Hawai'i Natural Energy Institute Research Highlights

Electrochemical Power Systems

Battery Intelligence: Diagnosis and Prognosis

OBJECTIVE AND SIGNIFICANCE: This project aims at the development of approaches, tools, and protocols to improve batteries diagnosis and prognosis via non-invasive in-operando techniques.

BACKGROUND: Battery diagnosis and prognosis is a difficult task. Lithium- and Sodium-ion batteries are much more complex than traditional batteries and their degradation is path dependent as different usages (current, temperature, SOC range, SOC window, etc.) will lead to different type of degradation. In addition, since large battery packs are composed of thousands of cells, the use of complex models or multitude of sensors is precluded.

Traditionally, battery diagnosis is handled via two opposite approaches. The academic route aims for maximum accuracy and achieves it by inputting a lot of resources. The second route – the one usually used on deployed systems – uses as little resources as possible and must not be destructive. As a result, it is ineffective in predicting the true state of health.

This assessment of state of the art led HNEI to define and develop a third industry-compatible intermediate route to reach an accurate diagnosis with cost-effective and non-destructive methods, using only sensors already available in battery packs while requiring limiting computing power. HNEI developed a mechanistic modeling framework where a battery digital twin is built from individual electrode data and where the battery degradation is emulated by the scaling or the translation of one electrode versus the other. Using this framework, the voltage variations associated with the degradation mechanisms can be predicted.

Machine learning and artificial intelligence are also starting to play a crucial role in diagnosing and prognosing batteries. However, their accuracy is limited by the little to no training data available to validate algorithms. To solve this issue, HNEI applied the mechanistic modeling approach to develop the first synthetic training datasets. Recent work highlighted the possible opportunistic diagnosis of battery usage for photovoltaic-connected batteries using models trained and validated on synthetic datasets.

Research conducted for this project is completed in the **PakaLi Battery Laboratory**.

PROJECT STATUS/RESULTS: This project is currently ongoing with three industrial collaborations on different aspects of the problem including blends, silicon content, relaxation, and metal plating. A full suite of software and models were developed. The main model has been licensed by more than 135 organizations worldwide. This work has also led to 51 publications, many of which are linked on the following pages, and one patent.

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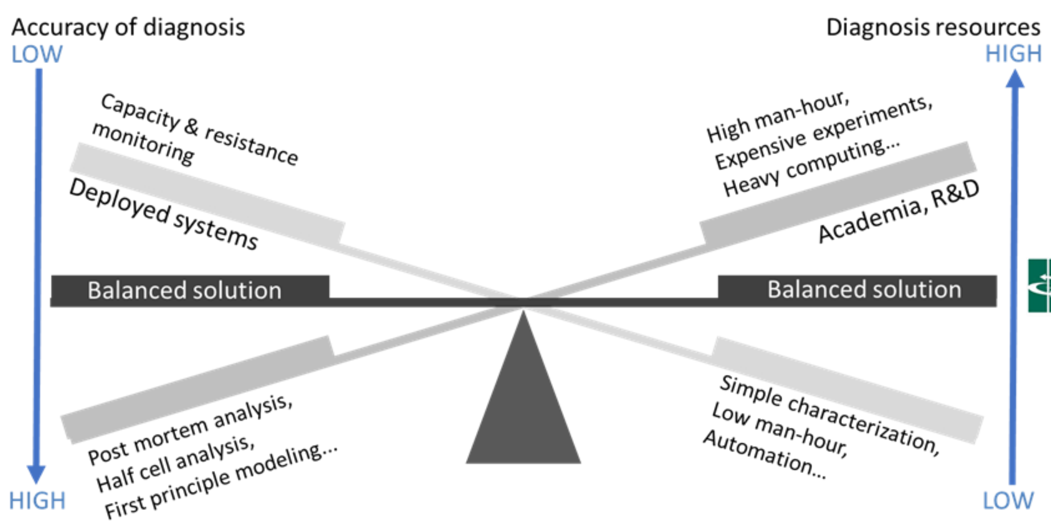

ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

Battery Testing

1. 2024, M. Dubarry, et al., **Communication—Forecast of the Impact of Degradation Modes on a Commercial Hard Carbon/$Na_3V_2(PO_4)_2F_3$-based Na-ion Battery**, Journal of the Electrochemical Society, Vol. 171, Issue 8, Paper 080541. (Open Access: **PDF**)
2. 2024, A. Fernando, et al., **Voltage relaxation characterization methods in lithium-ion batteries**, Measurement: Energy, Vol. 3, Paper 100013. (Open Access: **PDF**)
3. 2024, A. Fernando, M. Kuipers, G. Angenendt, K-P. Kairies, M. Dubarry, **Benchmark dataset for the study of the relaxation of commercial NMC-811 and LFP cells**, Cell Reports Physical Science, Vol. 5, Issue 1, Paper 101754. (Open Access: **PDF**)
4. 2022, M. Dubarry, et al., **Best practices for incremental capacity analysis**, Frontiers in Energy Research, 10:1023555. (Open Access: **PDF**)
5. 2022, L. Ward, et al., **Principles of the Battery Data Genome**, Joule, Vol. 6, Issue 10, pp. 2253-2271. (Open Access: **PDF**)
6. 2022, N. Costa, et al., **Li-ion battery degradation modes diagnosis via Convolutional Neural Networks**, Journal of Energy Storage, Vol. 55, Part C, Paper 105558. (Open Access: **PDF**)
7. 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**)
8. 2021, M. Dubarry, et al., **Analysis of Synthetic Voltage vs. Capacity Datasets for Big Data Li-ion Diagnosis and Prognosis**, Energies, Vol. 14, Issue 9, Paper 2371. (Open Access: **PDF**)
9. 2020, M. Dubarry, et al., **Big data training data for artificial intelligence-based Li-ion diagnosis and prognosis**, Journal of Power Sources, Vol. 479, Paper 228806.
10. 2020, D. Anseán, et al., **Mechanistic investigation of silicon-graphite/$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ commercial cells for non-intrusive diagnosis and prognosis**, Journal of Power Sources, Vol. 459, Paper 227882.
11. 2020, M. Dubarry, et al., **Perspective on Commercial Li-ion Battery Testing, Best Practices for Simple and Effective Protocols**, Electronics, Vol. 9, Issue 1, Paper 152. (Open Access: **PDF**)
12. 2019, A. Barai, et al., **A comparison of methodologies for the non-invasive characterisation of commercial Li-ion cells**, Progress in Energy and Combust. Sci., Vol. 72, pp. 1-32. (Open Access: **PDF**)
13. 2018, M. Dubarry, et al., **Calendar aging of commercial Li-ion cells of different chemistries – A review**, Current Opinion in Electrochemistry, Vol. 9, pp. 106-113.
14. 2018, A. Devie, et al., **Intrinsic Variability in the Degradation of a Batch of Commercial 18650 Lithium-Ion Cells**, Energies, Vol. 11, Issue 5, Paper 1031. (Open Access: **PDF**)
15. 2018, C.T. Love, et al., **Lithium-Ion Cell Fault Detection by Single-Point Impedance Diagnostic and Degradation Mechanism Validation for Series-Wired Batteries Cycled at 0 °C**, Energies, Vol. 11, Issue 4, Paper 834. (Open Access: **PDF**)
16. 2017, D. Ansean, et al., **Operando lithium plating quantification and early detection of a commercial $LiFePO_4$ cell cycled under dynamic driving schedule**, Journal of Power Sources, Vol. 356, pp. 36-46.
17. 2016, D. Ansean, et al., **Fast charging technique for high power $LiFePO_4$ batteries: a mechanistic analysis of aging**, Journal of Power Sources, Vol. 321, pp. 201-209.

Battery Modeling

1. 2024, M. Dubarry, et al., **Investigation of the impact of different electrode inhomogeneities on the voltage response of Li-ion batteries**, Cell Reports Physical Science, Vol. 5, Paper 102138. (Open Access: **PDF**)
2. 2024, D. Beck, et al., **Electrode Blending Simulations Using the Mechanistic Degradation Modes Modeling Approach**, Batteries, Vol. 10, Issue 5, Paper 159. (Open Access: **PDF**)

3. 2024, N. Costa, et al., **ICFormer: A Deep Learning model for informed lithium-ion battery diagnosis and early knee detection**, Journal of Power Sources, Vol. 592, Paper 233910. (Open Access: **PDF**)
4. 2023, M. Dubarry, et al., **Data-Driven Diagnosis of PV-Connected Batteries: Analysis of Two Years of Observed Irradiance**, Batteries, Vol. 9, Issue 8, Paper 395. (Open Access: **PDF**)
5. 2023, M. Dubarry, et al., **Accurate LLI and LAM_{PE} Estimation Using the Mechanistic Modeling Approach with Layered Oxides**, Journal of The Electrochemical Society, Vol. 170, Paper 070503. (Open Access: **PDF**)
6. 2023, M. Dubarry, D. Howey, B. Wu, **Enabling battery digital twins at the industrial scale**, Joule, Vol. 7, Issue 6, pp. 1134-1144. (Open Access: **PDF**)
7. 2023, M. Dubarry, N. Costa, D. Matthews, **Data-driven direct diagnosis of Li-ion batteries connected to photovoltaics**, Nature Communications, Vol. 14, Paper 3138. (Open Access: **PDF**)
8. 2022, M. Dubarry, et al., **Perspective on Mechanistic Modeling of Li-Ion Batteries**, Accounts of Material Research, Vol. 3, Issue 8, pp. 843-853.
9. 2019, S. Schindler, et al., **Kinetics accommodation in Li-ion mechanistic modeling**, Journal of Power Sources, Vol. 440, Paper 227117.
10. 2019, M. Dubarry, et al., **Battery energy storage system modeling: Investigation of intrinsic cell-to-cell variations**, Journal of Energy Storage, Vol. 23, pp. 19-28. (Open Access: **PDF**)
11. 2019, M. Dubarry, et al., **Battery energy storage system modeling: A combined comprehensive approach**, Journal of Energy Storage, Vol. 21, pp. 172-185. (Open Access: **PDF**)
12. 2017, M. Dubarry, et al., **State of Health Battery Estimator Enabling Degradation Diagnosis: Model and Algorithm Description**, Journal of Power Sources, Vol. 360, pp. 59-69.
13. 2016, M. Dubarry, et al., **Cell-balancing currents in parallel strings of a battery system**, Journal of Power Sources, Vol. 321, pp. 36-46.
14. 2016, M. Berecibar, et al., **Degradation Mechanism Detection for NMC Batteries based on Incremental Capacity Curves**, World EV Journal, Vol. 8, Issue 2, pp. 350-361. (Open Access: **PDF**)
15. 2016, M. Berecibar, et al., **Online State of Health estimation on NMC cells based on Predictive Analytics**, Journal of Power Sources, Vol. 320, pp. 239-250.

PRESENTATIONS:

1. 2023, M. Dubarry, et al., **Effect of Temperature on Lithium-Ion Battery Voltage Response and How to Model It in the Mechanistic Modeling Approach**, Presented at the 244th Electrochemical Society Meeting, Goteborg, Sweden, October 8-12.
2. 2023, M. Dubarry, et al., **Big data for the diagnosis and prognosis of deployed energy storage systems**, Presented at the Energy Storage Systems Safety & Reliability Forum, Santa Fe, NM, June 6-8.
3. 2023, A. Fernando, et al., **A Study of the Relaxation Patterns of Commercial Cells**, Poster presented at the International Battery Association Conference, Austin, TX, March 5-10.
4. 2022, M. Dubarry, **Big Data in Diagnostics Data-Driven Direct Diagnosis of PV Connected Batteries**, Presented at the Advanced Automotive Battery Conference, San Diego, California, December 7-9.
5. 2022, M. Dubarry, et al., **Mechanistic Li-Ion Battery Modeling, What's Next?**, Presented at the 242th ECS Meeting, Atlanta, GA, October 9-13.
6. 2022, M. Dubarry, **Battery energy storage system modeling: A combined comprehensive approach**, Presented at the IEEE Power & Energy Society General Meeting, Denver, CO, July 17-21.
7. 2022, M. Dubarry, et al., **Big Data for Li-Ion Battery Diagnosis and Prognosis**, Presented at the Material Research Society Spring Meeting, May 8-13.
8. 2021, M. Dubarry, et al., **A New Insight into Blended Electrodes**, Presented at the 240th ECS Meeting, Orlando, Florida, October 10-14.
9. 2020, M. Dubarry, et al., **Synthetic Training Data for Artificial Intelligence-Based Li-Ion Diagnosis and Prognosis**, Presented at the ECS PRiME Meeting, October 4-9.