# Hawaiʻi Natural Energy Institute Research Highlights

*Electrochemical Power Systems*

## *Path Dependence of Battery Degradation*

**Objective and Significance**: The objective of this project is to characterize the impact of different stresses on the durability of lithium- and sodium-ion batteries using large experimental campaigns and design of experiments. Studies address, among others, the impact of fast charging and grid-vehicle interactions on the performance of batteries for electric transportation. The knowledge gained in this project informs best practices to successful battery durability, safety, fast charging, or vehicle-to-X integration.

**Background**: Electrification of transportation and grid-storage are crucial to combat climate change. Understanding and mitigating battery degradation is key to improving durability of electric transportation and the reliability of power grids. Complexity stems from the fact that battery degradation is path dependent. This implies that usage affects not only the degradation pace, but also the type of degradation the batteries experience. Lithium-ion batteries are known to degrade slowly at first before a rapid acceleration of which starting time will depend on the mix of degradation mechanisms and thus on how the battery was used. To maximize the utility of large battery systems, it is essential to understand the impact of all the stress factors associated with an application and their combined effects.

**Project Status/Results**: Work with the Defence Science and Technology Group (DSTG, Australia) involving an experimental campaign of more than 700 cells tested for three years under a HNEI-defined design of experiments to predict the degradation of MW systems and maximize durability and reliability in the field was completed.

Further research is continuing with collaborative work with Sandia National Laboratories, the University of Aachen (Germany), and the University of Oviedo (Spain) to address the performance and safety of newly released commercial sodium-ion batteries. Research conducted for this project is completed in the **PakaLi Battery Laboratory**.

This work has led to 15 publications and 10 presentations, all available on the **project page** with the most recent linked on the following page.

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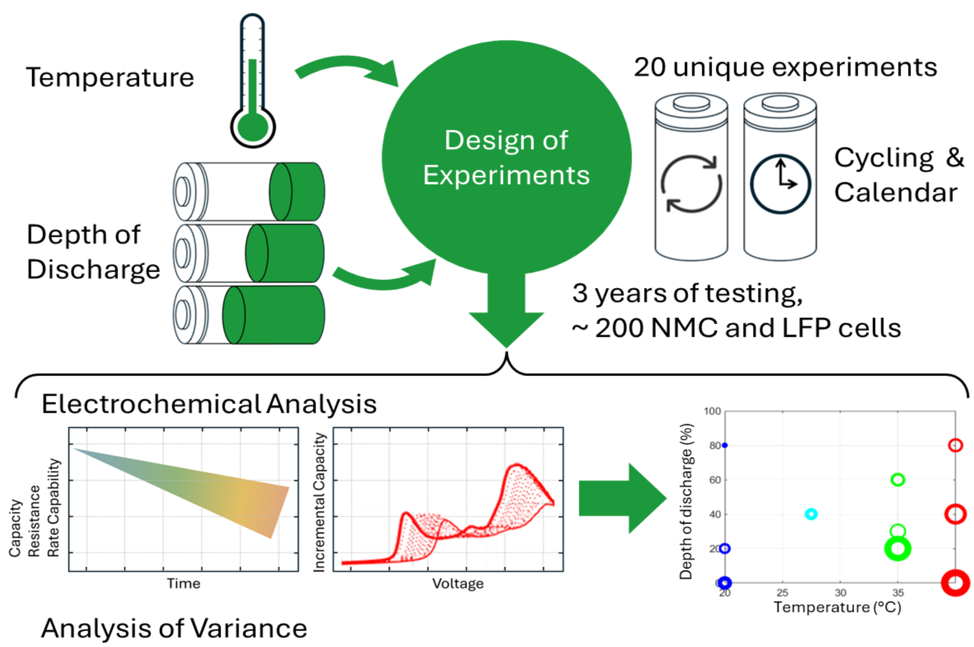


$$Q, R, RC = a.T + b.DOD + c.T.DOD + d.T^2 + e.DOD^2$$

Figure 1. Summary overview of the project's DSTG study.

## ADDITIONAL PROJECT RELATED LINKS

### PAPERS AND PROCEEDINGS:

1. 2026, R.M. Wittman, et al., **Initial characterization and cycling of two batches of commercial hard-carbon/$Na_xNi_yFe_zMn_{1-y-z}O_2$ sodium ion 18650 batteries as a potential replacement for lithium-ion batteries**, EES Batteries. (Open Access: **PDF**)
2. 2025, M. Dubarry, et al., **Impact of Temperature and Depth of Discharge on Commercial Nickel Manganese Oxide and Lithium Iron Phosphate Batteries After Three Years of Aging**, Batteries, Vol. 11, Issue 7, Paper 239. (Open Access: **PDF**)
3. 2025, S. Klick, et al., **Failure Mode and Degradation Analysis of a Commercial Sodium-Ion Battery With Severe Gassing Issue**, Batteries & Supercaps, Paper e202400546. (Open Access: **PDF**)
4. 2023, R. Wittman, et al., **Characterization of Cycle-Aged Commercial NMC and NCA Lithium-ion Cells: I. Temperature-Dependent Degradation**, Journal of The Electrochemical Society, Vol. 170, Issue 12, Paper 120538. (Open Access: **PDF**)
5. 2023, A. Gismero, et al., **The Influence of Testing Conditions on State of Health Estimations of Electric Vehicle Lithium-Ion Batteries Using an Incremental Capacity Analysis**, Batteries, Vol. 9, Issue 12, Paper 568. (Open Access: **PDF**)
6. 2022, P.M. Attia, et al., **Review—"Knees" in Lithium-Ion Battery Aging Trajectories**, Journal of The Electrochemical Society, Vol. 169, Issue 6, Paper 060517. (Open Access: **PDF**)
7. 2021, D. Beck, et al., **Inhomogeneities and Cell-to-Cell Variations in Lithium-Ion Batteries, a Review**, Energies, Vol. 14, Issue 11, Paper 3276. (Open Access: **PDF**)
8. 2020, M. Elliott, et al., **Degradation of electric vehicle lithium-ion batteries in electricity grid services**, Journal of Energy Storage, Vol. 32, Paper 101873.
9. 2020, G. Baure, et al., **Durability and Reliability of EV Batteries under Electric Utility Grid Operations: Impact of Frequency Regulation Usage on Cell Degradation**, Energies, Vol. 13, Issue 10, Paper 2494. (Open Access: **PDF**)

### PRESENTATIONS:

1. 2025, R.M. Wittman, et al., **Analysis of Iron Manganese Nickel Oxide/Hard Carbon Na-Ion Battery Degradation Modes and Mechanisms**, Presented at the 248th ECS Meeting, Chicago, IL, October 12-16.
2. 2024, R.M. Wittman, et al., **Analysis of Commercial Na-Ion 18650 Cell Performance: Cell-to-Cell Variation and Long-Term Cycling**, Presented at the 246th ECS Meeting, Honolulu, HI, October 6-11.
3. 2022, R. Wittman, et al., **Path Dependence of Li-Ion Battery Degradation During Cycling to 80% Capacity**, Presented at the Material Research Society Spring Meeting, May 8-13.
4. 2021, R. Wittman, et al., **Characterizing Materials and Electrochemical Changes in a Range of 18650 Li-Ion Cells Cycled to 80% Initial Capacity**, Presented at the 239th ECS Meeting, Chicago, IL, May 30-June 3.