Energy Storage Technology Advancement Partnership (ESTAP) Webinar

Energy Storage 101, Part 1: Battery Storage Technology, Systems and Cost Trends

March 26, 2019

U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories

CleanEnergy States Alliance

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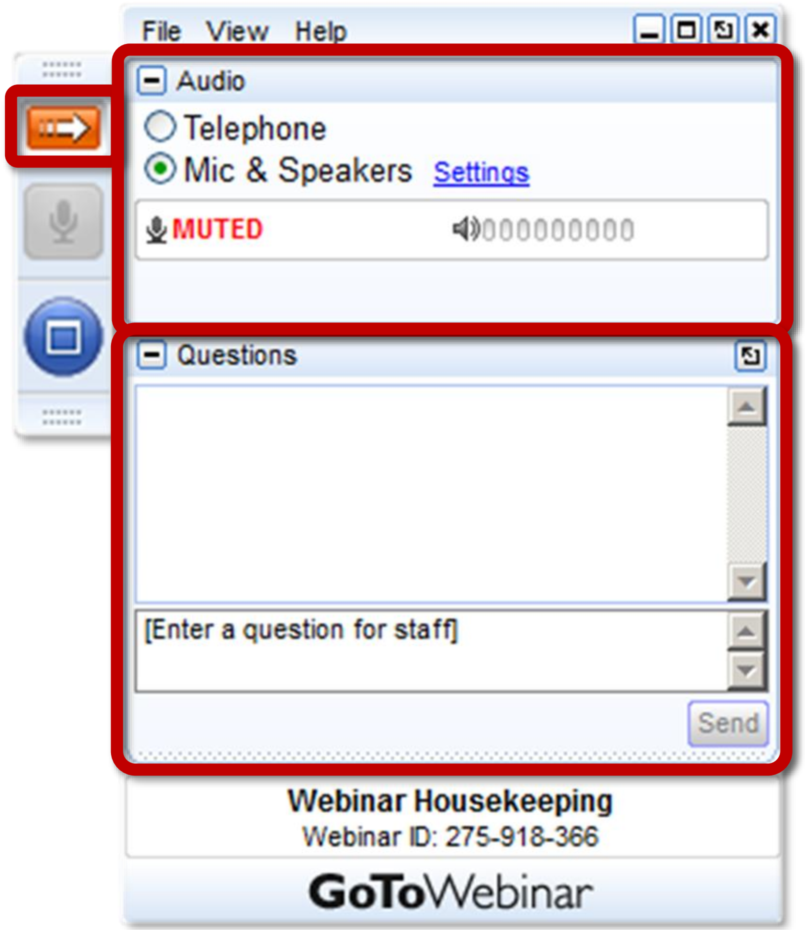

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CleanEnergy States Alliance

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Alaska Energy Authority

State of California Energy Commission

Department of Energy & Environment

Energy Trust of Oregon

Iowa Economic Development

Massachusetts Clean Energy Center

IPA Illinois Power Agency

New Mexico EMNRD Energy, Minerals and Natural Resources Department

OEI Wisconsin Office of Energy Innovation

New York State of Opportunity | NYSERDA

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www.cesa.org

Energy Storage Technology Advancement Partnership (ESTAP) (bit.ly/ESTAP)

ESTAP is supported by the U.S. Department of Energy Office of Electricity and Sandia National Laboratories, and is managed by CESA.

ESTAP Key Activities:

1. Disseminate information to stakeholders
   - ESTAP listserv >5,000 members
   - Webinars, conferences, information updates, surveys.
2. Facilitate public/private partnerships to support joint federal/state energy storage demonstration project deployment
3. Support state energy storage efforts with technical, policy and program assistance

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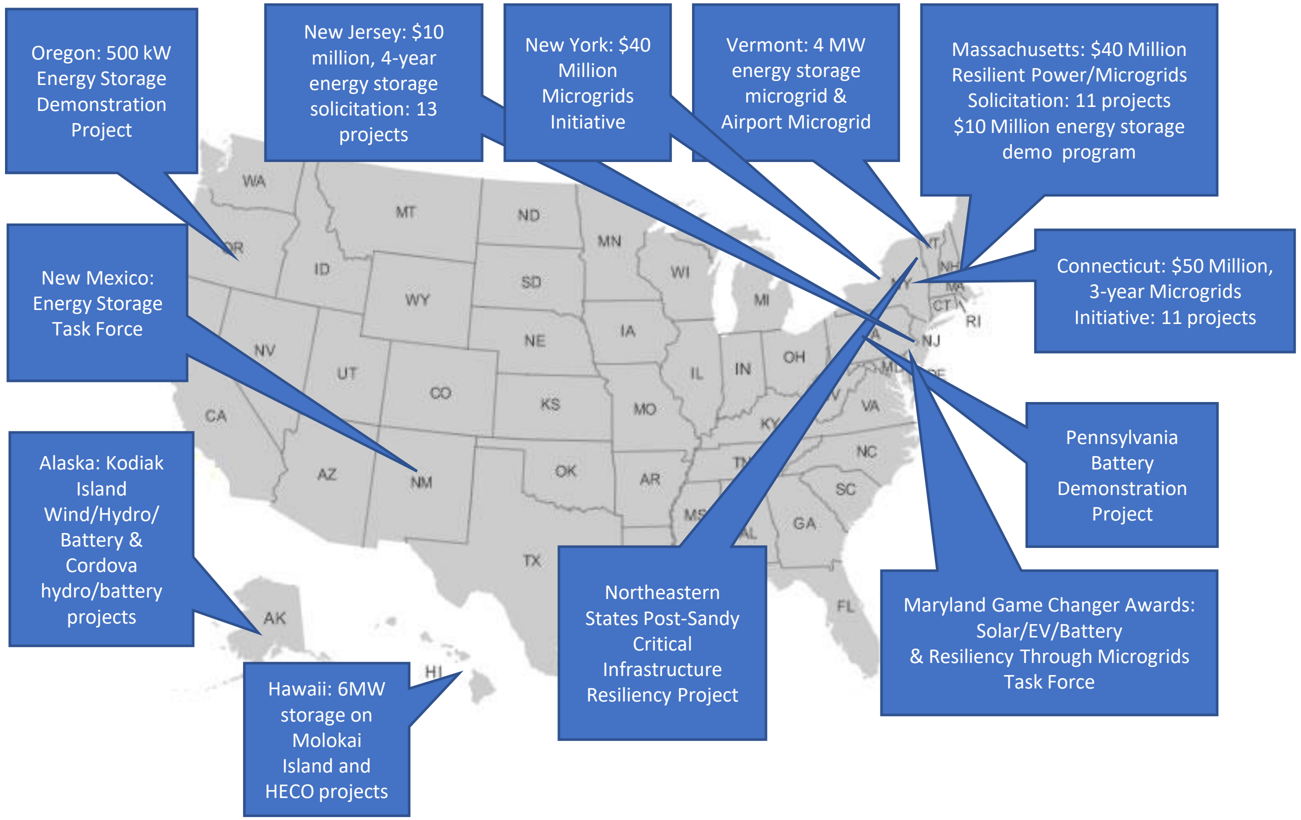
ESTAP Project Locations:



Webinar Speakers

Dr. Imre Gyuk
Director, Energy Storage Research, U.S. Department of Energy

Dan Borneo
Engineering Project Manager, Sandia National Laboratory

Vince Sprenkle
Chief Scientist, Electrochemical Materials and Systems Group, Pacific Northwest National Laboratory

Todd Olinsky-Paul
Project Director, Clean Energy States Alliance (moderator)

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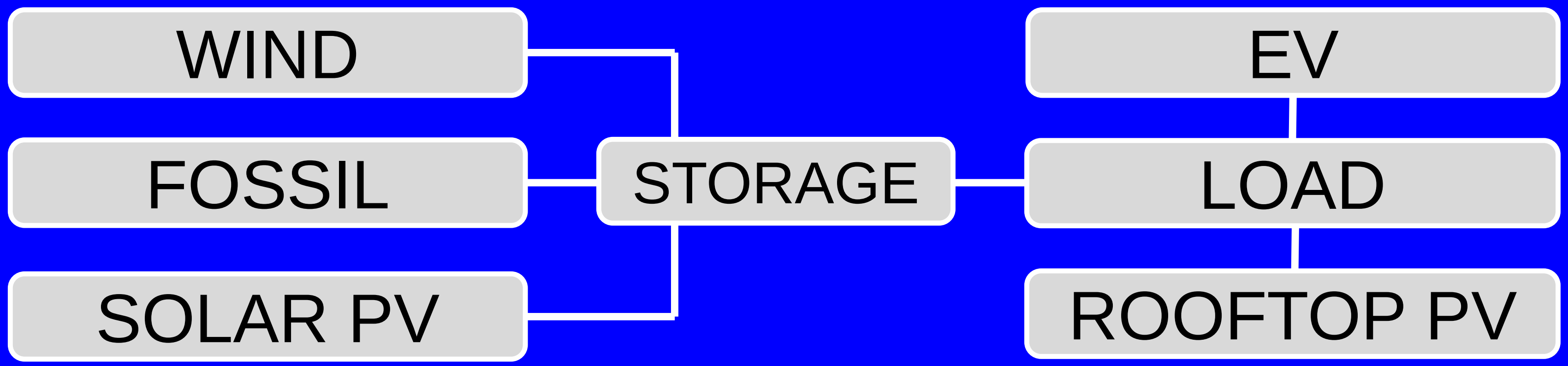
Towards Sustainable Gridscale Electrical Energy Storage

IMRE GYUK, DIRECTOR,
ENERGY STORAGE RESEARCH, DOE-OE

The grid has become stochastic!



Electricity Storage provides a buffer between Electrical Generation and Electrical Load

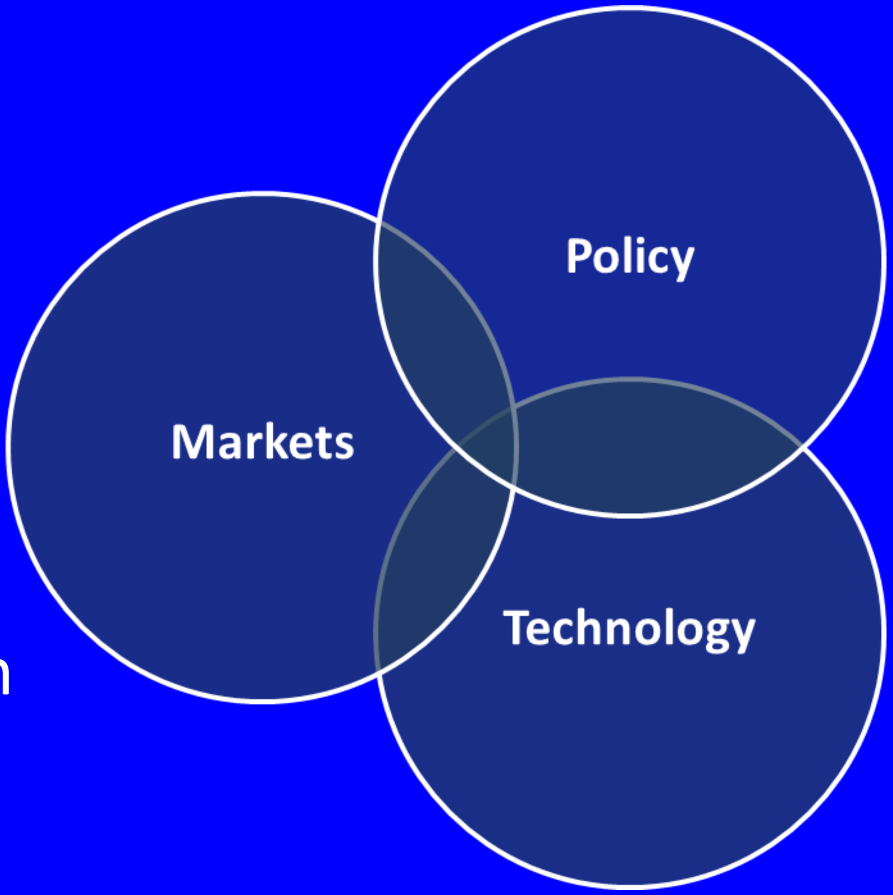
Balancing Technologies: Demand Management
Thermal Storage, Chemical Storage
Building Technology

Proper Development of Energy Storage Requires Consideration and Interplay of different Areas

Climate

Disasters

Resource Competition



Politics

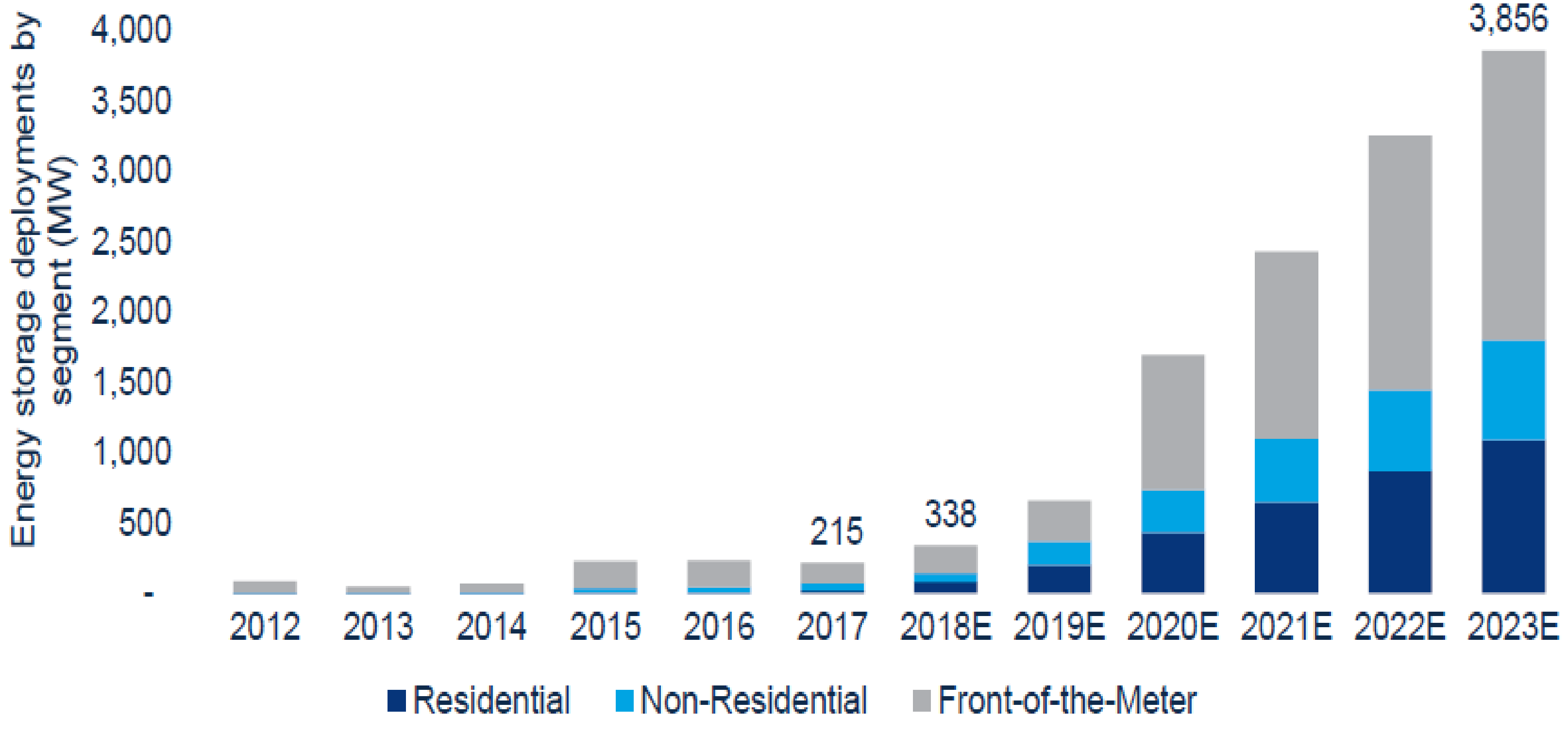
Economics

Social Movements

U.S. energy storage annual deployments will reach 3.9 GW by 2023

Utility procurements, changing tariffs and grid service opportunities all drive the market forward

U.S. energy storage annual deployment forecast, 2012-2023E (MW)

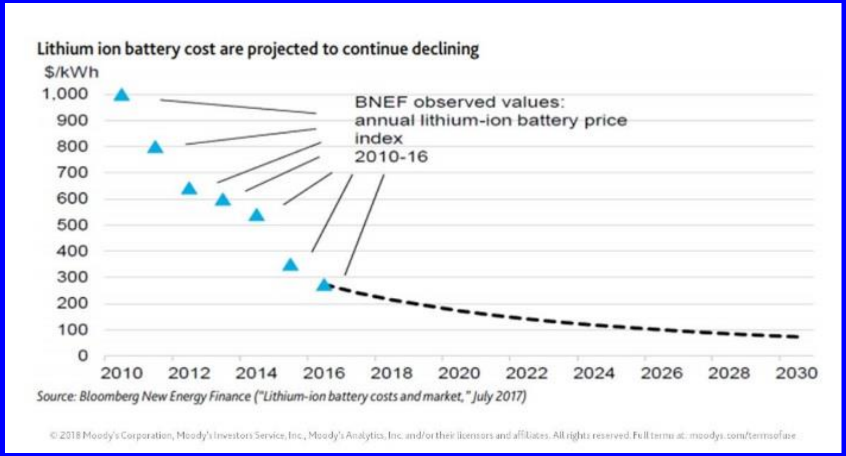


Source: Wood Mackenzie Power & Renewables

Li-ion Batteries?

Low cost, market ready
Tie-in with EV development

Cycle life <<20years
Safety Concerns.
No Recycling!
No U.S. Manufacture



Obstacles and Impediments to Sustainability:

Safety, Reliability,

Ecological and Sociological Issues,

Re-Use, Recycling, Disposal

27 MW in 2017!

Co Mining in Africa!

A Stream of Trash!

Safety is Essential!!

Research and Statistics urgently needed

How much should Liability Insurance be?

- Can the Technology be improved? E.g. seatbelts
- Should the Technology be replaced? E.g. H_2 airships

Safety should not be a Patch but part of Design!

Reliability is also Essential!!

Energy Storage is introduced to make the Grid more reliable!

Do we go for Cheap Replacement or Durability?

Reliability should be part of the Design!

Ecological and Sociological Issues.

Cheap for whom?
Who will pay?
Who will benefit?

What is the Total Carbon Footprint?

Will this help with Global Warming?
Does it promote Social Equity?

Is the Technology Sustainable?

Re-Use, Recycling, Disposal

EV Batteries retain ~80% Capacity

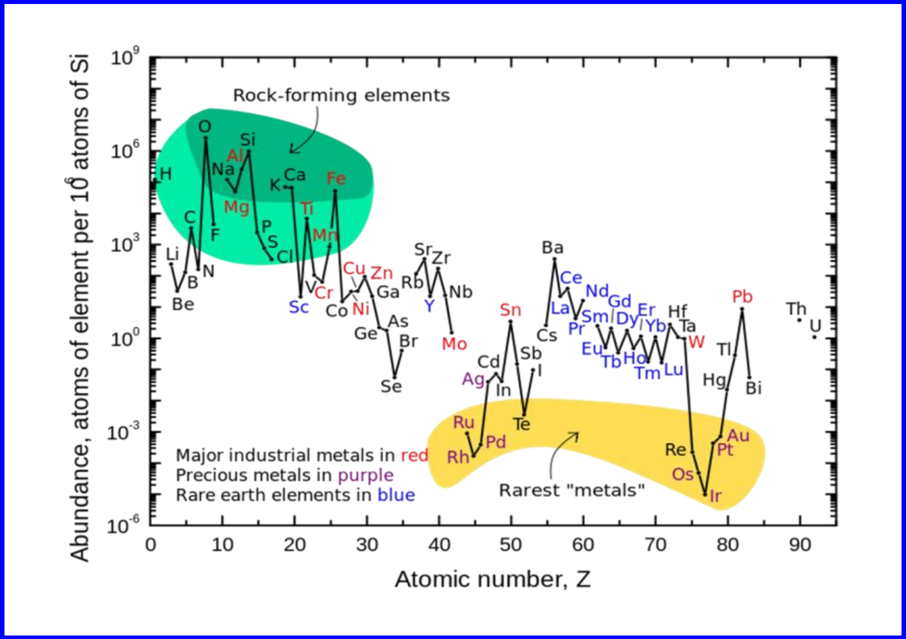
- Reuse for Stationary Application?
- or the Trash-heap?

Recycling – is it commercially feasible
Or does Entropy win again?

The Midden is not an Answer!
We must design for the Waste Stream!!

→ DOE Lithium-Ion Battery Recycling Prize

To develop Safe, Inexpensive, and Environmentaly Benign Batteries We must look towards Earth-Abundant Materials



Cost Goals for Focus Technologies

Manufactured at scale

Li-ion Batteries (cells)	\$250/kWh
V/V Flow Batteries (stack+PE)	\$300/kWh
Zinc Manganese Oxide (Zn-MnO_2) 2 Electron System	\$ 50/kWh
Low Temperature Na-NaI based Batteries	\$ 60/kWh
Aqueous Soluble Organic (ASO) Redox Flow Batteries (stack+PE)	\$125/kWh
Advanced Lead Acid	\$ 35/kWh

New Technology Solutions will cut Costs, increase Safety and Reliability.

Re-Use, Recycling, Disposal Issues will be Resolved.

But, can new Technologies Prevail in the Marketplace??

Grid Energy Storage Introductory Training
Part 1 – Technology, Systems and Cost Trends

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Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Dan Borneo – Sandia National Laboratories

Susan Schoenung – Longitude122 West

March 26, 2019

SAND2018-13308 PE

Contributors

Imre Gyuk – DOE

Vince Sprenkle – PNNL

Babu Chalamala – Sandia

Ray Byrne – Sandia

Dan Borneo – Sandia

Jeremy Twitchell – PNNL

Todd Olinsky-Paul – CESA

Susan Schoenung – Longitude122 West

Agenda

- This first Energy Storage 101 webinar covers state of the technology, energy storage systems and cost trends.
- Future installments will cover additional topics:
  - Applications and economics
  - Policy and regulations
  - Safety and reliability
  - Project development, commissioning and deployment.

Energy Storage:

Technologies, Terms, and Fundamentals

Grid Energy Storage Deployments

Energy Storage Comparison

Globally

- 1.7 GW - Battery Energy Storage
- ~170 GW - Pumped Storage Hydropower

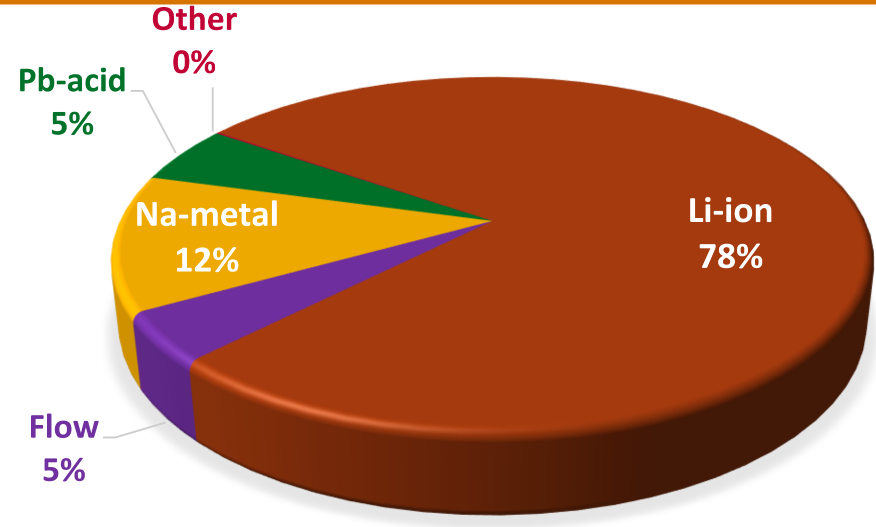
U.S.

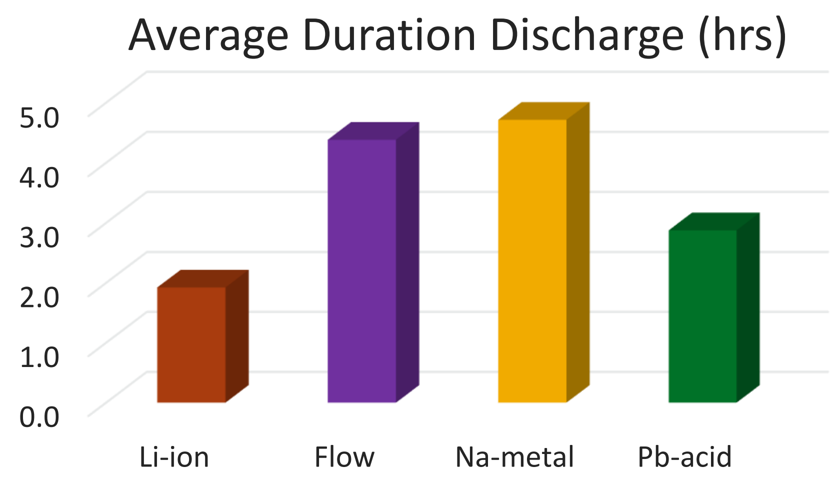
- 0.75 GW BES
- 23.6 GW PHS

% of U.S. Generation Capacity

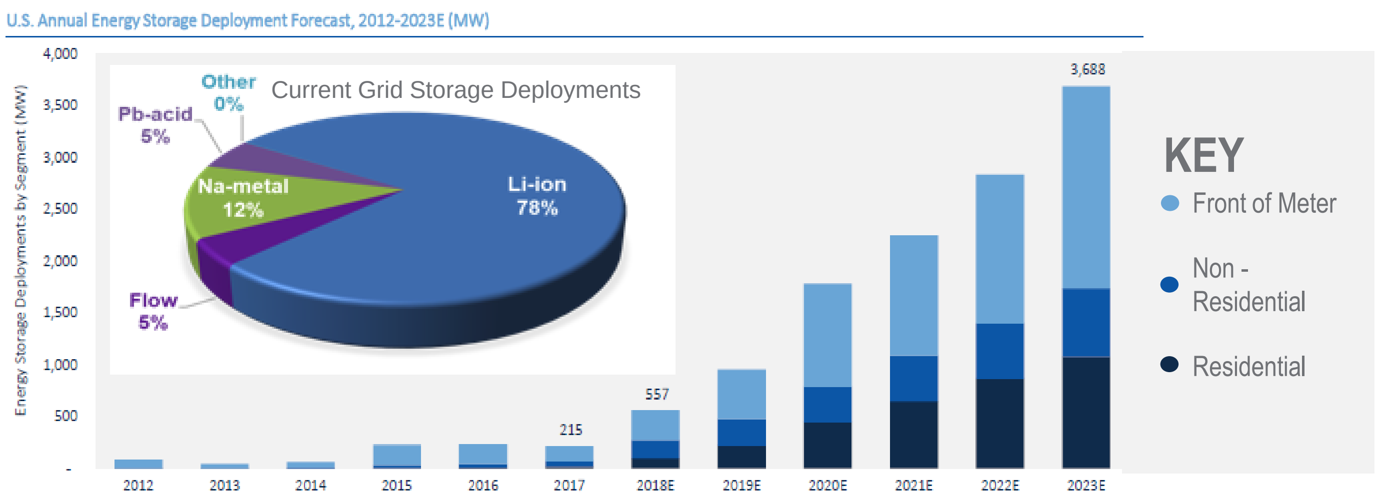
- 0.03% Battery Energy Storage
- 2.2% Battery + Pumped Storage

Source: DOE Global Energy Storage Database
http://www.energystorageexchange.org/





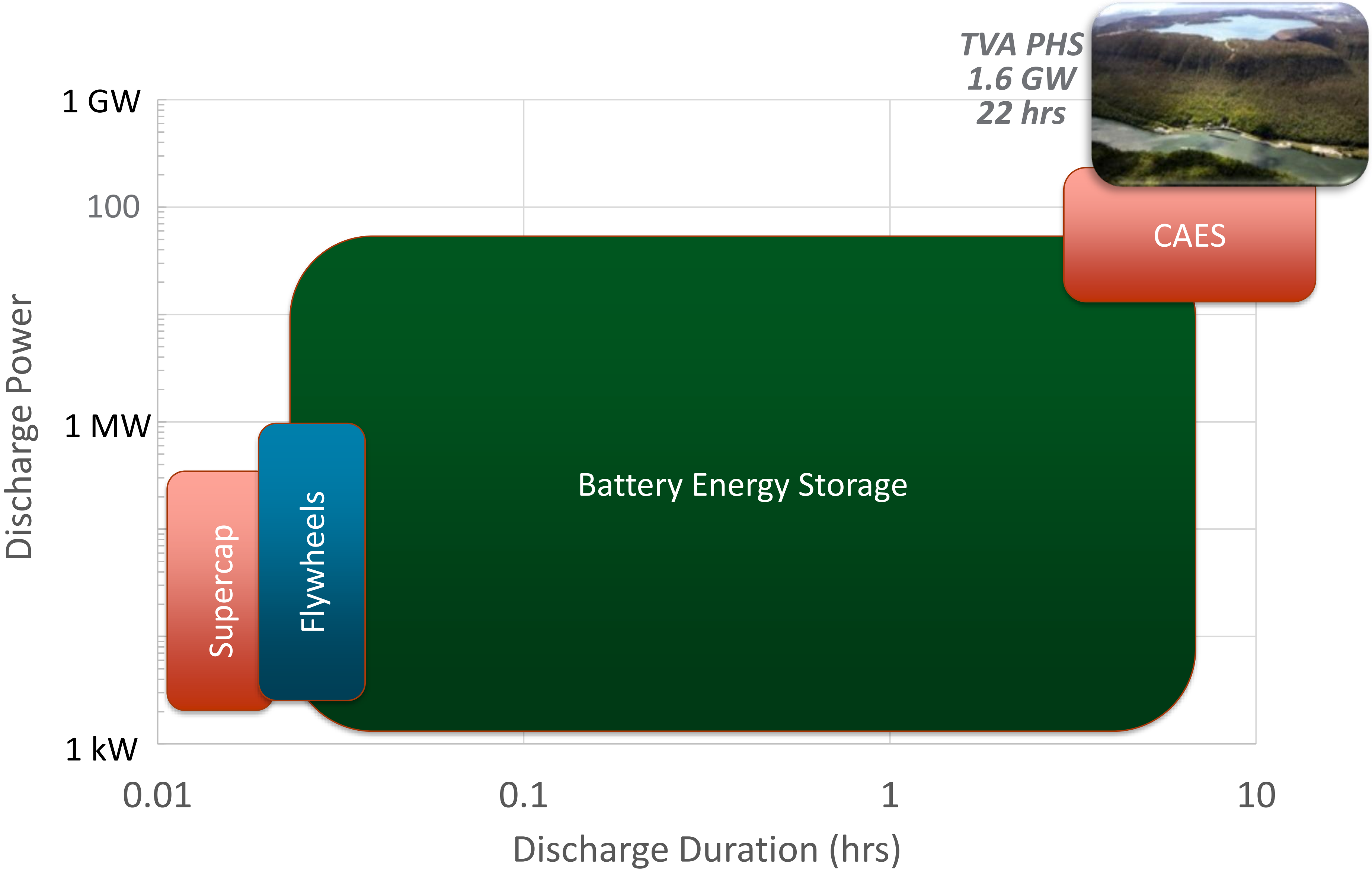
Growth in Battery Energy Storage over Past Decade



However

- Grid-Scale Energy Storage still < 0.1% of U.S. Generation Capacity
- EV's < 1% of vehicles sold in U.S.

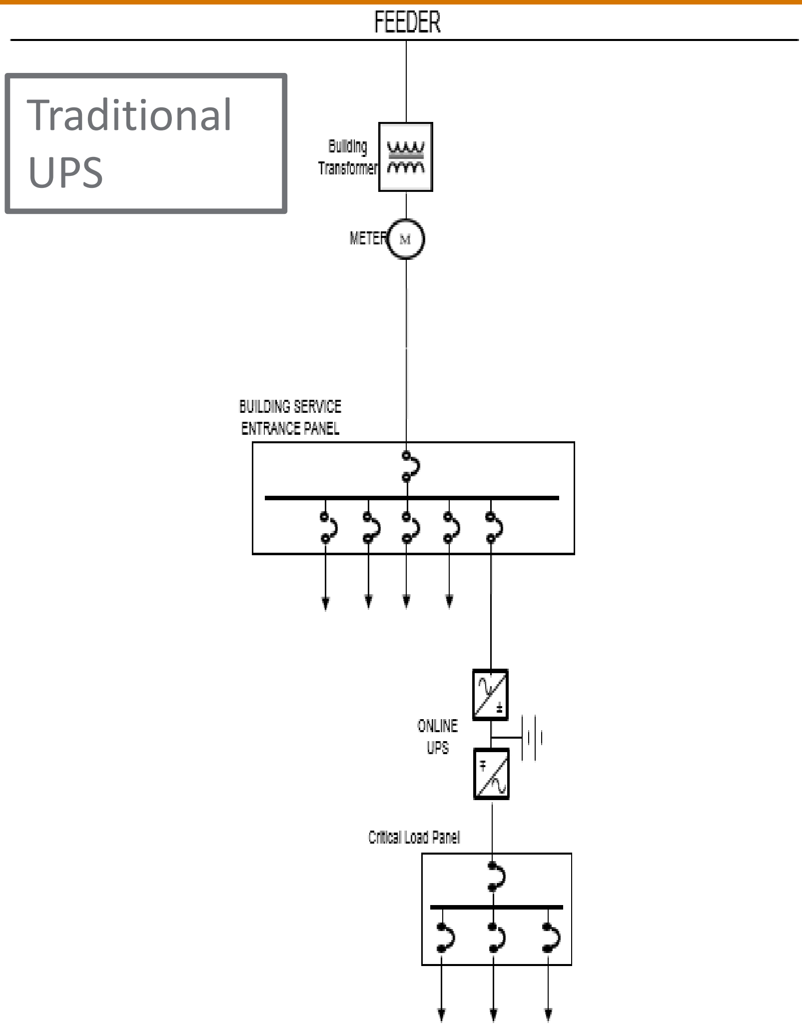
Energy Storage Performance Ranges

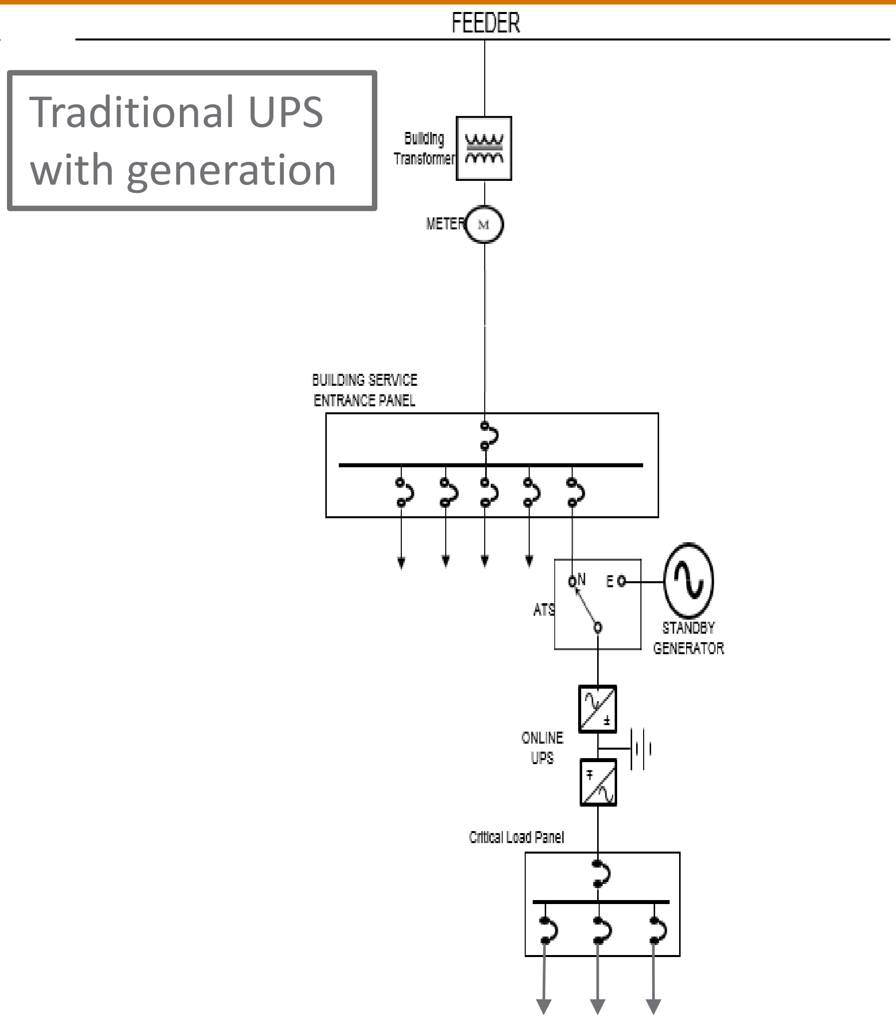


Basic Battery Terminology

- Electrochemical Cell: Cathode(+), Anode (-), and Electrolyte (ion conducting intermediate)
- Energy (KWh) = Ability to do work.
- Power (KW) = The rate at which the work is being done.
- Dan's definition
  - ES- KW – The Capacity of the Energy Storage System i.e, 1KW
  - ES – KWh – The Capacity multiplied by the time (hour) rating of the system
    - A 1KW 2 hour system = 2KWh
    - Example - If 10 – 100 watt light bubs need to operate for an hour then:
      - 10 x 100W = 1KW * 1 hr = 1KWh
- Energy Density (Wh/kg or Wh/L): used to measure the energy density of battery.
  - Note: number often given for cell, pack, and system
  - Generally: pack = ½ cell energy density, and system is fraction of the pack.
- $/KWh = Capital cost of the energy content of a storage device.
- $/KW – Capital cost of power content of a storage device.

Energy Storage System (ESS) is NOT the same as an Uninterruptable Power Supply (UPS)





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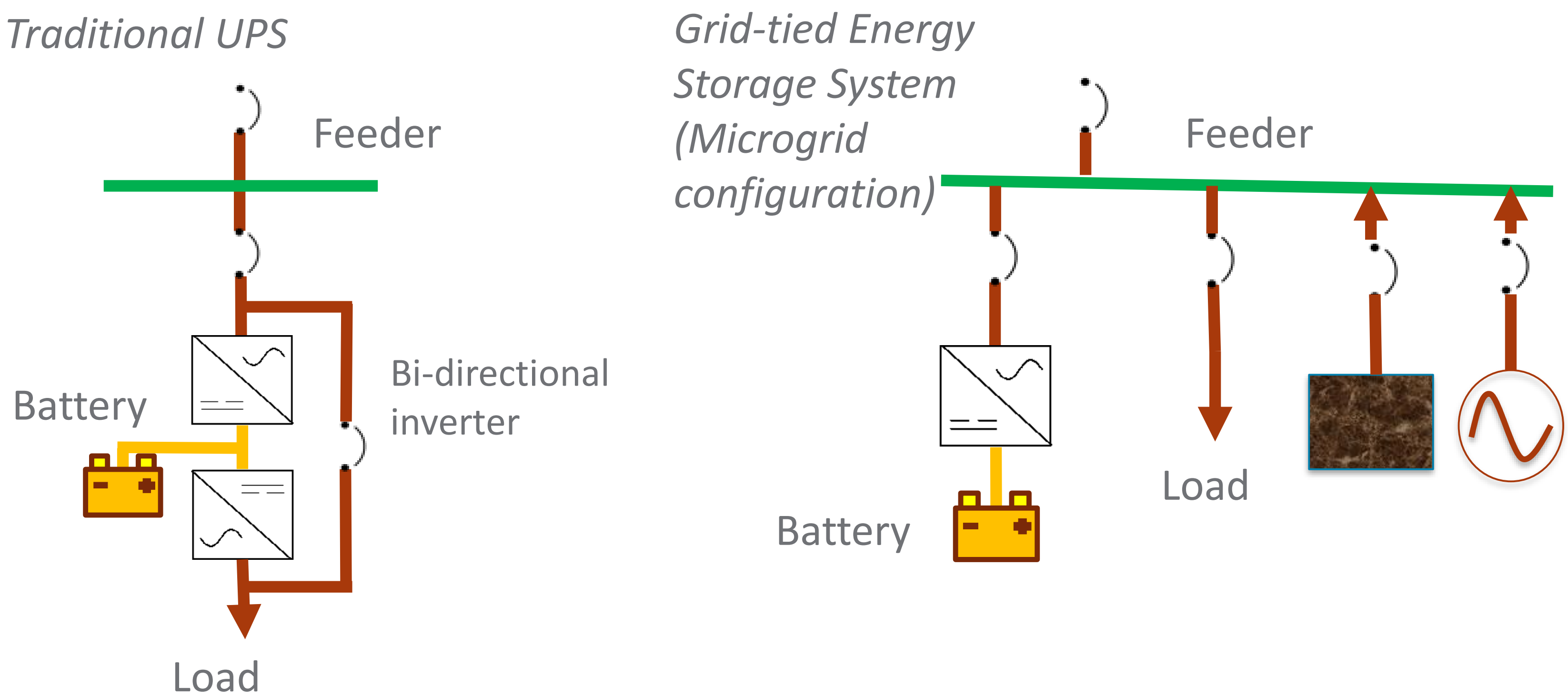


- Seamless Transition is Possible
- Does not require external signal to trigger Voltage source mode

- Less Equipment = Lower Capital Cost
- Easily Expandable
- Simple Controls
- To date seamless transition is difficult

Elements of Battery Energy Storage

Storage

- Storage device
- Battery Management & Protection (BMS)
- Racking
- $/KWh
- Efficiency
- Cycle life

Power Control System (PCS)

- Bi-directional Inverter
- Switchgear
- Transformer
- Interconnection
- $/KW

Energy management System (EMS)

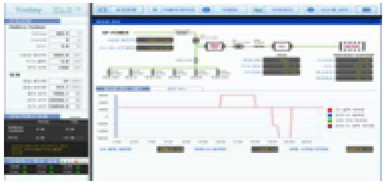
- Charge / Discharge
- Load Management
- Ramp rate control
- Grid Stability
- Monitoring
- $

Site Management System (SMS)

- DER control
- Synchronization
- Islanding
- Microgrid
- $

Balance of Plant

- Housing
- Wiring
- Climate control
- Fire protection
- Permits
- $



NOTE: All–in can increase cost by 2-4x.

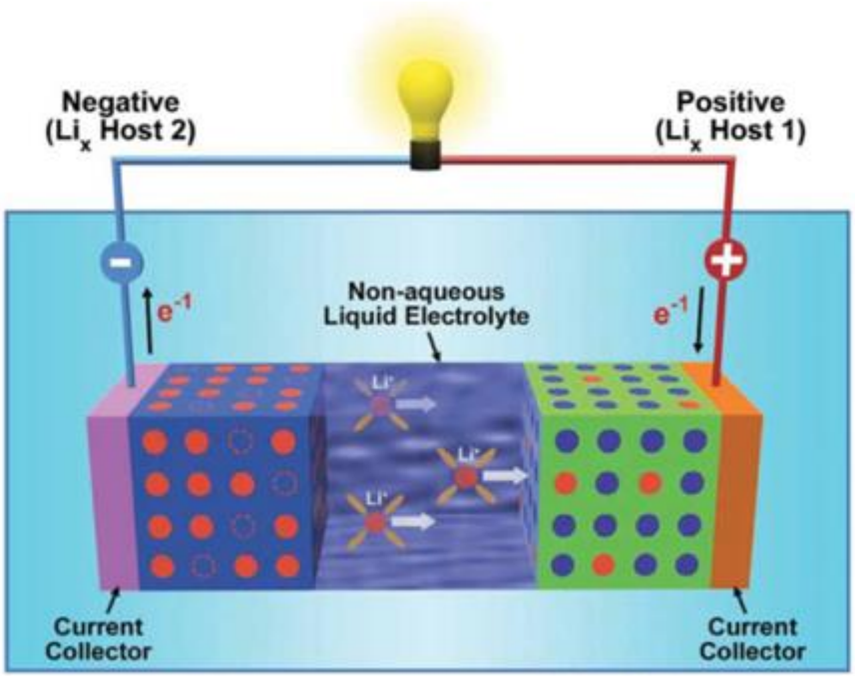
Lithium-ion Batteries

- <u>Advantages</u>
  - High energy density
  - Better cycle life than Lead - Acid
  - Decreasing costs – Stationary on coattails of increasing EV.
  - Ubiquitous – Multiple vendors
  - Fast response
  - Higher efficiency* (Parasitic loads like HVAC often not included)
- Applications
  - Traditionally a power battery but cost decreases and other factors allow them to used in energy applications

SCE/Tesla 20MW -80MWh Mira Loma Battery Facility

SCE Tehachapi plant, 8MW - 32MWh.

Lithium-ion: Basic Chemistries

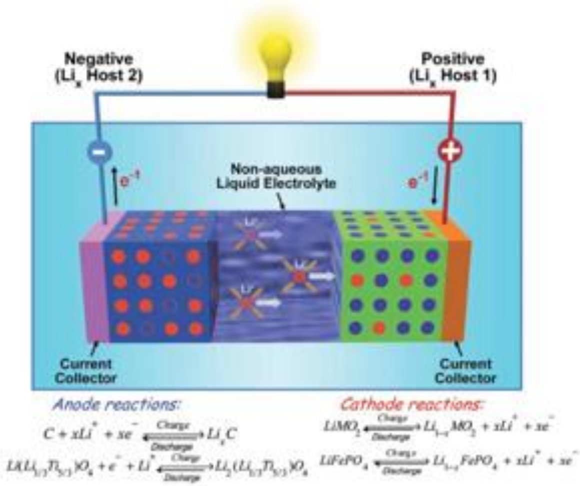


Anode: $$Li_xC_6 \xrightarrow{discharge} xLi^+ + xe^- + C_6$$

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

Source: Z. Yang JOM September 2010, Volume 62, Issue 9, pp 14-23

Lithium-ion: Basic Chemistries



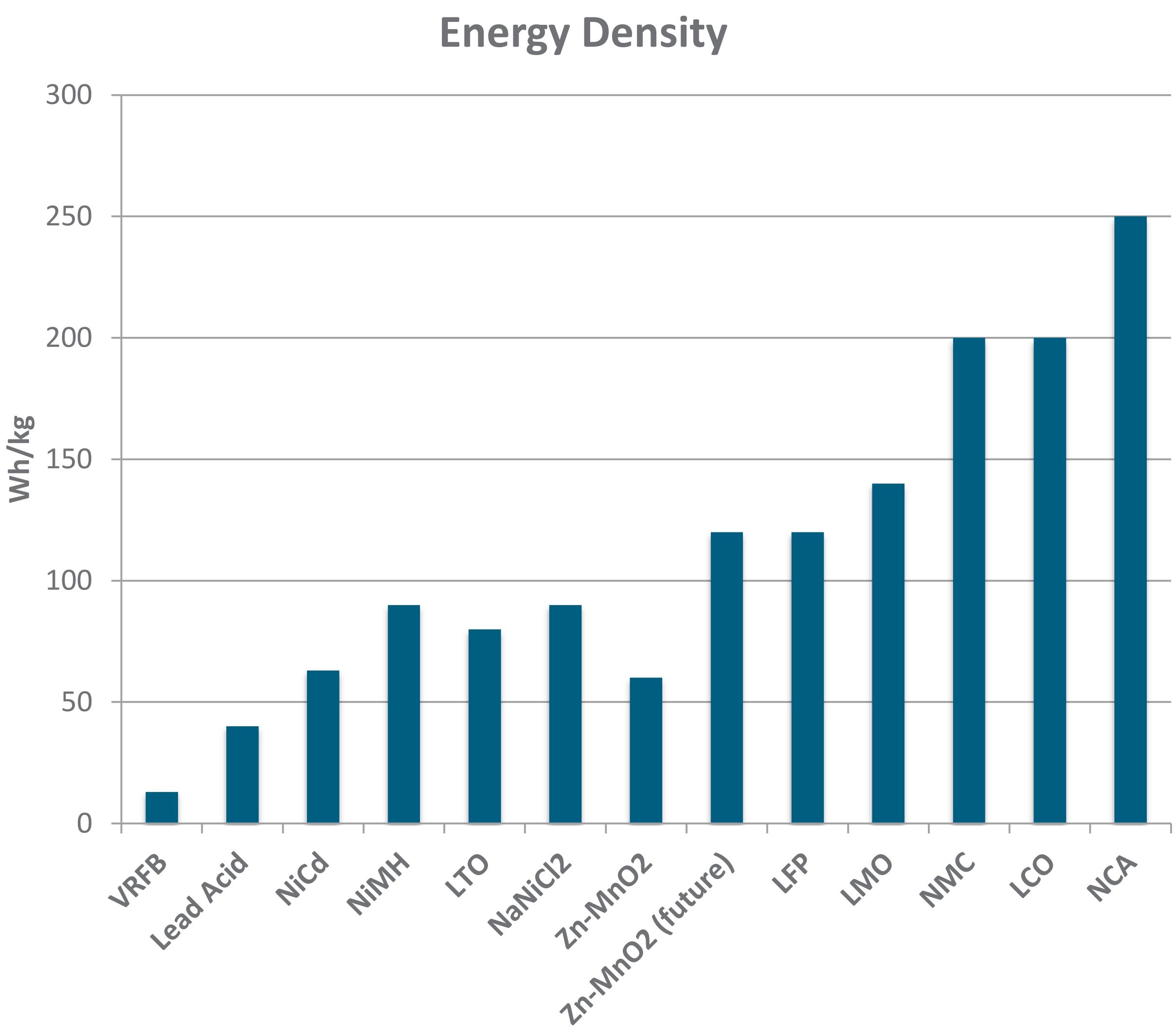
Anodes

Chemistry	Specific Capacity	Potential vs. Li⁺/Li	
Soft Carbon	< 700	< 1	
Hard Carbon	600	< 1	
$Li_4Ti_5O_{12}$	175 / 170	1.55	LTO
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	*iphone*
$LiNiO_2$	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	

Battery Technologies and their Energy Densities



Abbreviation	Name
VRFB	Vanadium Redox Battery
Lead Acid	Lead Acid
NiCd	Nickel Cadmium
NiMH	Nickel Metal Hydride
LTO	Lithium Titanate
LFP	Lithium Iron Phosphate
LMO	Lithium Ion Manganese Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
LCO	Lithium Cobalt Oxide
NCA	Lithium Nickel Cobalt Aluminum Oxide
Zn-MgO2	Zinc Manganese Oxide
NaNiCl2	Sodium Nickel Chloride (Zebra)

Curtesy of: Battery University

Tesla Battery Pack: 85 kWh

http://insideevs.com/look-inside-a-tesla-model-s-battery-pac/
http://club.dx.com/forums/forums.dx/threadid.457734

7,104 cells

18650 cell format used in 85 kWh Tesla battery

A system like 20MW -80MWh Mira Loma Battery Storage Facility would require at least 6.7 million of these 18650 cells

Why this form factor?

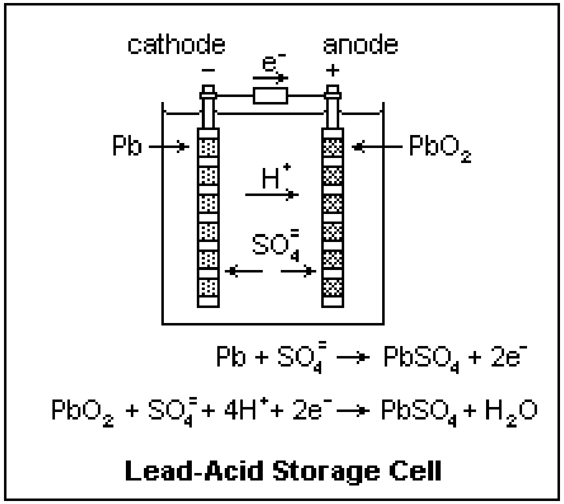
Li-ion Batteries: Summary

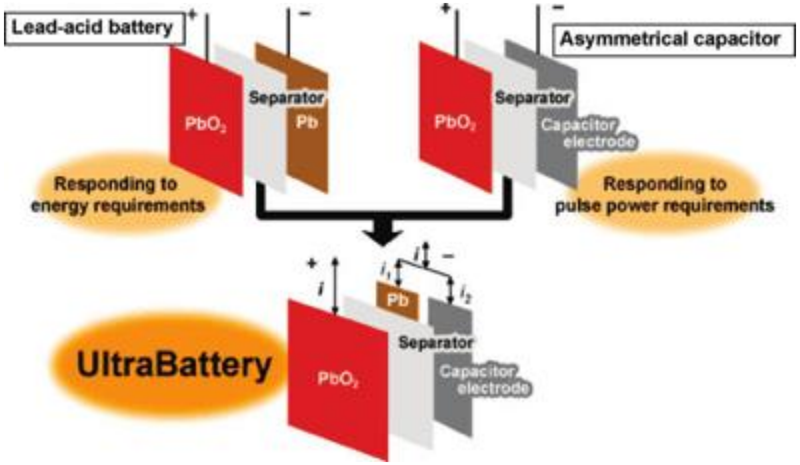
- For grid applications
  - Costs coming down in lithium-ion batteries. However, BOM constitute ~70-80% of cell cost.
  - Need lower manufacturing costs, currently in the $300-400 range for a 1KWh of manufacturing capacity
  - Excess capacity in the large format automotive batteries driving the market for applications in the grid
- However
  - Safety and reliability continues to be a concern
  - Power control and safety adds significant cost to Li-ion storage
  - Packaging and thermal management add significant costs
  - Deep discharge cycle life issues for energy applications (1000 cycles for automotive)

Takeaway:
Need to manage the battery to limit the DoD, charge rate, ambient temperature.

Lead-Acid: Basic Chemistry and Issues

- **Overall Reaction**
  - $Pb(s) + PbO_2(s) + 2H2SO_4(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l)$
  - OCV ~ 2.0 V
- **Flooded lead-acid**
  - Requires continuous maintenance
  - Most common
- **Sealed lead-acid**
  - Gel and Absorbed Glass Mat (AGM)
  - More temperature dependent
- **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 H_2 evolution.
  - Sulfation from prolonged storage

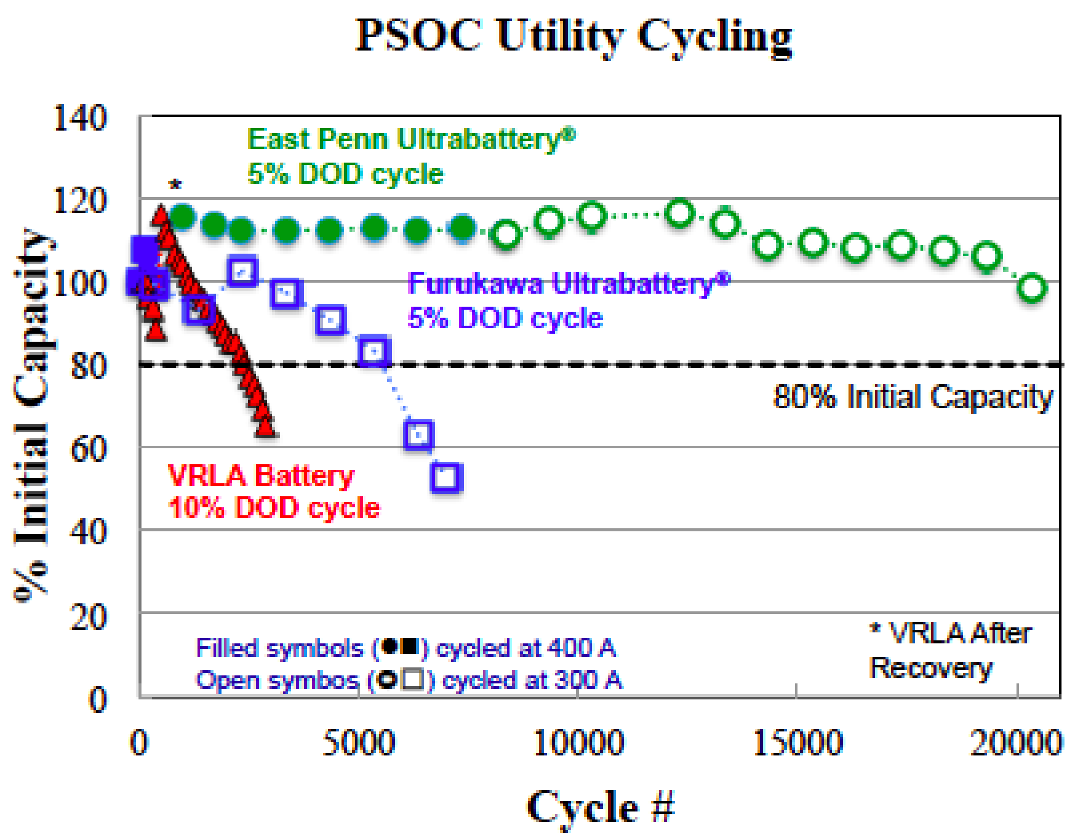




http://www.ultrabattery.com/technology/ultrabattery-technology/

Advanced Lead Acid: Testing at Sandia

East Penn



http://www.sandia.gov/batterytesting/docs/LifeCycleTestingEES.pdf

Sodium Metal Batteries (NaS, NaNiCl2..)

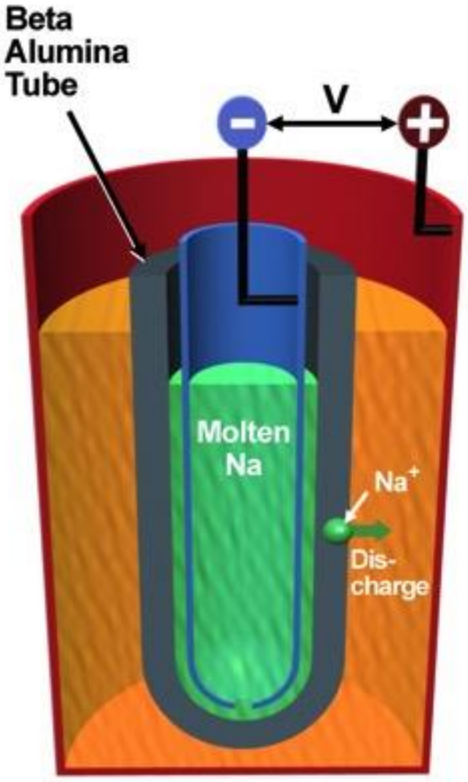
- Two primary Sodium chemistries
  - NaS mature grid technology developed in 1960's
    - High energy density -Long discharge cycles
    - Fast response- Long life
    - High operating temperature (250-300C)
    - 530 MW/3700MWh installed primarily in Japan (NGK)
  - $NaNiCl_2$, (Zebra)mature, more stable than NaS. Developed in South Africa in 1980's
    - FIAMM in limited production
    - Large cells and stable chemistry
    - Lower temperature than NaS
    - Cells loaded in discharge mode
    - Addition of NaAlCl4 leads to a closed circuit on failure
    - High efficiency, low discharge
    - Long warm up time (16 hr)
- Neither NaS nor $NaNiCl_2$ are at high volumes of production for economies of scale

NGK 34MW - 245 MWh NaS, Rokkasho, Japan

FIAMM Sonick Na-$NiCl_2$ Battery Module

Na-Metal Batteries: Basic Chemistry

- Batteries consisting of *molten sodium anode* and *β"-Al_2O_3 solid electrolyte* (BASE).
  - Use of low-cost, abundant sodium → low cost
  - High specific energy density (120~240 Wh/kg)
  - Good specific power (150-230 W/kg)
  - Good candidate for energy applications (4-6 hrs discharge)
  - Operated at relatively high temperature (300~350°C)



- **Sodium-sulfur (Na-S) battery**
  - **$2Na + xS \rightarrow Na_2S_x$** (x = 3~5)
    - E = 2.08~1.78 V at 350°C
- **Sodium-nickel chloride (Zebra) battery**
  - **$2Na + NiCl_2 \rightarrow 2NaCl + Ni$**
    - E = 2.58V at 300°C
    - Use of catholyte ($NaAlCl_4$)

Na-Metal Batteries: Advantages/Issues

- **Temperature**
  - Less over-temperature concerns, typical operating window 200-350C. additional heaters needed when not in use.
  - At < 98°C, Na metal freezes out, degree of distortion to cell dictated by SOC of battery (amount of Na in anode)
- **Charging/Discharging Limitations**
- **Safety Concerns**
  - Solid ceramic electrolyte keeps reactive elements from contact. Failure in electrolyte can lead to exothermic reaction (Na-S)

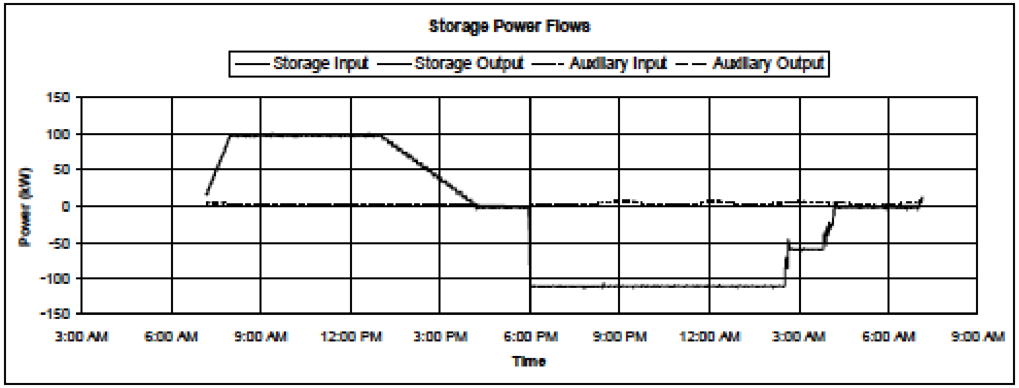


Figure 2. Regime 6 storage charge/discharge profile (measured 2/5/2004).

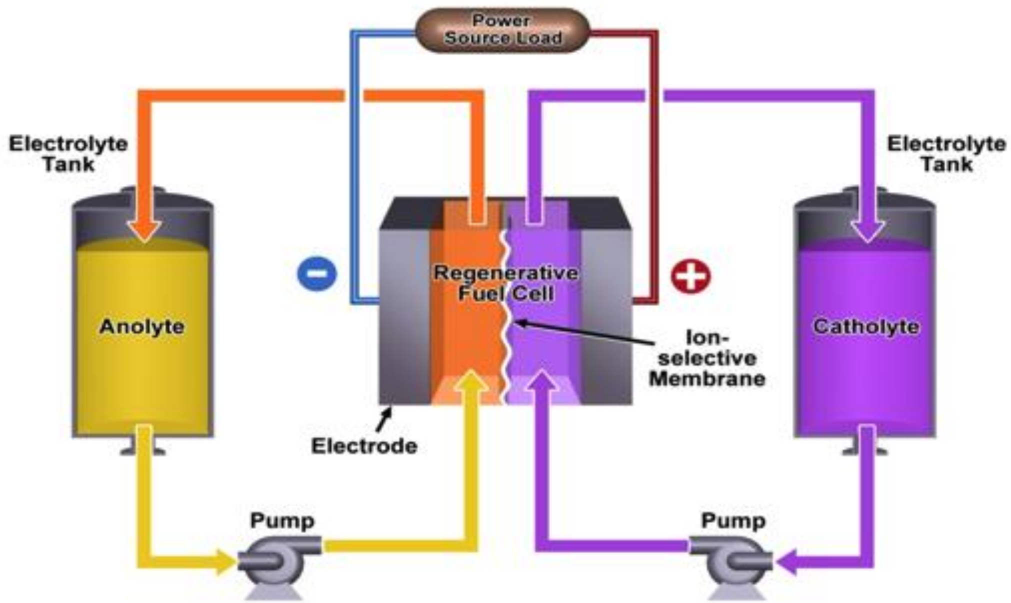
Flow Batteries

- Flow Battery Energy Storage
  - Long cycle life
  - Power/Energy decomposition
  - Lower efficiency
- Applications
  - Ramping
  - Peak Shaving
  - Time Shifting
  - Power quality
  - Frequency regulation
- Challenges
  - Developing technology
  - Complicated design
  - Lower energy density

UET - AVISTA, Pullman, WA. 1.0MW – 3.2 MWh.

Vionx Vanadium Redox Flow battery, 65kW - 390kWh

Redox Flow Battery: Basic Chemistry



Key Aspects

- Power and Energy are separate enabling greater flexibility and safety.
- Suitable for wide range of applications 10's MW to ~ 5 kw
- Wide range of chemistries available.
- Low energy density ~ 30 Whr/kg
- Lower energy efficiency

Flow Batteries - Future

- The flexibility of redox flow battery technology offers the potential to capture multiple value streams from a single storage device.
- Current research has demonstrated high power conditions can be achieved with minimal impact in stack efficiency.
- Next generation RFB technology based on Aqueous Soluble Organics (ASO) being developed to replace vanadium species.
- Continued cost reductions in Li-ion technology will be driven by EV/PHEV deployments. RFB may be able to achieve similar cost targets at ~ 100X lower production volume.

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

Note: Looking for operational data to evaluate claims.

Rechargeable Alkaline Batteries

Primary Chemistries

- NiMH
- Ni-Fe
- Zn-Ni
- Zn-MnO_2

For low cost grid storage applications, Zn-MnO_2 has compelling attributes.

History of Rechargeable Zn-MnO_2 Alkaline Batteries

- Long history of research on making Zn-MnO_2 rechargeable.
  - Several commercial products based on cylindrical formats (Rayovac, BTI).
  - All focused on cylindrical designs for consumer markets.

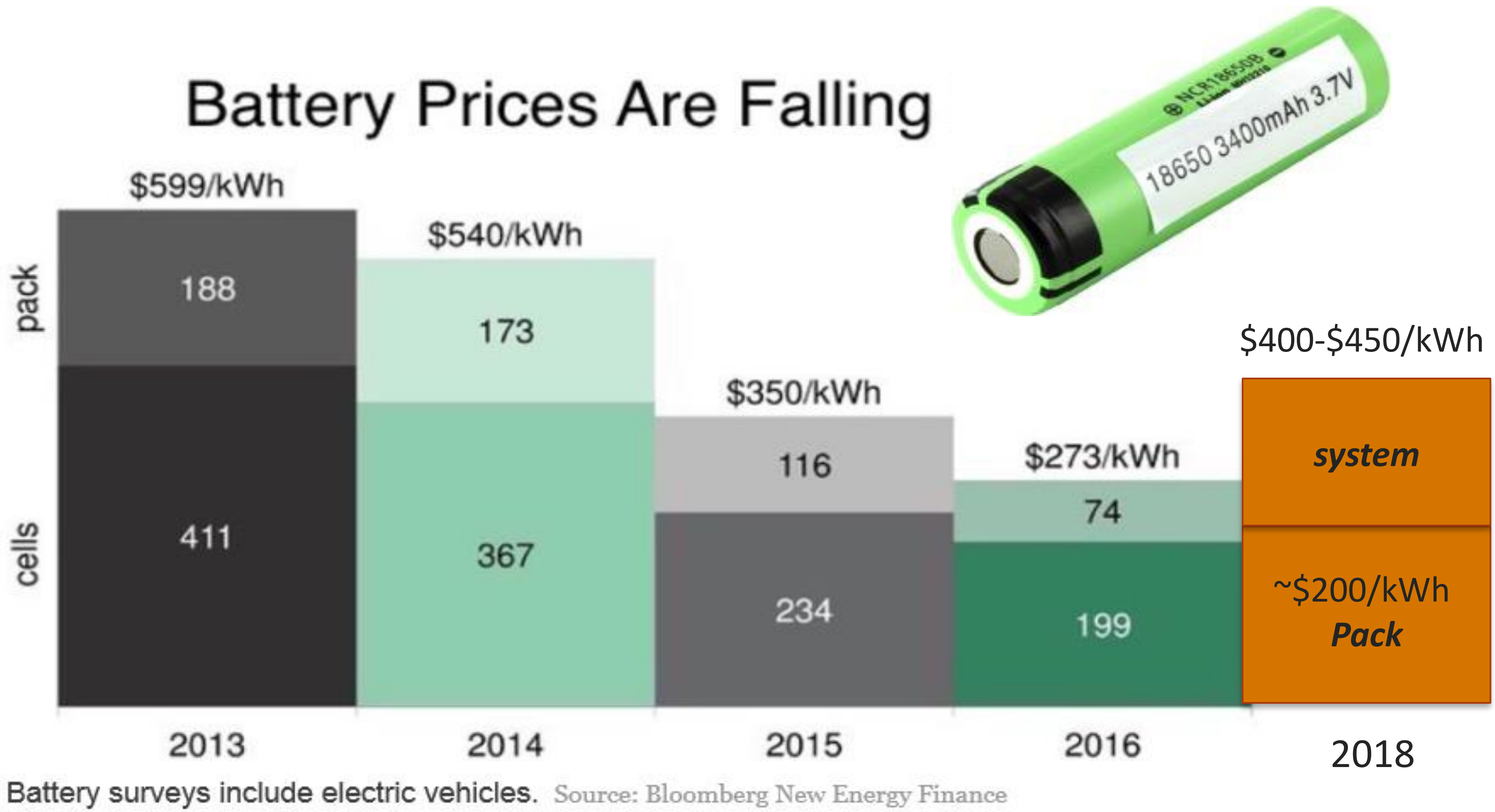
Cylindrical cells

No flexibility to change criticalparameters.

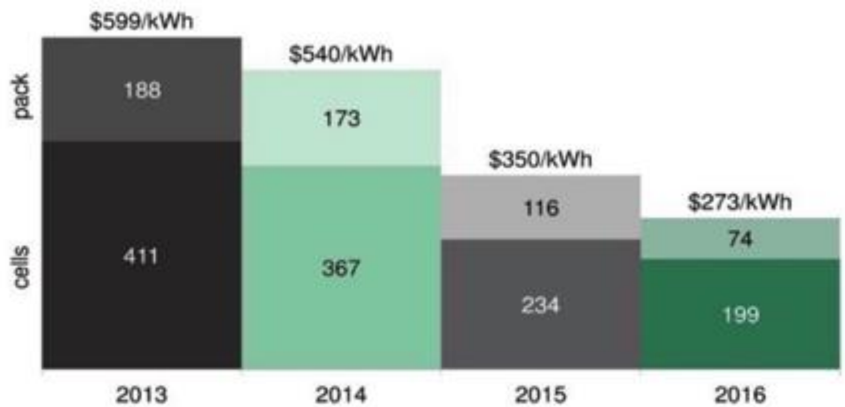
- Traditionally primary batteries
- Lowest bill of materials cost, lowest manufacturing capital expenses
- Established supply chain for high volume manufacturing
- Readily be produced in larger form factors for grid applications
- Do not have the temperature limitations of Li-ion/Pb-acid
- Are inherently safer, e.g. are EPA certified for landfill disposal.
- ❖ Until recently reversibility of Zn/MnO2 has been challenging

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

Lithium Ion Battery Prices



Cell price is not only driver for further cost reduction

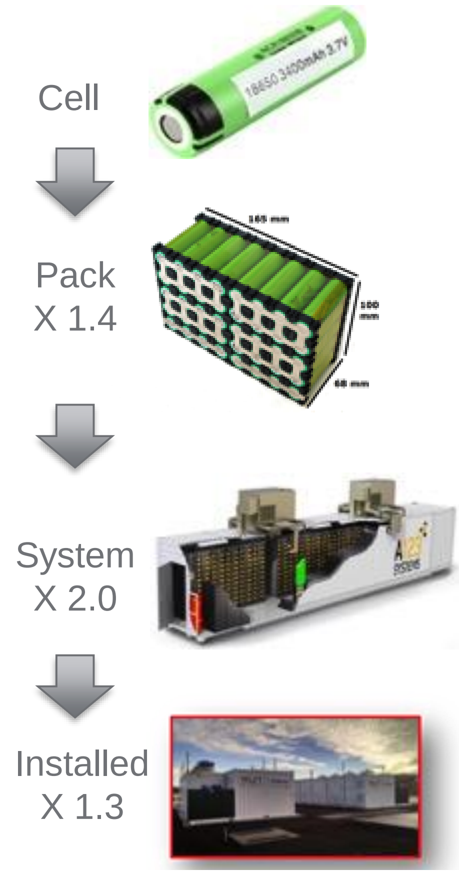


Battery surveys include electric vehicles. Source: Bloomberg New Energy Finance

$80/kWh cell

↓

$~300/kWh installed



Future cost reduction requires addressing the entire suite of barriers for continued deployment of energy storage

Cost Competitive Technologies

U.S. DEPARTMENT OF ENERGY | Electricity Delivery & Energy Reliability

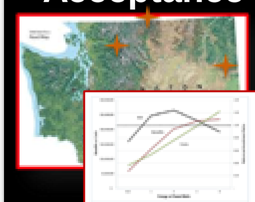
Redox Flow

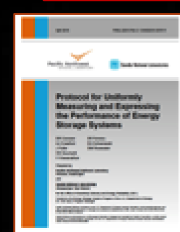
Sodium

Zn-MnO_2

Safety and Reliability

Industrial Acceptance





Regulatory Support

Oregon PUC Public Utility Commission

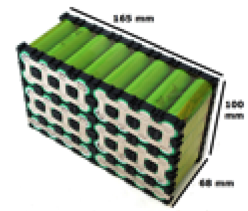
PUCN

CO DORA

WASHINGTON UTC UTILITIES AND TRANSPORTATION COMMISSION

Cell

Pack
X 1.4



System
X 2.0

Installed
X 1.3

Energy Storage Systems

- The process of making batteries into energy storage requires a significant level of systems integration including packaging, thermal management systems, power electronics and power conversion systems, and control electronics.
- System and engineering aspects represent a significant cost and component, and system-level integration continues to present significant opportunities for further research.

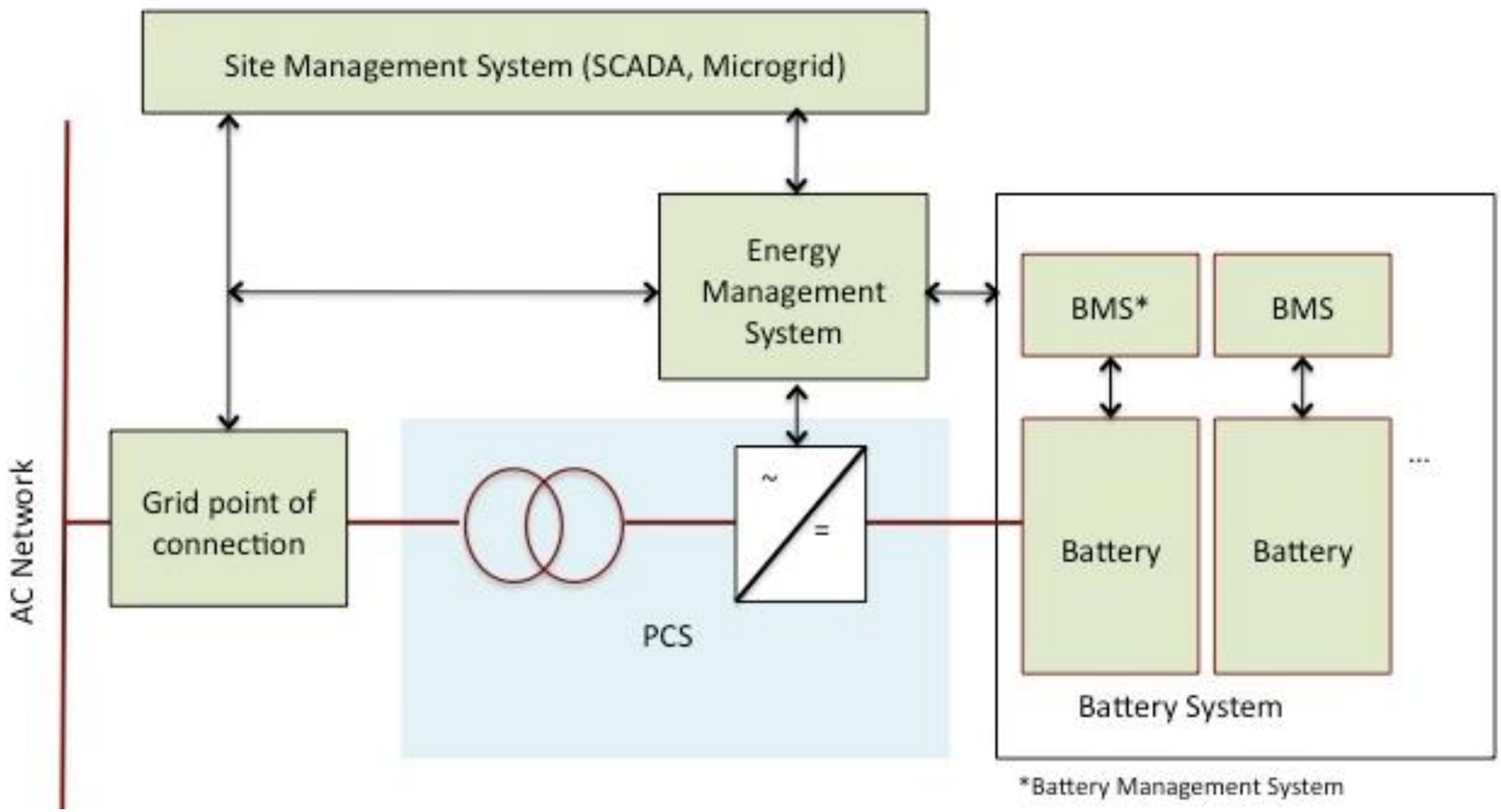
Random Musings:

1. Have an overall system integrator (Prime).
2. Assure the Prime is experienced with batteries.

Battery Energy Storage System

In addition to the Batteries:

- Battery Management System
- Power Conditioning System (PCS)
- Energy Management System
- Balance-of-Plant
- Site Management System
- Data Acquisition System



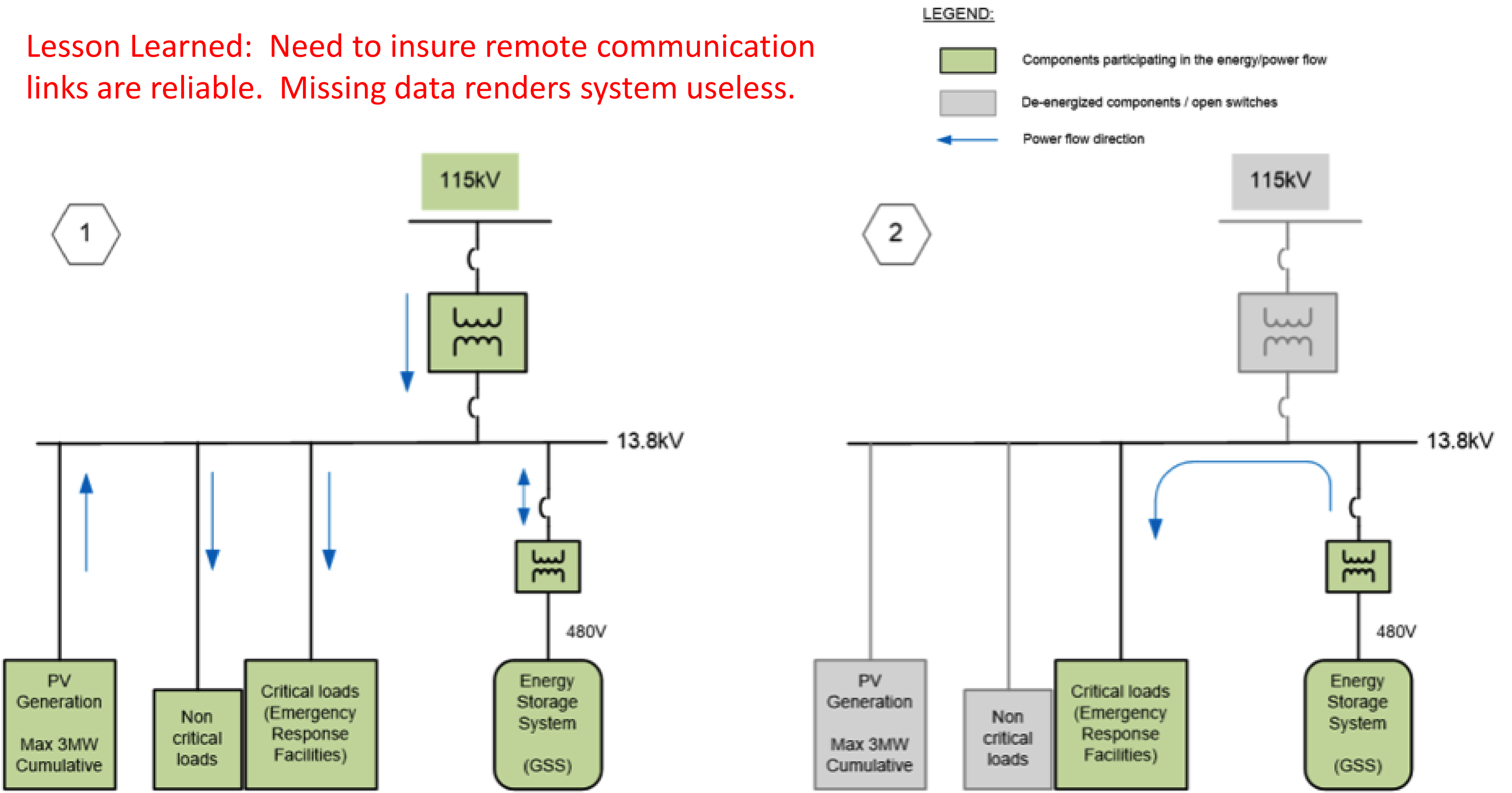
Data Acquisition System (DAS)

- DAS monitors battery performance for operation, performance, efficiency and capacity fade
- Remote access & Time stamp of data
- Sampling rate
- 30+ day on-board memory

General Monitoring Parameters for ESS and Balance of Plant	
AC Voltage(V)	Current(I)
Kwh in (efficiency)	Kwh out(efficiency)
Balance of plant monitoring	State of Charge(SOC)
System Temperature	Ambient Temperature
Frequency	DC Voltage
Cell Temperature	System KW
Ramp Rate	System KVA
Response Time	Grid Monitoring

Overview of DAS Connections

Lesson Learned: Need to insure remote communication links are reliable. Missing data renders system useless.



Acknowledgements

This work was supported by
US DOE Office of Electricity
We thank Dr. Imre Gyuk, Manager of the DOE Energy Storage Program.

U.S. DEPARTMENT OF ENERGY

Many thanks to the Grid Energy Storage teams at Sandia, PNNL, and numerous collaborative partners at universities and the industry.

Thank you for attending our webinar

Todd Olinsky-Paul
Project Director, CESA
todd@cleanegroup.org

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Upcoming Webinars

Enabling High Penetrations of Distributed Solar through the Optimization of Sub-Transmission Voltage Regulation
Thursday, March 28, 1-2pm ET

Energy Storage in State Energy Efficiency Plans: Lessons from Massachusetts
Thursday, April 4, 1-2pm ET

Net Energy Metering, Distributed Solar Valuation, and Rate Design
Tuesday, April 9, 1-2pm ET

Read more and register at: www.cesa.org/webinars