronics, sensors, SOH monitoring at the cell level.

High Conductivity Separators for Low Temperature Molten Sodium Batteries

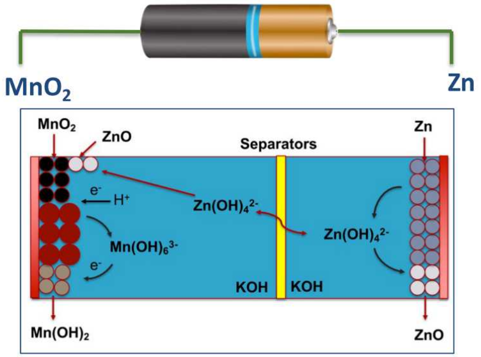
Robust ceramic separators exhibit low Na^{+} conductivity at lower, more cost effective temperatures (120-180 °C).

Crossover in Redox Flow Batteries



Cross over of the electroactive species through the separator leads to severe capacity decay in flow battery systems.

Zincate poisoning of MnO_2 in Zn/MnO_2 Batteries



Zincate diffusion and subsequent poisoning of MnO_2 impairs reversibility and significantly decreases lifetimes.

Safety of Battery Storage Systems

Ensuring safety of battery storage systems remains a major concern

Need significant advances at materials, engineering and systems level

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

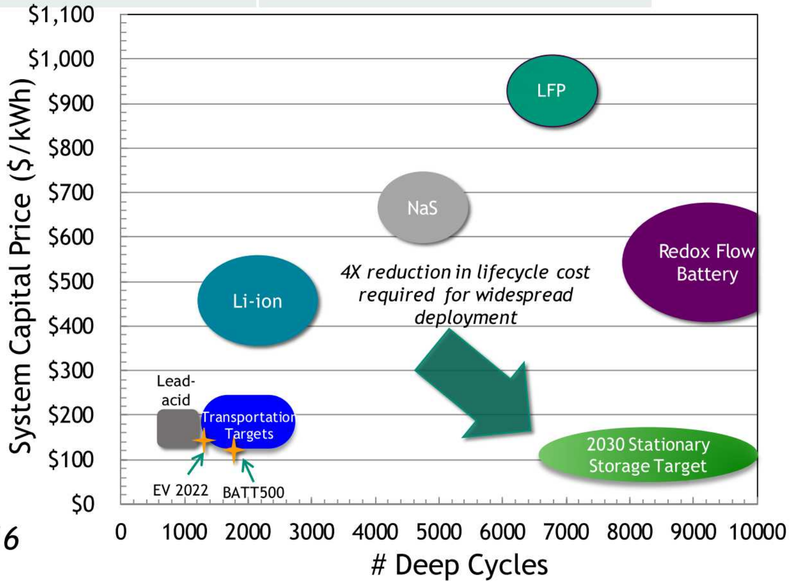
Figure courtesy of Summer Ferreira, Sandia, 2017

Future of Energy Storage

All about application driven cost and performance metrics

Application	Consumer Electronics, Hybrid EVs	Electric Grid Electric Vehicles	Electric Flight
Advance	Incremental	Significant	Breakthroughs
Technologies	Li-ion: Si anodes, low Co cathodes Adv. Pb-acid: Pb-carbon Adv. rechargeable alkaline	Adv. Li: Li metal anode, Solid state electrolytes Zn metal: adv. MnO2 cathodes Adv. Flow	Beyond Li-ion: Li-S, Li-Air Mg & Al Ion Zn-Air High voltage Zn Metal
Technology Risk	Modest	Significant	Major

Adapted from G. Crabtree's presentation at Xlab, 2018



Energy Storage Systems Cost
GTM/ESA US Energy Storage Monitor: Q2 2016

Sandia Grid Energy Storage R&D Program

Program Goal - To solve critical problems to make energy storage safe, reliable, and cost effective across all markets.

- Advancing new battery chemistries through technology development and commercialization
- Optimization at the interface between power electronics and electrochemistry. Power electronics including high voltage devices (SiC, GaN), high voltage passives and magnetics.
- Energy storage safety – cell and module level safety test and analysis. Engineered safety of large systems. Predictive models for ES safety
- Developing competencies in analytics and controls for integration of utility class storage systems. Lower BOS and Integration Costs
- Defining role in the Grid of the Future
- Energy storage project development

Support DOE’s demonstration projects and outreach to the industry

Summary

Battery technologies for grid applications are advancing rapidly.

Building energy storage systems with high energy and high power capabilities while keeping safety and reliability remains challenging with a lot of technical questions

- How do we manage the universal tradeoff between energy and power due to a combination of electrical, ionic, structural and chemical effects?
- How to improve energy capacity without sacrificing safety and cycle life?
- How do we optimize power and energy at multiple length scales, especially for large format cells?
- How do we enable fast ion and electron transport without sacrificing energy density, while maintaining safety, long calendar and cycle life?
- How do we design materials to realize high energy and power simultaneously?
- How to achieve high reversibility, with low capacity loss, and low over-potentials?

Market Gaps

- Existing battery technology solutions remain expensive for many applications
- Technologies not scalable to cover all markets and applications

Acknowledgements

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Energy Storage Systems Program

U.S. DEPARTMENT OF ENERGY