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Reliability Testing of kW Scale Battery Modules

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OE Energy Storage Peer Review
October 12, 2022
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U.S. DEPARTMENT OF ENERGY BATTELLE

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Battery Reliability Test Laboratory

Purpose

- *Accelerate* the development of grid energy storage technologies.
- *Validate* the performance of battery systems under standardized testing protocols.
- *Collaborate* with a variety of battery designers, manufacturers, utilities and system integrators to perform tests that examine battery operating conditions, lifetimes, and performance.

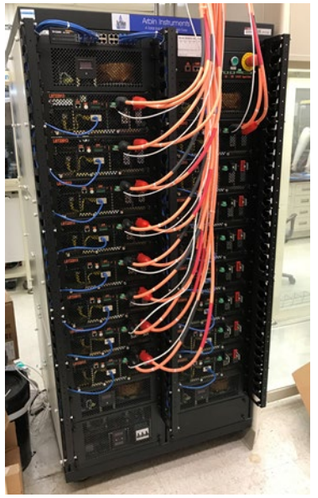
Outcome

- Provide operation guidelines and independent validation of performance to end users.
- Understand degradation mechanisms on batteries tested under grid duty cycles.
- Develop test platforms and protocols and use as a foundation for the new **Grid Storage Launchpad** (PNNL – Fall 2023)

Battery Reliability Test Laboratory

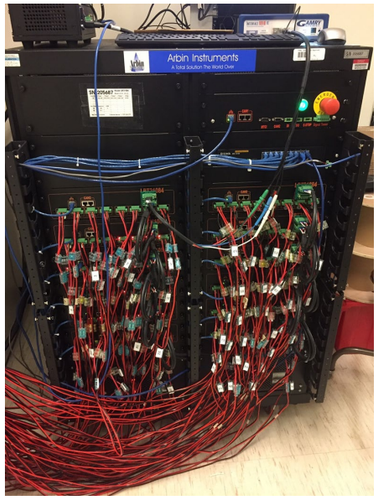
Battery Testing Capabilities

- 9 Ch for modules up to 10kW up to 120V and 200A DC regenerative discharge
- 4 Ch for modules up to 10kW up to 100V and 200A DC regenerative discharge
- 16 Ch for modules up to 3kW up to 60V and 50A DC
- Ability to communicate with and log BMS data (Modbus, Modbus TCP/IP, CAN)
- 384 Ch for cells up to 5V 10A with EIS capabilities
- 4 Controlled atmosphere chambers



Batteries Being Tested

- Sodium $NiCl_2$
- Vanadium Redox Flow Batteries
- Li ion modules
- Pb Acid
- Nickel - Iron
- Li ion single cells



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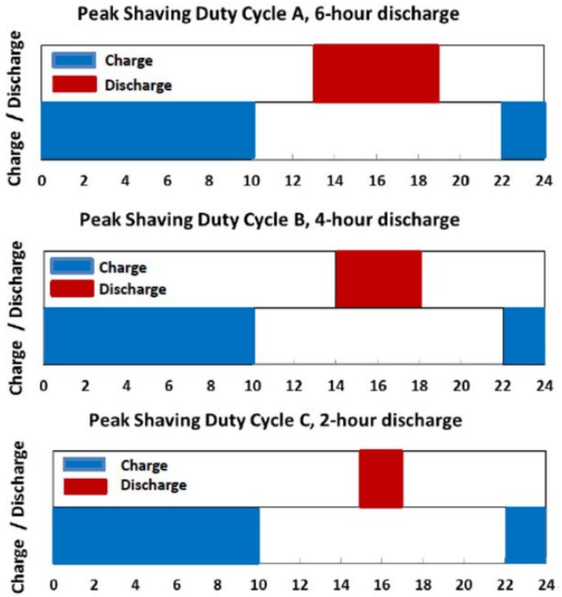
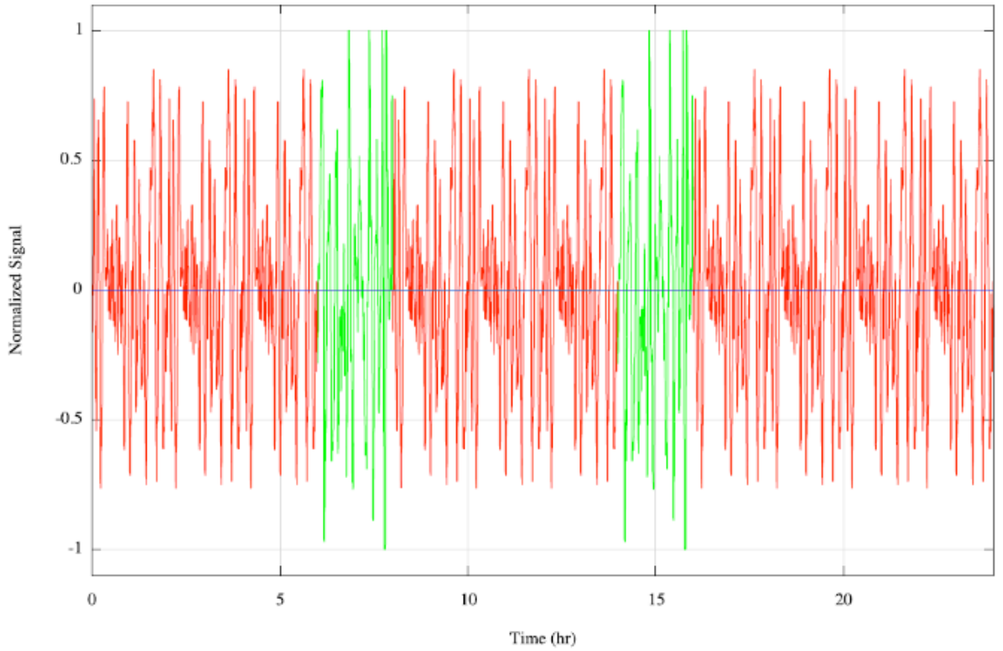
- Batteries being tested to grid duty cycles from “Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems” https://energystorage.pnnl.gov/pdf/PNNL-22010Rev2.pdf
- Mostly focused on Peak Shaving and Frequency Regulation





Peak Shaving Results

- Battery fully charged using manufacture recommended procedure
- Constant power discharge to target depth of discharge (DOD)
- Battery recharged using manufacture recommended procedure
- Round trip energy efficiency calculated
- Stability observed over many cycles
- Sodium $NiCl_2$ includes heating
- VRFB does not include auxiliary power

	Rate	Coulombic Efficiency	Energy Efficiency	Discharge Duration (hr)
AGM Lead Acid	C/8	97.4%	88.4%	3.8
Gel VRLA	C/8	97.4%	87.7%	2.8
Flooded Lead Acid	C/8	96.6%	84.9%	3
Nickel - Iron	C/4	76.9%	61.7%	6
Sodium $NiCl_2$	C/4	82.1%	71.6%	6
NMC Lithium Ion	C/4	98.3%	94.6%	2.8
Mixed Acid VRFB	C/14	96.7%	83.1%	5.6
Bi-Additive VRFB	C/15	97.6%	84.7%	3

Frequency Regulation Results

- Most batteries tested using frequency regulation duty cycle
- Volatile signal that changes every 4 seconds
- Battery starts at a suitable SOC to be able to absorb charge
- Duty cycle runs for 24 hours
- Duty cycle is energy neutral
- Battery recharged to original SOC
- Round trip efficiency and ability to track signal calculated
  - Stability in above metrics observed over multiple cycles

	Coulombic Efficiency	Energy Efficiency	Signal Tracking Charge	Signal Tracking Discharge	Start SOC	End SOC
AGM Lead Acid	99.2%	88.9%	99.9%	99.9%	80	60
Gel VRLA	99.4%	92.4%	99.9%	99.9%	80	72
Flooded Lead Acid	100.0%	92.6%	99.9%	99.9%	80	73
Nickel - Iron	86.2%	50.0%	99.9%	99.9%	50	20
NMC Lithium Ion	97.5%	95.4%	99.9%	99.9%	80	73
Mixed Acid VRFB	94.7%	86.8%	99.8%	99.9%	60	52
Bi-Additive VRFB	97.0%	87.0%	99.9%	99.9%	80	71

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Module testing under grid duty cycles – AGM Pb Acid Battery

Valve Regulated Pb acid batteries

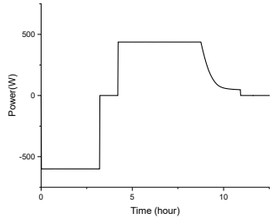
Nominal Voltage: 12 V
Capacity: 172 Ah
6 series connected cells

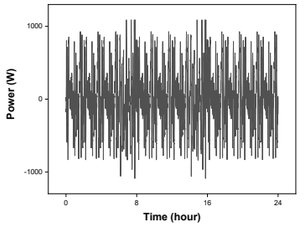
Peak Shaving

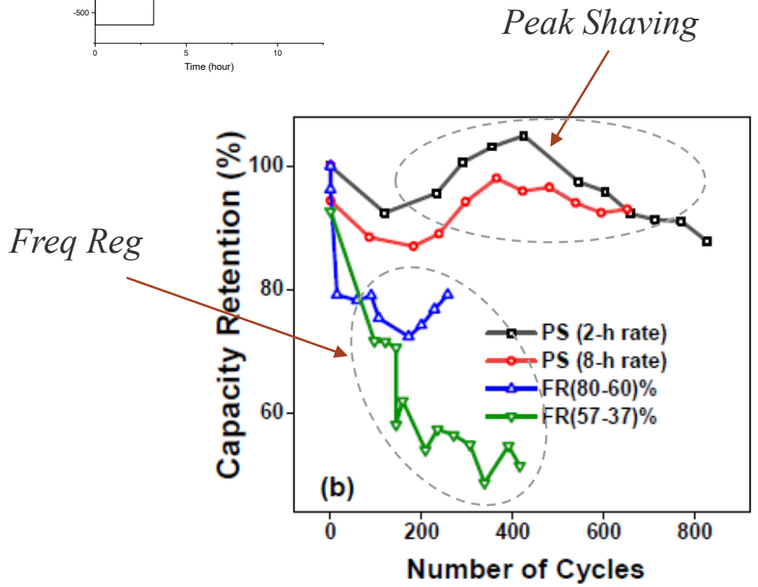
Peak shaving duty cycle (2 modules)	
Depth of discharge	50%
Initial SOC	100%
Discharge power (Watt)	730, 248
Discharge duration	~1.2hr, ~3.8 hr
Charge back power (Watt)	265
Total duration for each PS cycle	~14hr, ~11.5hr

Frequency Regulation

Frequency regulation (2 modules)	
Depth of discharge	20%
Initial SOC	80%, 57%
Discharge duration (Hr)	24
Maximum power (Watt)	1090
Charge back rate (A)	C/10
Total duration for each FR cycle	~29hr







- Greater capacity loss for Frequency Regulation

Performance test done periodically to evaluate degradation over time

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Module testing under grid duty cycles – AGM Pb Acid Battery

Peak Shaving Duty Cycle

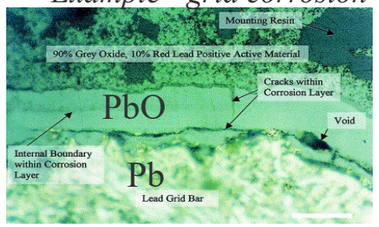
Degradation mechanisms (~ 2 yrs)

- Positive grid corrosion Pb → PbO

  PbO is highly resistive

- Electrolyte dry out

Example - grid corrosion

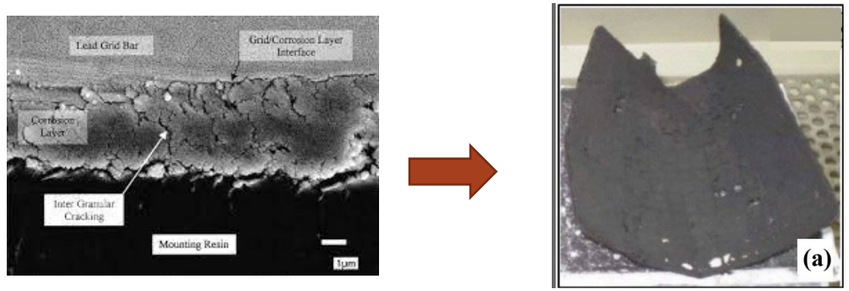


→ Positive grid corrosion mitigated using alloys (i.e., Sn and Ca) and avoiding water loss (electrolyte dry out)

Frequency Regulation Duty Cycle

Degradation mechanisms (~ 2.5 yrs)

- Shedding (large volume change during discharge ↔ many cycles)



→ Frequency regulation with volatile signals (many cycles) may not be ideal duty cycle for VRLA

Aged battery Modules will be disassembled and analyzed to verify degradation mechanisms

N. Shamim, V. Viswanathan, E. Thomsen, G. Li, D. Reed, V. Sprenkle, "Valve Regulated Lead Acid Battey Evaluation under Peak Shaving and Frequency Regulation Duty Cycles," *Energies*, **2022**, 15, 3389.

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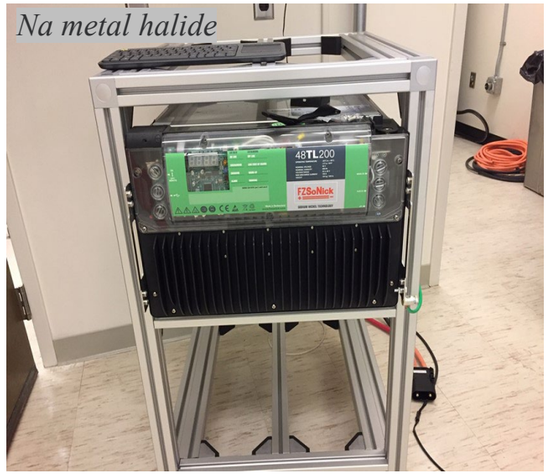
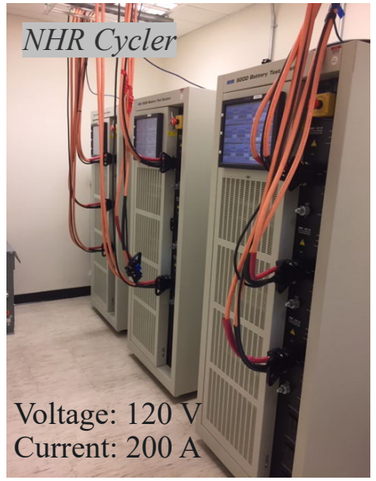
Module testing under grid duty cycles - Sodium $NiCl_2$





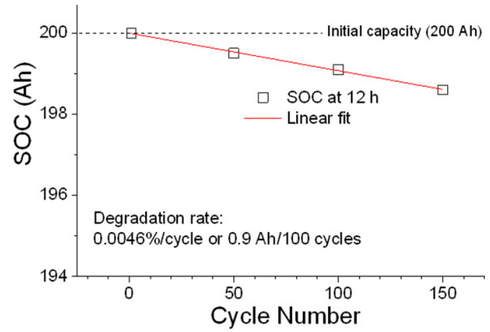
Peak Shaving Duty Cycle (690 days)

Charge time – 12 hrs
Discharge time (hrs) – 2, 4, and 6
Discharging energy (kWh) – 7.5, 8, and 8.5

Nominal Voltage: 48 V
Capacity: 200 Ah (40 Ah x 5 strings)
Module Energy: 9.6 kWh
Module Power: 2.3 kW
Operating Temp ~ 265°C (built-in BMS)

Hours on test – 15,200
Cycles – 635

- ~ 72% energy efficiency at 7.5 kWh energy utilization
- Degradation rate:
  - 0.0046% per cycle (150 days)
  - 0.9 Ah/100 cycles



- In general, good energy efficiency and slow degradation

Degradation mechanism unknown → needs analysis

N. Shamim, E. Thomsen, V. Viswanathan, D. Reed, V. Sprenkle, and G. Li, "Evaluating ZEBRA Battery Module under the Peak Shaving Duty Cycle," *Materials*, **2021**, 14, 2280.

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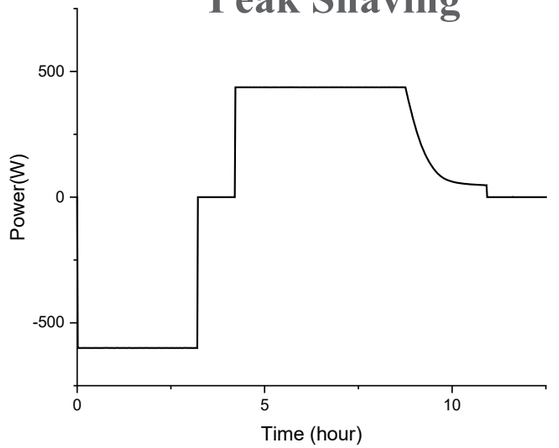
Module testing under grid duty cycles – Flooded Lead Acid

Module Capacity: 167 Ah
Nominal Voltage: 24V 12 Cell Module

Peak Shaving

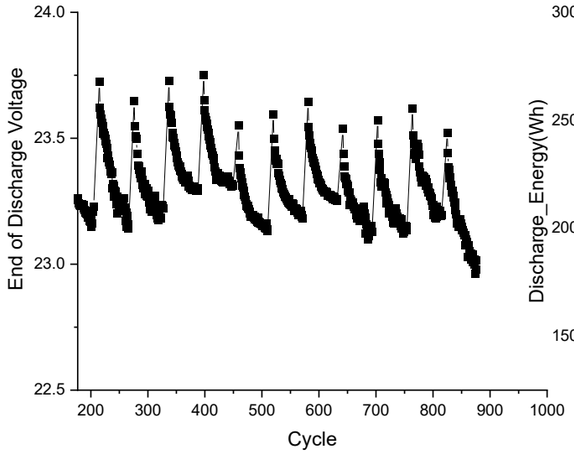


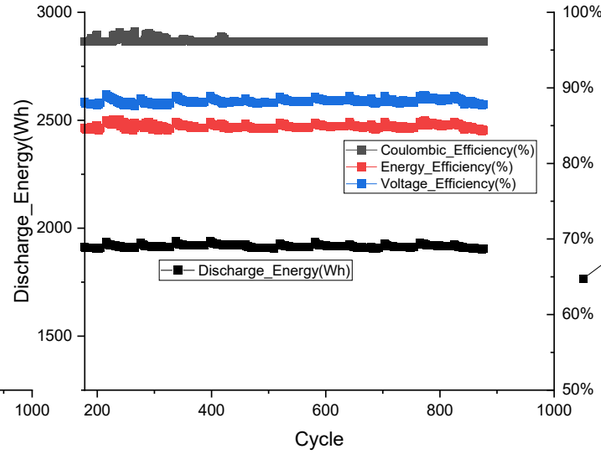
Test Conditions

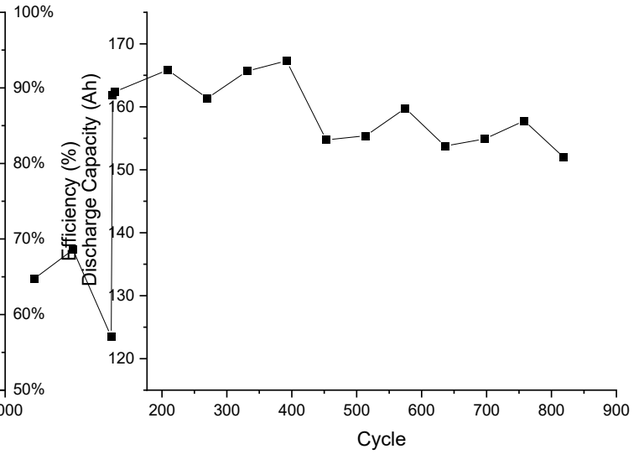
Battery Capacity test	
Charge (CC+CV+CC)	
Constant current (CC) charge	19A/ 2.4V/cell (28.8V)
Constant voltage (CV) charge	28.8V until 10A
Constant current (CC) charge	10A for 5 hrs or 2.7V/cell (32.4V)
Discharge	26.3A/ 1.85V/cell (22.2V)

Peak Shaving Test	
Depth of discharge	50%
Initial SOC	100%
Discharge power (Watt)	600 Watt
Discharge capacity	80 Ah (50% of rated capacity
Charge back power (Watt)	437 Watt
Total duration for each PS cycle	~10 hrs

Reference Performance Test







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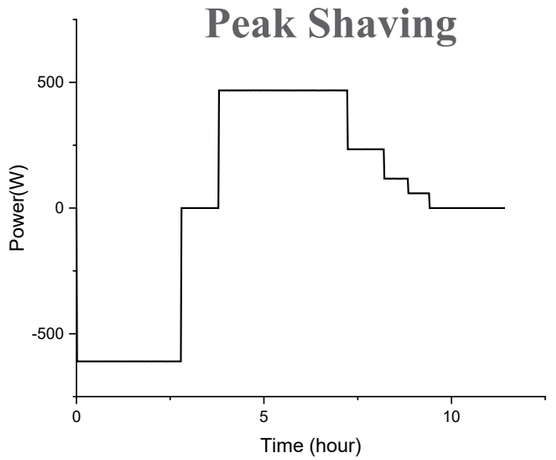
Module testing under grid duty cycles – Gel VRLA

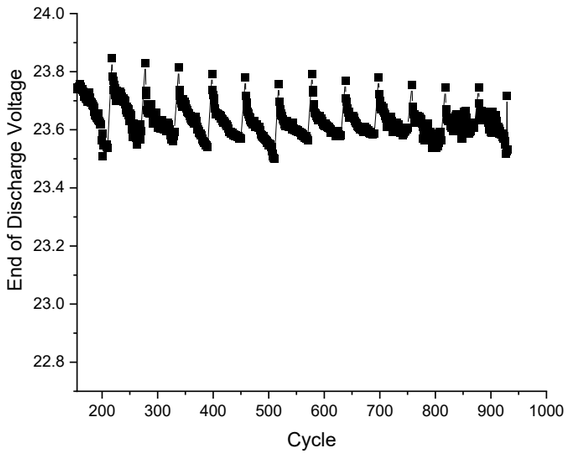
Nominal Voltage: 24 V 12 Cell Module
Module Capacity: 182 Ah (C10h,1.8V@20°C)

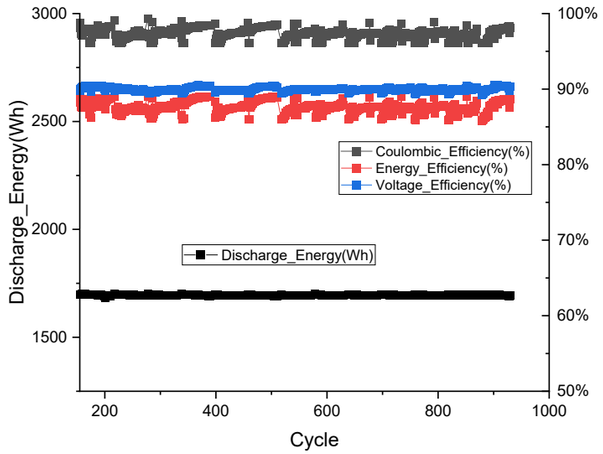
Test Conditions

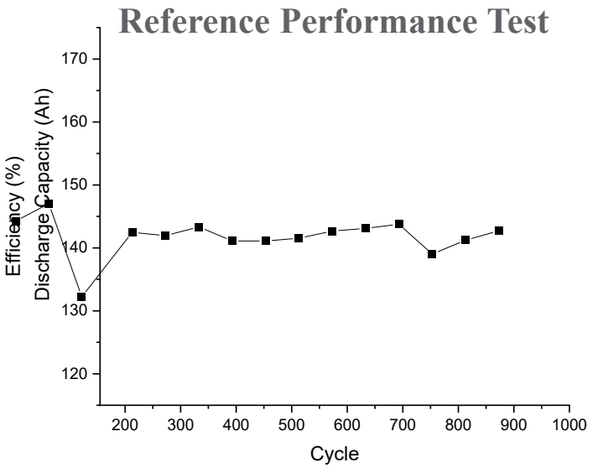
Battery Capacity test	
Charge (CC+CV+CC)	
Constant current (CC) charge	20A/ 2.35V/cell (28.2V)
Constant voltage (CV) charge	2.35V/cell until 2.8A
Constant current (CC) charge	2.8A for 5 hrs or 2.7V/cell (32.4V)
Discharge	26.3A/ 1.85V/cell (22.2V)

Peak Shaving Test	
Depth of discharge	50%
Initial SOC	100%
Discharge power (Watt)	610 Watt
Discharge capacity	75 Ah (50% of rated capacity
Charge back power (Watt)	468 Watt
Total duration for each PS cycle	~10 hrs









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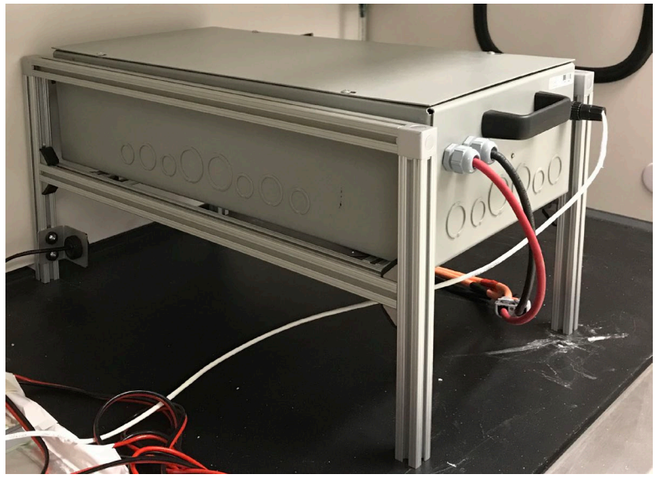
Module testing under grid duty cycles – NMC Lithium Ion

Nominal Voltage: 51V
Nominal Capacity: 150Ah
Energy: 7.6kWh

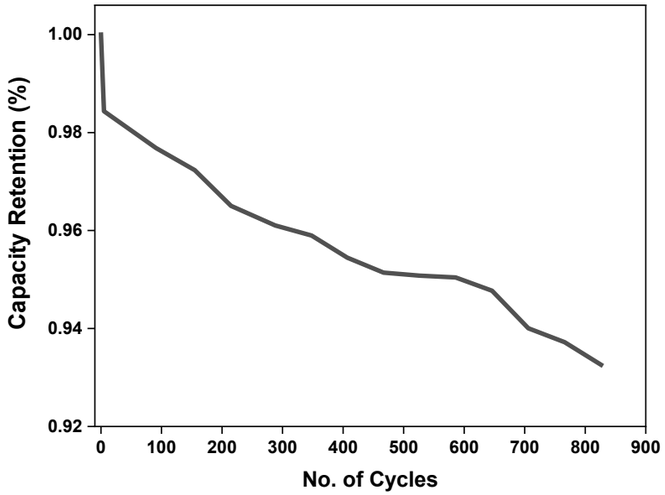
Test Conditions

Battery Capacity test	
Charge	
Constant current (CC) charge	37.5A/ 58.8V
Constant voltage (CV) charge	58.8V until 7.5A
Discharge	37.5A/ 46V

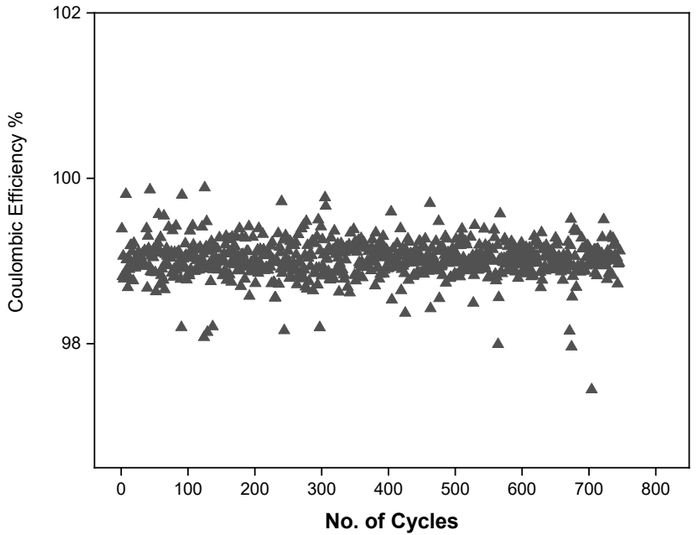
Peak Shaving Test	
Charge (CP+CV)	
Constant power (CP)	1940 Watt until 58.8 Volt or 90% SOC
Constant voltage (CV)	58.8 V until 90% SOC
Discharge power	1450 Watt
Discharging time	2.8 hrs

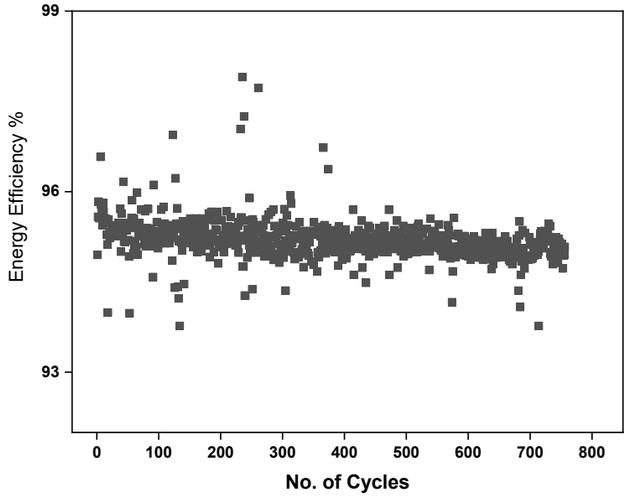


Reference Performance Test



Peak Shaving





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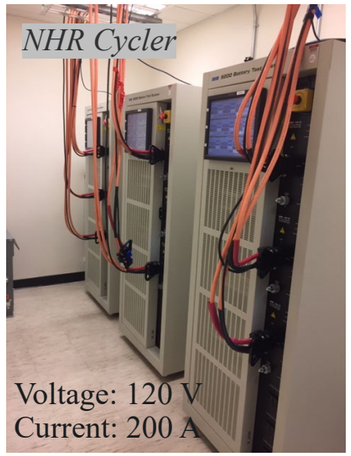
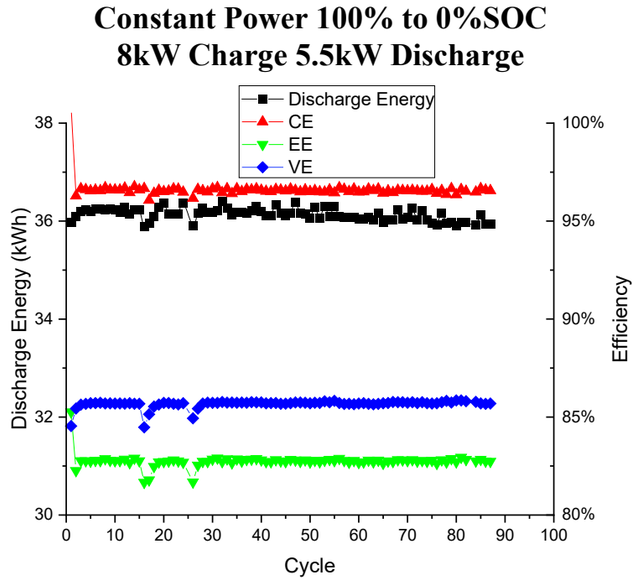
Module testing under grid duty cycles – Mixed Acid VRFB





Nominal Voltage: 48 V
Energy: 30 kWh
Hours on test – 3,380
Cycles – 275

Discharge Performance

Duration	Power (kW)	Energy (kWh)	Efficiency (%)
3.6 Hour	8	28.7	80.4
5.1 Hour	6	30.7	83.6
7.9 Hour	4	31.5	86.9
15.9 Hour	2	31.7	89.1

Very Little if any Degradation at 275 cycles

2nd Life Test Protocol Development, *Project Overview*

Ed Thomsen, Vish Viswanathan, Charlie Vartanian, Matt Paiss, Greg Coffey, and David Reed (PNNL)

Danny Ilioiu, and Talon Swanson (King County Metro)

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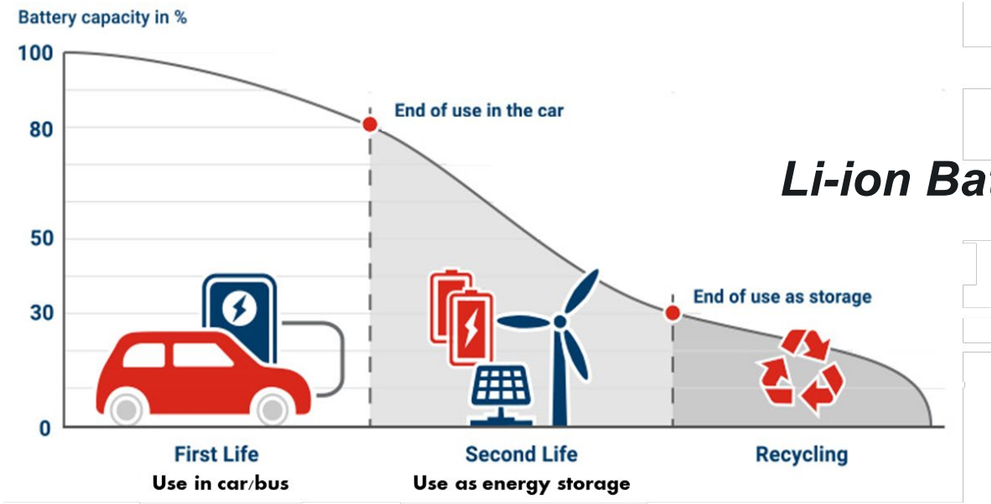
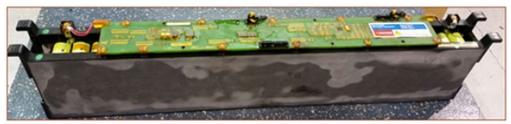
2nd Life Bus Batteries



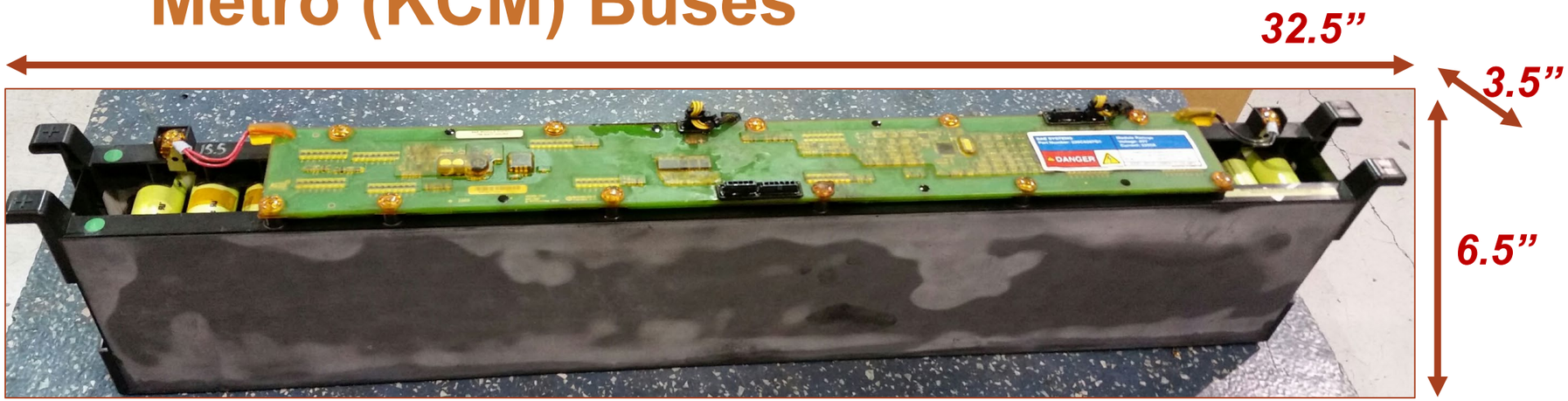
Li-ion Battery "life cycle"

Retired mobile packs



- Re-rate retired mobile batteries for stationary applications
- Provide cost analysis for re-rating
- Provide economic and environmental benefits

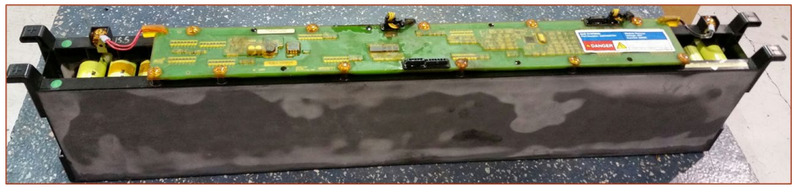
Hybrid Bus Battery Modules – From Retired Battery Packs Previously Used in King County Metro (KCM) Buses



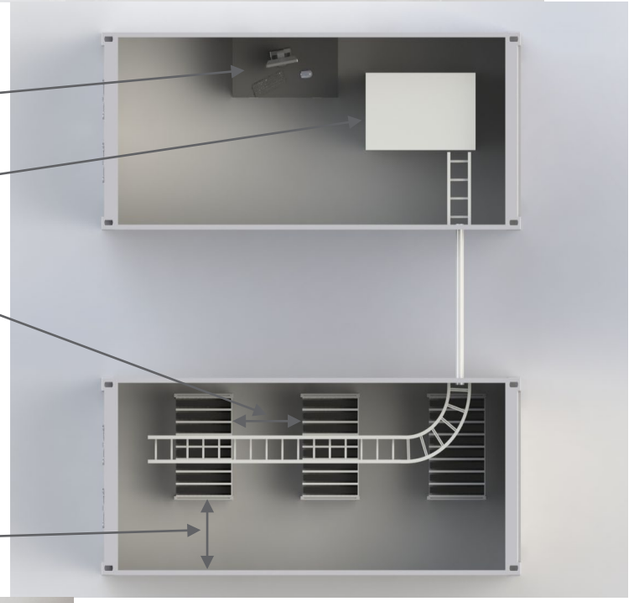
- Modules from KCM’s Hybrid Bus Fleet, *>MWh of capacity already retired*
- 2nd Generation BAE Hybrid Bus Packs
- Battery Modules manufactured by A123 Systems
- 12S A123 26650’s 39.6V per module.
- Orig.(New) Rating was 0.725kWh each
- Target Re-Rating is 0.56kWh each, (0.5 kWh is considered pass) with target 10 years of 2nd Life use
- Approx. 180 used modules to be tested by PNNL for re-rating, then returned to KCM

Photos provided by King County Metro, Seattle

PNNL 2nd Life Battery Test Pad



- Scope: Battery Module Qualification
  - Used modules from King County Metro hybrid buses
  - 24 modules under test, 17.4/12.7 kWh total capacity (initial/derated)
  - Modules 41.4V nominal voltage, 0.725 kWh
- Test site near Richland campus Bldg. 3820
- Supply chain issues on equipment impacting schedule
- Planned hand over from construction November 2022



Safety Systems

- Battery cycler and BMS voltage and temperature limits
  - Voltage and current will be kept within safe operating range
  - Individual string voltages will be monitored within each module and kept within safe limits
  - Temperature of each module will be monitored, and test stopped if not within safe limits
- Li-ion tamer system will shut down testing if battery off gas is detected
- Batteries will be separated by insulated board in order to prevent module to module failure
- Space will have a flammable gas detector, and heat detector that will activate room purge system
- Deflagration panels installed to allow pressure relief
- Dry fire department connection installed

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Acknowledgments

Dr. Imre Gyuk, DOE – Office of Electricity

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Mission – to ensure a resilient, reliable, and flexible electricity system through research, partnerships, facilitation, modeling and analytics, and emergency preparedness.

https://www.energy.gov/oe/activities/technology-development/energy-storage

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Thank you