Sandia National Laboratories

# Impact of Module Configuration on Li-ion Battery Performance and Degradation

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## Background and Objectives

- **Problem**: Many factors cause energy storage system-level performance to fall short of cell-level expectations ("pack penalty"), reducing reliability and increasing costs. One factor is how cells are electrically connected in series and parallel.
- **State of the field**: Module-level models extrapolate performance from single-cell cycling results and there is limited data to validate these models.
- **This work**: Evaluate the performance of six different series-parallel module configurations of NMC and LFP cells. A custom circuit design enabled measurement of cell-level values to understand causes of deviation.

**OE Mission Alignment:** Enable more reliable and inexpensive critical infrastructure by maximizing the utilization of all cells in an energy storage system.

**Motivating Questions**

- How do different module configurations (series versus parallel) impact battery performance and degradation?
- How does aging of a cell in a given module configuration compare with aging results observed in single cell studies?
- Given results to the questions above, how can we leverage new battery configurations or converter topologies to force cell performance closer to the ideal results indicated by cell-level studies?

**Milestones**

- Complete cycling and analysis of 12 modules of well-matched and randomly selected NMC cells for 400 cycles
- Assess cell-to-cell variation in a batch of 400 new LFP cells
- Begin cycling LFP cells in fully parallel configuration

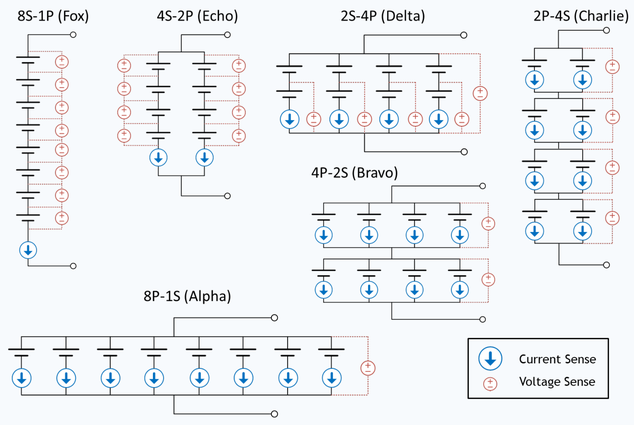
## Module Cycling Methodology

We explored all series and parallel combinations of an eight-cell module. Cells were selected from a lot of 400 3 Ah 18650 NMC cells and 400 1.2 Ah 18650 LFP cells. Cycling was done at 25 °C without balancing (baseline case). The program moved on to the next step once any cell in the module reached the voltage limit.

**Representative Module Board**

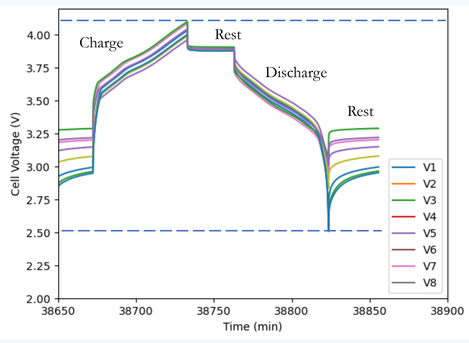
- Module-level voltage/current
- Cell-level temperature/voltage/current (Hall-effect sensors)
- Abort limits based on cell-level T/V/I


**Module Configurations**



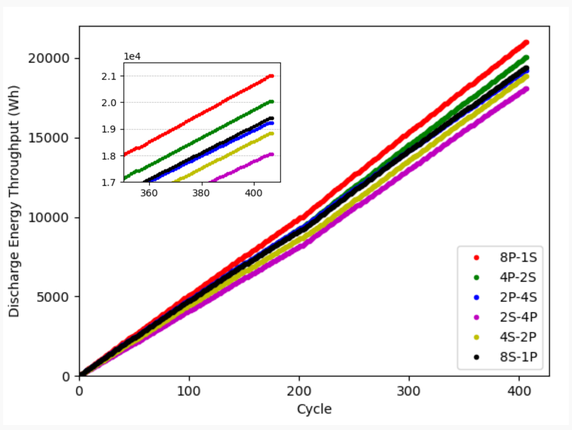

**Example Control Program**

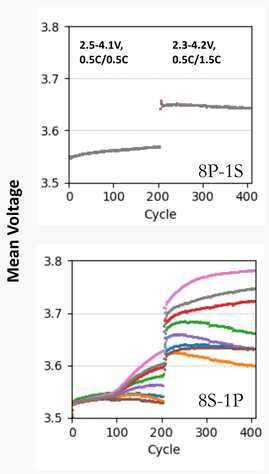
Module moves on to next step once any cell hits voltage limit



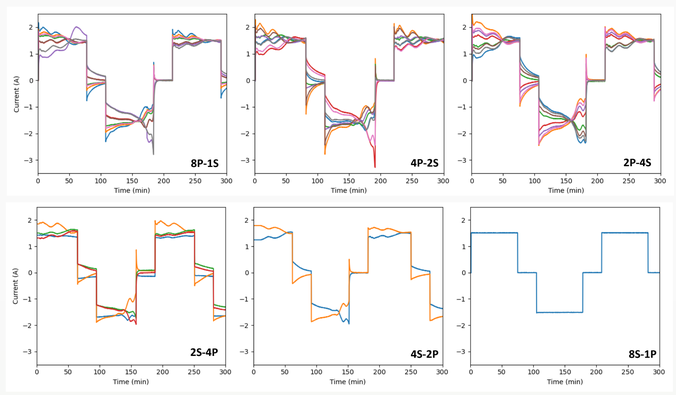

## NMC Modules

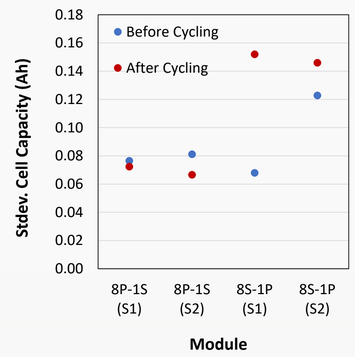
After 400 cycles, parallel modules show up to 15% higher energy throughput due to cell-level voltage divergence in series configurations.



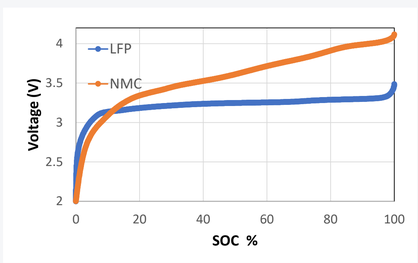

Notable current redistribution is evident in parallel cells (phenomenon validated with physics-based models), but it can lead to cell-level capacity convergence

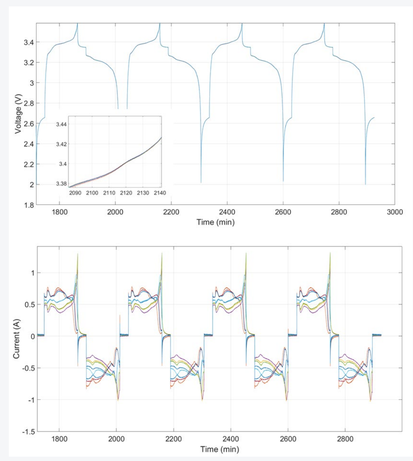


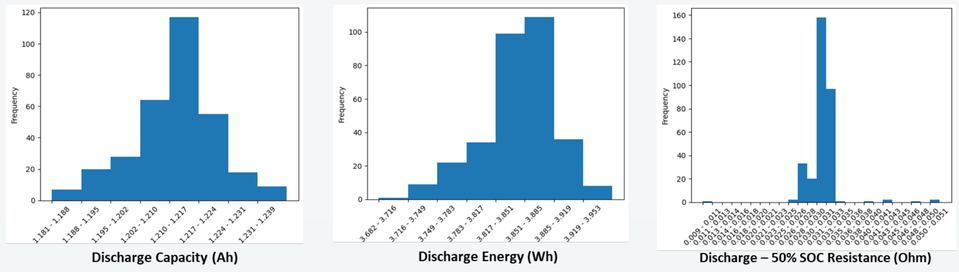

## Preliminary Results with LFP Modules

Randomly selected LFP cells in an 8P-1S configuration show the same general phenomena as NMC cells despite their different voltage profiles.




We characterized (dis)charge capacity, energy, and resistance (every 10% SOC) for a batch of 400 LFP cells for long-term cycling experiments of well-matched cells. This allows study of the impact of cell-to-cell variation on module performance.




## Innovation and Impacts

- Generated broadest module cycling dataset in open literature (Preger, Mueller et al. J. Electrochem. Soc., 2025, 172, 050540)
- Several ESS manufacturers and utilities have expressed significant interest in the data as they are in the process of vetting different energy storage product configurations and improving system models
- Data has informed recommendations in IEEE BMS Recommended Practice

## Future Work

- Complete cycling of LFP cells in additional module configurations
- Complete module cycling experiments with real power converters (e.g., with current ripple) and a battery management system

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NNSA National Nuclear Security Administration

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