Performance Data & Analysis for BESS Reliability Advancement

Phase 1 Final Report

PO 459914

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Project Status

Project/Deliverables Status

- Numerous Data Sets from fielded systems supplied to DOE (Task 1a-d)
  - Li Ion – well instrumented system – over 2 years granular data
  - Flow – over 1 year operation
  - Other less granular Li Ion data sets
  - Over 21 MW-years of data supplied
- Provided direct access mining scripts (Task 2)
- Protocols for testing delivered (Task 3a)
- Regular interaction on development of symbiotic degradation analysis approaches (Task 3b)
- Report out (Task 4a-b) – contained in this presentation and attached Appendix

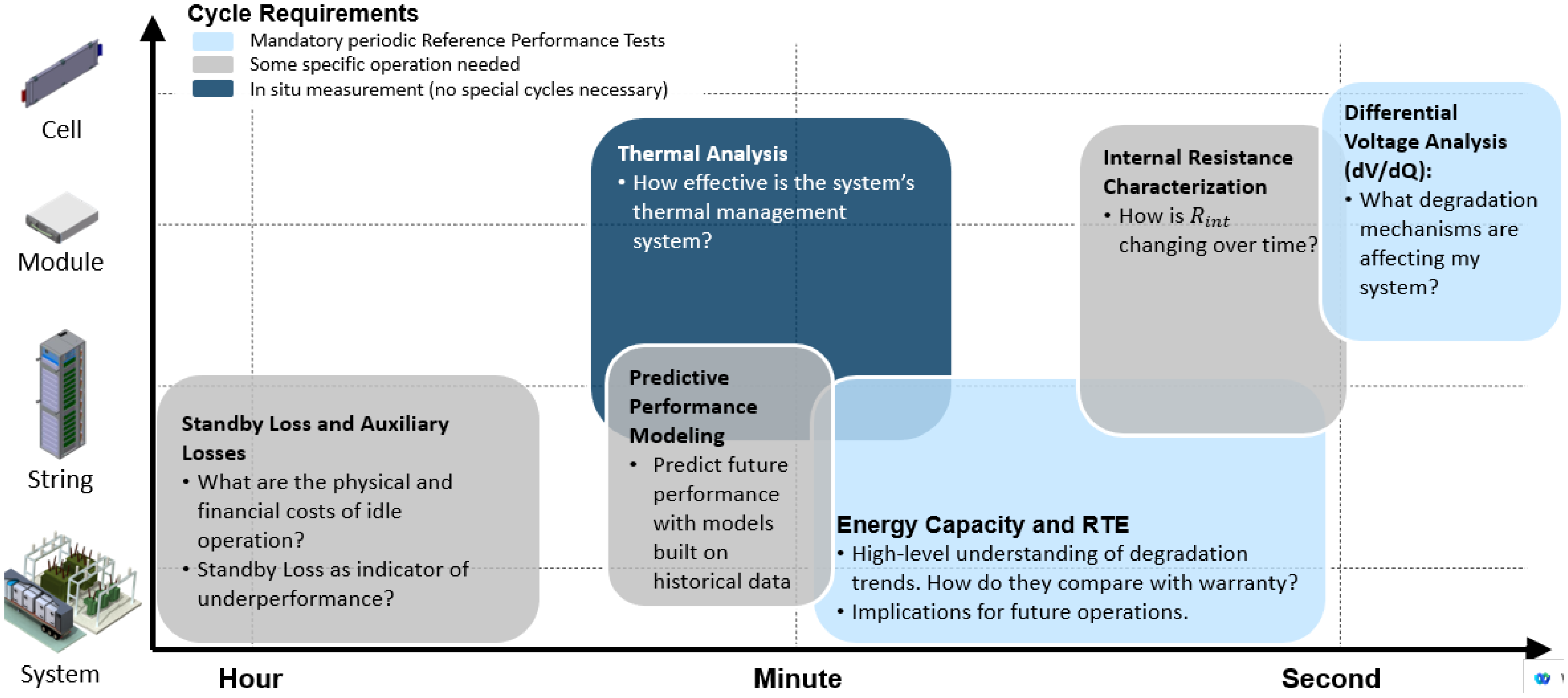
Foundational Issues

Data Requirements - Moving from R&D to Real World

New Players
- T,G,D Ops
- All Engineering Groups
- Field Services
- System modelers
- Risk Managers
- Portfolio Managers
- Customer Interface

Emerging Rules/Policies
- NERC
- FERC 2222
- Low Carbon Initiatives
- Equity

Defined Applications
- Capacity
- Ancillary Services
- Renewables Integration
- Arbitrage
- Resiliency



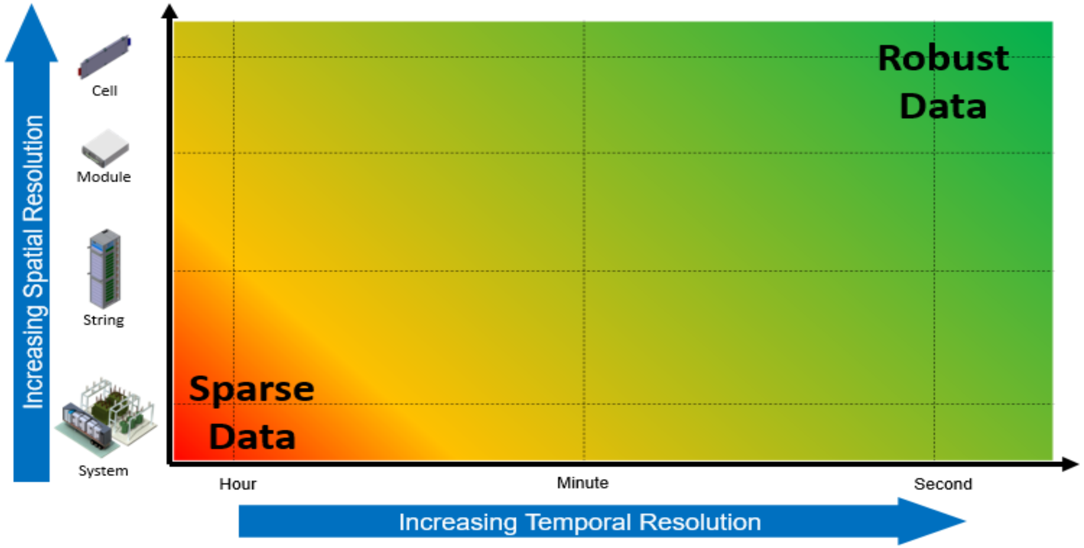
Data & Analysis Serving Specific yet Broader Needs

Understanding storage field performance is critical for all aspects of the utility business

Data Source Realities

- Non Uniform Data – issue noted by (National Electricity Reliability Corporation) NERC*
  - "Data on battery storage tends to be non-uniform and lacking in consistency across reporting entities necessitating a need for better reporting mechanisms for BESS data"
- Sparse vs Robust – Trade off on Cost vs Benefit

Low cost to transport and store but allows minimal insight to Performance

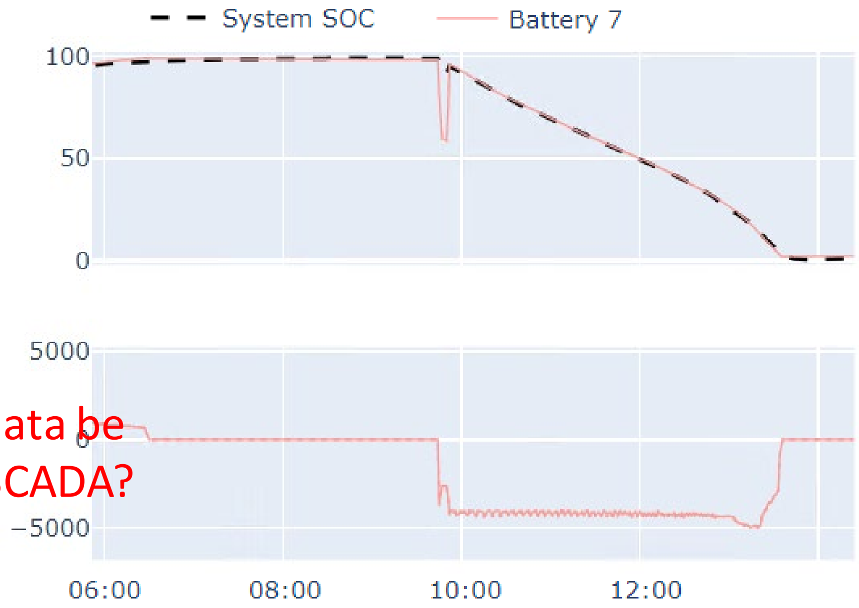


Higher cost to transport and store but allows deep insight to Performance

* https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/Master_ESAT_Report.pdf

Data Transport and Capture – System Impacts

- Data Gaps are typical – especially when data is transported via legacy SCADA
- Well instrumented fiber and/or modem based transport allows in depth analysis
- Many new and big systems rely on PI based historians and extraction of data can be costly and require specific software
  - Patching Data Gaps may be done differently

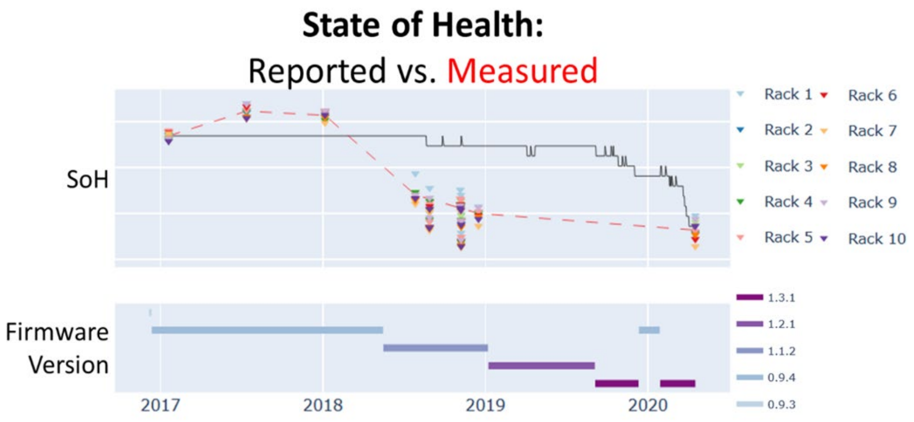


How will distribution data be captured? PI/fiber or SCADA?

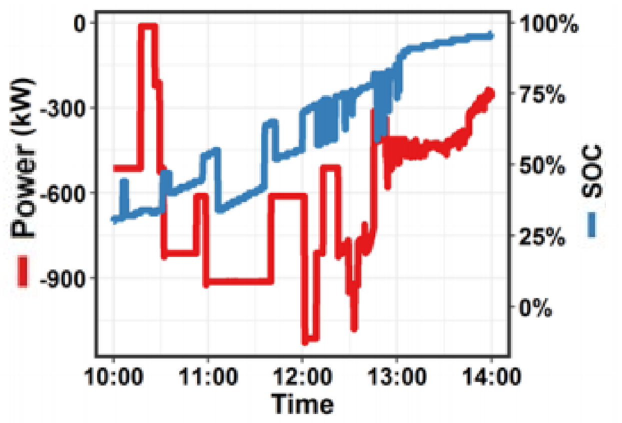
Discrepancies Noted in SOH/SOC Field Measurements

- Improbable values may be reported by systems
- Proprietary calculations obfuscate understanding

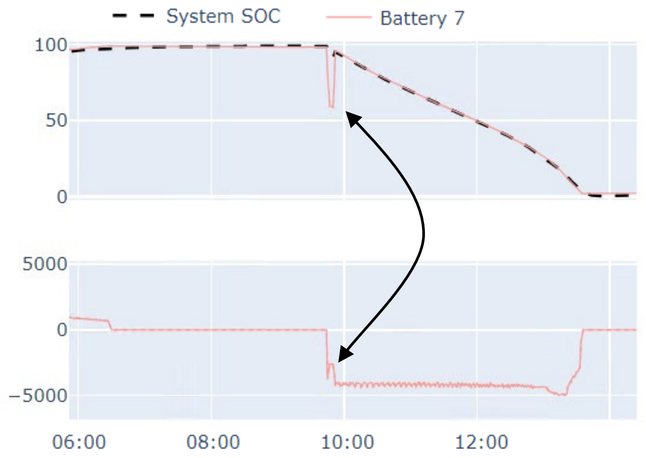
Examples from the Field:



Li-Ion (NMC): Reports SoH of 99.5% for 1.5 years. Firmware update closed apparent gap



Li-Ion (LFP): Large SOC swings, potentially being calculated by BMS from voltage rather than open circuit voltage?

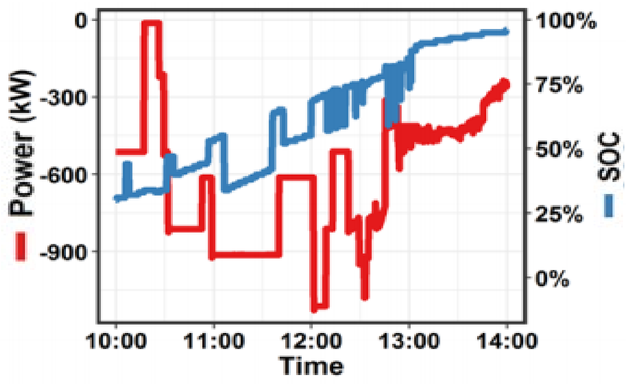


Flow Battery: Impossible decline and recovery of SoC affect the AC output of the entire system

PNNL Sources: PNNL Puget Sound Energy Glacier Energy Storage System, An Assessment of Battery Technical Performance, July 2019 PNNL-28379
Snohomish Public Utility District MESA-1 An Assessment of Battery Technical Performance January 2018 PNNL-27237

Data Access – Impacts to SOC Knowledge

- Operators base dispatch decisions on SOC
  - FERC is deriving rules on SOC Management - Order 841
  - Requires knowledge and field input on SOC intricacies
  - Various SOCM complexities apparent but all rely on accurate input metrics
  - Inaccuracies may compound over time – depending on method and accuracy (and drift) of sensors feeding calculation
- SOC is typically an "estimate of an unobservable quantity"*
- Typical Vendor A – Packaged Modular Unit
  - No Access to DC or temperature data
  - SOC is substituted by an estimate of energy remaining at a nominal temperature
  - Charge and discharge power and energy available are estimates
  - No knowledge on how estimates are derived
- Approaches to independent verification of SOC are being researched but require access to DC level sensors



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**Electrical Energy Storage Data Submission Guidelines, Version 2*. Electric Power Research Institute (EPRI) and Sandia National Laboratories (SNL): 2021. 3002022119. p 8-1

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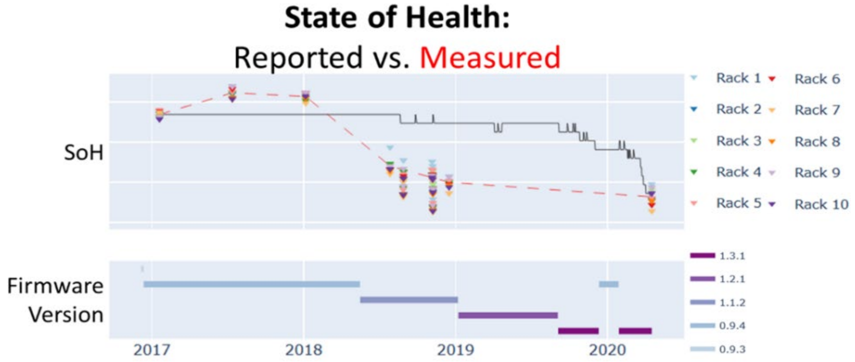
Data Access - SOH Inaccuracy Implications

- Performance Guarantees/Warranties are emerging that define
  - Promised availability
  - Capacity available over time
- Typically dependent on the use case(s) or applications defined that the frontend of a project
  - Deviations can void Warranties
  - Inaccuracies can throw off long-term commitments
- SOH can be independently verified
  - Current Methodologies require full cycle charge/discharge – temporary cessation of market duties
  - Researching "on the fly techniques" to allow SOH determination while remaining on market duty



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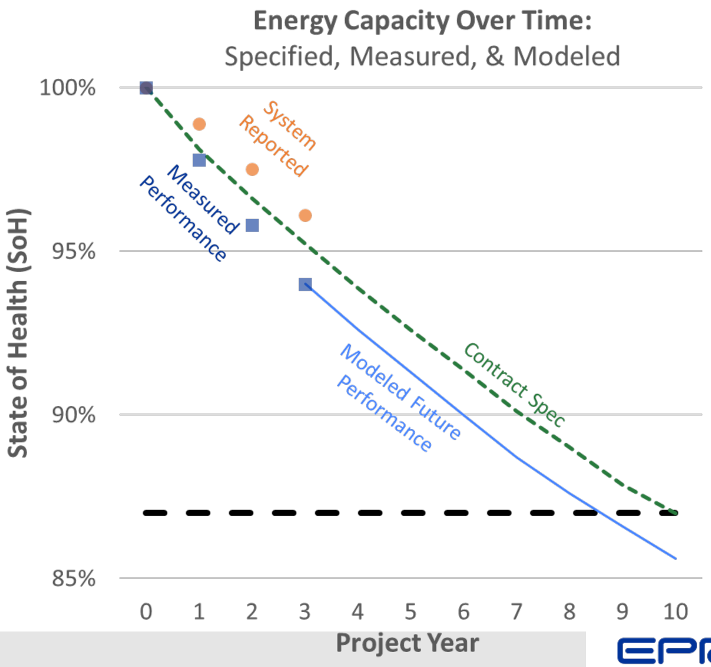
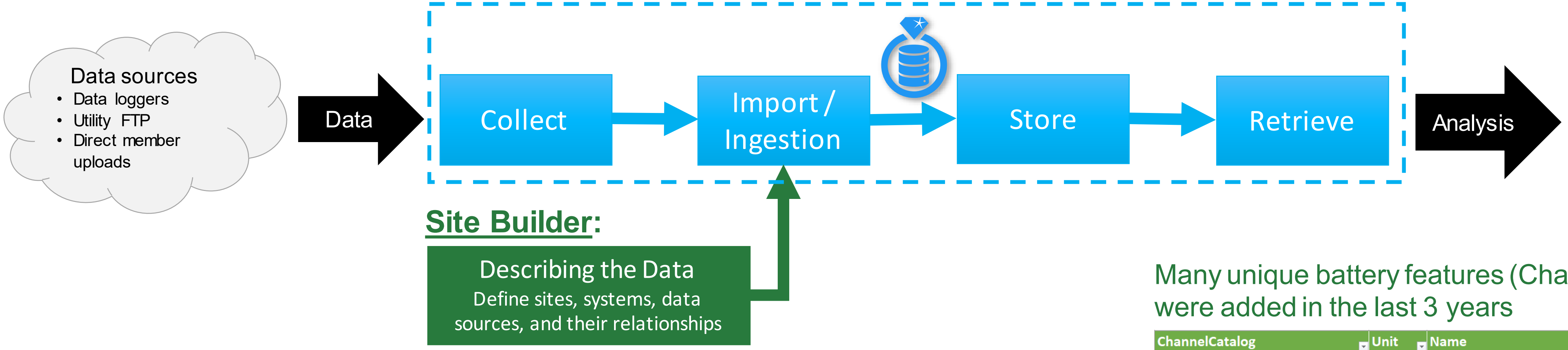
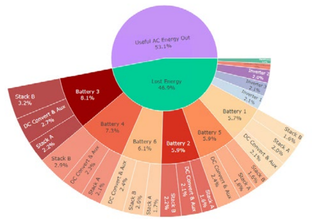


Data Structure Solutions

Improving Battery Data Integration





Many unique battery features (Channels) were added in the last 3 years

ChannelCatalog	Unit	Name
AC.Current	A	AC Current
AC.Power	kW	AC Power
State.AcquiSuite.Err		AcquiSuite Error Code
State.Alarm		Alarm
State.AvalonEMS.BankEnBits		Avalon EMS Bank-Enabled Bit Field
State.AvalonEMS.OpMode		Avalon EMS Operation Mode
State.AvalonEMS.PCSEnBits		Avalon EMS PCS-Enabled Bit Field
State.AvalonEMS.SystemBits		Avalon EMS System Status Bit Field
State.AvalonEMS.UnitCmd		Avalon EMS Unit Command
Temp.Battery.Cell	°C	Battery Cell Temperature
Temp.Battery.Module	°C	Battery Module Temperature
Temp.Battery	°C	Battery Temperature
AC.Energy.Cum.Charged	kWh	Cumulative Energy Charged
AC.Energy.Cum.Discharged	kWh	Cumulative Energy Discharged
AC.Energy.Cum.Q.Neg	kVARh	Cumulative Negative Reactive Energy
AC.Energy.Cum.Q.Pos	kVARh	Cumulative Positive Reactive Energy

- Describing and importing battery data is now more efficient and will continue to improve as we import more BESS data
- Much work remains to automate field data extraction from associated historian platforms

Every new Channel makes the next import easier.

Energy Capacity and RTE

Background: Need to monitor system's capabilities over time.

- Identify underperforming components

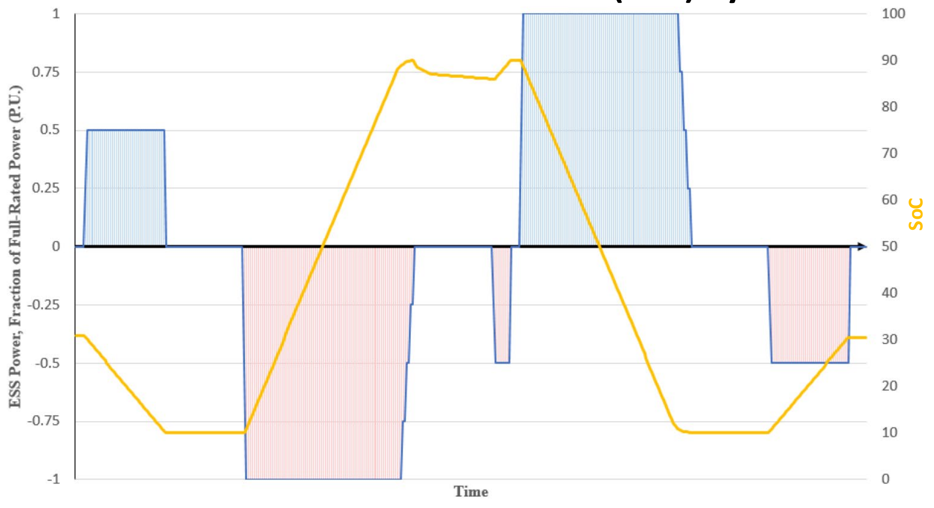
Data Requirements:

- Months – years of data
- High resolution data preferred, at least minute
  - **Minimum:** Site meters, SoC, environmental data
  - **Preferred:** DC metering and temperatures for subcomponents

Cycle Requirements: Periodic, consistent reference performance testing

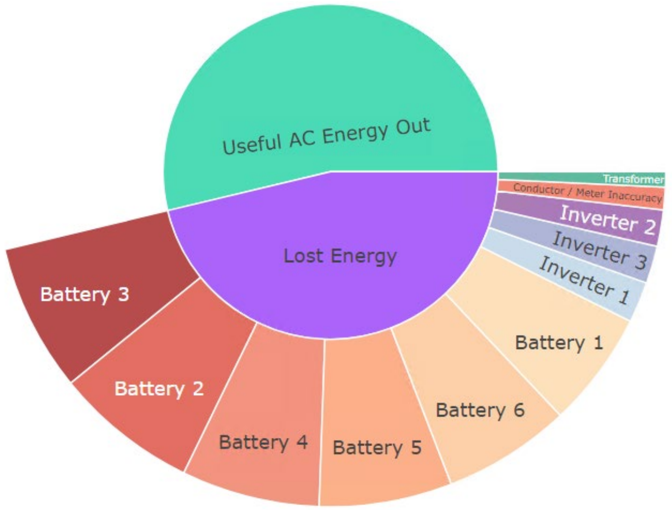
Desired Outcome: High-level understanding of operational trends.

Reference Performance Test (RPT) Cycle

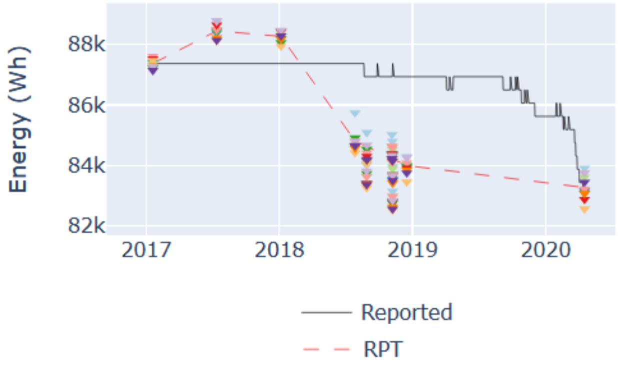


2019 ESIC Test Manual, www.epri.com (3002013530)

RTE of Different Components in Same Cycle



Energy Capacity Over Time:
Measured vs Vendor reported



Differential Voltage Analysis: dV/dQ

Background: Closely measure the relationship between electrons entering a battery (dQ) and the effect on voltage (dV)

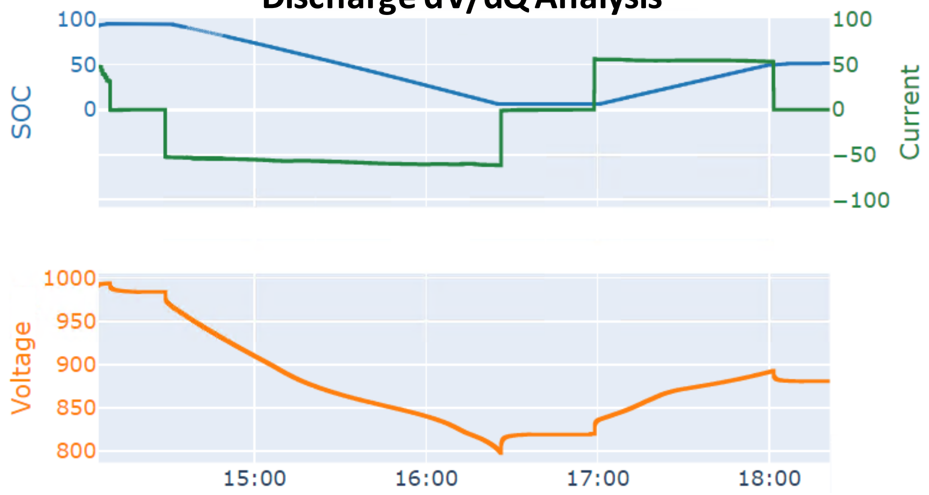
***Data Requirements*:**

- Second & sub-system resolution
  - **Minimum:** Rack-level DC voltage, current, temperature, SoC
  - **Preferred:** Rack subcomponent metering

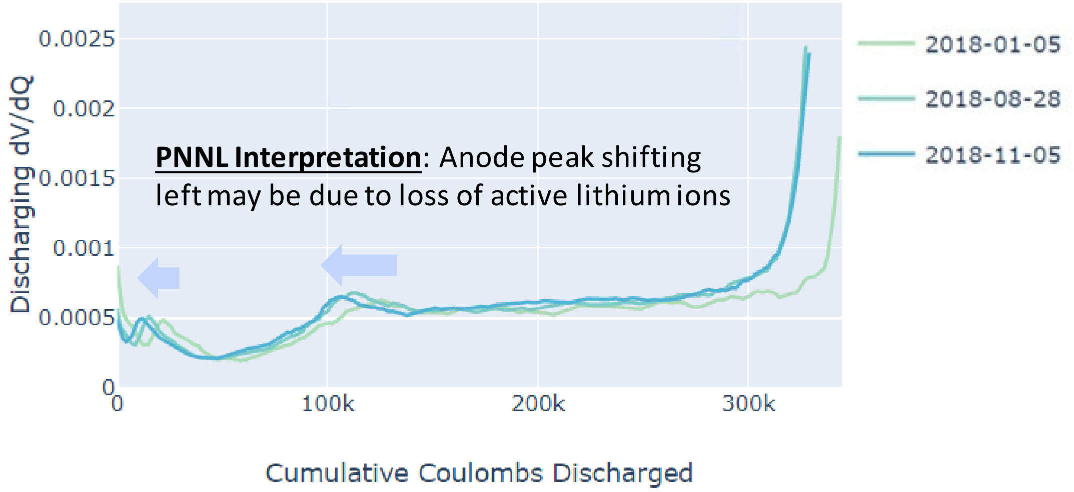
Cycle Requirements: Precise, near-full energy cycling. Similar to charge / discharge energy capacity cycling.

Desired Outcome: Understand specific physical degradation mechanisms underway inside a battery. "Fingerprint of Degradation"

Cycle Conducive to Discharge dV/dQ Analysis



Discharge dV/dQ Over Time



Methodology still under development

Internal Resistance Characterization

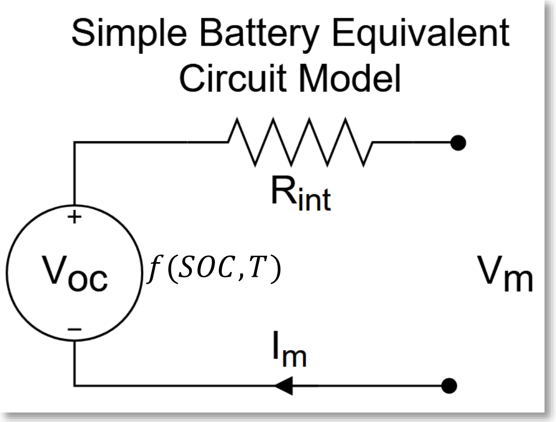
Background: Measure internal resistance (R_{int}) of components over time to assess degradation

Data Requirements:

- Years of 1-5 second resolution data
- Sub-system resolution
  - **Minimum:** Rack-level DC voltage, current, temperature, SoC
  - **Preferred:** Rack subcomponent data

Cycle Requirements: Requires cycles with periodic step changes in current over a broad range of operating conditions (SoCs & temperatures)

Desired Outcome: Calculate the internal resistance of a battery component and monitor its evolution

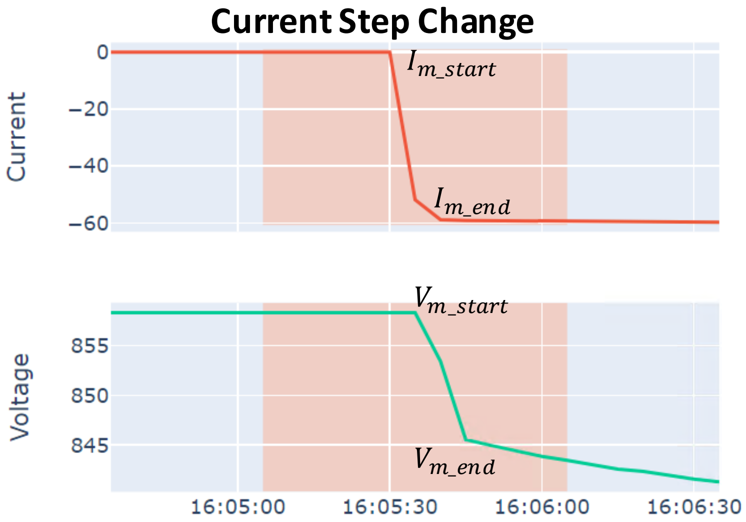


$$V_{measured} = V_{oc} + R_{int} * I_m$$

$$R_{int} = \frac{V_m - V_{oc}}{I_m - \cancel{I_{oc}}^{0}}$$

Generalized for any step change in current:

$$R_{int} = \frac{V_{m\_end} - V_{m\_start}}{I_{m\_end} - I_{m\_start}} = \frac{dV}{dI}$$



$$R_{int} = \frac{dV}{dI} \approx \frac{846 - 858}{-59 - 0} = 203\text{m}\Omega$$

Methodology still under development

Standby Losses: Self-discharge and Auxiliary Loss

Background: Idle operation incurs auxiliary and self-discharge energy losses.

- <u>Self-discharge</u>: Chemical processes within cells work to decrease SoC with no energy leaving battery.
- <u>Aux Losses</u>: Energy required to keep aux systems running

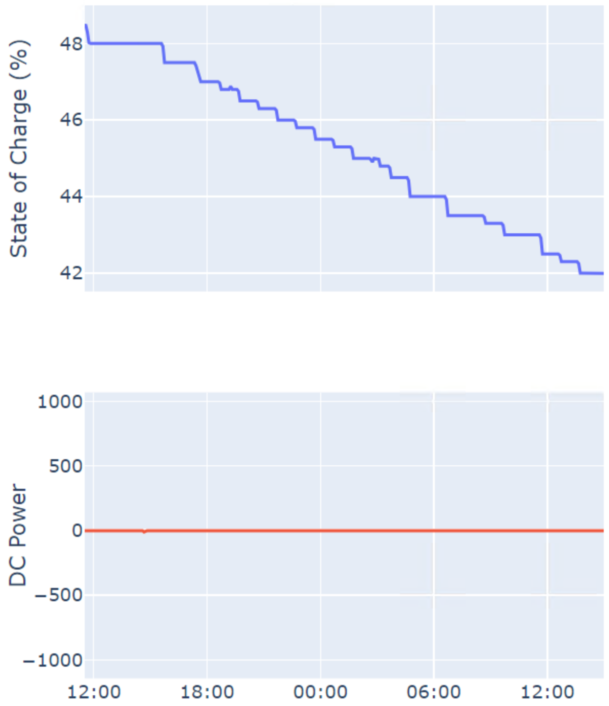
***Data Requirements*:**

- Months – years of data
  - **Minimum:** Site meters, environmental data, SoC, operating mode, auxiliary load meter (if applicable)
  - **Preferred:** System subcomponent DC metering, balancing

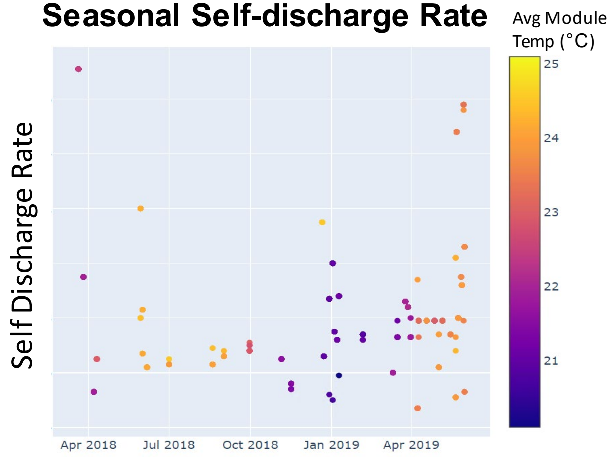
Cycle Requirements: Long periods of standby (i.e. ready for dispatch). Hours to days.

Desired Outcome: Understanding of the costs associated with standby operation. Possible high-level indicator of underperformance.

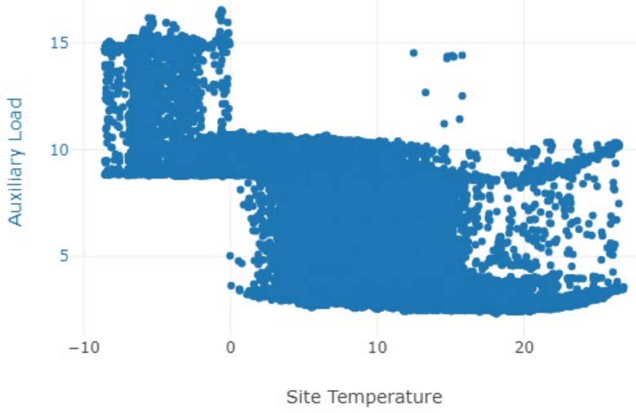
Standby "Cycle"



Seasonal Self-discharge Rate



Winter Auxiliary Loads



Thermal Analysis

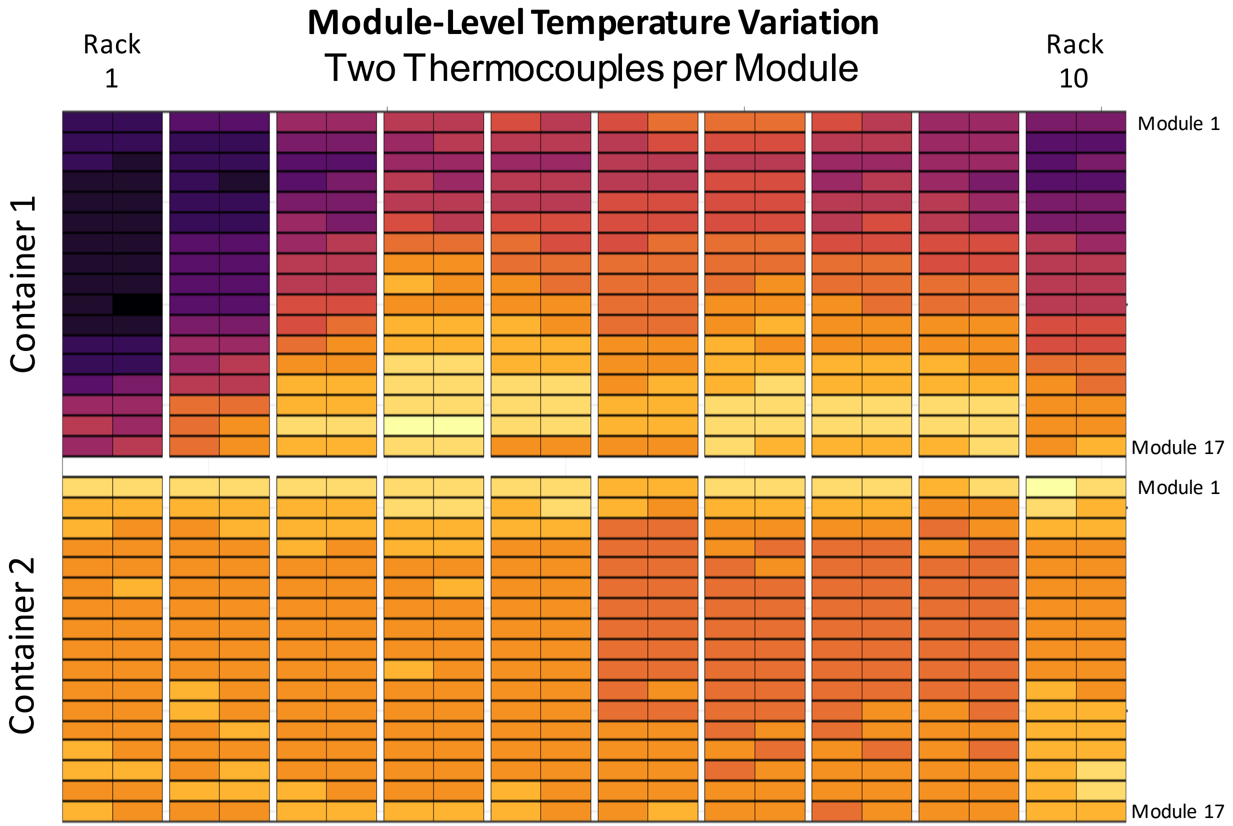
Background: Monitor and proactively manage underperforming thermal management systems

Data Requirements:

- Hours – years of data
- High resolution data necessary, at least minute with an array of thermocouples
  - **Minimum:** Rack-level DC voltage, current, temperatures
  - **Preferred:** Rack subcomponent metering

Cycle Requirements: No special operation

Desired Outcome: Prevent damage / prolong life by identifying and resolving possible weaknesses in thermal management system.



Findings: Predictive Performance Modeling

Background: Use the battery's historical data to predict how performance degrades.

- A model that accurately predicts degradation may be able to predict future SOC evolution
- Need to accurately characterize performance before we can predict performance degradation

Data Requirements:

- Years of data from a diverse set of systems and operating conditions
- Depends on model complexity. Minute-res, AC-level data may be sufficient.

Desired Outcome: Model which predicts how SOC will change as a function of power, SOC, temperature.

- Models that incorporate degradation will reflect performance changes over time.

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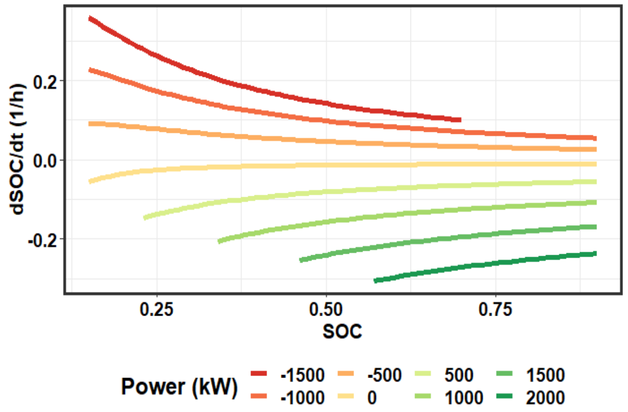
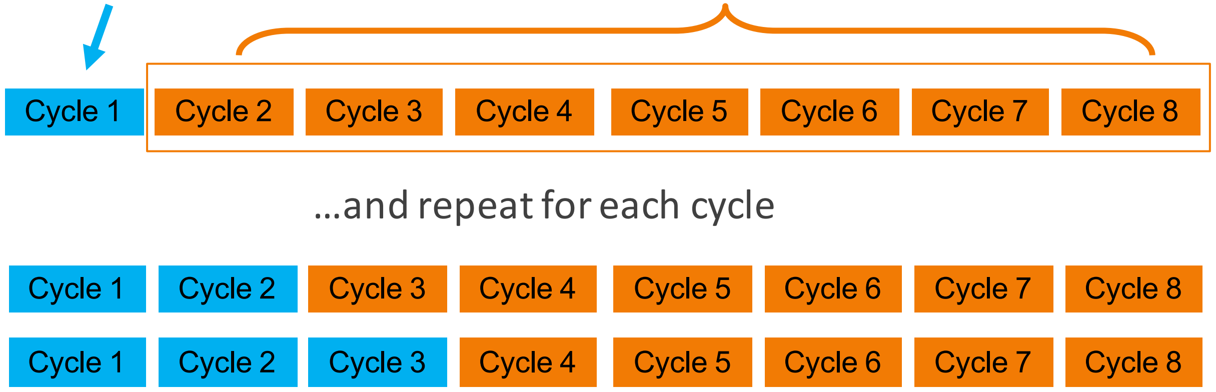
$$\frac{dSOC}{dt} = f(P, SOC, T, history)$$



Example of how SOC change varies with SOC and power for a flow battery

For this cycle, build model on
This historical data to predict this performance



Synergistic relationship between model development and performance metric calculations

Example: Data Analysis Descriptive & Predictive Analysis

Historical Operation

Future Performance

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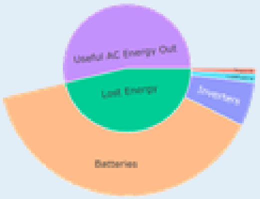
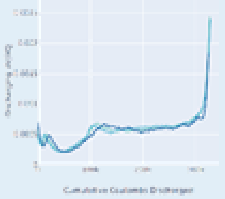
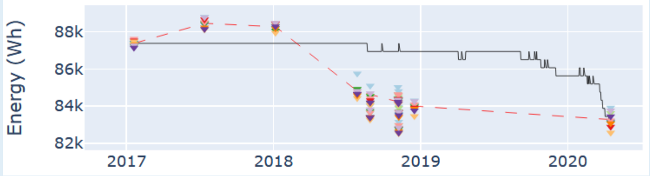
Diamond Database: Operational data collection and management

Develop Algorithms and Tools: To analyze historical system performance





Descriptive Analysis: Describe historical performance. Refine processes.



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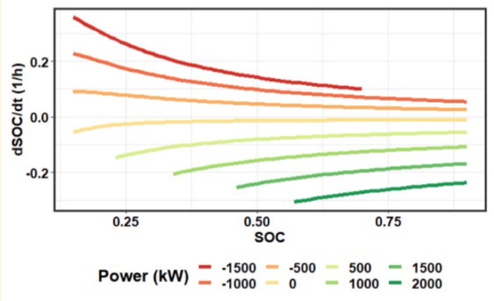
Train Predictive Models: Using historical data and battery chemistry expertise

Predict Future Performance:



Validate and Refine Predictions: Compare predictions with descriptions. Refine accordingly

Predicting future requires an accurate **description** of the past

Results Summary

Results Summary

- Performance Characterization is possible for even Sparse Data based systems
- Comparison of Sparse Data based systems is starting to be informative
- Most results are not matching vendor claims in many instances – mostly in emerging technologies but also with more mature technologies
- Robust Data based systems can be proxies for understanding other system behavior

Sparse Data based systems are prevalent as no standards or rules dictate otherwise

Round Trip Efficiency: High-Level Comparison

- AC Round Trip informs project economics and requires accurate metering
- DC Round Trip may or may not include ancillary loads
  - Gives more insight to internal degradation
- Data was not available for needed full cycle C/D in some instances

		Approximate Avg. AC RTE	Approximate Avg. DC RTE
Aux Loads (e.g., thermal mgmt.) **NOT** included in RTE calcs	**System A** LG Chem Li Ion	No AC data	96%
	System B LG Chem Li Ion	No AC data	97%
Aux Loads (e.g., thermal mgmt. or electrolyte pumps) included in RTE calcs	**Invinity** Vanadium Flow	54%	57%
	System C Tesla Li Ion	84%	No DC data
	System D Tesla Li Ion	No valid test cycles	No DC data

Standby Loss: High-Level Comparison

- Initial Posture: Monitor Standby Losses for economic (cost) impact
- Subsequent Finding: Standby Losses may indicate excessive cell balancing and potentially provide an indication of degradation

approximate standby loss values

		Measured Standby Loss (% SOC Loss/day)	
Aux Loads (e.g., thermal mgmt. or electrolyte pumps) **NOT** included	**System A** LG Chem Li Ion	0.7	
	System B LG Chem Li Ion	0.4 - 9.3	Excessively high losses, Robust dataset
	Invinity Vanadium Flow	0.49	
	System C Tesla Li Ion	0.14	
	System D Tesla Li Ion	0.23	Sparse dataset

Cost/Benefit Approach and Solutions

Cost/Benefit of Data - Implications

- Large amounts of continuous streaming *robust* data can be costly
  - Data archiving costs (server space)
  - Data quantity transport (Cloud based subscriptions)
  - High labor set up costs (due to lack of uniformity) on database structuring
  - But…allows deep analysis
- True performance is hidden for *sparse* data systems
  - Imbibes reliance on underperforming data transport systems (just use SCADA)
  - Degradation analysis becomes problematic
- Lack of current uniformity on data systems and the variety of use cases makes cost/benefit ratio analysis difficult

Cost/Benefit of Data - Potential Solutions (Interim)

- For large storage systems
  - Utilize fiber connection (fair assumption) to host historian
    - Also potential to store on on-site historian
  - Containerize specific data sets (periodic full C/D cycles) for analysis
  - Set thresholds to enable queries for unexpected behavior or dropped data/communications
  - Some analysis may only require periodic uploads to analysis platform rather than streamed data – minimize subscription based cloud service
  - Work with NERC to direct minimal but acceptable data access
- For smaller systems (BTM)
  - Create well instrumented proxy systems to characterize fleets
    - Lower costs of data but still perform analysis – assuming a uniform fleet of very similar systems
    - Specific locations and service duty have 1 out of TBD systems from a manufacturer specific model
    - All utilizing the same firmware

Specific Potential Products that Embody Solutions

- EPRI/DOE Data Guideline V3
  - Address Lack of Uniformity via CSRs
  - NERC Data Reporting Requirements
    - Flows to big systems
    - Maybe even smaller systems via FERC 2222
    - Align to NERC and Interoperability efforts (IEC 61850, MESA)
- Push on Utility IT/OT infrastructure modifications needed to meet NERC requirements
  - This has to include new reliability based metrics (outage durations, outage reasons, availability etc.)
- Enhance Standard Specifications (via EPRI ESIC)
  - Tune to larger systems and require the needed data from vendors up front
    - Align vendor scope to modified utility OT/IT infrastructure
  - Prescribe a well instrumented proxy unit for smaller system fleets
- PNNL ES Protocol tuned to RTE, Standby Losses in field
  - Better prescribe field performance test protocols
  - Align to NERC reporting accuracy expectations
  - Also display test protocols and NERC requirements as a driver for specification
- EPRI ESIC O&M Reporting Tool
  - Refined to above requirements
  - Tuned to new NERC data labels
  - More refinement to IEC 61850 etc

Furthering Collaboration on Independent Analysis

- Energy Storage Grand Challenge
  - "Data collection and analysis activities help establish clear goals and objectives for the National Laboratories, other partners, and the Department by facilitating the evaluation of best practices and effective metrics. This data supports ESGC metric development, helps track progress to ESGC goals, and informs ESGC strategy."
- EPRI/PNNL Phase 2 efforts can extend application of various performance assessment approaches to a broader set of data, applications and technologies
  - Pursue accuracy comparison of various algorithms for specific Li-Ion and flow chemistries
  - Determine best independent analysis approach for a given situation and associated data needs
  - Further refine the cost/benefit parameters to inform standards and rules
  - Pursue further studies of standby loss indication of degradation
  - Align EPRI/DOE efforts on low cost DC monitoring

Acknowledgements

- EPRI would like to acknowledge Dr Imre Gyuk and the DOE Office of Electricity, Energy Storage Program for the funding contribution and deep collaborative efforts aimed at further understanding Energy Storage performance and reliability

Together…Shaping the Future of Electricity