Performance and degradation of Li-ion batteries from cells to systems

PRESENTED BY

Yuliya Preger

Presentation #404
DOE Energy Storage Peer Review
August 6, 2025

SAND2026-16089PE

Research Overview

Problem
Full energy storage systems (ESSs) tend to perform more poorly than would be predicted based on single cell results ("pack penalty")

Project Goal
Systematically characterize performance of batteries from cells to modules to integrated systems to understand causes of degradation and safety issues

Current Practice
Most battery testing focuses on precisely-controlled single cell cycling without considering non-idealities from balance-of-plant components in real systems

Why SNL?
Cross-disciplinary expertise and nationally unique labs in battery testing, safety, metrology, and power electronics

Innovation
Collecting data across scales and standardizing/sharing the data to facilitate analysis by SNL and other ESS stakeholders

Impact
Maximize availability and economic value of all cells in a system and minimize safety concerns for utilities and critical infrastructure owners
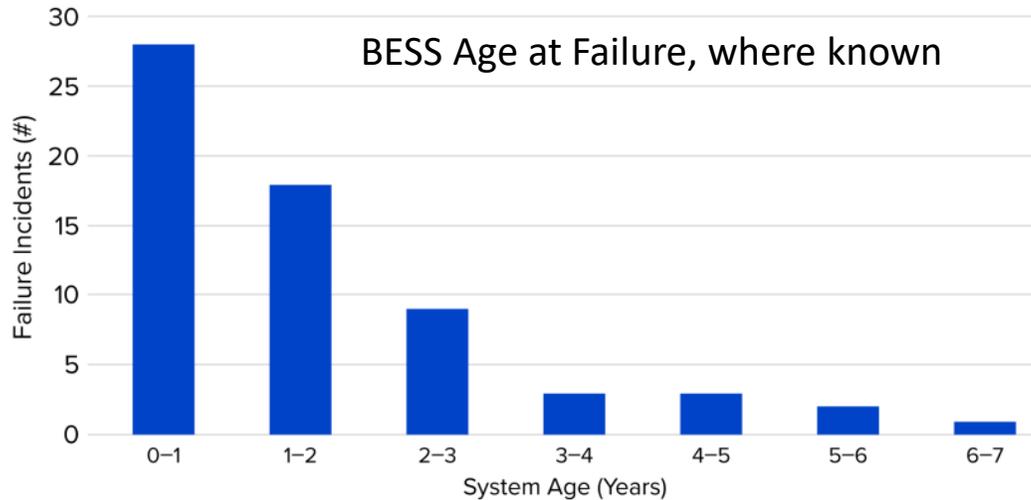
Alignment
Enhancing the reliability and performance of ESSs enables them to better provide baseload power and critical facility resilience
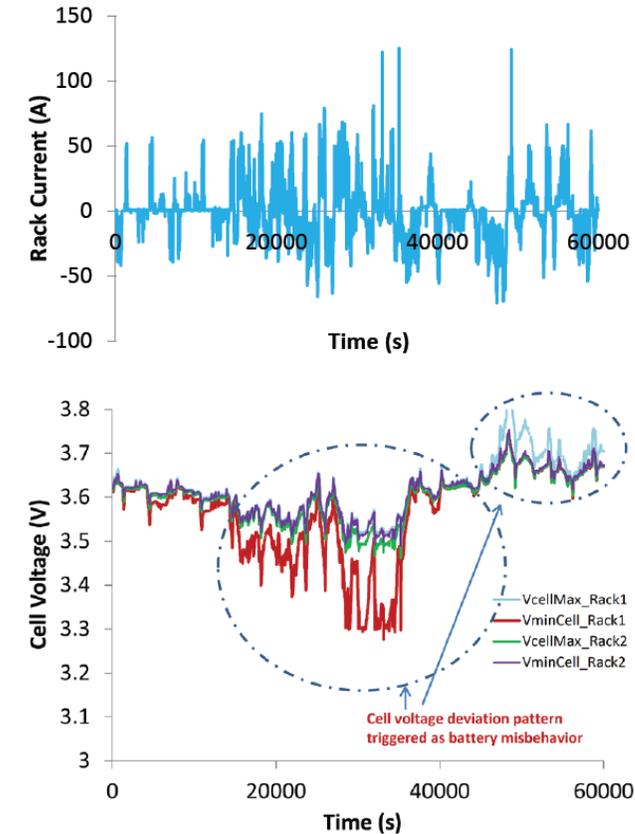
Energy storage industry is still learning…

Failure can be sudden, due to inadequate commissioning and systems integration

BESS Age at Failure, where known

Even if systems are well-engineered, they degrade without proper controls

Source: "Insights from EPRI's Battery Energy Storage Systems Failure Incident Database"
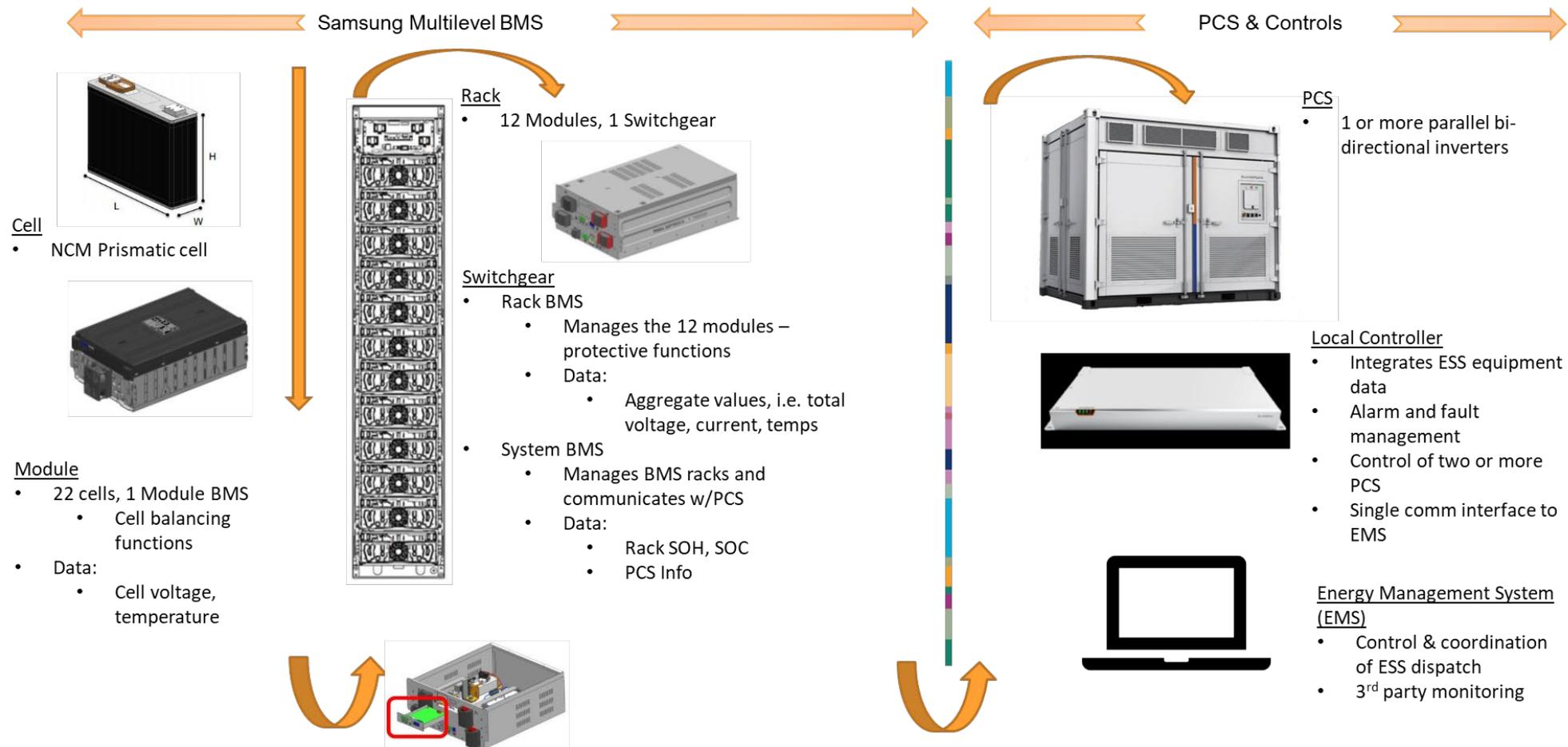
Source: R. Fioravanti, K. Kumar, S. Nakata, B. Chalamala, Y. Preger "Predictive-Maintenance Practices: For Operational Safety of Battery Energy Storage Systems" IEEE Power Energy Mag., 2020, 18, 86.

…because systems have complex interactions between many components

2.5 MW/2.9 MWh Li-ion SNL project supported by Office of Electricity:

Samsung Multilevel BMS

PCS & Controls

Cell
- NCM Prismatic cell

Module
- 22 cells, 1 Module BMS
  - Cell balancing functions
- Data:
  - Cell voltage, temperature

Rack
- 12 Modules, 1 Switchgear

Switchgear
- Rack BMS
  - Manages the 12 modules – protective functions
  - Data:
    - Aggregate values, i.e. total voltage, current, temps
- System BMS
  - Manages BMS racks and communicates w/PCS
  - Data:
    - Rack SOH, SOC
    - PCS Info

PCS
- 1 or more parallel bi-directional inverters

Local Controller
- Integrates ESS equipment data
- Alarm and fault management
- Control of two or more PCS
- Single comm interface to EMS

Energy Management System (EMS)
- Control & coordination of ESS dispatch
- 3rd party monitoring

With OE investment, we established labs to systematically collect data across scales
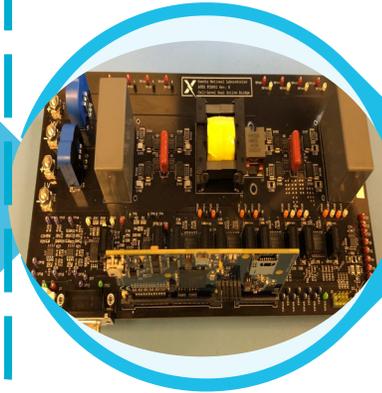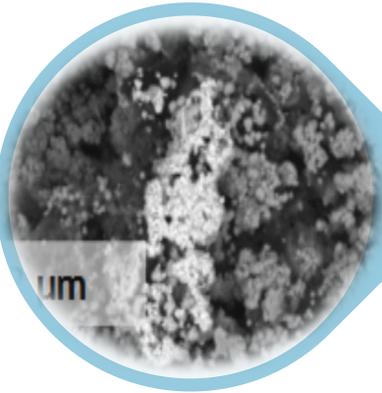

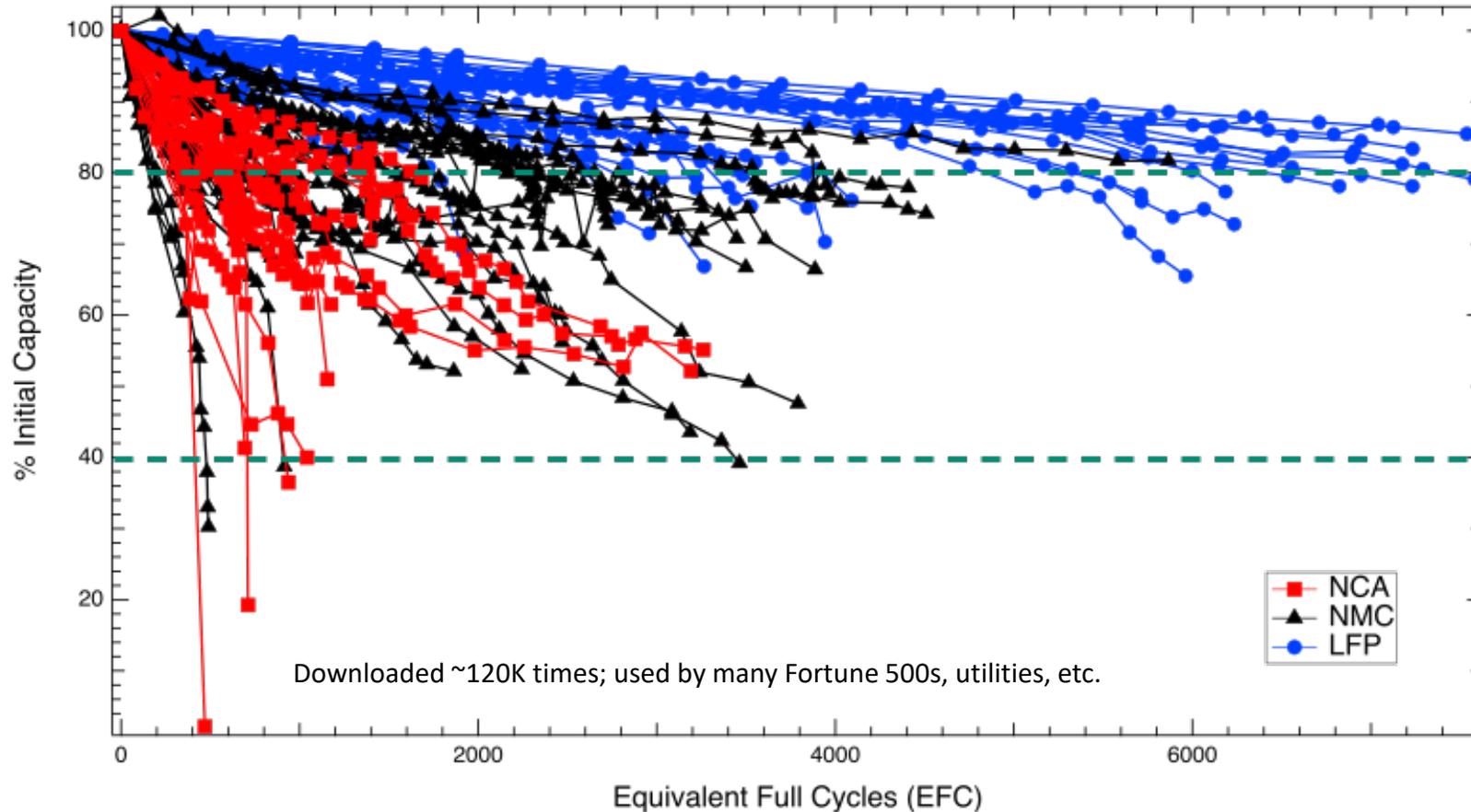Materials   Single Cells   Modules   Power Electronics   Batteries + Power Electronics   Systems

Stack testing is often overlooked, but critical for identifying integration issues

Images: Sandia Materials Labs, Battery Test Facility (BTF), Battery Abuse Lab (BatLab), Battery Energy Storage Test Lab (BEST), Advanced Power Electronic Conversion Systems Lab (APEX), Energy Storage Control and Analytics Lab (ESCAL), Energy Storage Test Pad (ESTP)

8+ year single-cell study has provided a key reference for impact of cycling conditions on degradation

Preger et al. *J. Electrochem. Soc*. **2020**, *167*, 120532.
Witmann, Upadhya et al. "Degradation of 18650 Lithium-ion Cells Beyond 80% Capacity" To be submitted.

We correlated single-cell materials and electrochemical changes to understand variations in degradation rate

Capacity Fade

Materials Characterization

X-Ray Diffraction (XRD)

Understand trends in materials degradation

Electrochemical Characterization

Electrochemical Impedance Spectroscopy (EIS)

Understand trends in electrochemical changes

250+ characterization datasets

X-ray Computed Tomography (XCT)

SEM and EDX

Incremental Capacity Analysis (ICA)

Link trends to understand degradation mechanisms

Materials and electrochemical data informed our understanding of the impact of battery aging on safety

- To assess risk, there are many battery safety test standards, but they're only required for fresh cells

- Approach:
  - Completed first comprehensive review of safety of aged cells with UL Electrochemical Safety Research Institute
  - Published broadest public assessment of impact of testing method, degradation mechanism, and chemistry on safety of aged cells with ZSW

Cell with Li plating burst its calorimetry vessel

Aged LFP cell shows additional electrolyte leakage during overcharge

Overdischarge of aged NMC cell with SEI formation showed no change

Preger, Jeevarajan et al. *J. Electrochem. Soc.*, **2022**, *169*, 030507.

Preger, Waldmann et al. *J. Electrochem. Soc.*, **2025.**

See Poster: Impact of Aging on the Safety of Lithium-ion Batteries
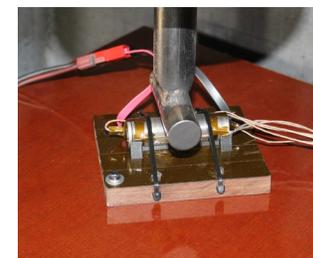
To support comparison, we launched Battery Archive as a repository for public battery data

Users range from high schoolers to PhD students and startups to Fortune 500 employees in over 70 countries
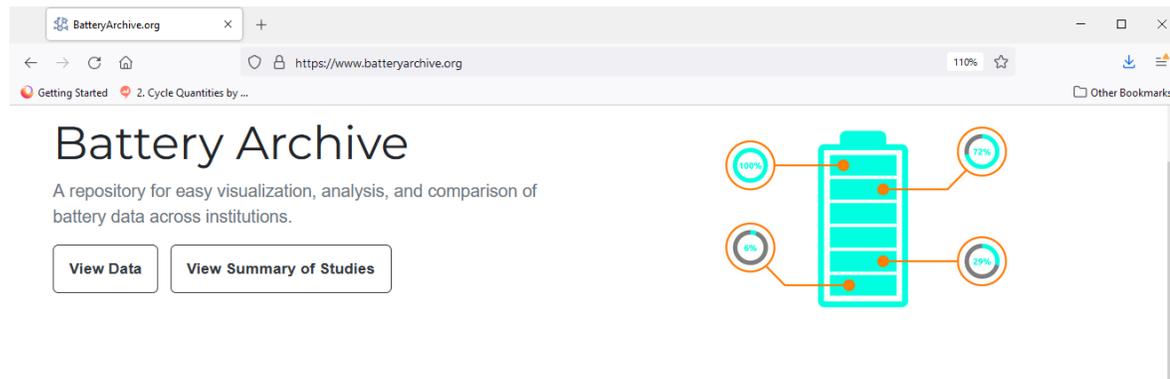
Cycling data

Safety data

https://github.com/battery-lcf (granted SNL copyright)

See Poster: Battery Archive – A Standardized Data Repository....

Battery Archive tools for data aggregation and cleaning have enabled AI-ML

- **Example: predict Li-ion cell cycle life with just 100 cycles of data (weeks/months instead of years of testing), using defined features**

- We can reasonably accurately predict cycle life for most of our larger datasets (method: elastic net regression, leave-one-out cross validation).

- Working with diverse datasets reveals the caveats to successful prediction


J. Lubars, Y. Preger, V. De Angelis, L. Kassabian, I. Derin, V. Subramanian, S. Verzi. Under review.

See Poster: Battery Archive – A Standardized Data Repository….
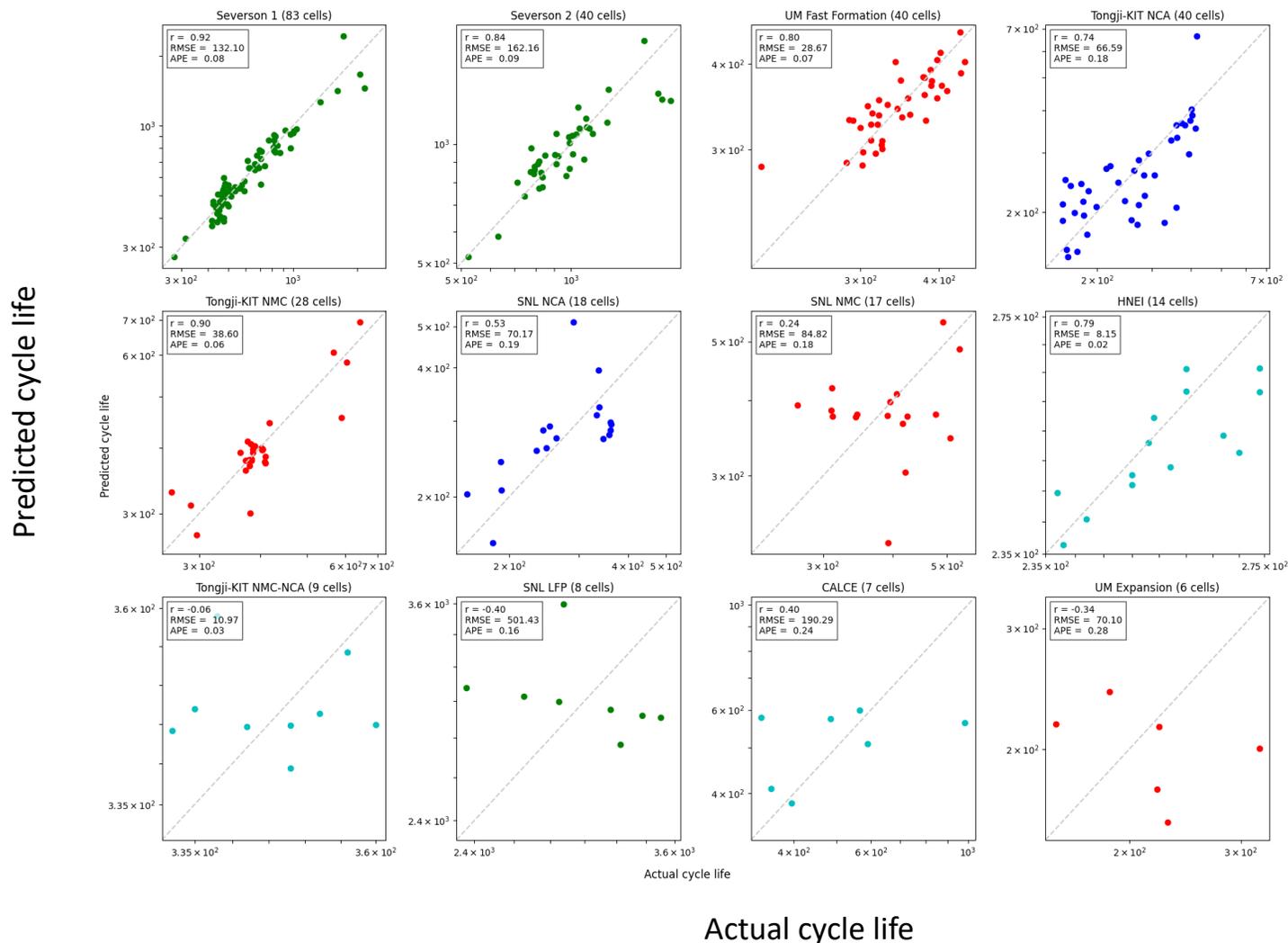
# Transition to module cycling allows assessment of "pack penalty"

Many factors cause system performance to fall short of cell expectations

Custom SNL PCB with cell- and module-level monitoring has enabled the broadest study on the impact of module configuration on performance and degradation
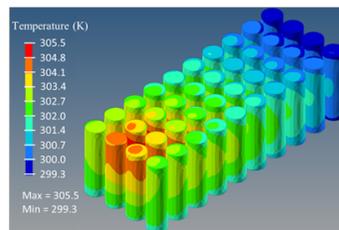
Module configuration (parallel/series)
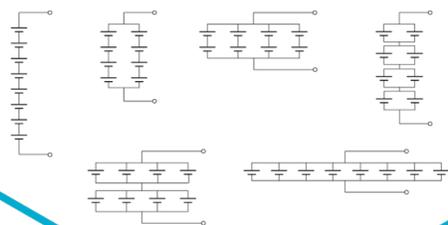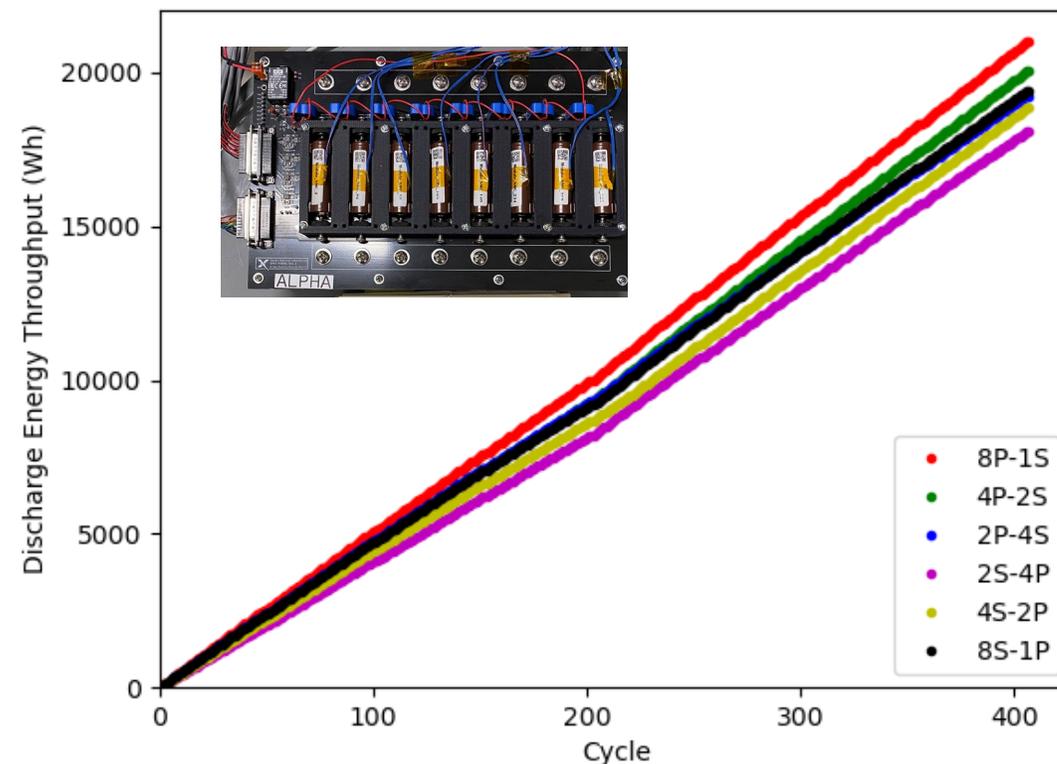

Cell to cell manufacturing variation
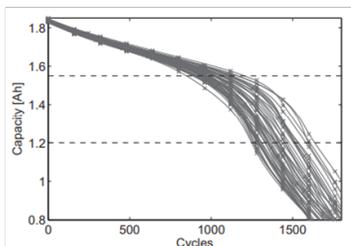
Baumhofer et al. *J. Power Sources*, **2014**, *247*, 332.

Thermal variation

Kremer et al. ACM/IEEE ISLPED, **2021.**

Y. Preger, J. Mueller, A. Fresquez, S. Allu, C. Rich, J. Electrochem. Soc., **2025**, 172, 050540.

See Poster: Impact of Module Configuration on Li-ion Battery Performance and Degradation

Impacts to date

Scientific recognition
- First cell cycling paper downloaded nearly 120K times, Electrochemical Society Top 10 Most Read for 5+ years
- Two other papers in Electrochemical Society Top 10 Most Read for months + Top 1% Most Cited '21-'23 and '22-'24

Industry value
- Performance and materials data used by startups, Fortune 500s, insurance, and utilities for state-of-health model development, technoeconomic analysis, testing software, vetting new products
- SNL cycling study alone has generated at least $100 million worth of value for users*

Informing standards
- Module cycling data informed IEEE BMS Recommended Practice and Energy Storage Data Management Recommended Practice
- Safety of aged batteries analysis has informed battery safety standards committees

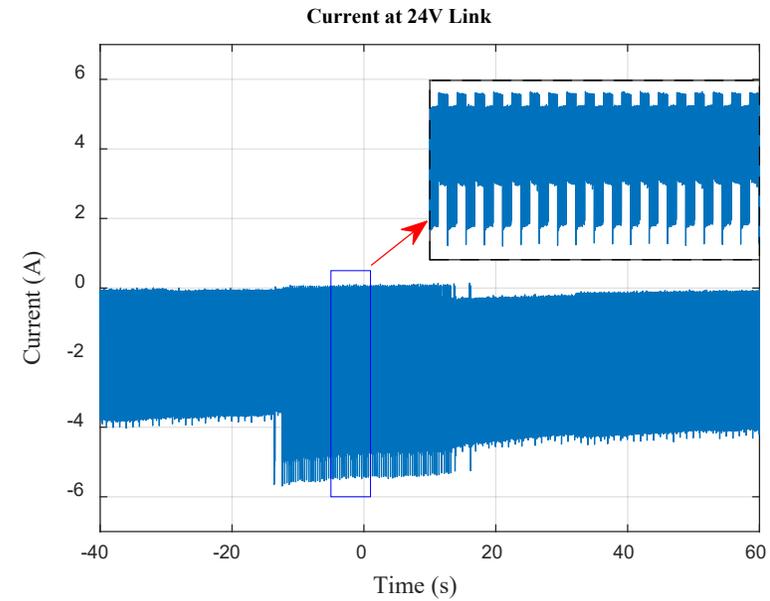*based on cost of users generating similar data with a typical testing lab

Moving beyond conventional battery testing

Lab: battery tester
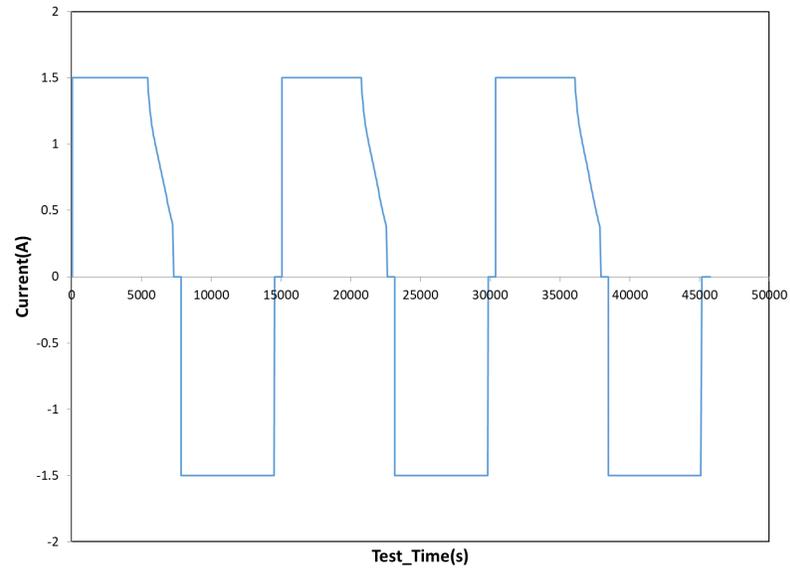
Field: power electronics

O. Dutta, *et al., IEEE PES General Meeting*, 2022.

Moving beyond conventional battery testing

We have developed a new testing platform that allows us to evaluate the performance of modules under more realistic conditions than conventional battery testers: with power converters and battery management systems.

All Equipment and Connections

→ Digital I/O: Used for contactor enable signals.

→ Communications – Ethernet: Basic commands issued from DAQ to Power Supply.

┈┈→ Communications – CAN: Comm links between DAQ, converter, and BMS for exchanging control commands.

→ Communications – Serial: Comm link between DAQ and converter

→ Analog signal measurements
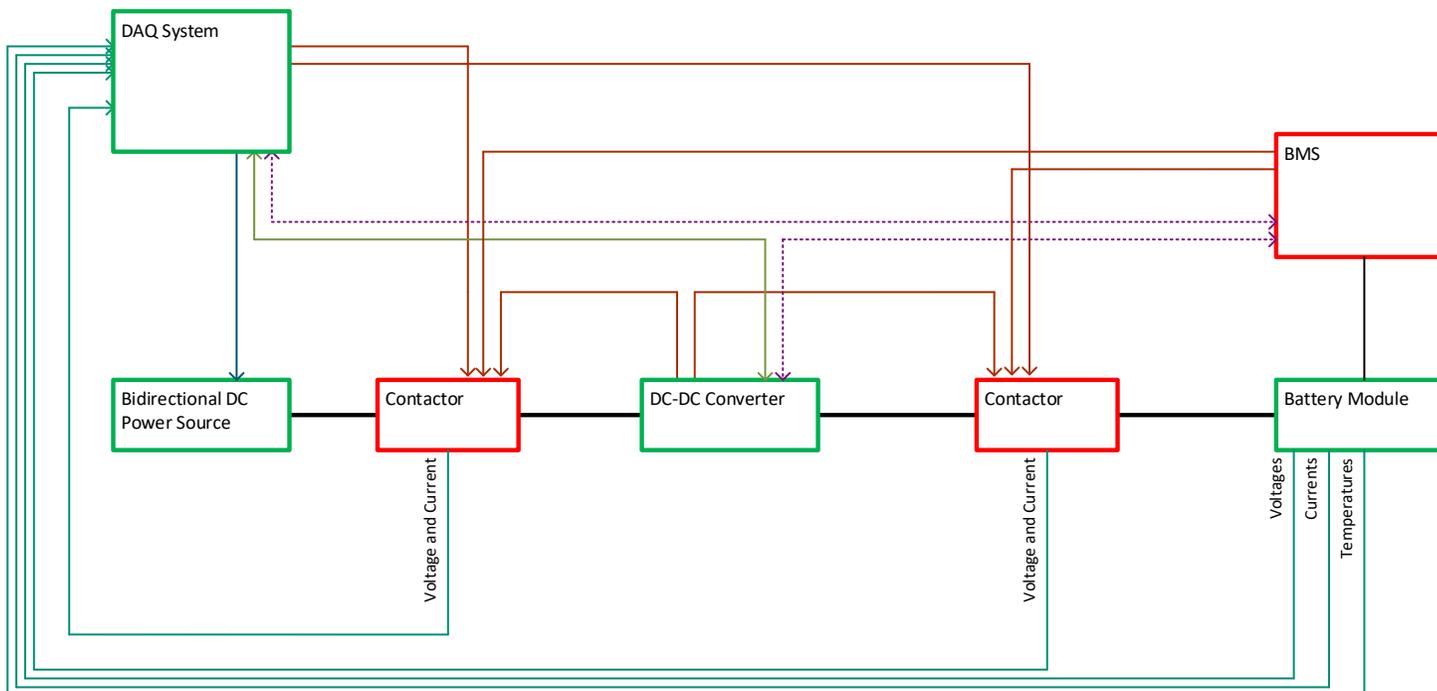
Representative synchronous buck converters

Converters built by SNL APEX lab

Individual projects support a broader vision for system integration

Components

Integrated System

Thursday presentation: Victoria O'Brien

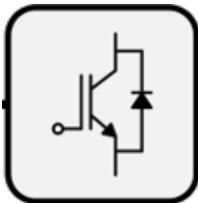**Enabling Critical New Research Areas**

Batteries
This presentation

Single cell and module cycling, battery modeling and ML

Power Electronics
Thursday presentation: Jake Mueller

Component and converter testing, simulation

EMS

BMS   DC-DC   AC-DC

DC Bus

Battery type A   DC/DC Converter   PCS   Grid

...

Battery type N   DC/DC Converter   Flexible design
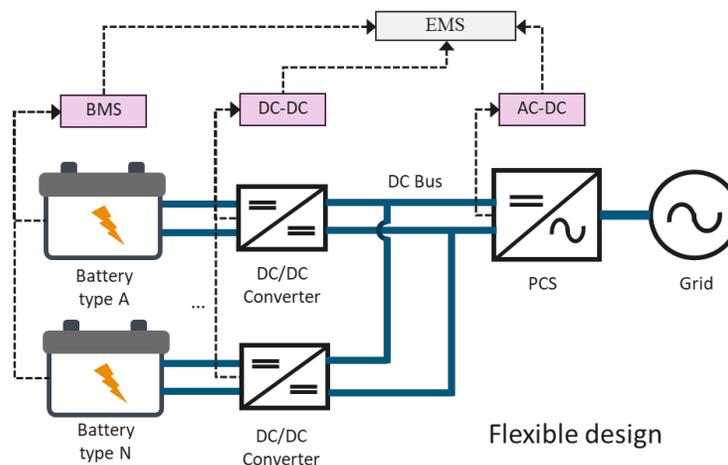
Four parallel modules, each with: (1) battery packs, (2) DC-DC converter, (3) BMS, (4) Fans, (5) E-stop Contactors, (6) Power and Communication cables

- Cybersecurity of ESS

- Testing new economical non-Li batteries and converters

- Testing firmware updates/control strategies to support applications with new duty profiles (e.g., data centers)

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.

For questions about this presentation: ypreger@sandia.gov