Grid Energy Storage Chemistries and Technologies

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Agenda

- Brief Overview of DOE Office of Electricity (OE) Energy Storage Program
- Current State of Battery Chemistries and Technology
- Introduction to Topic Areas for Consideration
Grid Scale Energy Storage Market is growing

2018
• 310 MW/777 MWh new storage deployments in US.¹

Market Penetration
• Grid-Scale Battery Storage still < 0.1% of U.S. Generation Capacity
• EV’s < 1% of vehicles sold in U.S.

¹ Market Penetration data from Wood Mackenzie P&R / ESA | U.S. energy storage monitor 2018 YIR and Q1 2019
Grid Energy Storage deployments  
(Operational as of Nov. 2017)

Energy Storage Comparison

Globally

- 1.7 GW - Battery Energy Storage (BES)
- ~170 GW - Pumped Hydro Storage (PHS)

U.S.

- 0.33 GW BES
- 22.7 GW PHS

% of U.S. Generation Capacity

- 0.03% BES
- 2.2% BES + PHS

Source: DOE Global Energy Storage Database
http://www.energystorageexchange.org/  Nov. 2017
Mapping of Grid Scale Energy Storage Deployments from DOE Energy Storage Database.
OE Energy Storage Program

Objectives

Cost Competitive Technology
- Materials and chemistry
- Systems and manufacturing
- Cost reduction
- Expanded applications

Reliability & Safety
- Lab testing
- Codes and standards
- Expected lifetime
- R&D Improvements

Regulatory Environment
- Policy analysis
- Valuation methods
- Resolution of benefits

Industry Acceptance through Demonstrations
- Stakeholder engagement
- Proving success
- Seamless integration
- Consumer benefits
OE Energy Storage Program Engagement Map

Utility Partners
AL, AK, AZ, CA, CO, MA, HI, NM, NY, OR, TN, VT, WA, VA

University Partners
AK, CA, KY, MA, MI, MO, NC, NM, NY, OH, PA, SC, SD, TN, TX, UT, WA, WV

Regulatory Engagements
CA, HI, NV, OR, UT, WA

Laboratories
Where Energy Storage Technologies Fit In
Storage Technology and Application Markets

However

- Grid-Scale Energy Storage still < 0.1% of U.S. Generation Capacity
- EV’s < 1% of vehicles sold in U.S.
Increased adoption a result of Falling Lithium Ion Battery Prices

Battery surveys include electric vehicles.  Source: Bloomberg New Energy Finance
Li-ion Batteries

► Advantages
  ■ 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.
Li-ion: Basic Chemistry

Anode: \[ Li_xC_6 \xrightarrow{\text{discharge}} xLi^+ + xe^- + C_6 \]

\[ Li_{1-x}CoO_2 + xLi^+ + xe^- \xrightarrow{\text{discharge}} LiCoO_2 \quad \text{Cathode:} \]

### Li-ion: Basic Chemistries

#### Cathodes

<table>
<thead>
<tr>
<th>Chemistry</th>
<th>Specific Capacity</th>
<th>Potential vs. Li⁺/Li</th>
<th>Anode: Cathode Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCoO₂</td>
<td>273 / 160</td>
<td>3.9</td>
<td>iphone</td>
</tr>
<tr>
<td>LiNiO₂</td>
<td>274 / 180</td>
<td>3.6</td>
<td>NMC – LG/Volt</td>
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<tr>
<td>LiNi₄Co₄Mn₂O₂</td>
<td>~ 270 / 150~180</td>
<td>3.8</td>
<td></td>
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<tr>
<td>LiNi₄Co₄Al₂O₂</td>
<td>~ 250 / 180</td>
<td>3.7</td>
<td>NCA - Tesla</td>
</tr>
<tr>
<td>LiMn₂O₄</td>
<td>148 / 130</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>LiMn₁₅Ni₀₅O₄</td>
<td>146 / 130</td>
<td>4.7</td>
<td></td>
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<tr>
<td>LiFePO₄</td>
<td>170 / 160</td>
<td>3.45</td>
<td></td>
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<tr>
<td>LiMnPO₄</td>
<td>171 / 80~150</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>LiNiPO₄</td>
<td>166 / -</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>LiCoPO₄</td>
<td>166 / 60~130</td>
<td>4.8</td>
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</table>

#### Anodes

<table>
<thead>
<tr>
<th>Chemistry</th>
<th>Specific Capacity</th>
<th>Potential vs. Li⁺/Li</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Carbon</td>
<td>&lt; 700</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Hard Carbon</td>
<td>600</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Li₄Ti₅O₁₂</td>
<td>175 / 170</td>
<td>1.55</td>
</tr>
<tr>
<td>TiO₂</td>
<td>168 / 168</td>
<td>1.85</td>
</tr>
<tr>
<td>SnO₂</td>
<td>782 / 780</td>
<td>&lt; 0.5</td>
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<tr>
<td>Sn</td>
<td>993 / 990</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Si</td>
<td>4198 / &lt; 3500</td>
<td>0.5 ~ 1</td>
</tr>
</tbody>
</table>

#### LFP

- TiO₂
- LiFePO₄

#### LTO

- SnO₂
- LiNiPO₄
- LiCoPO₄

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*Graphical representation of Li-ion cell with negative (Li⁺ Host 2) and positive (Li⁺ Host 1) electrodes.*

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*Table showing specific capacity and potential vs. Li⁺/Li for various cathode materials.*
Energy Density of Li-ion Chemistries

1.Courtesy courtesy of Battery University
Tesla Battery Pack
85 kWh

7,104 cells

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: SOA

For grid applications
- Costs coming down in LIB. However, BOM constitute ~70-80% of cell cost in a LiB.
- Need lower manufacturing costs, currently in the $300-400M range for a 1GWh of manufacturing capacity
- Grid batteries in addition to low BOM and cost of manufacturing
- Excess capacity in the large format automotive batteries driving the market for applications in the grid

However
- Safety and reliability continues to be significant concerns
- 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)

Take Away: Need to manage the battery to limit the DoD, charge, ambient temperature.
Lead-Acid: Basic Chemistry and Issues

**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

**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

http://www.ultrabattery.com/technology/ultrabattery-technology/
Advanced Lead Acid: Testing at Sandia National Laboratories

Take Away: Lower energy density than lithium ion and shorter cycle life

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 (250-300°C)
    - 530 MW/3700MWh installed primarily in Japan (NGK)

  - NaNiCl₂ (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 NaNiCl₂ are at high volumes of production for economies of scale
Na-Metal Batteries
Basic Chemistry

- Batteries consisting of *molten sodium anode* and *β"'-Al₂O₃ 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**
  - \(2\text{Na} + x\text{S} \rightarrow \text{Na}_2\text{S}_x\) (\(x = 3\sim5\))
    - \(E = 2.08\sim1.78\) V at 350°C

- **Sodium-nickel chloride (Zebra) battery**
  - \(2\text{Na} + \text{NiCl}_2 \rightarrow 2\text{NaCl} + \text{Ni}\)
    - \(E = 2.58\) V at 300°C
    - Use of catholyte (NaAlCl₄)
Na-Metal Batteries
Advantages/Issues.

**Temperature**
- Less over-temperature concerns, typical operating window 200-350°C. 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)

**Take Away:** Limited commercially availability for deployment and requires constant energy input to maintain temperature
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
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
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.

Take Away: Flow batteries are potentially well suited to grid storage but not as mature as lithium ion
Non-Aqueous Flow Chemistries

- Wider voltage window
- Higher charge cycle efficiency
- Decreased temperature sensitivity
- Increased cycle life
- Favorable cost projections

Aqueous vanadium (+5) speciation chemistry is complex!

**Major Challenge:** Getting high concentrations of redox active species.
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

Take Away: 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.

- Traditionally primary batteries
- Lowest bill of materials costs and manufacturing capital expenses
- Established supply chain for high volume
- 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.

- Reversibility of Zn/MnO$_2$ has been challenging


Take Away: Low cost and robust to temperature but cycle life needs a breakthrough to be viable.
Super Capacitors

- **Capacitor Energy Storage**
  - Very long life
  - Highly reversible and fast discharge, low losses

- **Applications**
  - Power quality
  - Frequency regulation
  - Regenerative braking (vehicles)

- **Challenges**
  - Cost

Ultra capacitor module, designed for vehicle applications (e.g., buses, trains)
## Battery Technologies

### Mature Technologies

<table>
<thead>
<tr>
<th></th>
<th>World Wide Capacity (GWh/y)</th>
<th>Cost and Performance Improvements</th>
<th>Key Challenges for Energy Storage</th>
<th>Major Suppliers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lead Acid Batteries (LAB)</strong></td>
<td>300</td>
<td>2%/year ((30 year data). $150/kWh</td>
<td>Cycle life. Advanced lead acid cycle life on par with EV grade LIB</td>
<td>JCI, GS Yuesa, EastPenn, EnerSys, Exide, Hagen, Amara Raja</td>
</tr>
<tr>
<td><strong>Lithium Ion Batteries (LIB)</strong></td>
<td>50</td>
<td>8%/year (20 year data). Cell level price reaching $200/kWh</td>
<td>Cycle life for deep discharge. Safety. Thermal management</td>
<td>Panasonic, Samsung, LG Chem, BYD, GS Yuesa (Nissan, Honda JVS), Lishen, JCI, A123, Toshiba. EV Batteries: Converging to NMC chemistry</td>
</tr>
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### Emerging Technologies

<p>| | | | | |</p>
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</thead>
<tbody>
<tr>
<td><strong>NaS and NaNiCl</strong></td>
<td>300 MWh</td>
<td>No economies of scale</td>
<td>High temperature chemistry. Safely, Cost</td>
<td>NGK, GE, FIAMM</td>
</tr>
<tr>
<td><strong>Flow Batteries</strong></td>
<td>&lt;200 MWh</td>
<td>Not fully mature. Potential for lower cost. $400/kWh. Reach $270/kWh</td>
<td>Not mature. Has not reached manufacturing scale.</td>
<td>Sumitomo, UET, Rongke Power, ZBB, Gildenmeister. Only Sumitomo provides 18 yr. warranty</td>
</tr>
<tr>
<td><strong>Alkaline chemistries (Na, Zn-MnO2,..)</strong></td>
<td>&lt;100 MWh</td>
<td>Not fully mature. Lowest cost BOM</td>
<td>Has not reached manufacturing scale.</td>
<td>Aquion (Na), UEP (Zn-MnO2), Fluidic Energy (Zn-air)</td>
</tr>
</tbody>
</table>
Cost Trends
Lead Acid Battery business continues to be highly profitable
Li-ion struggling with low factory utilization rates of ~10-20%

Source: Avicenne (2015), DOE
Manufacturing Capex and Starting Materials

- Capex for GWh/yr production capacity
  - Lead acid: $50-60M
  - LIB: $300-400M

- For lead acid and Li-ion, BOM is 80-85% of the cell cost
  - Large format LIB: BOM $180-200/KWh

- For flow batteries, electrolyte cost ~30-40% overall cost

- For comparison, primary alkaline batteries: $18-20/KWh

Source: Roland Berger, 2013
Capex intensive $300-400M /GWh capacity addition
Continued consolidation in the Automotive Li Battery business
Excess capacity driving the need for applications beyond EVs

Source: D. Chang, et al, Automotive Li-ion Battery (LIB) Supply Chain and U.S. Competitive Considerations, NREL/PR--6A50--63354, June 2015
Lithium Ion Battery Prices

Battery surveys include electric vehicles.  Source: Bloomberg New Energy Finance
Cell price not only driver for further cost reduction.

$80/kWh cell

$~300/kWh installed

Battery surveys include electric vehicles. Source: Bloomberg New Energy Finance
Future Cost Reduction requires addressing the Entire Suite of Barriers for Continued Deployment of Energy Storage

**Cost Competitive Technologies**
- Redox Flow
- Sodium
- Zn-MnO$_2$

**Safety and Reliability**

**Industrial Acceptance**

**Regulatory Support**

- Cell X 1.4
- Pack X 1.4
- System X 2.0
- Installed X 1.3
Battery to an Energy Storage system
Elements of an Energy Storage System

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
- $

**Take Away:** All in can increase cost by 2-4x
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.

1. Have overall system integrator (Prime).
2. Insure the Prime is experienced with Battery.
Energy Storage Safety and Reliability
Safety-Related Issues

- ESS ‘product’ configuration and how safety validation is addressed
- New versus existing systems and new versus existing building/facility applications
- Siting (location, loads, protection, egress/access, maximum quantities of chemicals, separation, etc.)
- Ventilation, thermal management, exhausts (when necessary, flow rates, etc.)
- Interconnection with other systems (electrical, any non-electrical sources)
- Fire protection (detection, suppression, containment, smoke removal, etc.)
- Containment of fluids (from the ESS and from incident response)
- Signage
Improving Storage Safety

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
Many ESS safety related issues are identical or similar to those associated with other technologies

Some safety issues are unique to energy storage in general and others only to a particular energy storage technology

Current codes and standards provide a basis for documenting and validating system safety

- prescriptively
- through alternative methods and materials criteria

Codes and standards are being updated and new ones developed to address gaps between ESS technology/applications and criteria needed to foster initial and ongoing safety
Companies looking for an accurate method to gauge how well large batteries and other grid-scale energy storage systems work now have a new set of evaluation guidelines, called the Energy Storage Performance Protocol, at their disposal. The guidelines currently evaluate three energy storage performance uses: *Peak shaving, Frequency Regulation, and Islanded Microgrids*

**Additional Lab Protocols:**
- Duty Cycle for ESS Firming
- Duty Cycle for PV Smoothing
SNL Documents for Evaluation of ES Systems

SANDIA REPORT
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Unlimited Release
Printed September, 2016

Energy Storage Procurement Guidance Documents for Municipalities

Daniel Borrego (SNL)
With contributions from:
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Approved for public release, further dissemination unlimited.
Energy Storage Applications and Economics
Energy Storage Applications

- 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

<table>
<thead>
<tr>
<th>Energy Applications</th>
<th>Power Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arbitrage</td>
<td>Frequency regulation</td>
</tr>
<tr>
<td>Renewable energy time shift</td>
<td>Voltage support</td>
</tr>
<tr>
<td>Demand charge reduction</td>
<td>Small signal stability</td>
</tr>
<tr>
<td>Time-of-use charge reduction</td>
<td>Frequency droop</td>
</tr>
<tr>
<td>T&amp;D upgrade deferral</td>
<td>Synthetic inertia</td>
</tr>
<tr>
<td>Grid resiliency</td>
<td>Renewable capacity firming</td>
</tr>
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# Energy Storage Services (Value Streams)

<table>
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<tr>
<th>Bulk Energy Services</th>
<th>Transmission Infrastructure Services</th>
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</thead>
<tbody>
<tr>
<td>Electric Energy Time-Shift ( Arbitrage)</td>
<td>Transmission Upgrade Deferral</td>
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<tr>
<td>Electric Supply Capacity</td>
<td>Transmission Congestion Relief</td>
</tr>
<tr>
<td><strong>Ancillary Services</strong></td>
<td><strong>Distribution Infrastructure Services</strong></td>
</tr>
<tr>
<td>Regulation</td>
<td>Distribution Upgrade Deferral</td>
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<tr>
<td>Spinning, Non-Spinning and Supplemental Reserves</td>
<td>Voltage Support</td>
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<tr>
<td>Voltage Support</td>
<td><strong>Customer Energy Management Services</strong></td>
</tr>
<tr>
<td>Black Start</td>
<td>Power Quality</td>
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<tr>
<td>Other Related Uses</td>
<td>Power Reliability</td>
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<td></td>
<td>Retail Electric Energy Time-Shift</td>
</tr>
<tr>
<td></td>
<td>Demand Charge Management</td>
</tr>
</tbody>
</table>

ES Policy and Market Implications (for the future)

- The Federal Energy Regulatory Commission (FERC), which oversees U.S. energy markets, is in the midst of re-evaluating several policies that could open up more of a market for storage.
  - FERC order 755 and FERC order 784: “pay-for-performance”
    - More fairly compensates “fast responding” systems (e.g., storage)
    - Market redesign for frequency regulation compensation
      - Separate signals for “fast” devices
      - Mileage payment in addition to capacity payment

- Currently, California and the regional grid PJM Interconnection (excluding New Jersey) together account for 92 percent of U.S. energy storage deployments.
  - California energy storage mandate (California Public Utilities Commission) 10/17/2013
    - 1.3 GW by 2020
    - More Energy Storage to come – Non-Fossil Generation by year ????

- There's a short-term frequency regulation market in PJM and incentives for self-generation in California.

- The storage industry is working to encourage FERC to apply changes such as these in services and benefits more broadly.

Why is Storage Valuation Difficult?

- **Location/Jurisdiction**
  - Market area, e.g., California ISO
  - Vertically integrated utility, e.g., PNM
  - Transmission and distribution deferral is very location specific

- Many applications require a combination of technical and financial analysis
  - Dynamic simulations (requires an accurate system model)
  - Production cost modeling (requires an accurate system model)

- Difficult to break out current cost of services, especially for vertically integrated utilities

- Identifying alternatives can be difficult

- Many storage technologies are not “off-the-shelf”, proven technology (e.g., O&M costs, warranty???)

- Storage is expensive
An Example
Energy Storage Value Streams – Renewable Firming

► Renewable firming
  ■ Duck curve (CA is starting to be concerned)

For vertically integrated utilities – increased regulating and spinning reserves. In market areas, adding ramping products.
Energy Storage Applications and Economics: Take Aways

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

- Storage is expensive
- Electricity markets/utilities do not properly allocate payments/costs for services provided
  - Voltage support
  - Inertia
  - Renewable integration
  - Reliability

The future ….

- Greater penetration of renewables – storage becomes essential;
- Higher energy prices – storage starts looking better
- Lower technology costs – storage starts looking better
- Efficient market design – helps pay for storage costs

Potentially large market
Energy Storage Optimization Tool

Battery parameters:
- Discharging efficiency: 0.80654
- Charging efficiency: 0.83594
- Energy capacity: 16 MWh
- Power capacity: 4 MW
- Initial SOC: 0.5

Location:
- Bainbridge Island
- Baker River 24

Services:
- Arbitrage
- Balancing
- Capacity value
- Distribution deferral
- Planned outage
- Random outage

Input files:
- Prices: .\Input\price.xlsx
- Balancing sig: .\Input\PSE_Resize_2020_W_1.xlsx
- Capacity value: .\Input\Bl\CapacityValue.xlsx
- Deferral: .\Input\Bl\TDdeferral.xlsx
- Outage: .\Input\Bl\Outage.xlsx
- Outage power: .\Input\Bl\OutagePower.xlsx

Output:
- .\Output\Bl

Price select:
- All 50 prices
- Single price

Run
Cancel
Plot
Bundling Services: how to do it optimally?

![Energy price ($/MWh)](chart)

- **Arbitrage only**
- **Arbitrage + Balancing**
- **Arbitrage + Balancing + T&D deferral**
- **Arbitrage + Balancing + T&D deferral + volt/var**

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National Laboratories

Pacific Northwest

Proudly Operated by Battelle Since 1995
Example: Hourly value at Bainbridge Island for 24-hour period
Summary of Results (NPV benefits and revenue requirements over 20-year time horizon) – Bainbridge Island

Do You notice the biggest contributor?

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Random Outages – Mid-C Capacity Value</th>
<th>Projected Outages – Mid-C Capacity Value</th>
<th>Projected Outages – Peaker-Driven Capacity Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$21,233,715</td>
<td>$21,453,652</td>
<td>$26,647,715</td>
</tr>
<tr>
<td>2</td>
<td>$21,453,652</td>
<td>$26,867,652</td>
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<tr>
<td>3</td>
<td>$26,647,715</td>
<td>$21,453,652</td>
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</tr>
<tr>
<td>4</td>
<td>$20,340,000</td>
<td>$20,340,000</td>
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</tr>
</tbody>
</table>

- Revenue Requirements
- Arbitrage and Energy Costs
- Balancing Services
- Outage Mitigation
- Distribution Upgrade Deferral
- Capacity Value

Total Revenue Requirements: $20,340,000
WA CEF Battery Testing Began with Comprehensive Test Plan and Data Requirements

- Baseline tests
  - Stored energy capacity
  - Response time and ramp rate
  - Internal resistance
  - Peak shaving
  - Frequency regulation
- Use-case based duty cycles specific to each utility and battery system; detailed duty cycle tables in appendices
- Critical and optional AC- and DC-side data requirements specified by time increments
- Detailed performance metrics
# Washington CEF Matrix for Testing Program

<table>
<thead>
<tr>
<th>Use Case and application as described in PNNL Catalog</th>
<th>Avista</th>
<th>PSE</th>
<th>Sno – MESA1</th>
<th>Sno – MESA2</th>
<th>Sno - Controls Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UC1: Energy Shifting</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy shifting from peak to off-peak on a daily basis</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>System capacity to meet adequacy requirements</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td><strong>UC2: Provide Grid Flexibility</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regulation services</td>
<td>Y</td>
<td>Y</td>
<td>Y*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load following services</td>
<td>Y</td>
<td>Y</td>
<td>Y*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Real-world flexibility operation</td>
<td>Y</td>
<td>Y</td>
<td>Y*</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UC3: Improving Distribution Systems Efficiency</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Volt/Var control with local and/or remote information</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load-shaping service</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>Deferment of distribution system upgrade</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td><strong>UC4: Outage Management of Critical Loads</strong></td>
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<tr>
<td></td>
<td>Y</td>
<td></td>
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<tr>
<td><strong>UC5: Enhanced Voltage Control</strong></td>
<td></td>
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</tr>
<tr>
<td>Volt/Var control with local and/or remote information and during enhanced CVR events</td>
<td>Y</td>
<td></td>
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</tr>
<tr>
<td><strong>UC6: Grid-connected and islanded micro-grid operations</strong></td>
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<tr>
<td>Black Start operation</td>
<td>Y</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Micro-grid operation while grid-connected</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Micro-grid operation in islanded mode</td>
<td>Y</td>
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<td></td>
</tr>
<tr>
<td><strong>UC7: Optimal Utilization of Energy Storage</strong></td>
<td>Y</td>
<td>Y</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Non-Linear Battery Model Summary

- Model allows estimation of state of charge (SOC) during operation taking into account:
  - Operating mode
  - Power
  - SOC
  - Temperature

- Model has been validated with data

- Allows calculation of one way efficiency from rate of change of SOC

- Actual battery performance can be anticipated, thus providing a high degree of flexibility to the BESS owner/operator

- Self-learning model applicable to energy type of storage system

- Model will be fine tuned as more data are gathered.
Non-Linear Battery Model Used to Enhance Arbitrage Value Estimated for SnoPUD

- 50% more arbitrage revenue possible for SnoPUD when optimized using self-learning non-linear battery model
- Battery characterization based on data collected from Avista-operated UET battery deployed in Pullman, WA.
Acknowledgements

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We thank Dr. Imre Gyuk, Manager of the DOE Energy Storage Program.

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