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Emerging eT&D Grids

Energy Storage, Electrification, and the Increasing Role of Power Electronics

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U.S. Electric Grid Today

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.

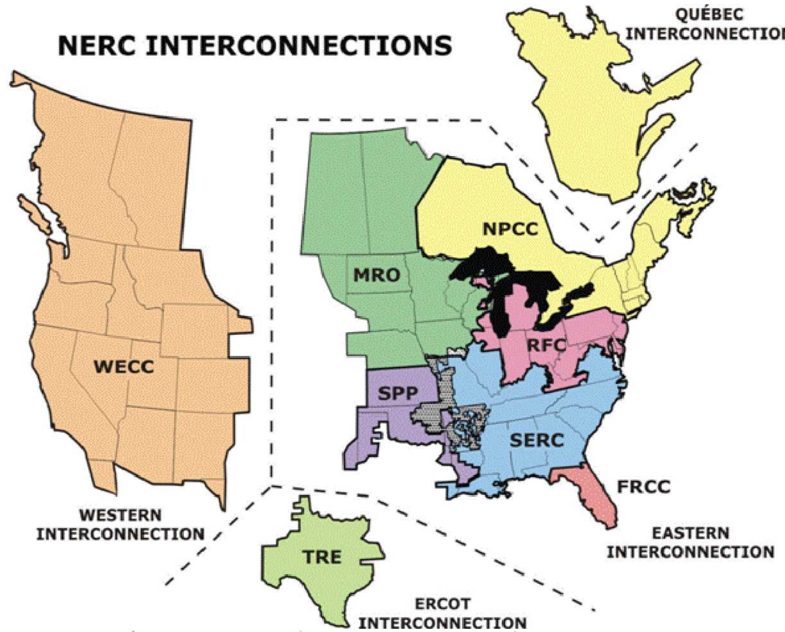
In 2015, total U.S. electricity generation was 4,087,381 GWh

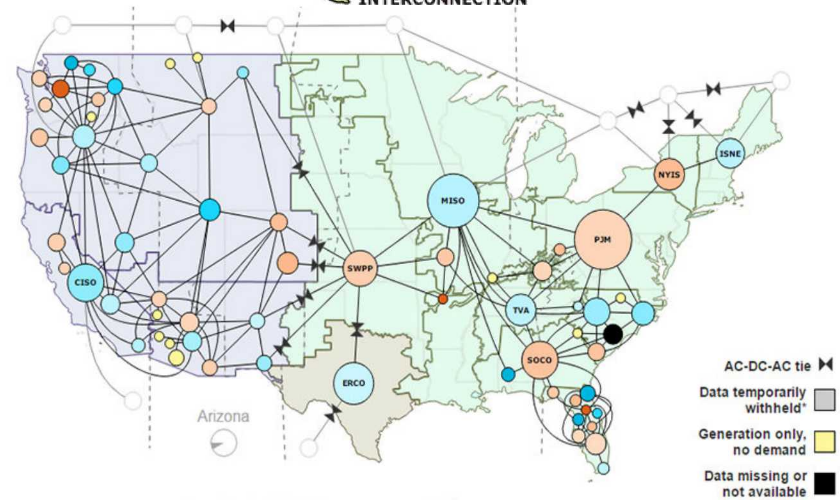
- Increasing NG and renewable generation (6.1% hydropower and 7.3% from wind and solar)

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

U.S. Electric Grid Today

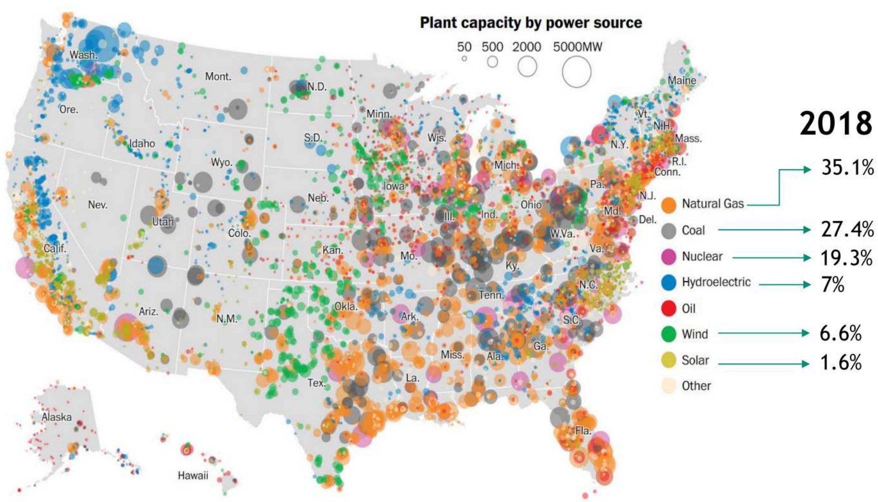
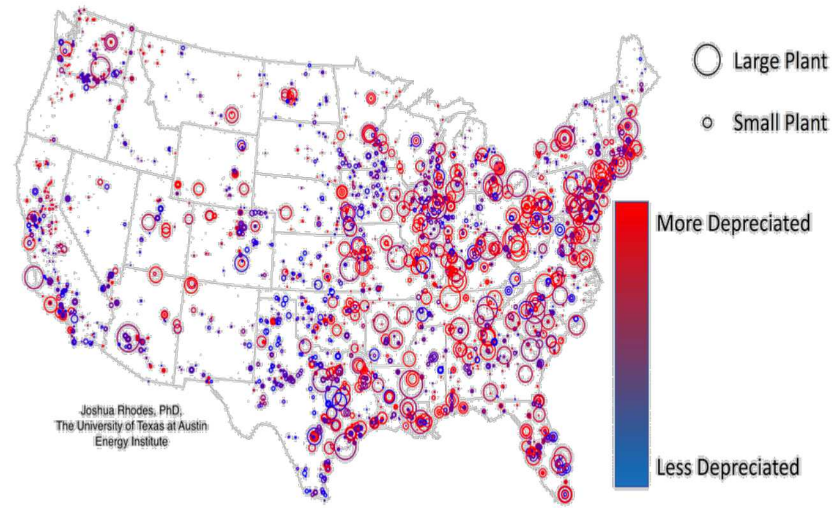


Image credit: Washington Post



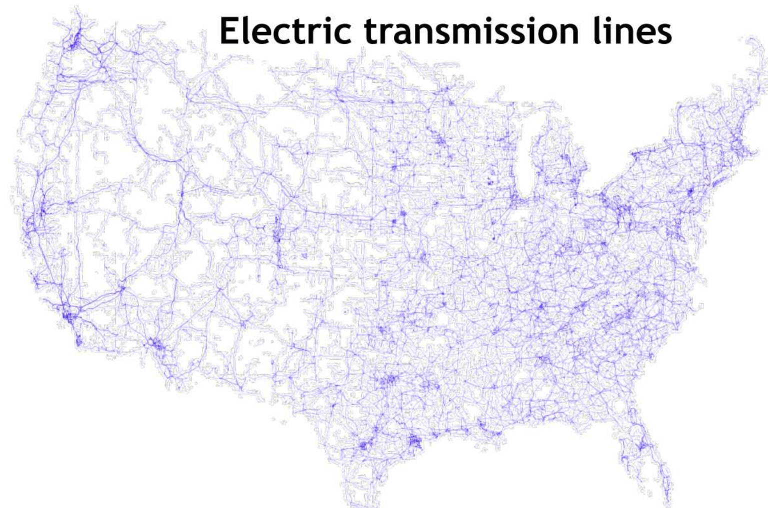
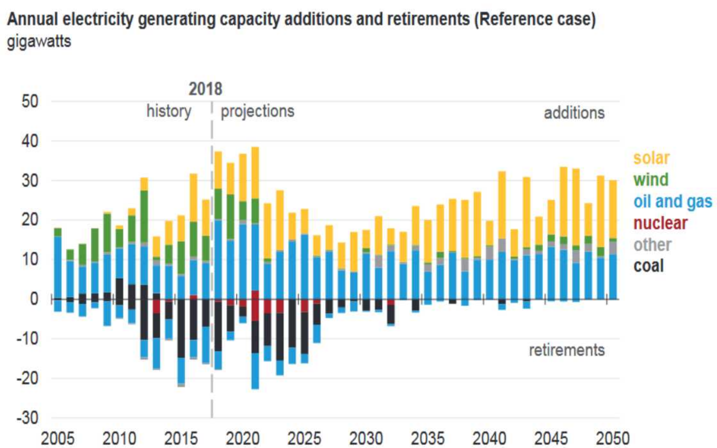


Image credit: Washington Post

- Major grid infrastructure is aging
- Accelerating retirements of coal fired power plants
- T&D congestion starting to impact deployment of renewables

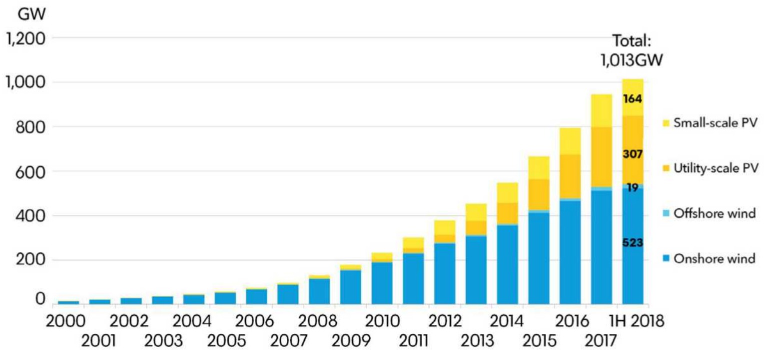
Major Trends – Growth of NG, Renewables, Cost Reductions

Capacity Additions and Retirements



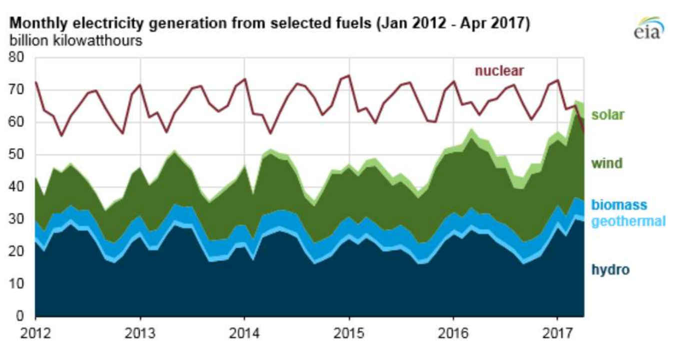
EIA Annual Energy Outlook 2019

Cumulative global solar and wind capacity (June 2018)

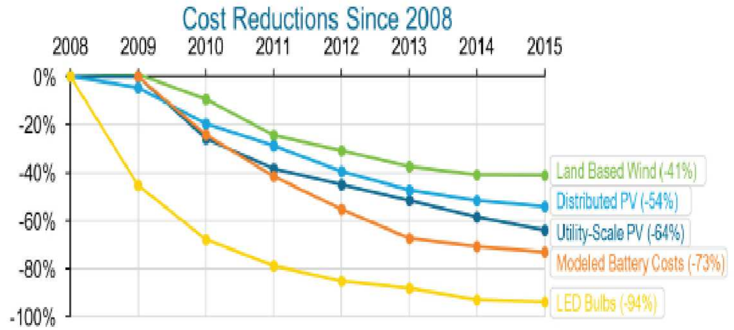


Source: Bloomberg NEF. Note: 1H 2018 figures for onshore wind are based on a conservative estimate; the true figure will be higher. BNEF tyipcally does not publish mid-year installation numbers.

Utility-scale Renewables Generation surpassed Nuclear Generation (April 2017)



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

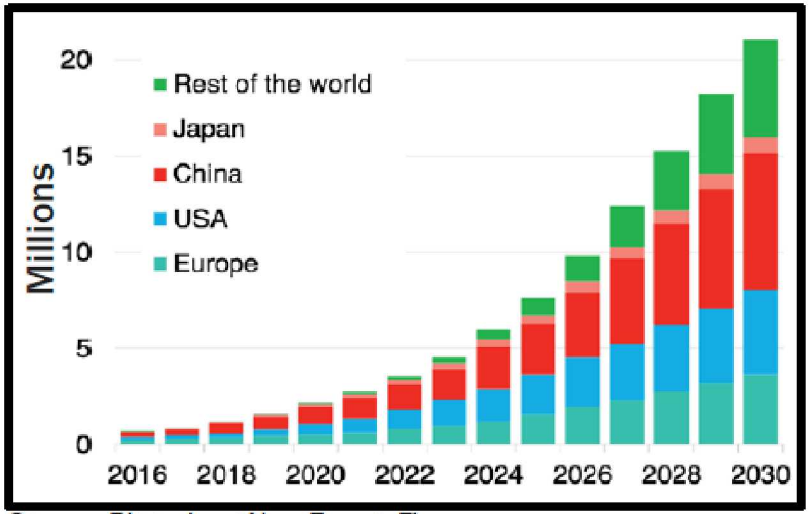


http://energy.gov/eere/downloads/revolutionnow-2016-update

Coal-fired unit retirements driven by low NG prices (EIA, 2017)

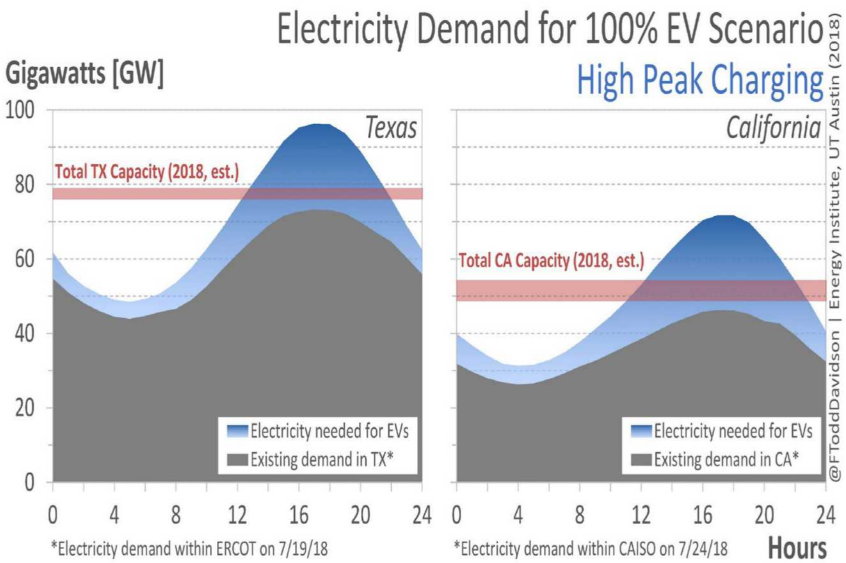
In California, solar, storage and wind capacity additions expected to exceed NG by '21(GTM)

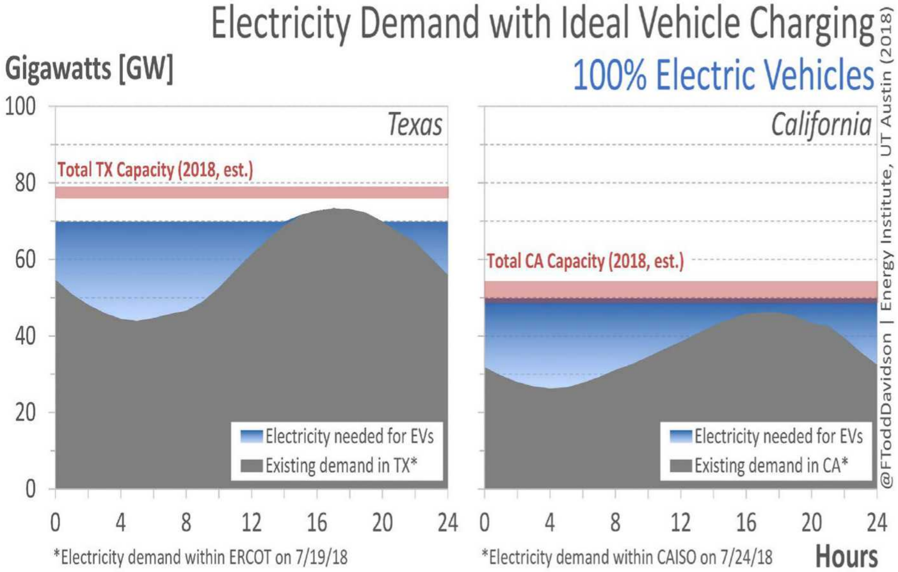
Another Trend – Electrification of Transportation Fleet



Source: Bloomberg New Energy Finance

- Projections for annual production of electric vehicles reaching 20 Million by 2030 and a fleet of 130M (mostly passenger vehicles) on road as base case; 230M vehicles optimistic case (BNEF, IEA, 2018)
- Electrification will drive demand growth, overloading distribution systems and causing transmission congestion. Total load may double.
- Needs major T&D upgrades if EVs are mainly charged from the grid.





Another Trend – States Driving Major Policies for Clean Energy

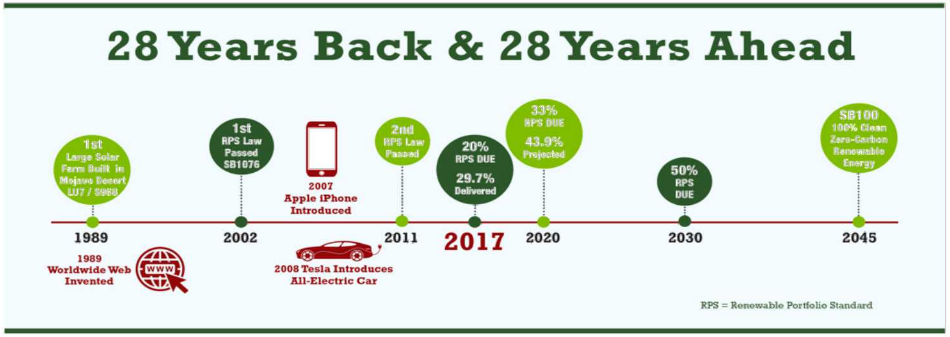
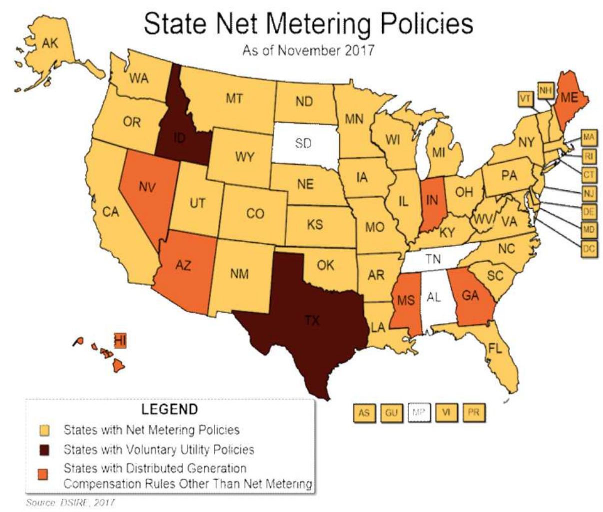
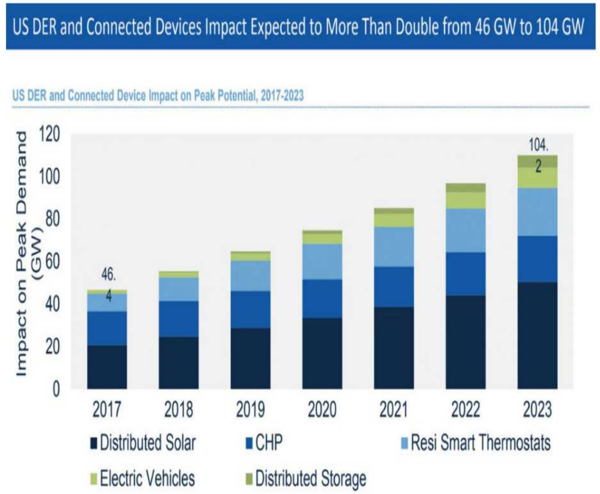


Image Source: California Senate





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.

Disruptions at the Grid Edge

Electrification of the Transportation Sector

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

Behind-the-meter solar and energy storage

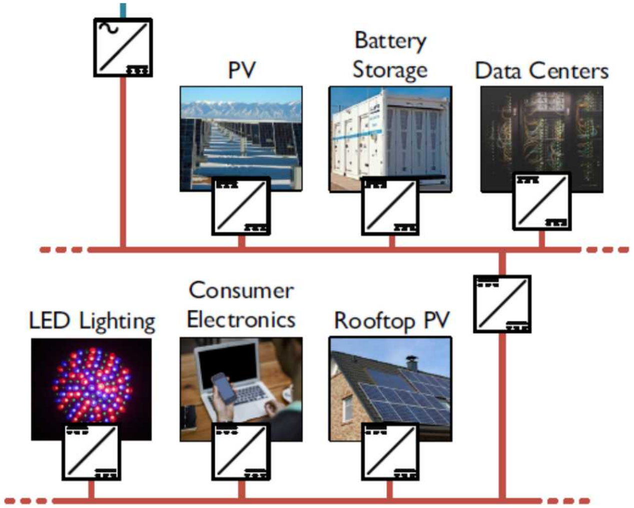
Rapid evolution of off-grid and micro-grids

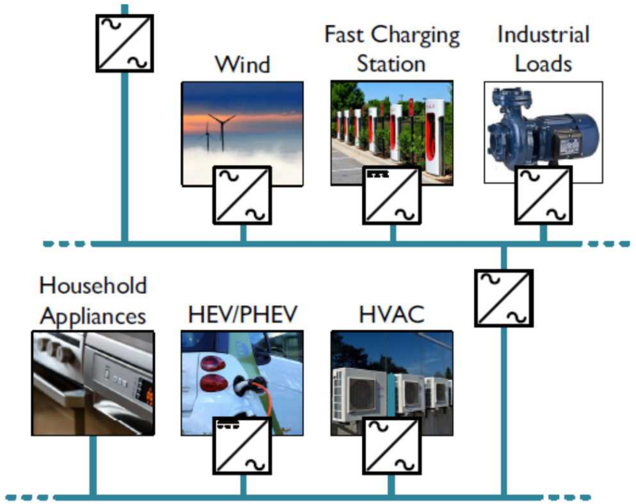
- Potential to disrupt existing electricity market structures

Behind-the-meter technologies with bi-directional communication

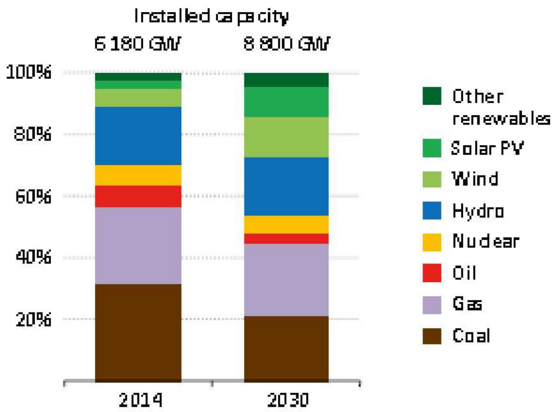
- Smart meters, smart loads, rooftop solar, electric vehicles, battery storage

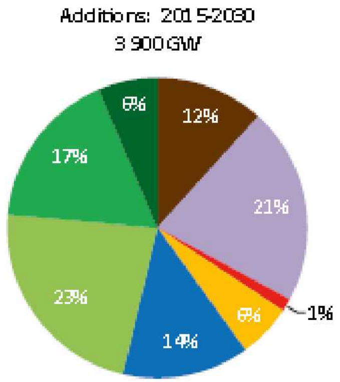
Computation challenges associated with distributed sensing, control, and big data

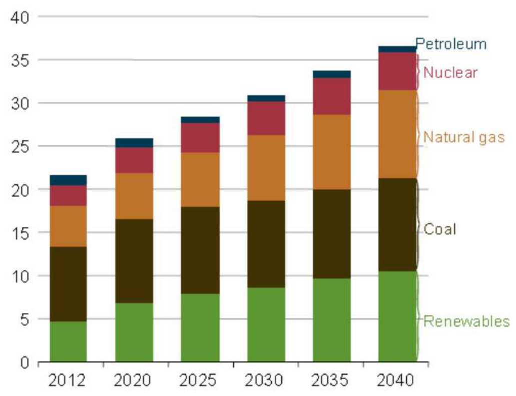




Are We at the Cusp of a Major Transformation?







Source: International Energy Outlook, EIA

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
- Electric vehicles are coming
- Electrification of aviation is next

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

Evolution of the Grid

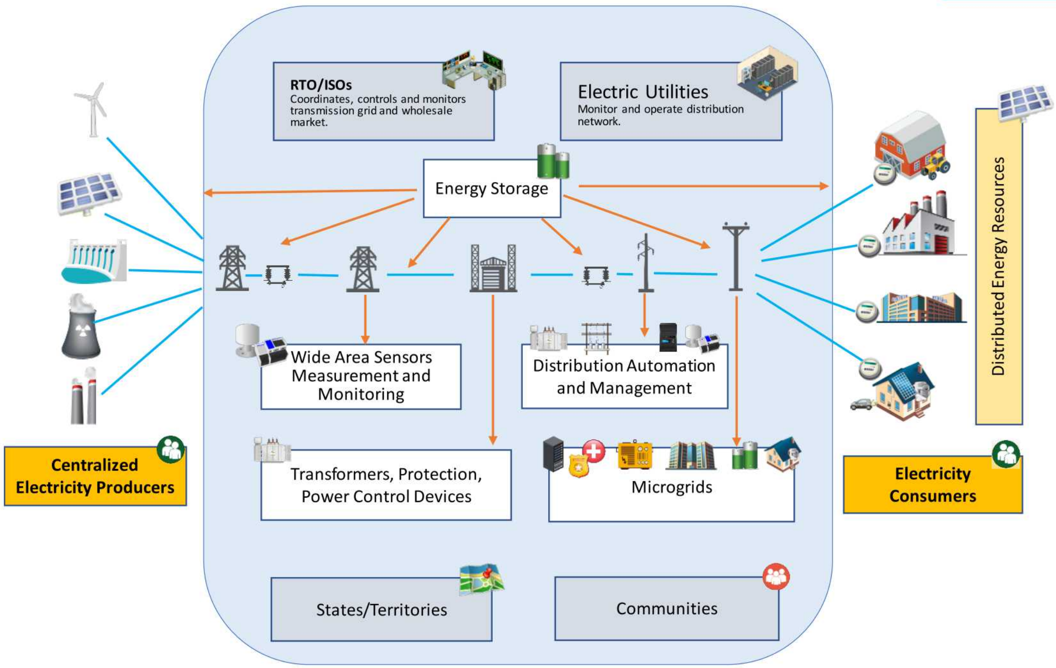
We are beginning to see existing business models not keeping pace with changes

Conservative regulated utility industry
- Not open or reluctant to change business models
- IOUs and PUCs struggling to adapt to rapid change

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

Rapid change is bottom-up, with major transformation at the grid edge
- EVs, DER, Smart metering, microgrids, demand response, energy efficiency

Changes cut across technology, economics, policy, and markets

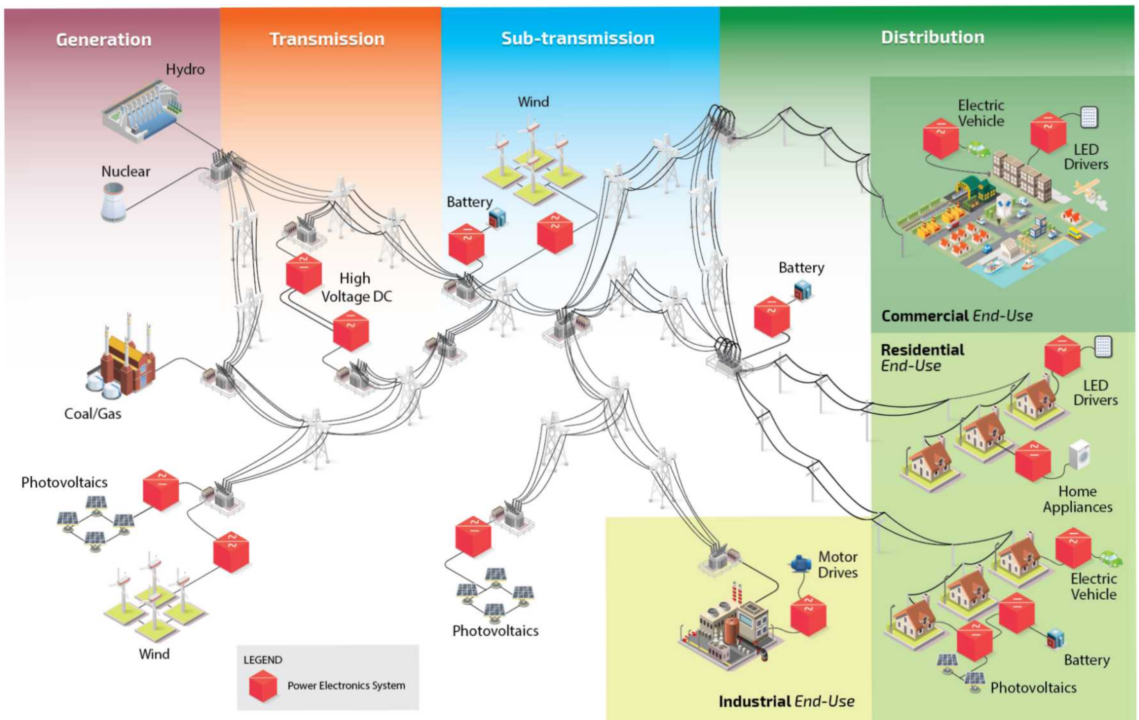


Source: US DOE Office of Electricity

Energy Storage, Electric Vehicles, Power Electronics, and Communications at the center of grid modernization

Increasing Role of Power Electronics in Electricity Infrastructure

The power conversion system is at the center of DER, Energy Storage, and EV infrastructure



Source: K. Cheung, US DOE

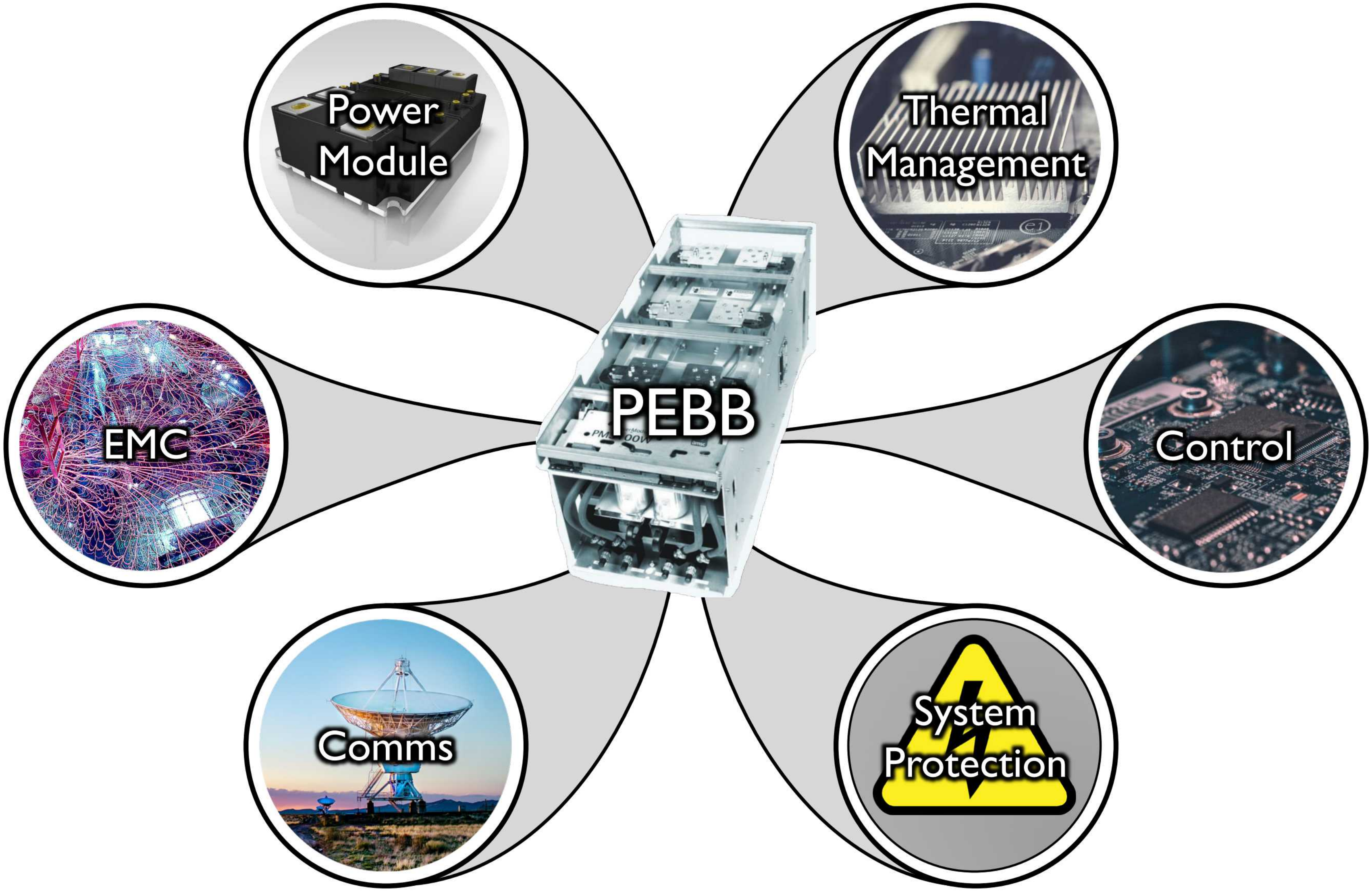
Approximately 30% of all electric power currently generated uses PE somewhere between the point of generation and distribution.

By some estimates, 80% of energy will flow through power electronics.

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

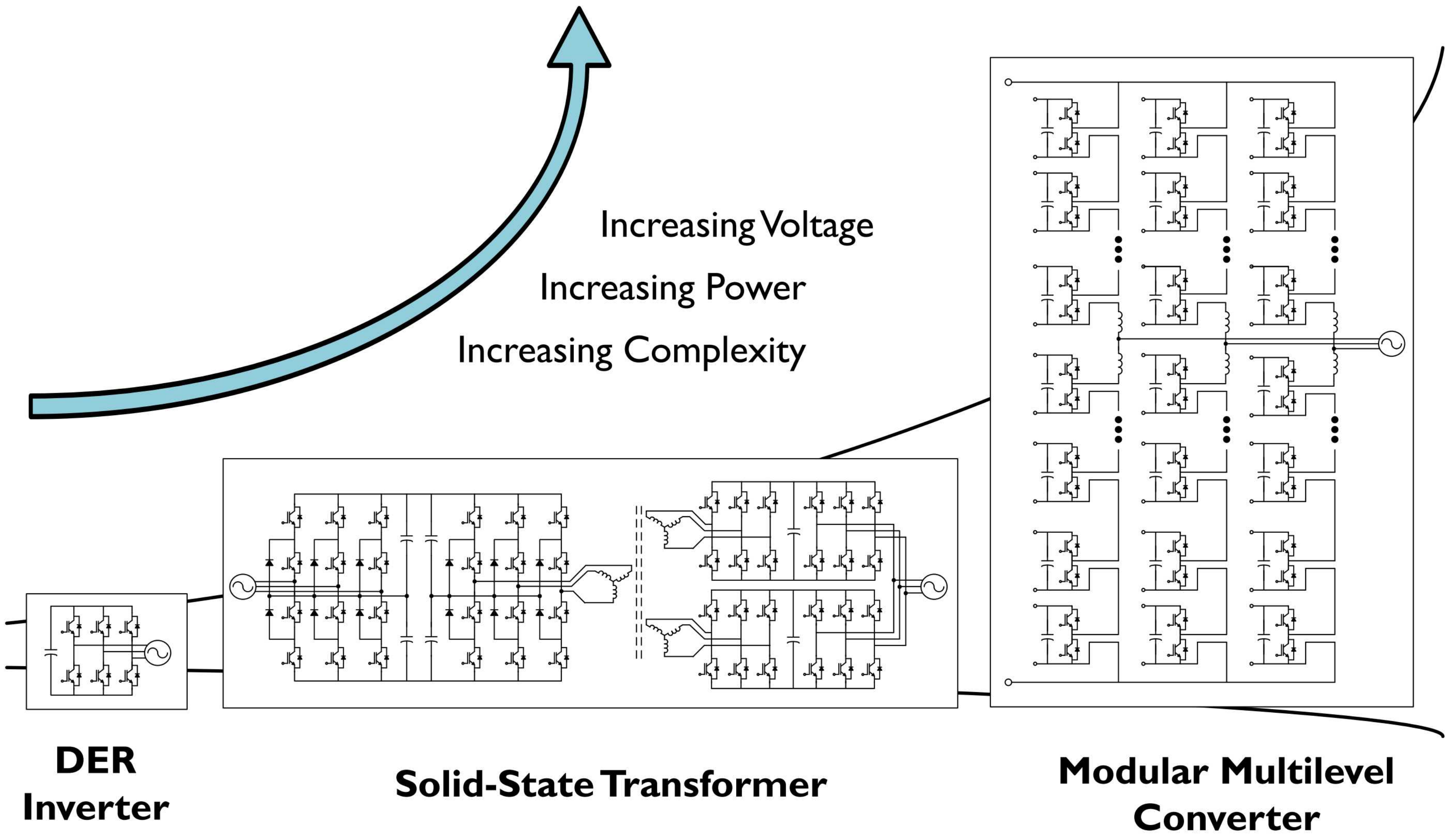
- Bringing in WBG devices can make format factor smaller, reducing thermal management issues
- New magnetics and high temperature capacitors can make the systems more compact and robust

Power Electronic Building Blocks



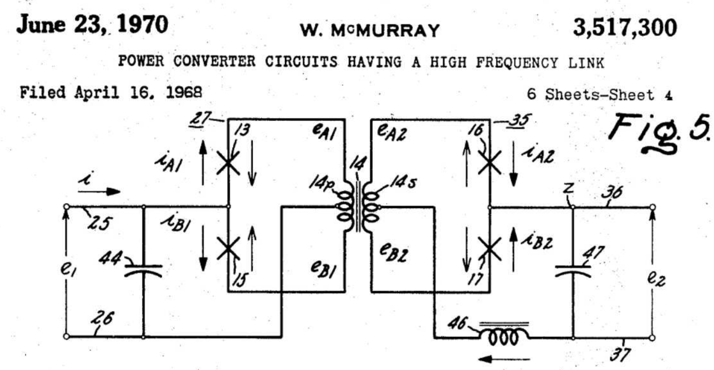
Power Module image from www.semikron.com
PEBB image from www.amsc.com

Modular Power Conversion Systems



Resilient Power Electronic Infrastructure

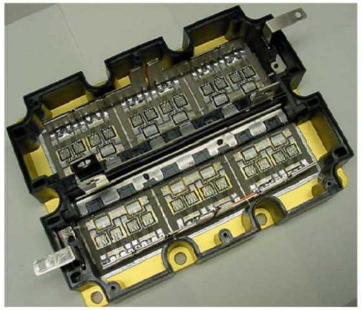
Power electronic infrastructure makes it possible to exert control over power flow at any point in the power delivery system.



Increased control agency is a potent tool for:

- Eliminating T&D losses
- Improving power quality
- Increasing system visibility
- Protecting critical assets
- Improving grid resiliency

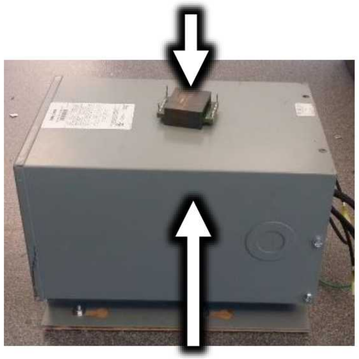
Benefits are clear, but implementation is challenging. New materials, components, topologies, and control strategies are needed.



10kV/120A SiC Half H-Bridge Module [1]

1 MVA Single-Phase Solid State Power Substation [1]

100 kHz Ferrite Transformer
8 kW – 0.72 lbs



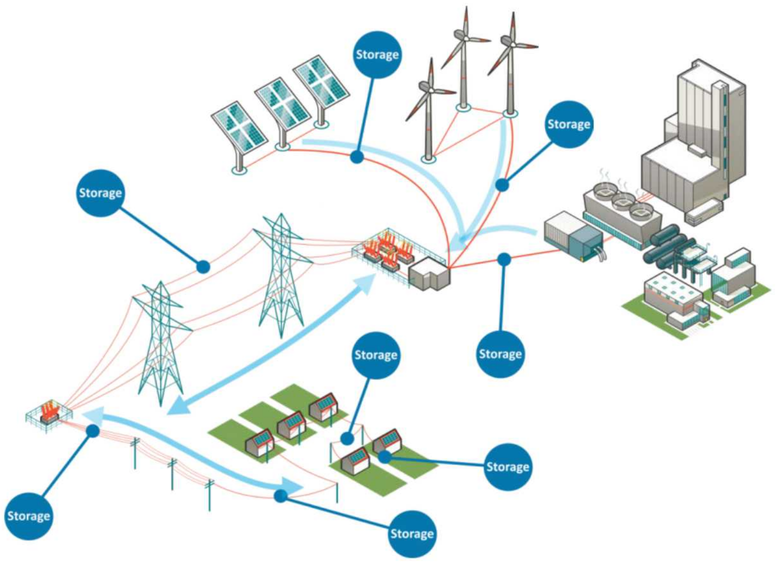
60 Hz Si-Steel Transformer
7.5 kVA – 150 lbs
Source: Wolfspeed

Power Electronics and Energy Storage

Multi-port Power Electronics

Opportunities for integration of storage in power conversion infrastructure:

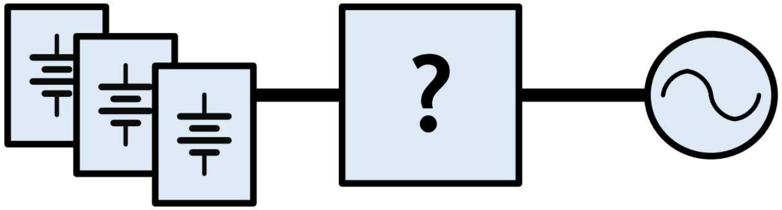
- Storage-integrated MMC at HVDC interconnects
- SSTs with DC port
- Multi-port hybrid ESS (e.g. flow battery + supercapacitor)



Scalability Challenges for Battery Storage

- Higher working voltage is preferred for power system assets to minimize I^2R losses
- However, electrochemical cells are low voltage, high current devices
- Naïve extension of conventional single-stage ESS designs results in decreased efficiency and reliability

New topologies are needed to introduce large-scale storage in MV grids and beyond



Electronic T&D Grids are Communications Intensive

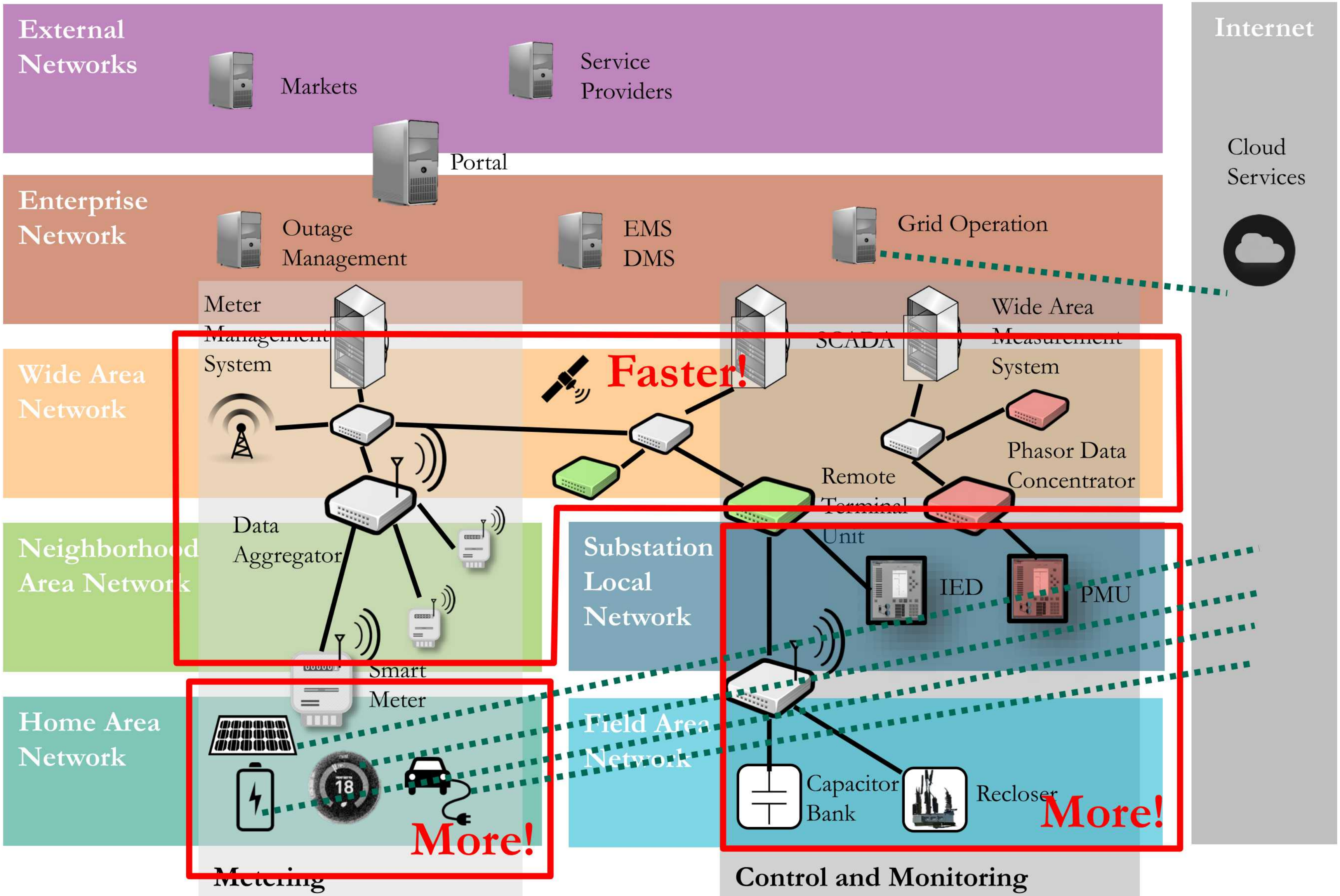
Many technologies that will fulfill requirements of the grid of the future are communication-intensive

- Pervasive communication systems with low latency and high bandwidth
- Sensors with high sampling rates in great numbers
- Response to fast grid dynamics
- IP-based communication protocols
- More fiber optics and cellular network links (LTE, 5G)

Change of paradigm from centralized to decentralized

- Agents that participate actively in power grid will be more granular
- Coordinated participation of large numbers of small energy resources will require fast and reliable communications
- Cybersecurity will be a challenge with distributed resources actively participating

Need for Modernized Communications



Ref.: E. Hossain, Z. Han, H. V. Poor, Smart Grid Communications and Networking, Cambridge University Press, 2012.

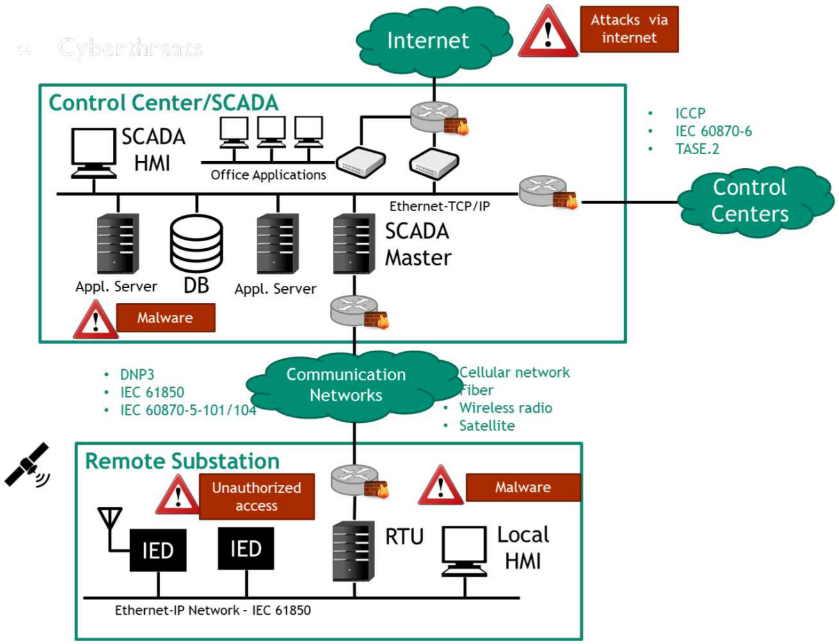
Security of eT&D Grids

Physical Security

- EMP, GMD, and other large scale disturbances
- Weather related

Cyber Security

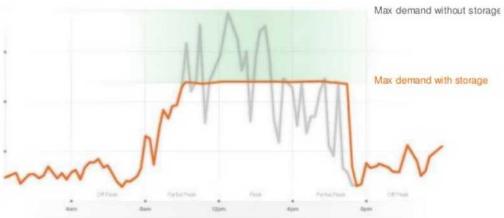
- Increased connectivity of grid assets can improve its performance, but comes with risks
  - Coordination between electric vehicles
- Social Engineering - Credential capture
- Data privacy
  - Smart meters: consumer behavior tracking
  - Communication over public networks
- Operation dependent on consumer/third party assets
  - Demand management



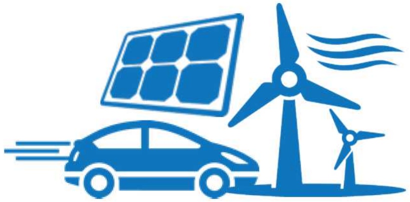
Role of Energy Storage in the Grid

- 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

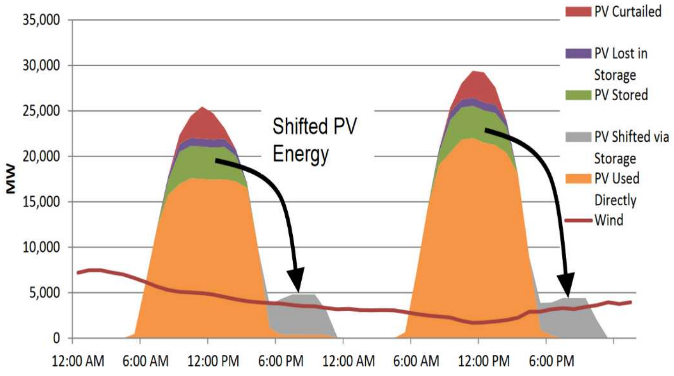
Mitigate $79B/yr in commercial losses from outages



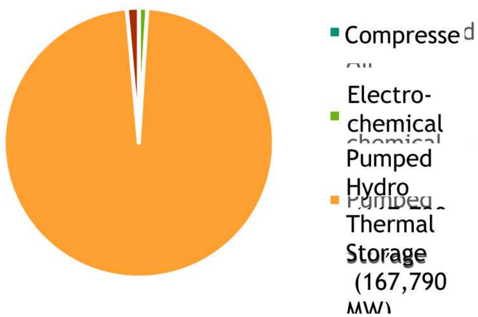
Reduce commercial and industrial electrical bills through demand charge management. 7.5 million U.S. customers are enrolled in dynamic pricing (EIA 2015)



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

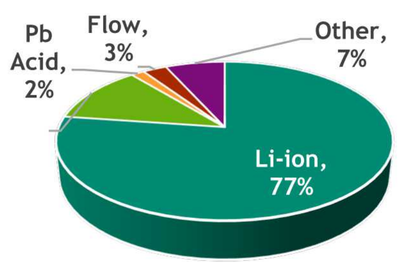


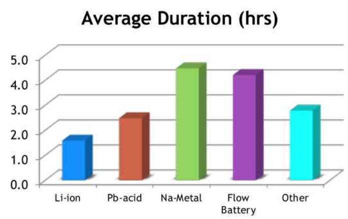
Energy Storage in the Grid Today



Technology Type	Projects	Rated Power (MW)
Electro-chemical	733	1,729
Pumped Hydro Storage	325	167,790
Thermal Storage	206	2,444
Compressed Air	1	0.660

Global Installed Storage Capacity





Globally

- 1.7 GW Battery Storage, ~170 GW Pumped Hydro

U.S.

- 0.7 GW BES, 22.6 GW PHS

% of U.S. Generation Capacity

- 0.06% Battery Storage, 2.2% All Storage

US Battery Energy Storage Deployed Reached over 2 GW in 2018

Grid-Scale Energy Storage still < 0.1% of U.S. Generation Capacity

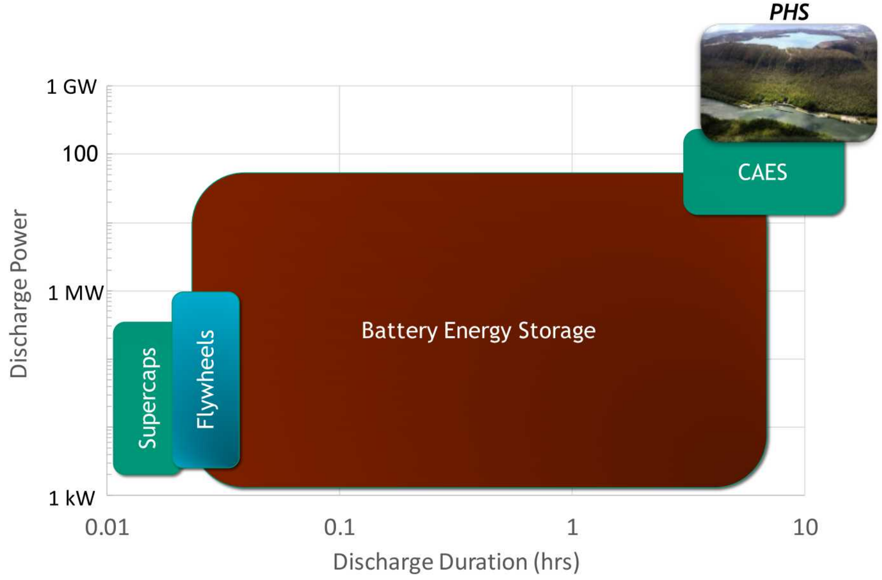
US installed energy storage capacity of 32 GW represents 15 min ride through

EV's < 1% of vehicles sold in U.S.

Compared to the need, the scale of energy storage deployments is insignificant.
In US, we have a 1 TW grid, even 1 hr of energy storage means 1 TWh

DOE Global Energy Storage Database
www.energystorageexchange.org

Energy Storage System Needs and Applications



Range of applications and storage system needs [Adapted from: *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

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

Rechargeable Battery Technologies

Current 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

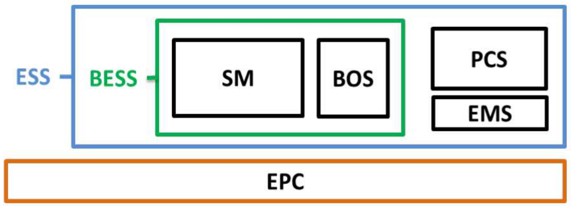
Lithium Batteries
e.g. Li-ion, Li-polymer, Li-metal, Li-S

High-temperature Batteries
e.g. Na-S, Na-$NiCl_2$

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

	World Wide Production Capacity	Cost and Performance Improvements
Lead Acid Batteries	350 GWh	2%/year (30 year data). $80-150/kWh
Li-ion Batteries	220 GWh and growing rapidly	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

Energy Storage is Not Just Batteries



SM **Storage Module**
Rack Level System (DC)

BESS **Battery Energy Storage System**
Containerized System (DC)

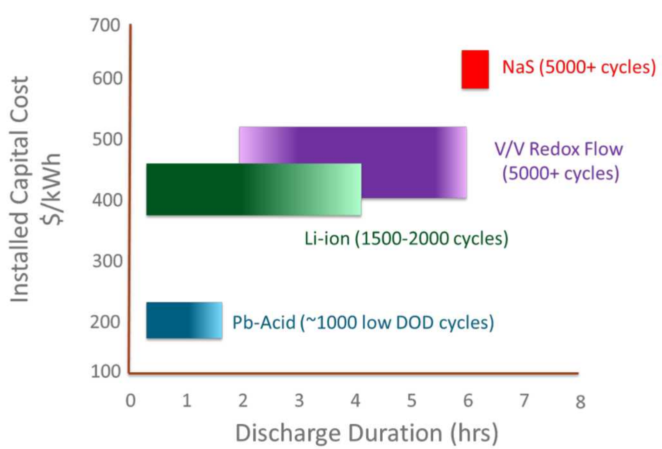
ESS **Energy Storage System**
Complete Storage System (AC)

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

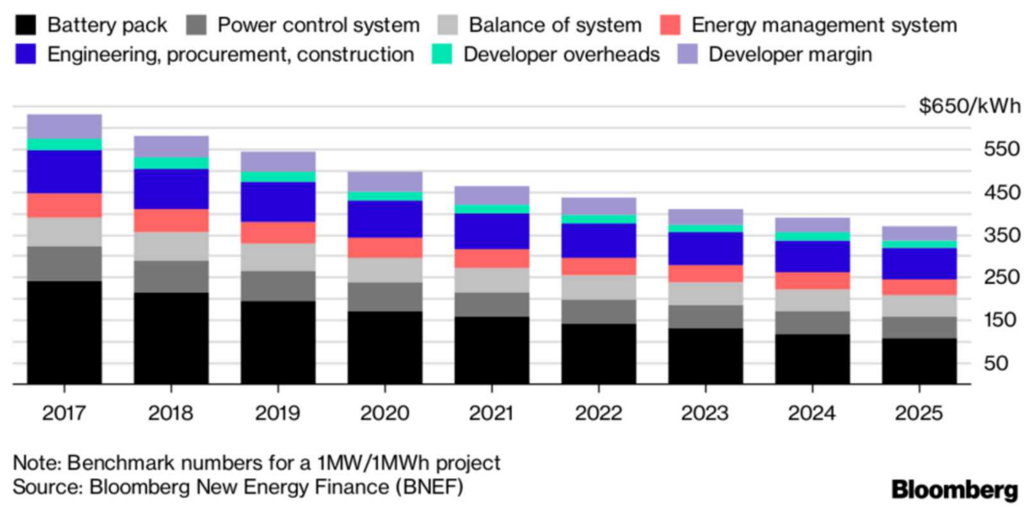
Source: R. Baxter, I. Gyuk, R.H. Byrne, B.R. Chalamala, IEEE Electrification, Aug 2018

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

PCS forms a significant part of the cost and performance of energy storage systems



Source: V. Sprenkle, PNNL, 2017



Energy Storage Installed Costs (BNEF, 2018)

Battery Energy Storage - Design and Application Aspects

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

Cell Chemistry
- Aqueous
- Non-aqueous

Thermal management
- Heating
- Cooling

Safety
- Abuse resistance
- Flammability
- Toxicity
- Containment

Plant Models
- Modularized

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

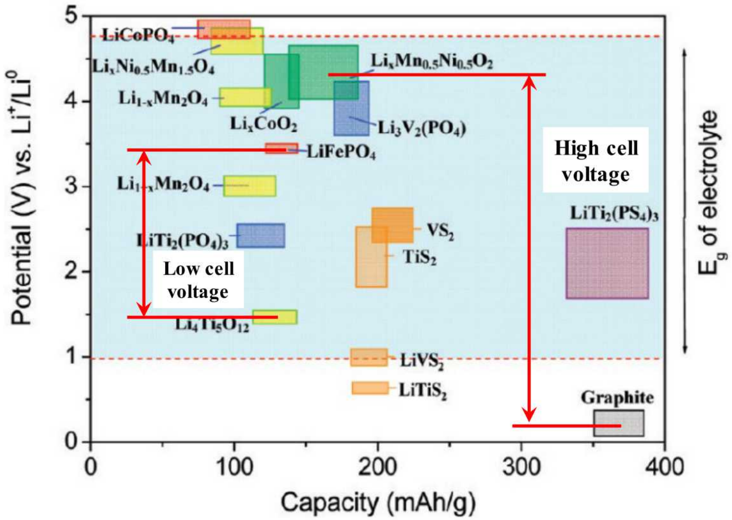
- Graphite and other carbons
- Lithium titanate

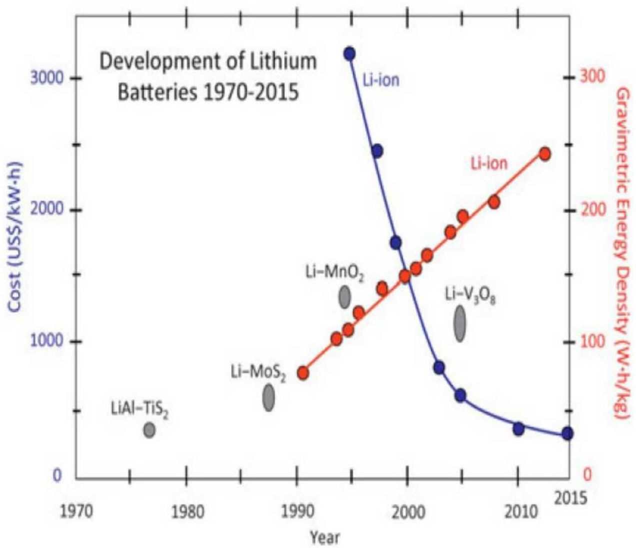
SOA EV batteries - Specific energies near 250 Wh/kg

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

Large Commercial Li-ion Deployments

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

Saft 6 MW / 4.2 MWh ESS
Kauai - Grid Stability

Tesla 100 MW / 129 MWh ESS
Australia - Grid stability

Li-ion Batteries – Challenges for Power and Energy Applications

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

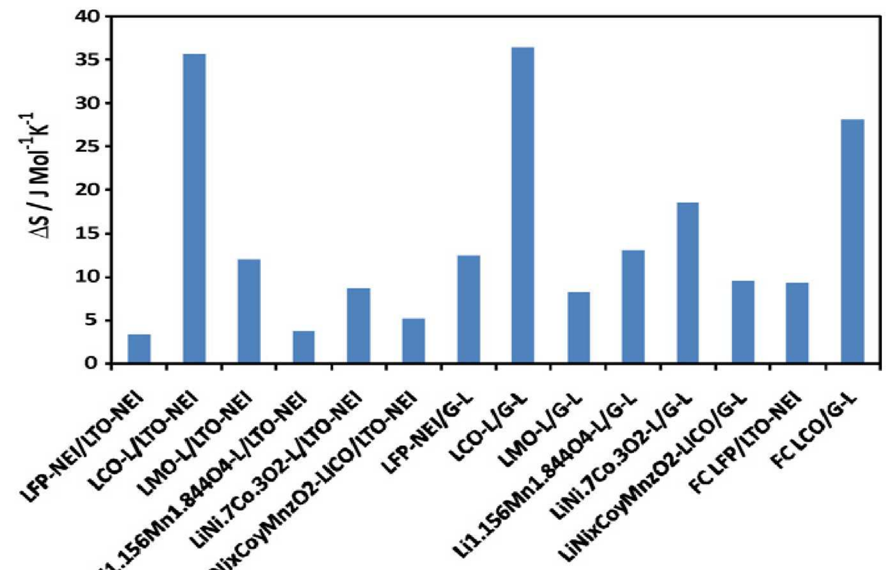
High Temperature

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

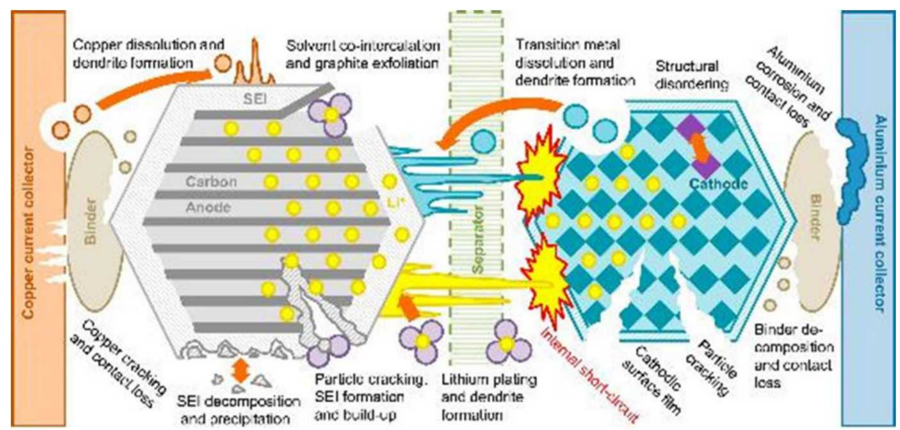
Overcharging

- 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

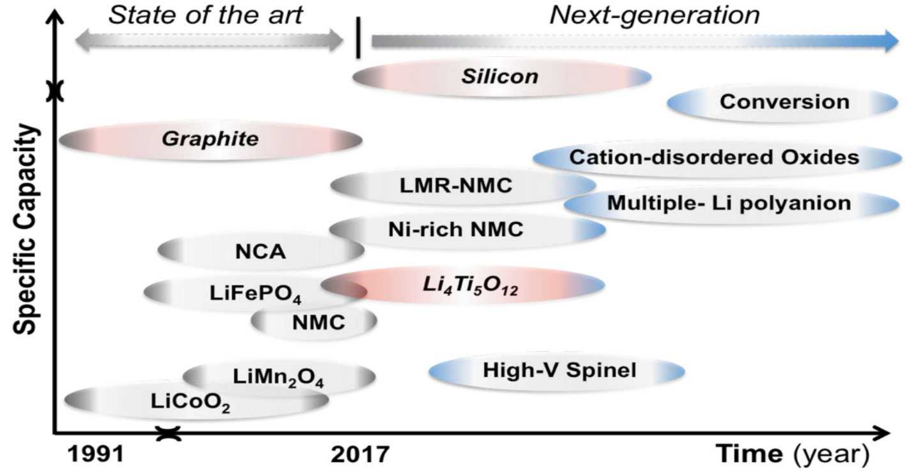
- Silicon-based

Safer electrolytes

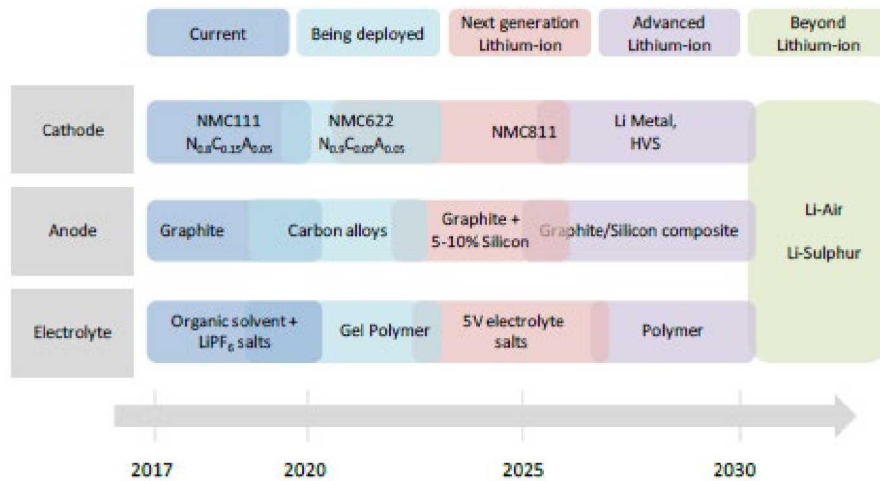
- Inorganic
- Solid-state electrolytes

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

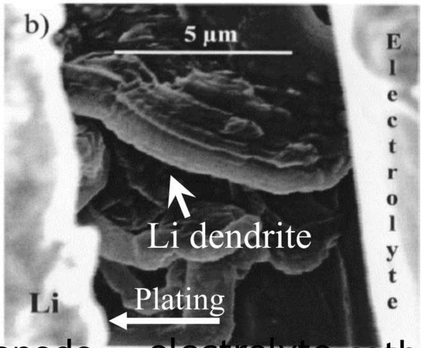
- Suffers from self discharge and poor life
- Breakthroughs needed with Li electrodes
- Managing the Sulphur shuttle reactions

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

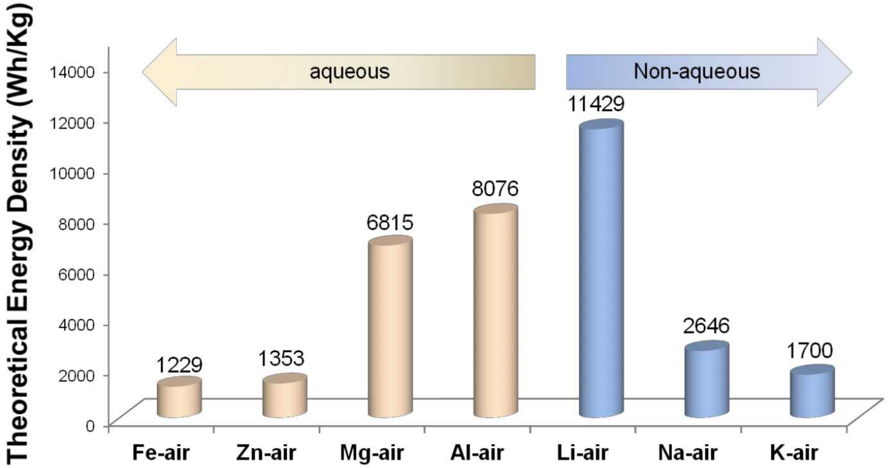
Li-Air combines difficulties of air and lithium electrodes

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



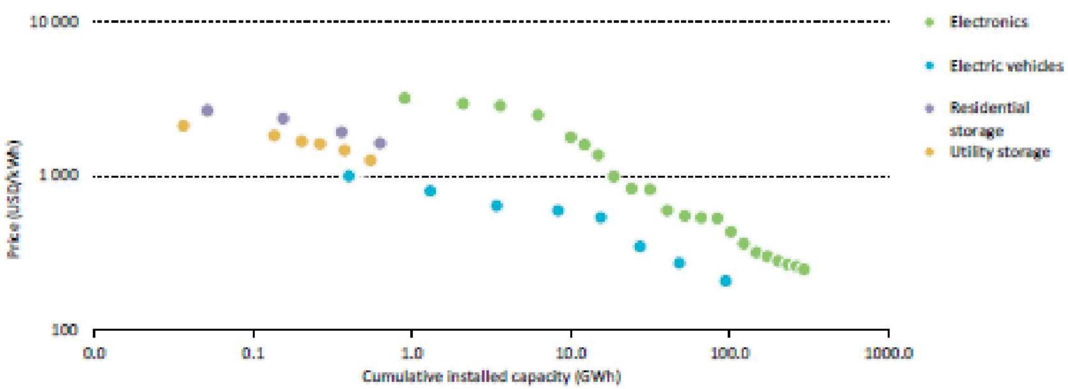
anode electrolyte cathode
Li dendrite growth

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



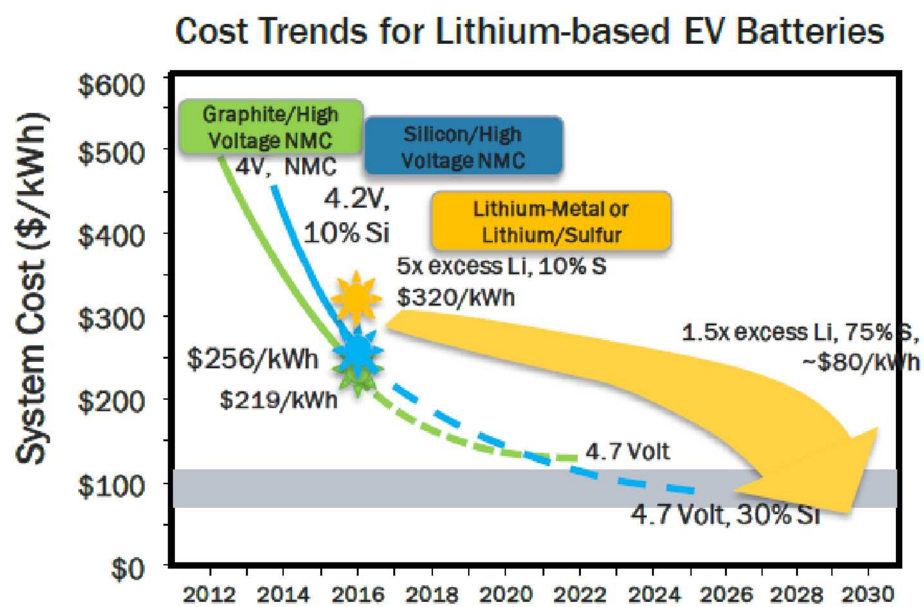
Y. Li and J. Lu, "Metal-Air Batteries: Future Electrochemical Energy Storage of Choice?," PNNL, 2017

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

Overall Reaction
- $Pb(s) + PbO_2(s) + 2H_2SO_4(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l)$
- OCV ~ 2.0 V

Flooded lead-acid
- Requires continuous maintenance
- Most common

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

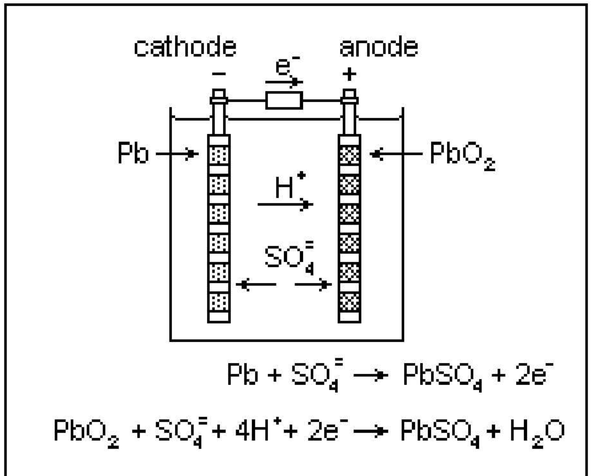
Advanced Lead Acid Energy Storage
- Carbon plates significantly improve performance

Mature technology

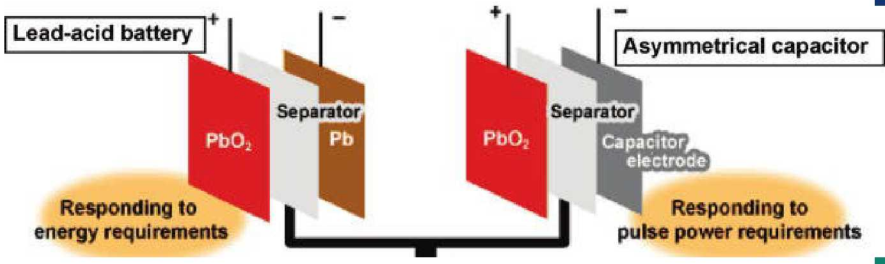
High recycled content

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



Lead-Acid Storage Cell



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

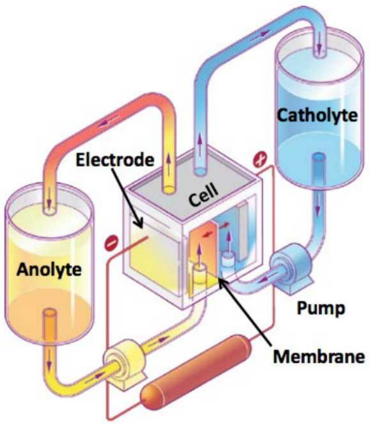
Energy storage technology utilizing redox states of various species for charge/discharge purposes

Key Aspects

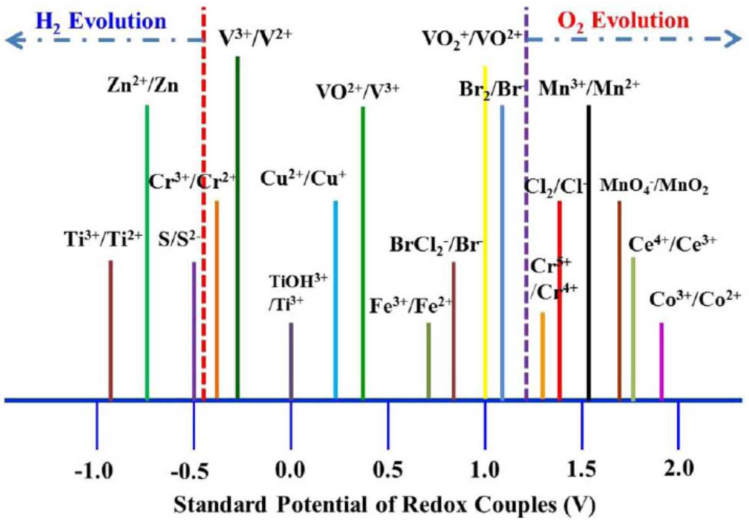
- Power (kW) and energy (kWh) separation
- Greater flexibility and safety
- Modular and scalable across a wide range of power and energy
- Long cycle life
- Low energy density ~ 30 Wh/L

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

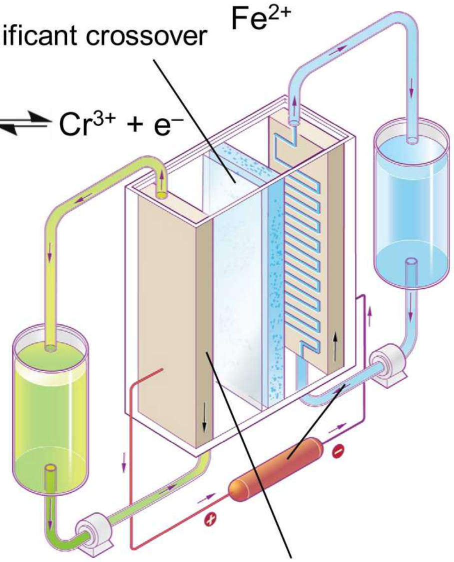


Source: Travis Anderson, Sandia National Laboratories, 2013



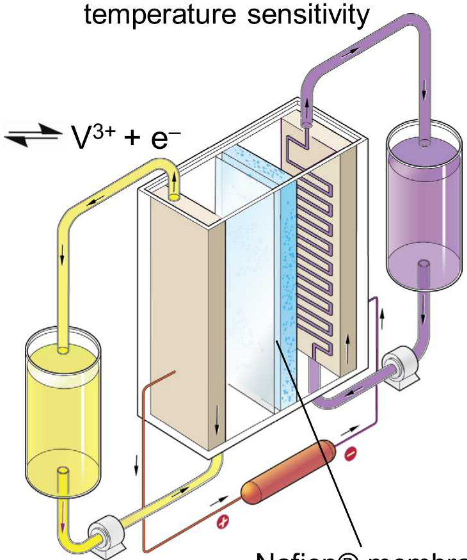
B.R. Chalamala, et.al., Proc IEEE, vol. 102, pp. 976-999, June 2014

Early Development (Aqueous)



Open Circuit Potential (OCP)[1] **1.2 V**

[1]Skyllas-Kazacos, M. J. Electrochem. Soc., 158 (8) R55-R79 (2011)



Open Circuit Potential (OCP)[2] **1.3 V**

[2]Li, L. *et al.,* Adv. Energy Mater. 2011, 1, 394–400

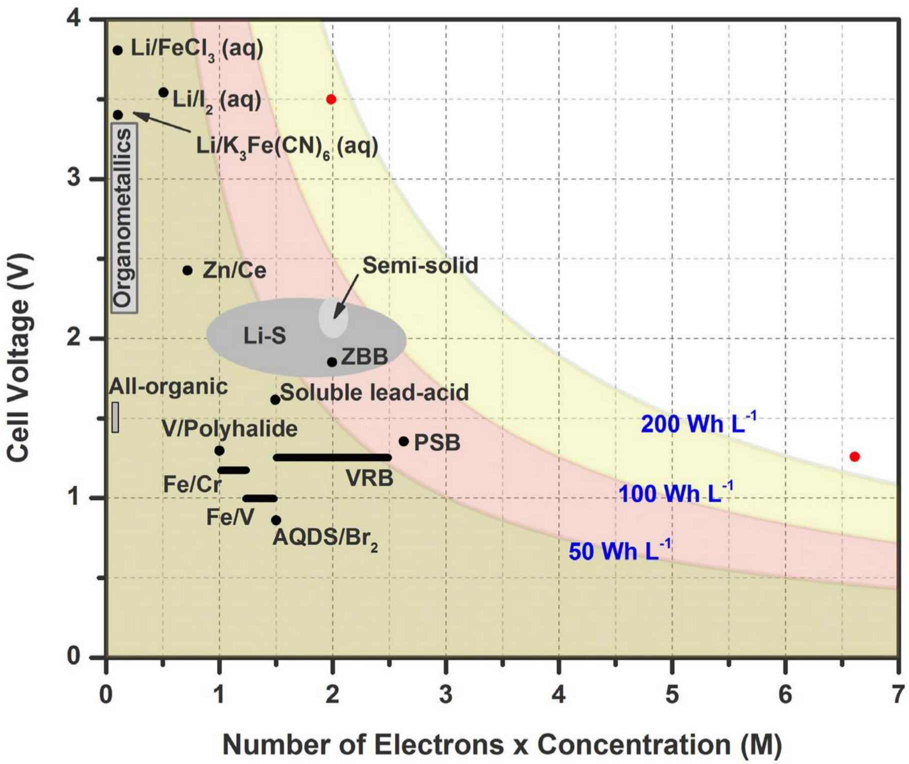
Redox Flow Batteries – Technical Challenges

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

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

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)

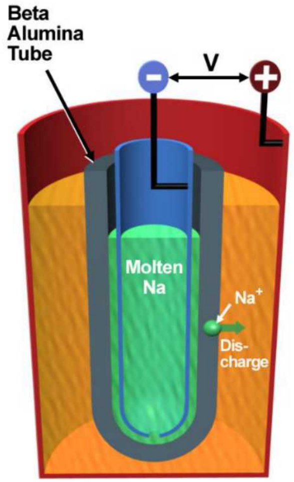
Two primary chemistries

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

NaNiCl2 (Zebra) developed in the 1980's

- 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

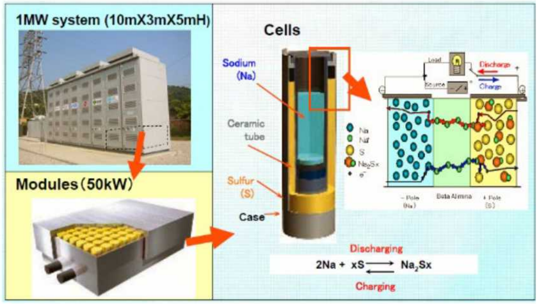
NaS first developed by Ford Motor Co. in 1960's
- Commercialized by NGK in Japan
- 530 MW/3700 MWh of installed capacity, primarily in Japan

NaS battery
- $2Na + xS \rightarrow Na_2S_x$ $(x = 3\sim5)$
  - $E = 2.08\sim1.78$ 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

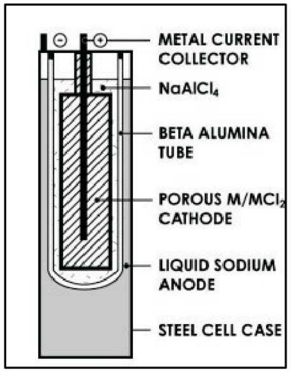
- Lower temperature than NaS
- Cells loaded in discharge mode
- Improved safety compared to NaS. Addition of catholyte $NaAlCl_4$ leads to a closed circuit on failure

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

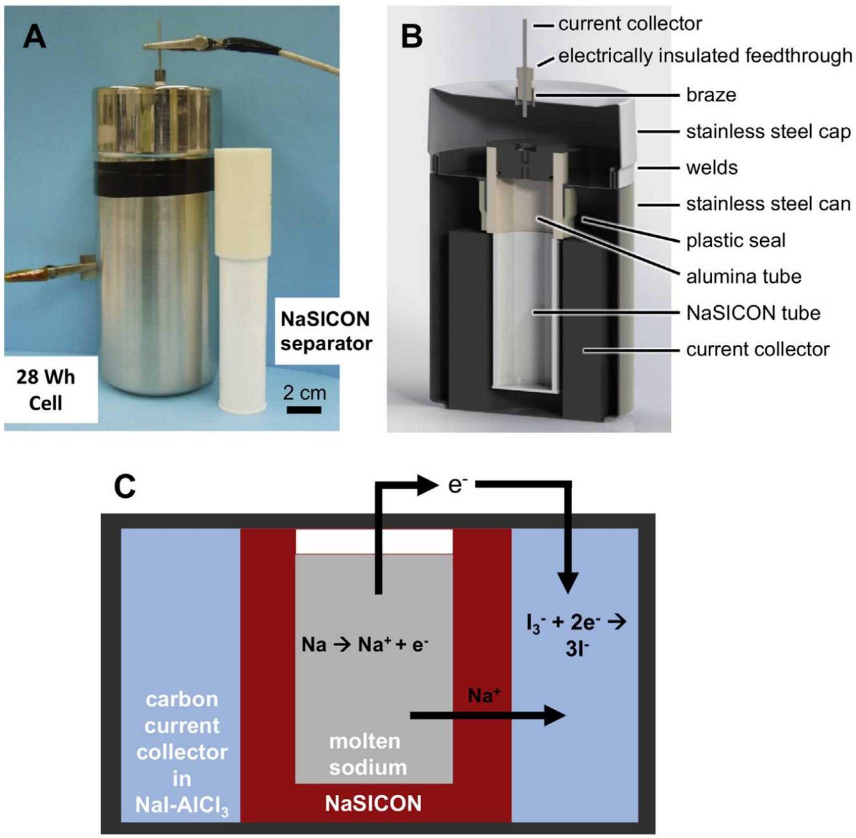
Low cost active materials, but challenging systems engineering

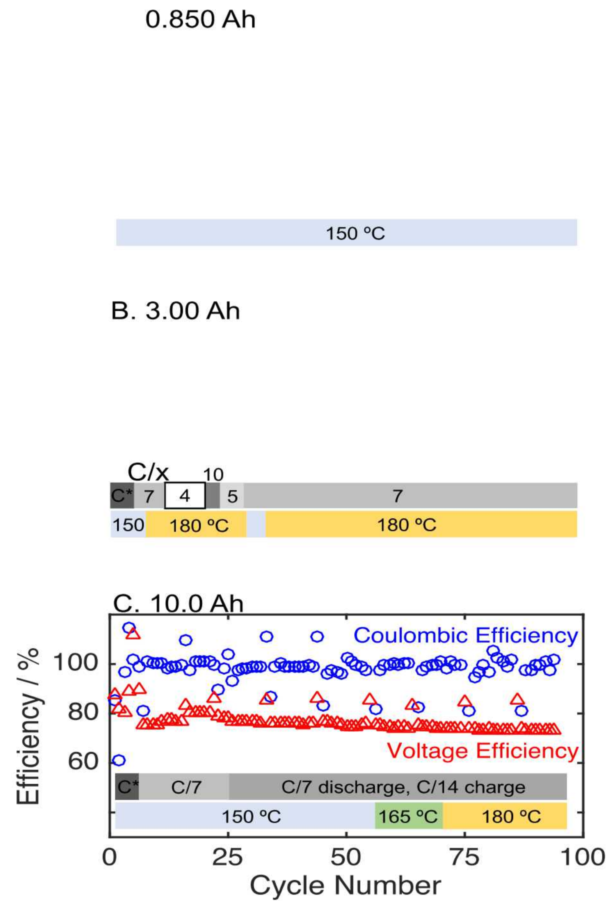
- Need for high temperature operation, kinetics driven by the solid ceramic electrolyte
- Typical operating window 250-350^{o}C. Need for continuous thermal management even when not in use. At lower T, Na metal freezes out, degree of distortion to cell dictated by SOC of battery
- Safety concerns related 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^{o}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

Early Demonstration of Na-NaI Battery (150-180oC)

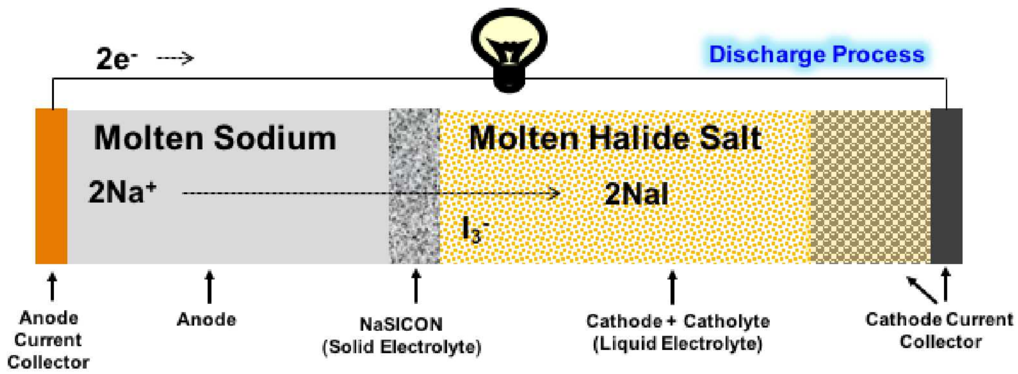




The catholyte is 60 mol% NaI-AlCl$_3$ (with 5-10 mol% NaI added) – Significant undissolved solids at 150^{o}C.

L.J. Small, *et al*. *J. Power Sources* (2017) **360** 569-574

Lower Temperature Sodium Halide Batteries

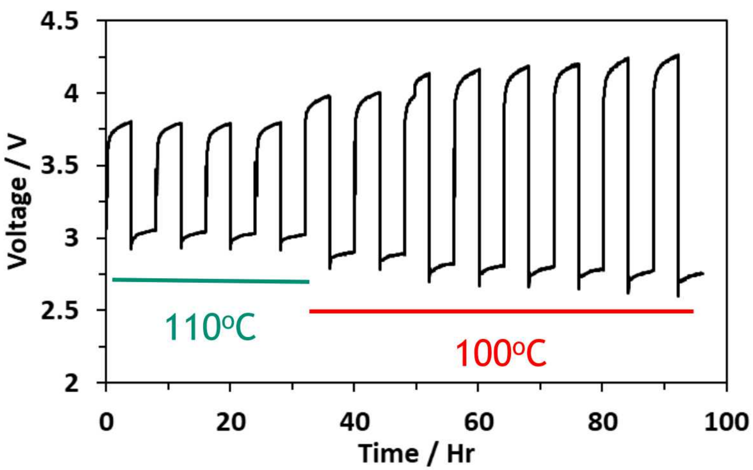


Na-NaI battery:

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

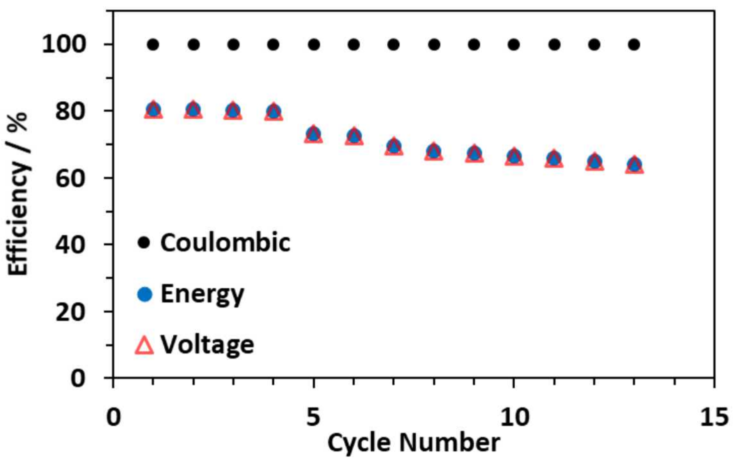
$I_3^- + 2e^- \rightarrow 3I^-$ $E^0 = 3.24$

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



Battery cycling at **100°C**!

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

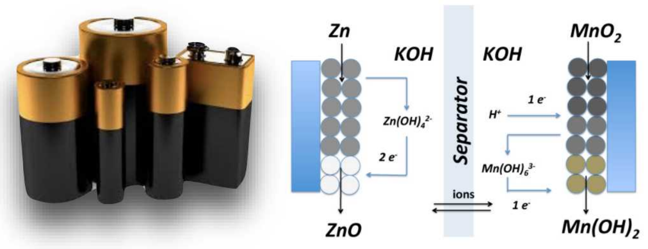
Zn-MnO_2 shows most promise for grid storage

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

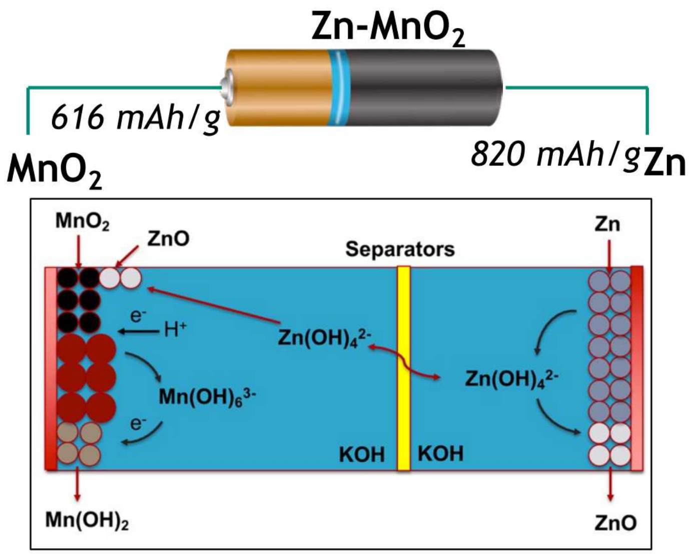
Safety
- Aqueous chemistry
- Non-flammable
- EPA certified for landfill disposal

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

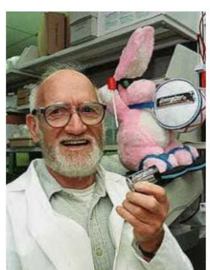
History of Rechargeable Zn-MnO_2 Batteries

- 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 — 2010-2014: CUNY Energy Institute shallow-cycle MnO_2; 2014-2016 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

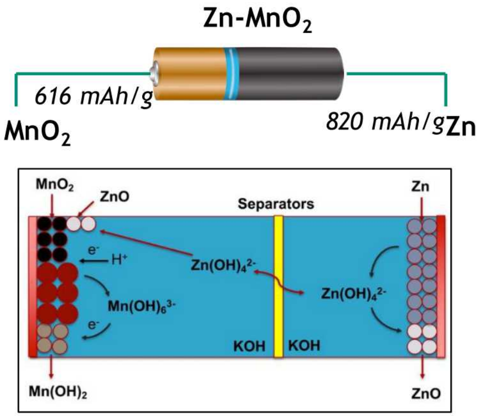
Separator

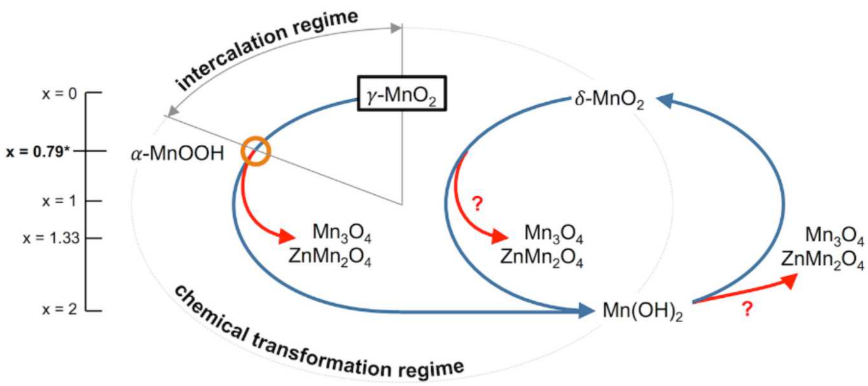
- Reduce Zincate crossover

On the Zn Anode

- Control shape change
- Passivation
- Reduce dendrite formation

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

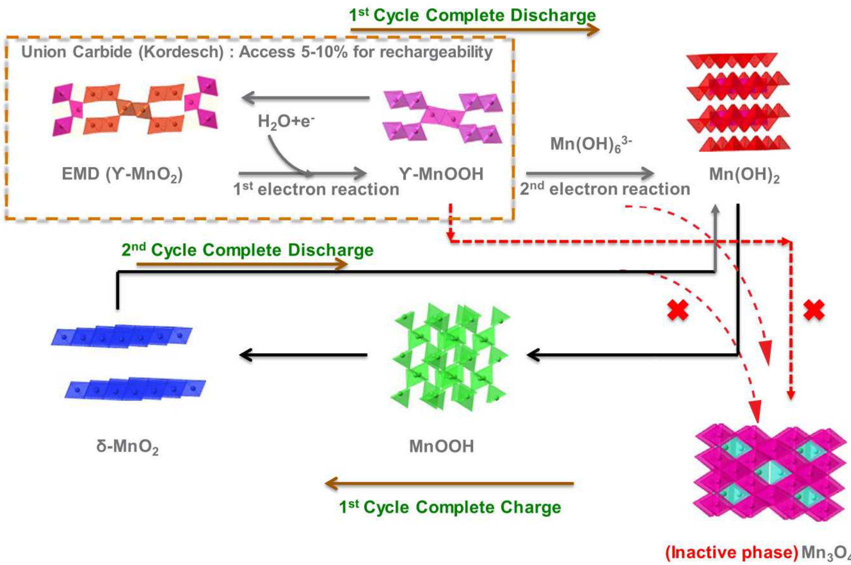


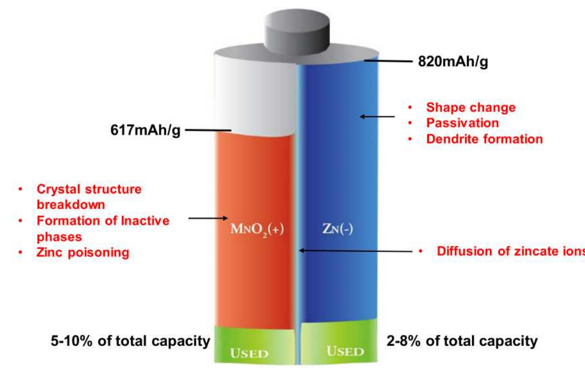


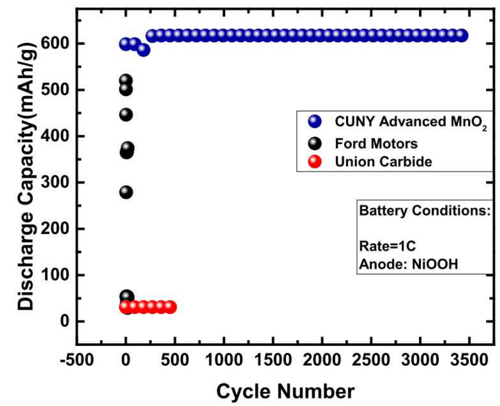
Failure Mechanisms of Cathode

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

Making MnO_2 Fully Rechargeable







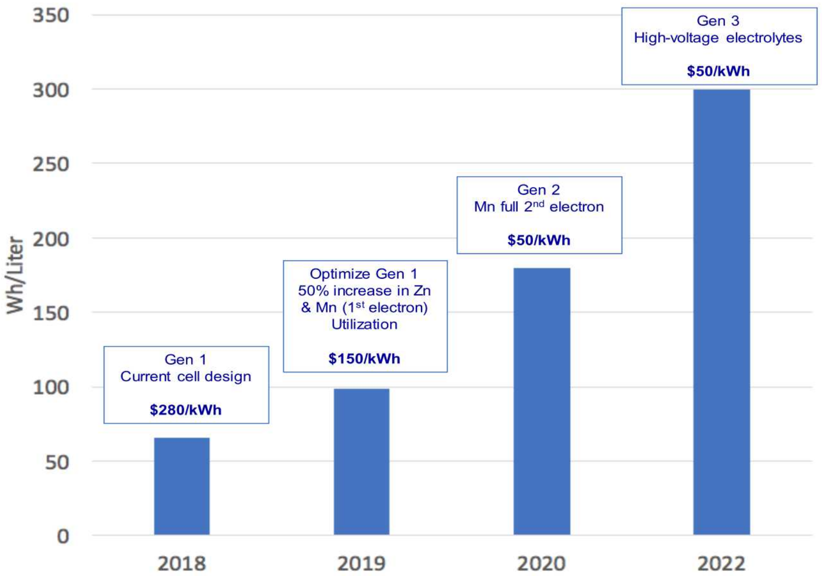
- Chemistry relies on formation of a **layered** birnessite MnO_2 structure and **stabilizing** this structure for thousands of cycles
- MnO_2 goes through a complete regeneration process during each cycle

MnO_2 cycling data against reference anode

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

Potential for $Zn\text{-}MnO_2$ 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 $Zn\text{-}MnO_2$



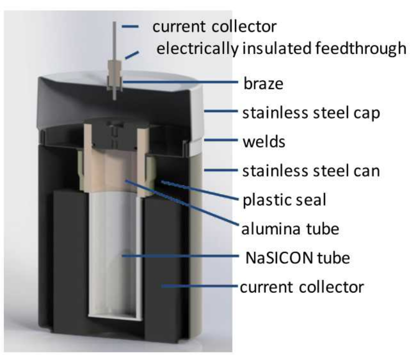
Source: CUNY Energy Institute

Grid Storage needs Large Format Cells

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

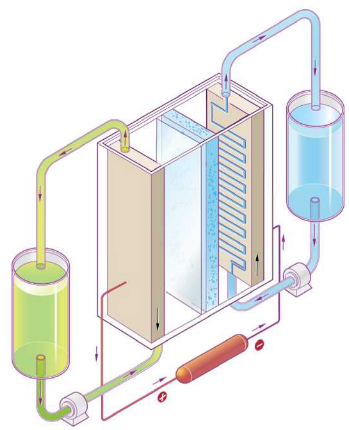
Large format cells also allow for tighter integration of power electronics, sensors, SOH monitoring at the cell level.

High Conductivity Separators for Low Temperature Molten Sodium Batteries



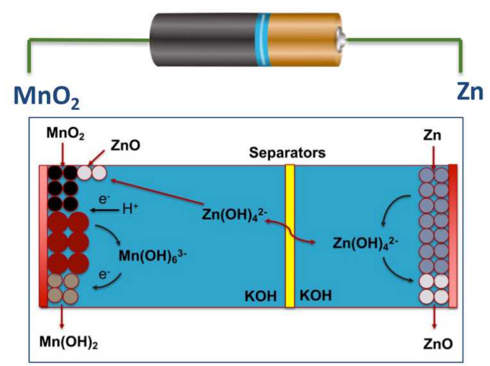
Robust ceramic separators exhibit low Na^+ conductivity at lower, more cost effective temperatures (120-180 °C).

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

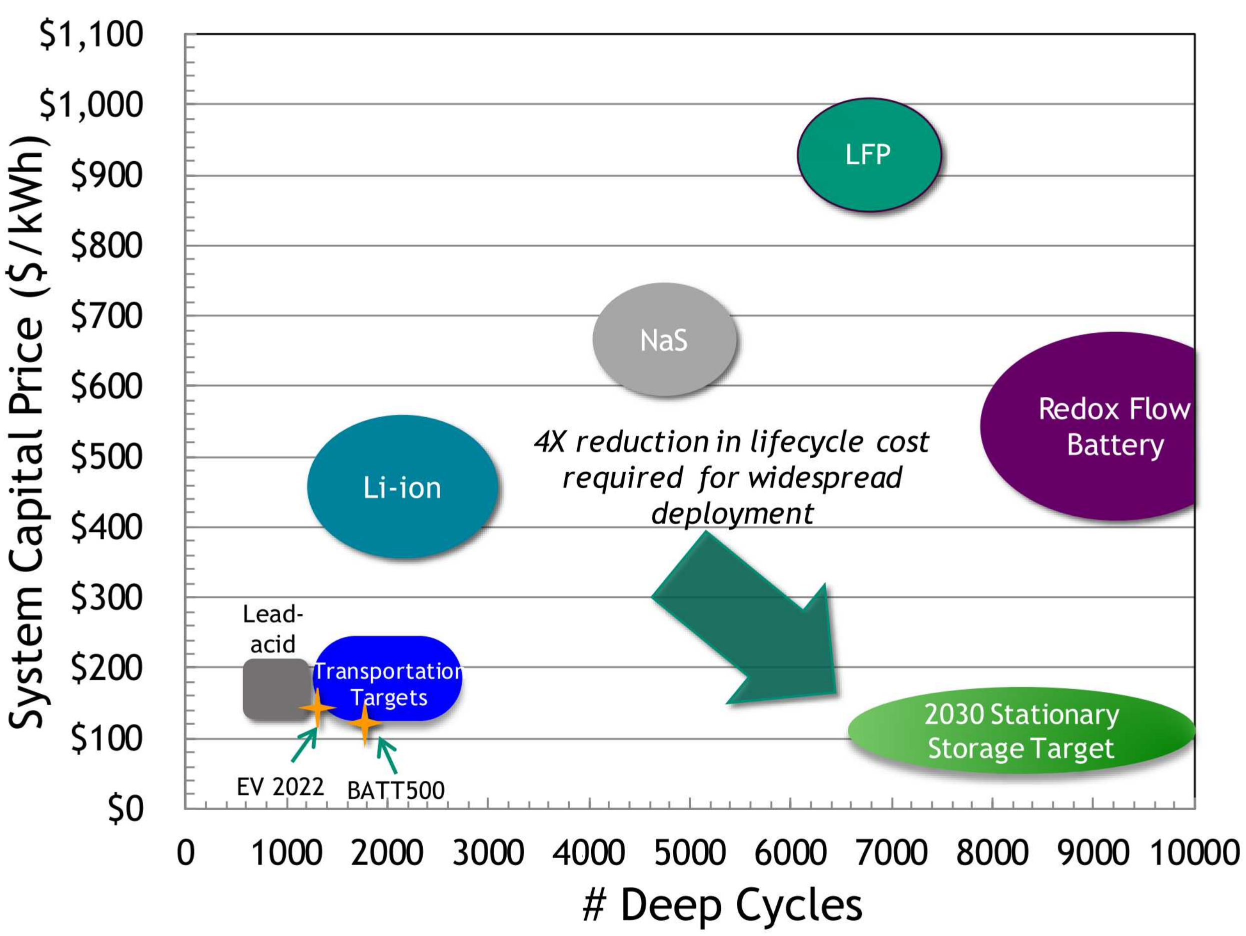
Safety Devices and Systems →

- 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

Future of Energy Storage Technologies



[1]*Energy Storage Systems Cost: GTM/ESA US Energy Storage Monitor: Q2 2016*

Advances in High Performance Rechargeable Batteries

No near term alternatives to Li-ion batteries for energy dense batteries for high performance applications including EVs, Electric Aircraft.

- Solid state batteries – promising, need significant improvements
- Metal-air batteries – energy dense, need technical breakthroughs to fully realize

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

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

Sandia Grid Energy Storage Program

Comprehensive R&D program with a focus on solving 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
- Analytics and controls for integration of utility class storage systems. Improved BMS, EMS systems. Control architectures.
- Standards development
- Grid of the Future
- Energy storage project development
- Support DOE's demonstration projects and outreach to the industry

Future Grid – Technology and R&D Gaps

For a future eT&D grid, we need significant cost reductions in power electronics

- Lower cost, longer duration energy storage - technologies that can scale from microgrids to large transmission applications
- Improvement in safety and reliability of power converters and energy storage systems
- Management of truly bidirectional power flows and stochastic loads

Coordinated sensing and control infrastructure

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Energy Storage Systems Program

U.S. DEPARTMENT OF ENERGY

THANK YOU

Grid R&D Needs

Electric systems	Traditional Grid	Development Trends and Needs	Future Grid
Generation	• Large centralized power plants • Dispatchable generation • Mechanically coupled • Minimal DER	• Growing role of DER • Energy storage • New planning tools to handle RE • Control coordination • NG replacing coal plants	• Hybrid control architectures • Bidirectional power flows and stochastic loads • Power electronic centric infrastructure across the grid
Transmission	• SCADA for status visibility • Operator-based controls • Aging infrastructure. Low peaking capacity utilization. • Threats/vulnerabilities not well defined	• HVDC transmission • Growing dc loads • Improving EMS • Integrated planning tools • Growing security awareness • Increasing role of storage	• Wide-spread PMU deployment • Coordinated sensing and control infrastructure • System-wide dynamic power flow management • Resilient and self healing
Distribution	• Minimal to non-existent sensing and automation • Radial design and one-way power flows • Aging distribution infrastructure	• Deployment of ADMS • FACT/inverter enabled voltage regulation • Early adoption of storage in distribution systems	• Truly bi-directional power flows and large scale DG • Pervasive sensing and communications • Local, autonomous coordination • Asynchronous networks
Consumption	• Regional, location and customer specific rate structure • Uniformly high reliability • Predictable behavior based on historical needs and weather • Reliable, yet inflexible	• Customer-determined reliability/power quality • Real time pricing, time of use rates, demand charges • Improved utility communications • Behind-the-meter storage	• Autonomous microgrids • Advanced EMS • Widespread DERs and transactive energy • Pervasive sensor environment
Operation/Market structure	• Vertically integrated utilities, wholesale markets	• Market reform to compensate for services provided	• Diversity of energy products and services

DOE QTR, 2015