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RE-EVALUATING STANDARD METRICS FOR BATTERY AGING REPORTING

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Presentation #405

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Project Overview

- **Goal**: Evaluate basic state-of-health metrics for battery single-cell aging reporting and determine if they are equally effective for full ESS lifetime prediction.

- **Current Practice**: Battery aging in research publications and manufacturer spec sheets for individual cells is commonly reported as capacity (Ah) versus cycle number. However, the key metric in battery-powered devices is energy (Wh), which is derived from integrating capacity with voltage.

- **Why Sandia?:** We amassed a significant amount of clean, standardized battery data from Battery Archive.

- **Innovation**: Demonstrated that a long-standing metric for reporting single cell battery aging (capacity-Ah) can overestimate battery lifetime in full systems (energy-Wh) and developed a mechanistic framework to anticipate this divergence under different operating conditions.

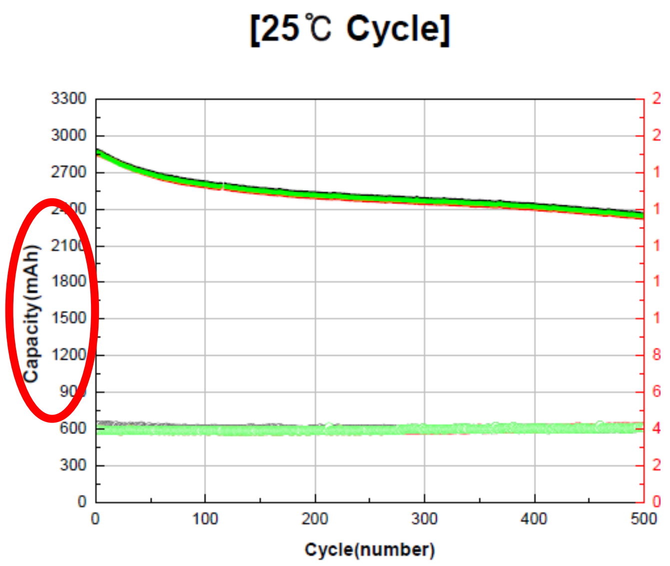
Project Overview

- **Duration**: FY26 (subset of Li-ion single cell cycling work)
- **Impact**: Validated an alternative metric to (1) reduce potential error in ESS lifetime prediction by 1 to 20% when scaling up Li-ion single-cell aging results (relevant for system developers using spec sheets) and (2) identify issues with emerging non-Li technologies early in development (relevant to investors).
- **Vertical/Investment Area**: Safety & Reliability
- **Alignment**: (1) Optimizes grid services by supporting better lifetime prediction of existing Li-ion ESS and (2) grows capacity by supporting earlier validation of emerging affordable ESS technologies.

Problem: Battery aging in research papers and cell spec sheets is commonly reported as **capacity (Ah)** versus cycle number

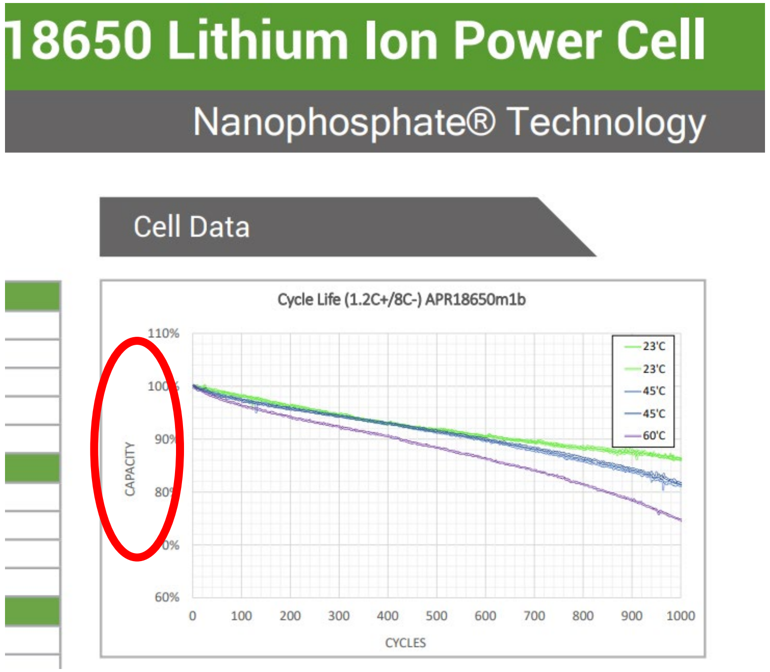
LG Chem testing report for NMC cell

- **Test Conditions**
  - **Charge : 4A, 4.2V, 500mA Cut-off at 25°C**
  - **Discharge : 7.5A, 2.5V cut-off at 25°C**

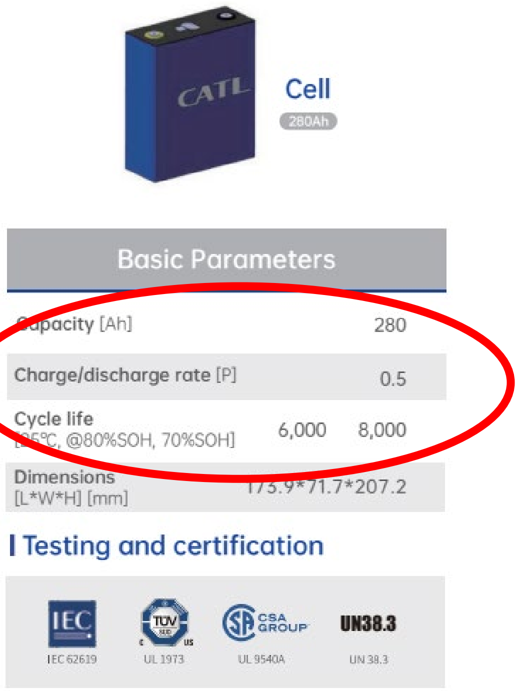


LG Chem
Mobile Battery Division

LithiumWerks spec sheet for LFP cell



CATL cell specs



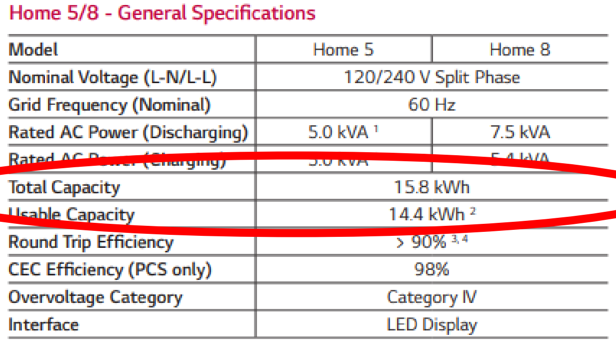
...But system performance is evaluated in **energy (Wh)**, which is derived from integrating capacity with voltage

Fluence ESS spec sheet

Specifications

BATTERY PACK OPTIONS	BATTERY
Cell Capacity	3xx Ah
Energy Capacity	7,308 - 7,523 kWh
Smart Skid Dimensions (L x D x H)	7,376 x 2,200 x 1,585 mm | 24 x 7.2 x 5.2 ft.
Pod Dimensions (L x D x H)	1,762 x 2,618 x 2,550 mm | 5.8 X 8.7 x 8.4 ft.
Weight	**Smart Skid:** ~11,500 kg (25,353 lbs) **Pod:** ~15,600 kg (34,392 lbs)

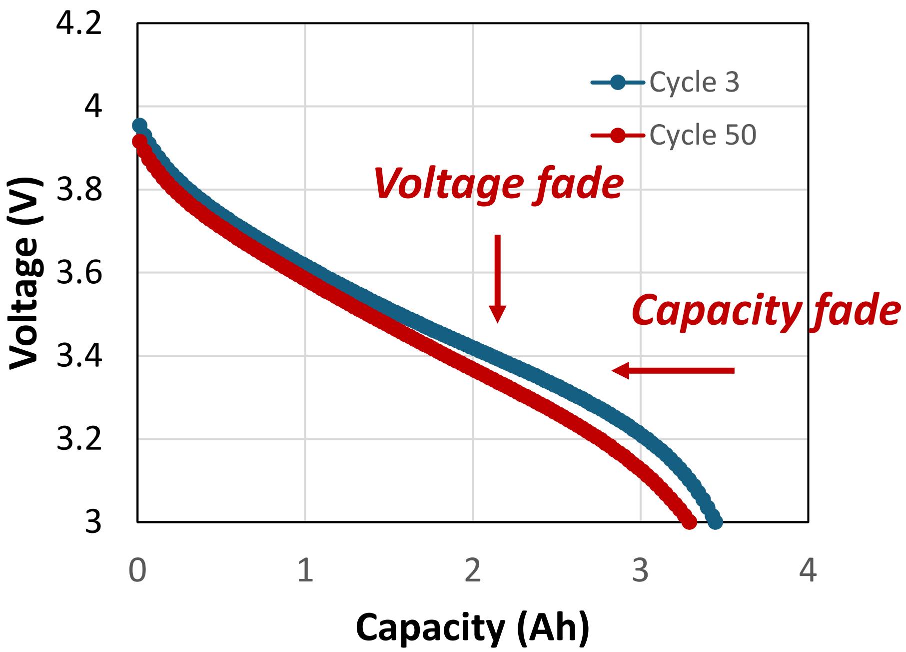
LG home storage spec sheet



Home 5/8 - General Specifications

Model	Home 5	Home 8
Nominal Voltage (L-N/L-L)	120/240 V Split Phase	
Grid Frequency (Nominal)	60 Hz	
Rated AC Power (Discharging)	5.0 kVA [1]	7.5 kVA
Rated AC Power (Charging)	3.0 kVA	5.4 kVA
Total Capacity	15.8 kWh	
Usable Capacity	14.4 kWh [2]	
Round Trip Efficiency	> 90% [3, 4]	
CEC Efficiency (PCS only)	98%	
Overvoltage Category	Category IV	
Interface	LED Display	

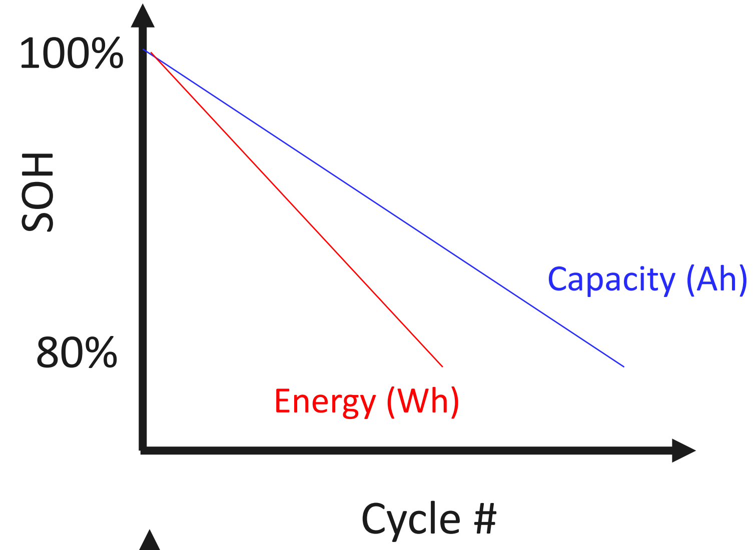
Capacity-focused reporting misses voltage (and energy) fade



How might focusing on capacity (Ah) fade impact battery technoeconomic analysis and lifetime prediction?

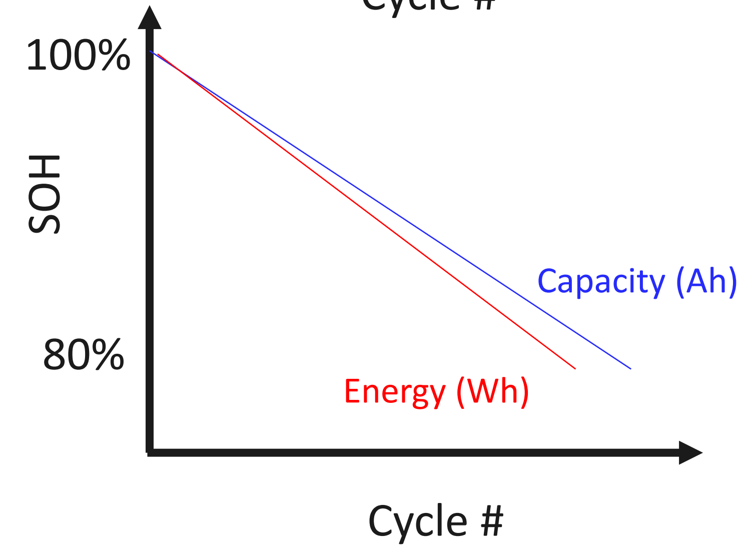
Worst Case Scenario: Significant voltage fade

- Example: Pre-commercial LMR-NMC cell samples exhibited 91% capacity (Ah) retention after 300 cycles, but only 60% energy retention (Wh) due to cycling-induced materials transformation[1]
- ***Outcome: Tech transfer abandoned after <u>years</u> of investment***



Best Case Scenario: Mild voltage fade

- Example: Gradual degradation (e.g., IR growth) reduces average voltage
- ***Outcome: Models based on Ah-capacity metrics overestimate battery lifetime***

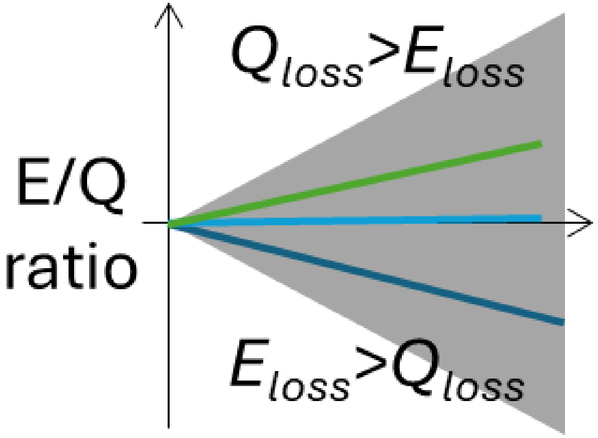


[1]Steve Levine – The Powerhouse

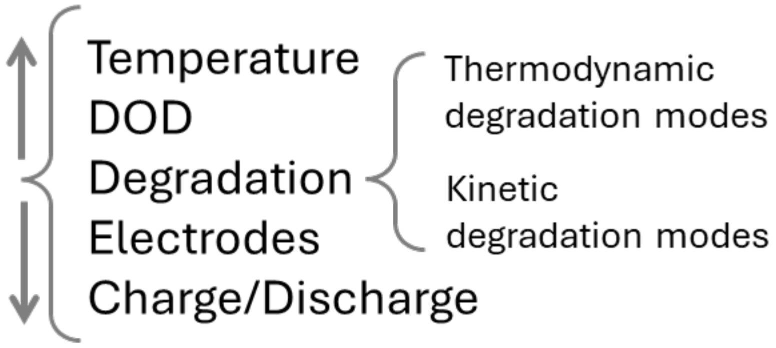
Our approach

We completed the first broad examination of capacity vs. energy loss in a variety of battery cycling studies (leveraging clean, standardized data from Battery Archive).

(1) Do capacity (Ah) and energy (Wh) fade at different rates? How much difference is there?



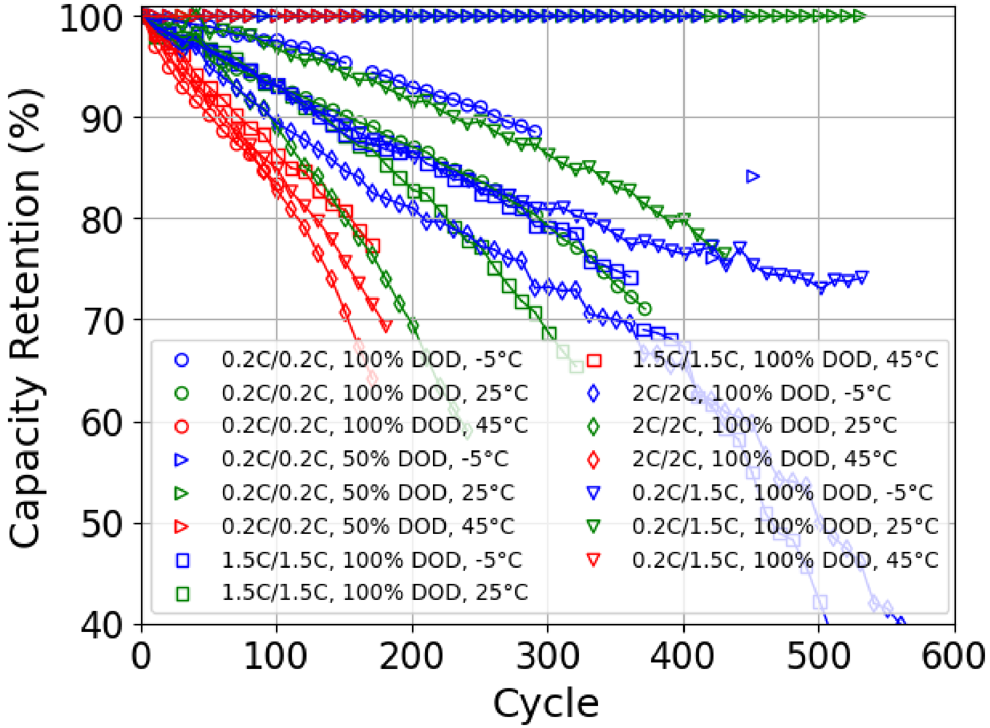
(2) What factors cause differences in fade rates? How can we use this info for better prediction/battery management?

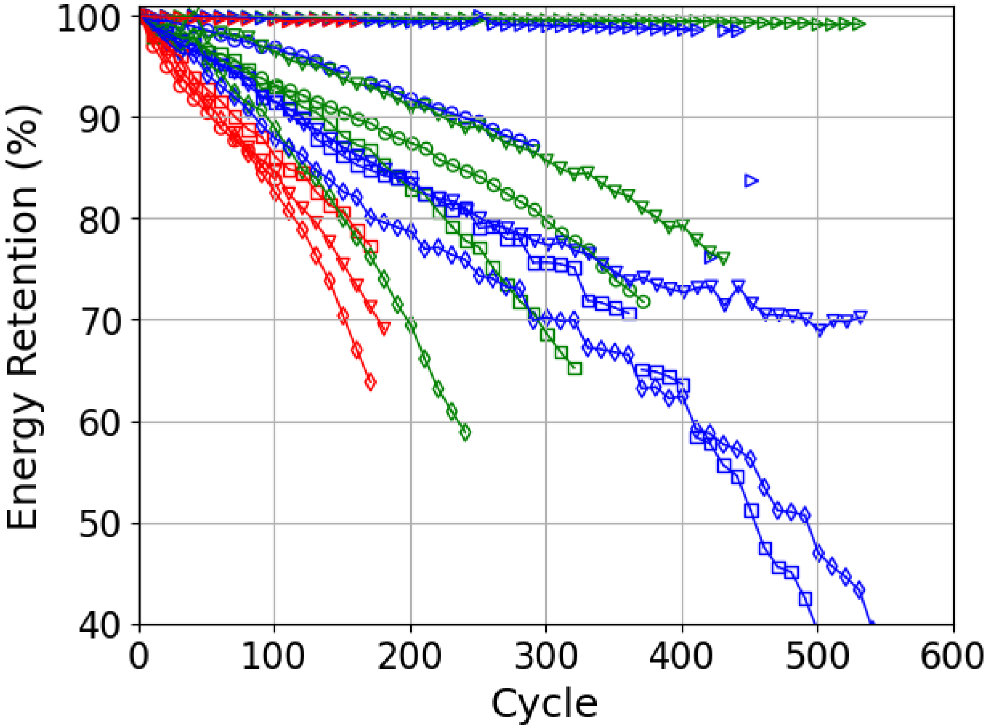


Capacity and energy retention may appear similar…

$$\text{Capacity Retention}_i\ (\%) = \frac{\text{Capacity}_i\ (\text{Ah})}{\text{Capacity}_{\text{ref}}\ (\text{Ah})} \times 100\%$$

$$\text{Energy Retention}_i\ (\%) = \frac{\text{Energy}_i\ (\text{Wh})}{\text{Energy}_{\text{ref}}\ (\text{Wh})} \times 100\%$$



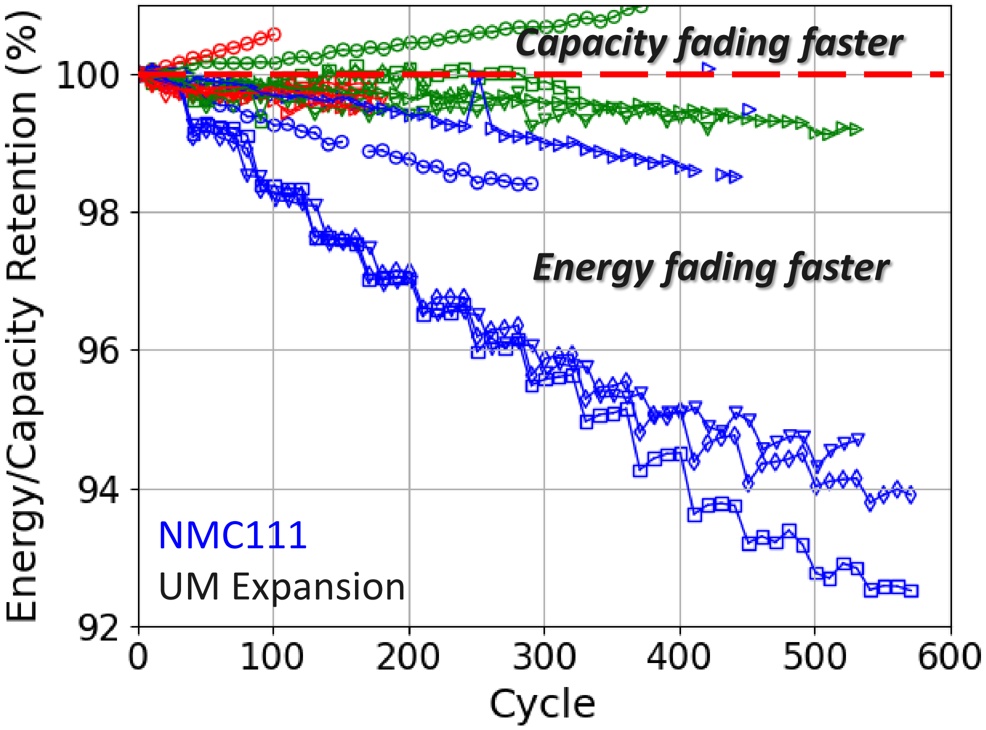


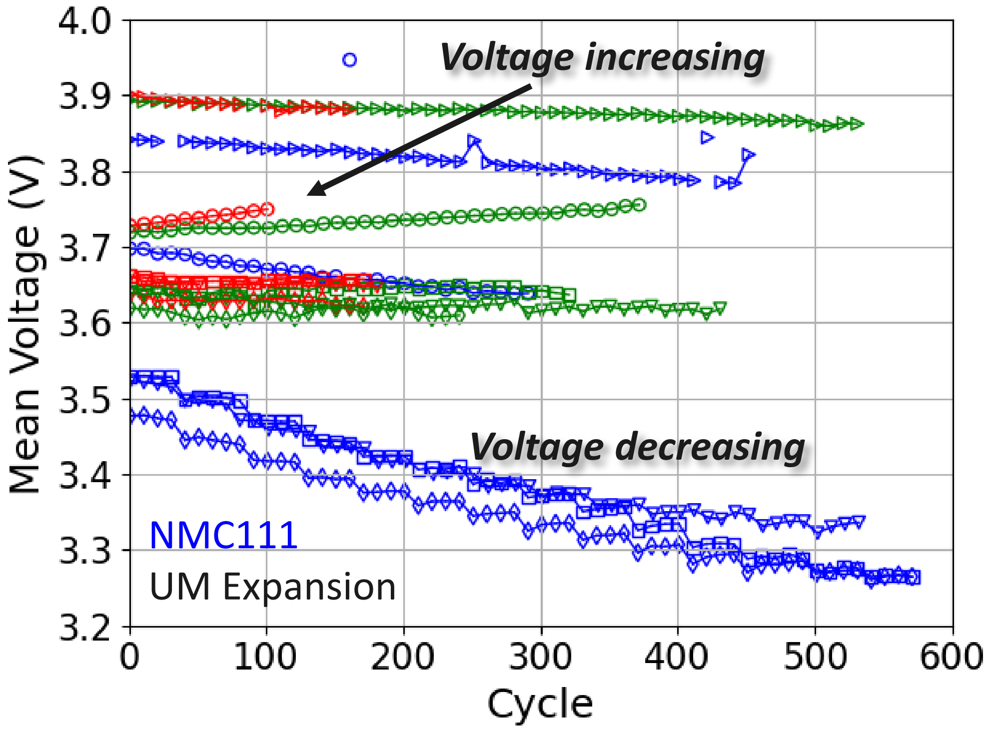
Example dataset from UMichigan: NMC111 cells cycled under various temperatures, DODs, and charge/discharge rates

Preger..Dubarry. “Are Capacity and Energy Equivalent Metrics for Battery Aging Reporting?” *J. Electrochem. Energy Convers. Storage*, **2026**, *23*, 021109.

…but they change at different rates depending on the cycling conditions

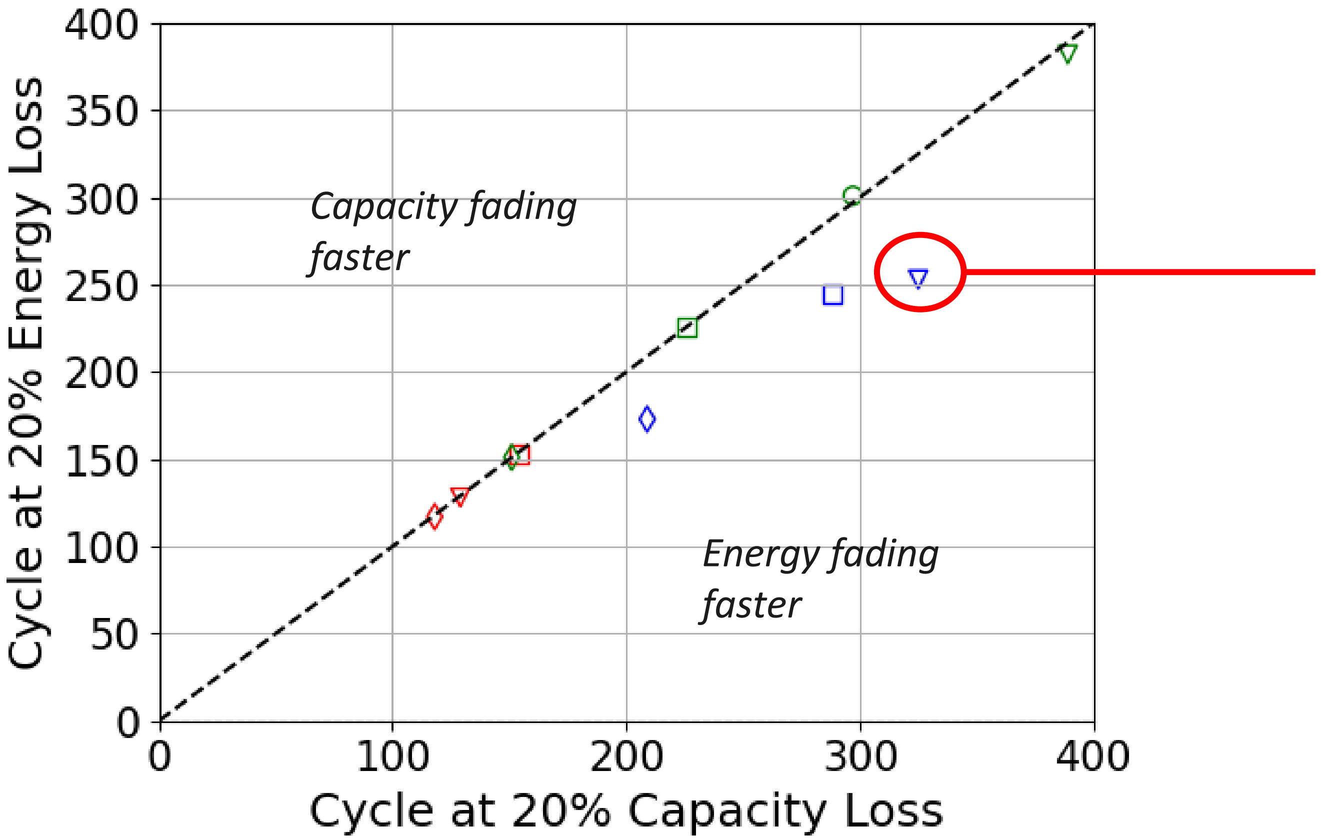
$$\text{Energy/Capacity}_i\ \text{Retention (\%)} = \frac{\text{Energy Retention}_i\ (\%)}{\text{Capacity Retention}_i(\%)} \times 100\% \qquad = \frac{\text{Mean Voltage}_i\ (\text{V})}{\text{Mean Voltage}_{ref}\ (\text{V})} \times 100\%$$





Preger..Dubarry. *J. Electrochem. Energy Convers. Storage*, **2026**, *23*, 021109.

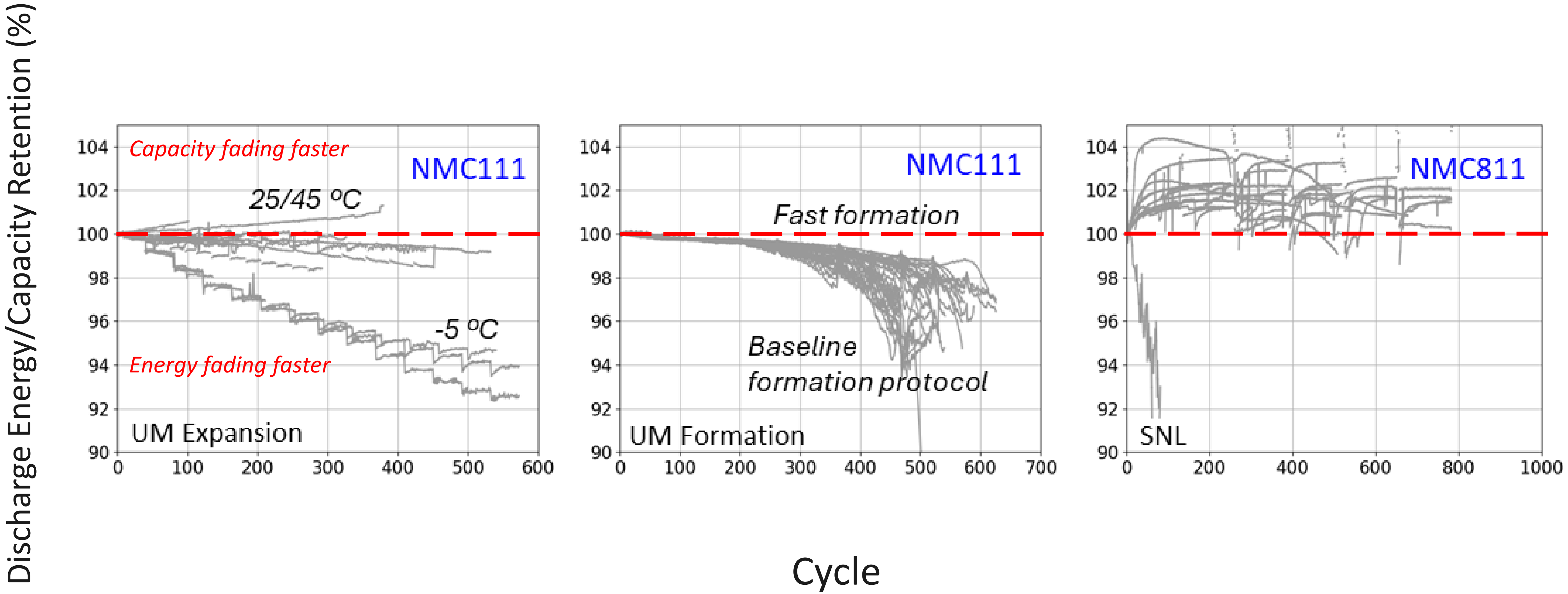
Differences in energy (Wh) and capacity (Ah) fade impact the reported cycle life



325 cycles if 20% capacity loss is “end-of-life,” but 253 cycles if 20% energy loss is EOL

*no marker shown if cell did not reach 80% capacity and energy retention

Discharge energy almost always fades faster than capacity, irrespective of chemistry and cycling conditions



Preger..Dubarry. *J. Electrochem. Energy Convers. Storage*, **2026**, *23*, 021109.

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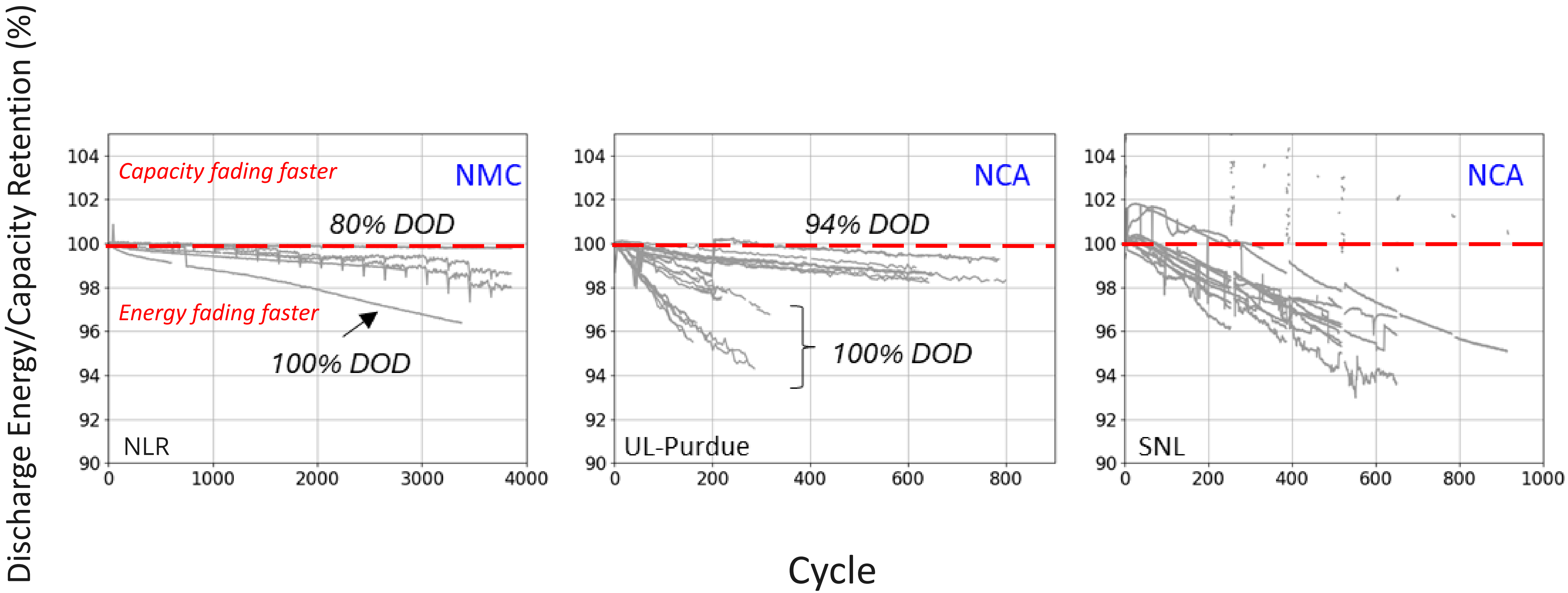

Preger..Dubarry. *J. Electrochem. Energy Convers. Storage*, **2026**, *23*, 021109.

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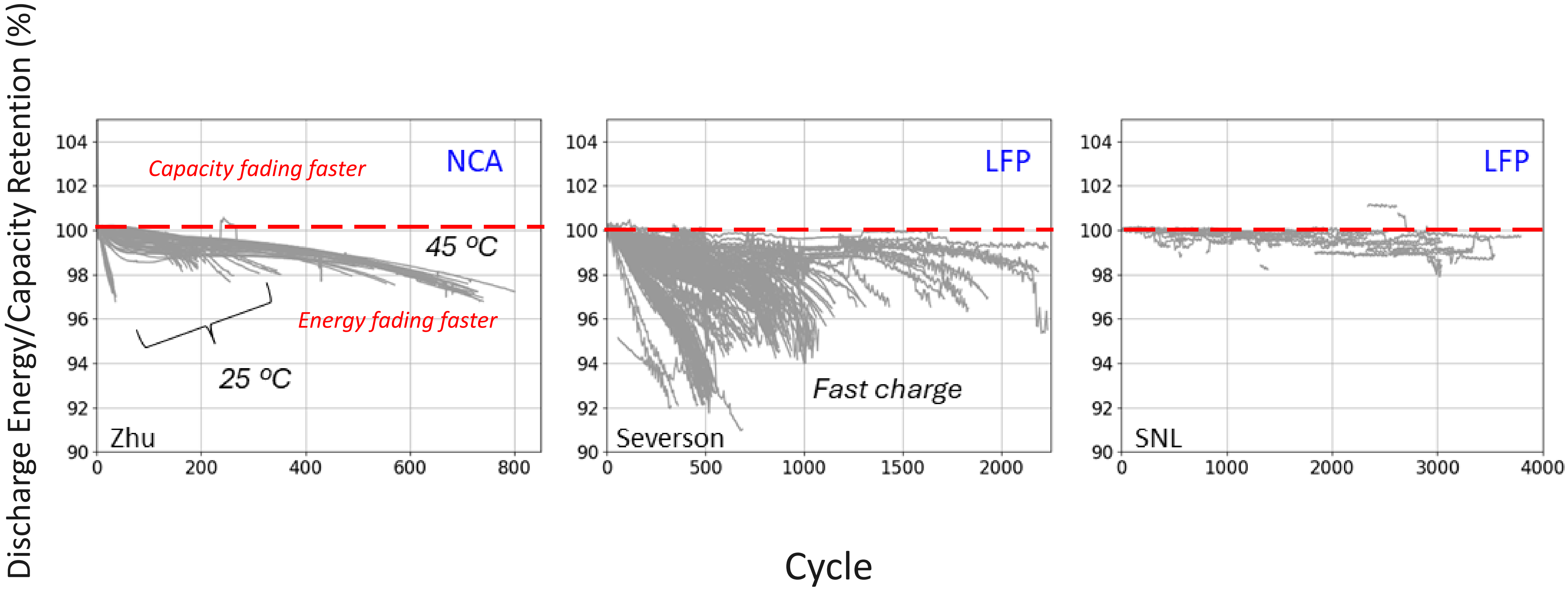
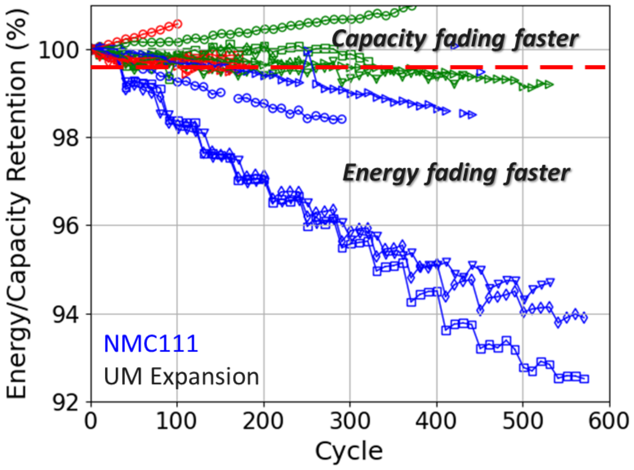
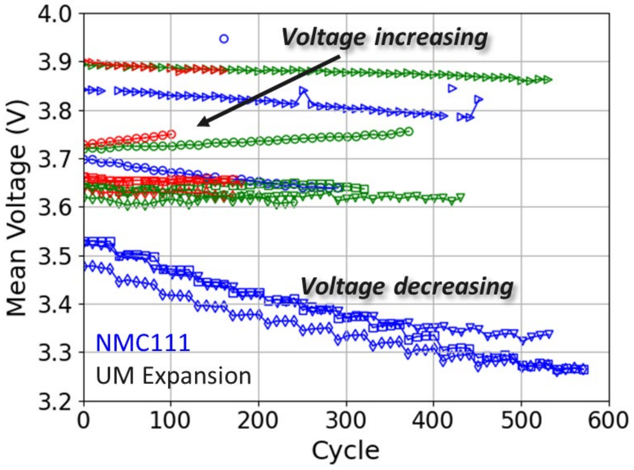
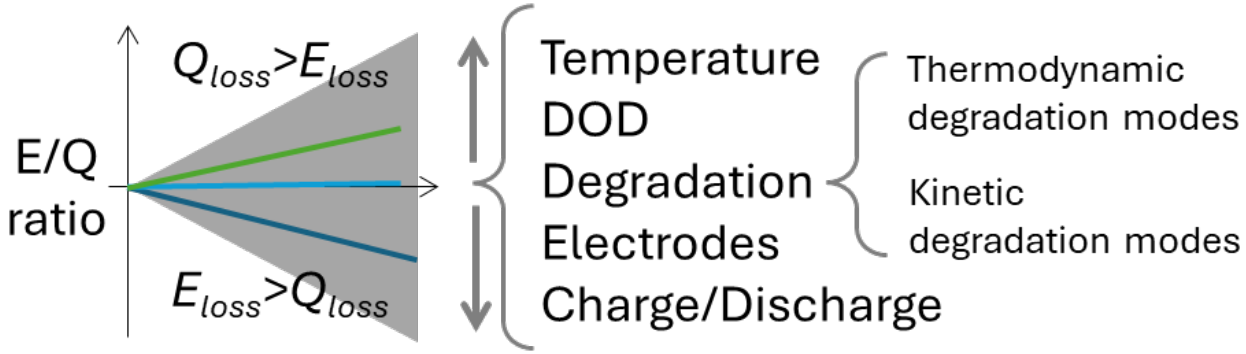


Preger..Dubarry. *J. Electrochem. Energy Convers. Storage*, **2026**, *23*, 021109.

We developed a mechanistic framework to explain and predict different energy/capacity fade trajectories

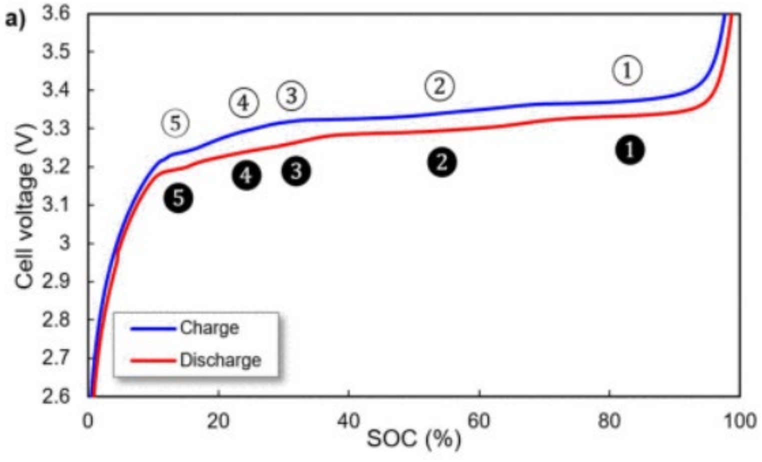




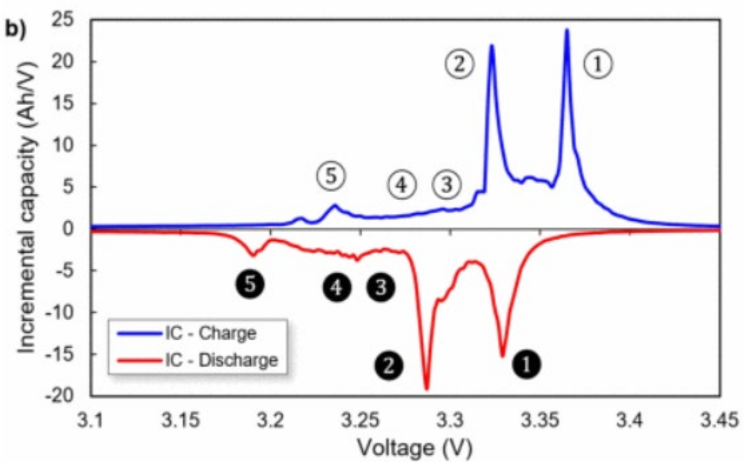


Capacity and voltage changes in Li-ion and Na-ion batteries can be studied using incremental capacity analysis (ICA)

LFP OCV curve (V vs. Q)

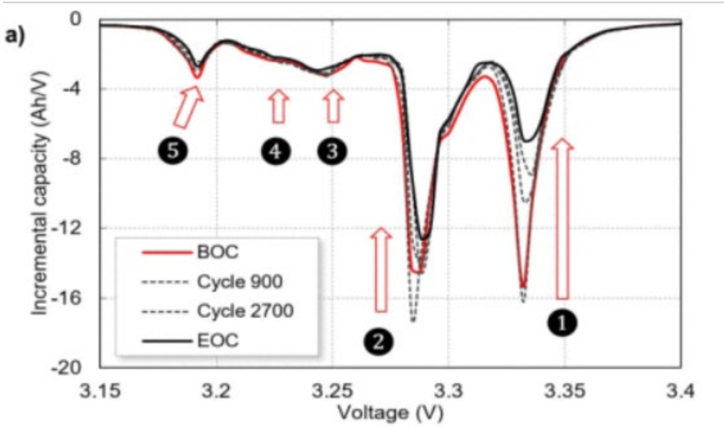


LFP differential capacity curve (dQdV vs. V)



Analysis captures capacity changes for particular voltage steps. Each peak corresponds to an electrochemical process taking place in the cell.

LFP dQdV evolution during cycling

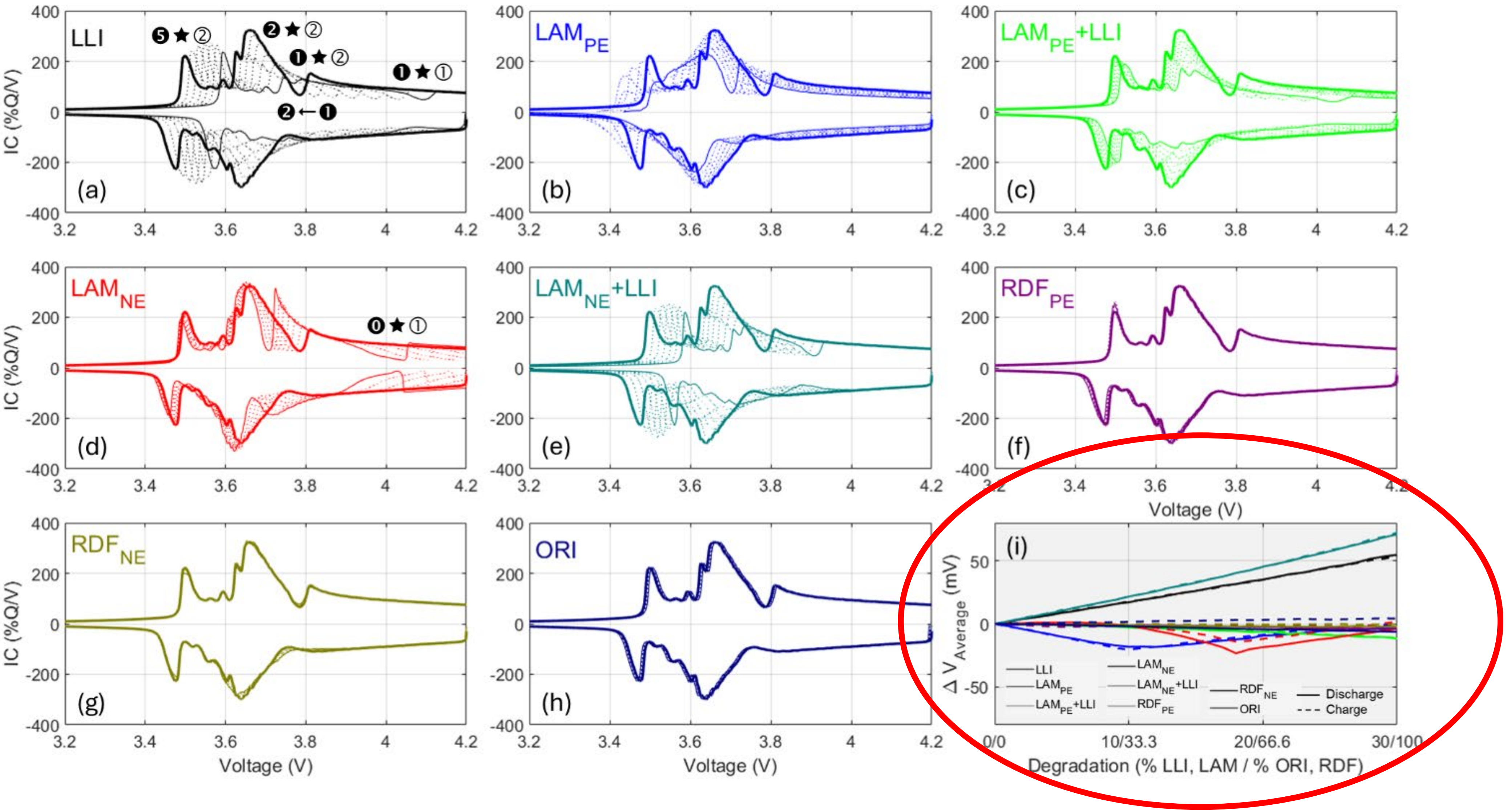


dQdV peak changes indicate thermodynamic/kinetic changes to the echem processes in the cell (e.g., aging degradation, different temp, etc.)

Ansean et al. *IEEE Transactions on Industry Applications*, **2019**, *55,* 2992.

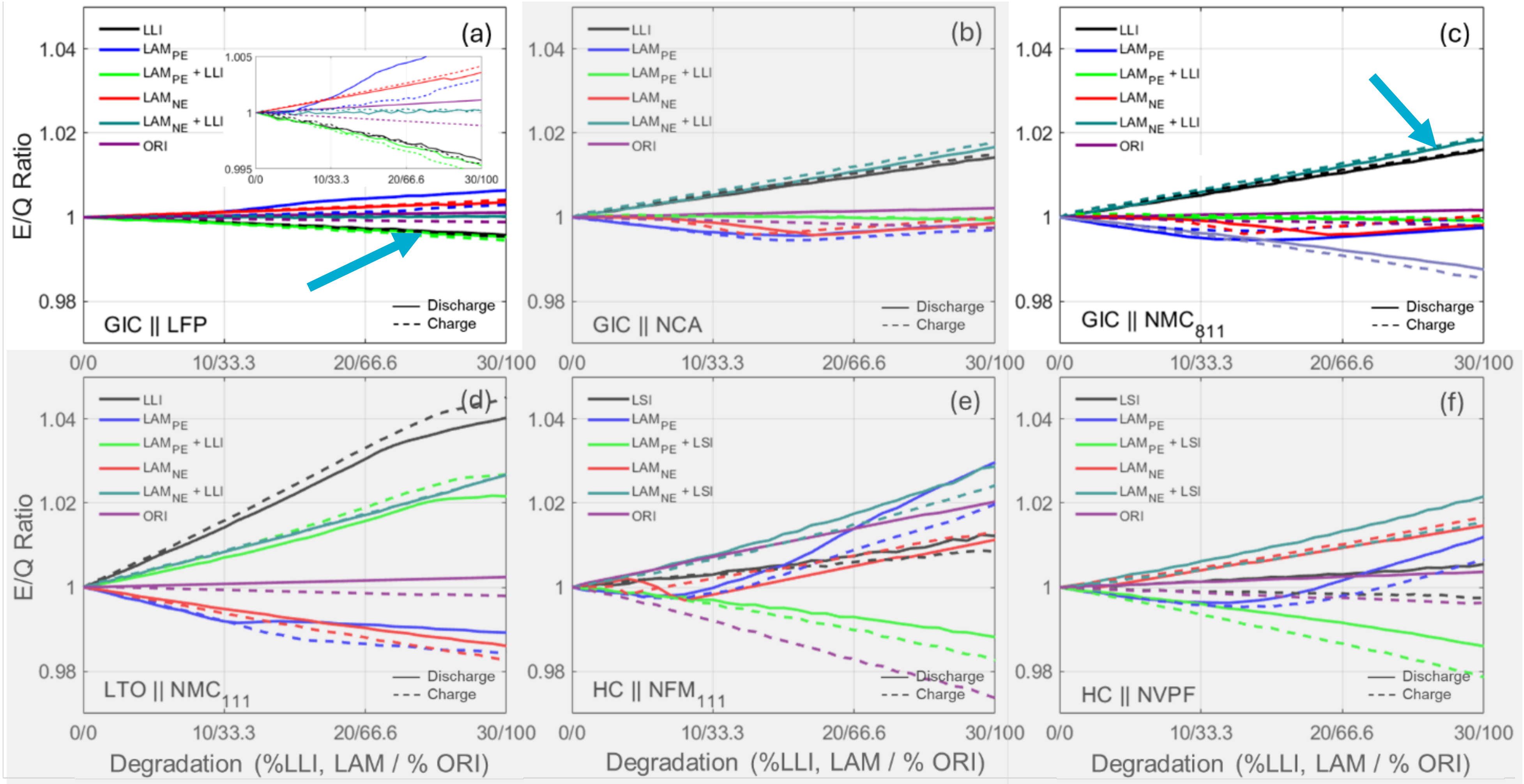
Average voltage (E/Q) trajectory varies with the **degradation mode**

Simulation for NMC111/Gr cell at C/20 (LLI = loss of Li inventory, LAM = loss of active material, PE = positive electrode, NE = negative electrode)



Average voltage (E/Q) trajectory varies with the **chemistry**

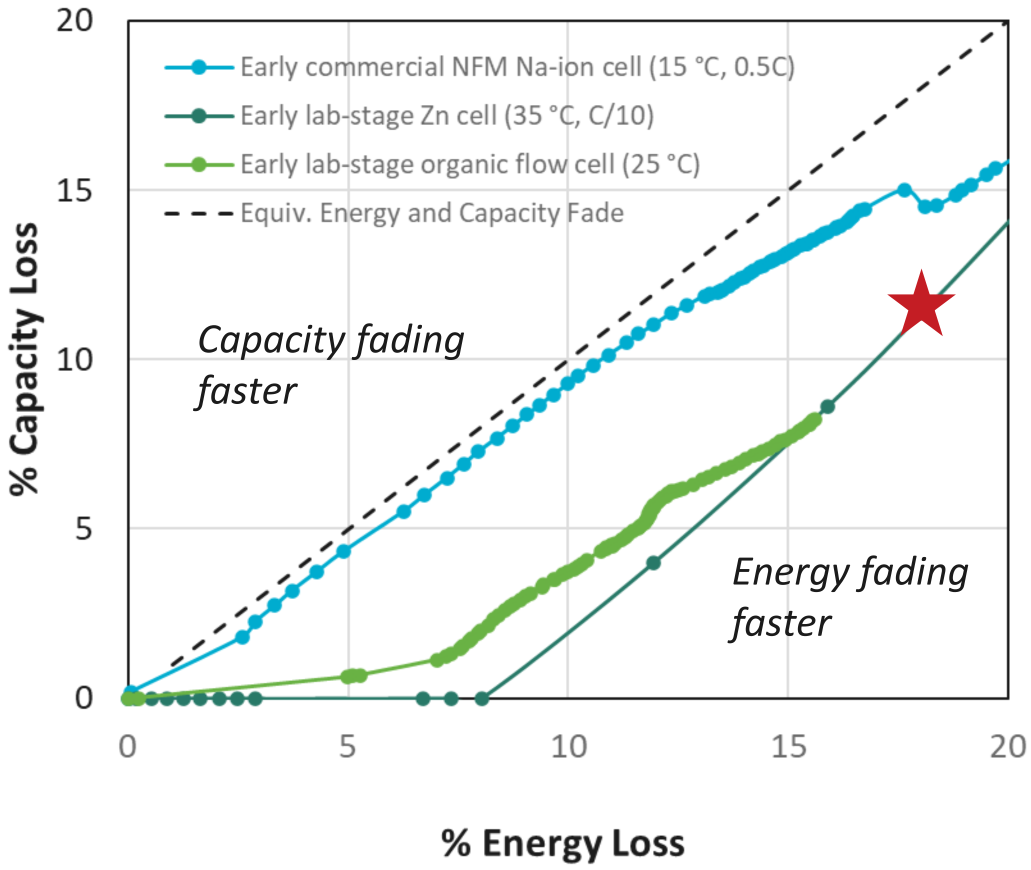
The most common degradation mode (loss of lithium inventory) causes voltage increase in NMC811, but voltage decrease in LFP (consistent with experimental results). Capacity-based lifetime prediction models will be worse for LFP cells.



Simulations at C/20, 100% DOD (LLI = loss of Li inventory, LAM = loss of active material, PE = positive electrode, NE = negative electrode)

What about emerging chemistries?

It is especially important to track voltage and energy fade data for emerging chemistries because they may be less optimized than commercial Li-ion cells (avoid the early LMR-NMC experience).



At same cycle, 11% capacity loss & 18% energy loss

Conclusions

- The standard metric for reporting single cell battery aging (capacity-Ah) can overestimate battery lifetime in full systems (energy-Wh)

- This highlights the risks with battery standards (e.g., IEEE) that use the term *capacity* inconsistently (coulombic vs. energy capacity)
  - *"Capacity" means something different to materials vs. electrical vs. power systems engineers*

- A new mechanistic framework based on ICA can anticipate the voltage trajectory (energy/capacity ratio) under different operating conditions for Li- and Na-ion chemistries

Impact: Validated an alternative metric for cell aging reporting to (1) reduce potential error in ESS lifetime prediction by 1-20% when scaling up Li-ion single-cell aging results and (2) identify issues with emerging non-Li technologies early in development.

Acknowledgements

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ICA framework

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Beyond Li perspective

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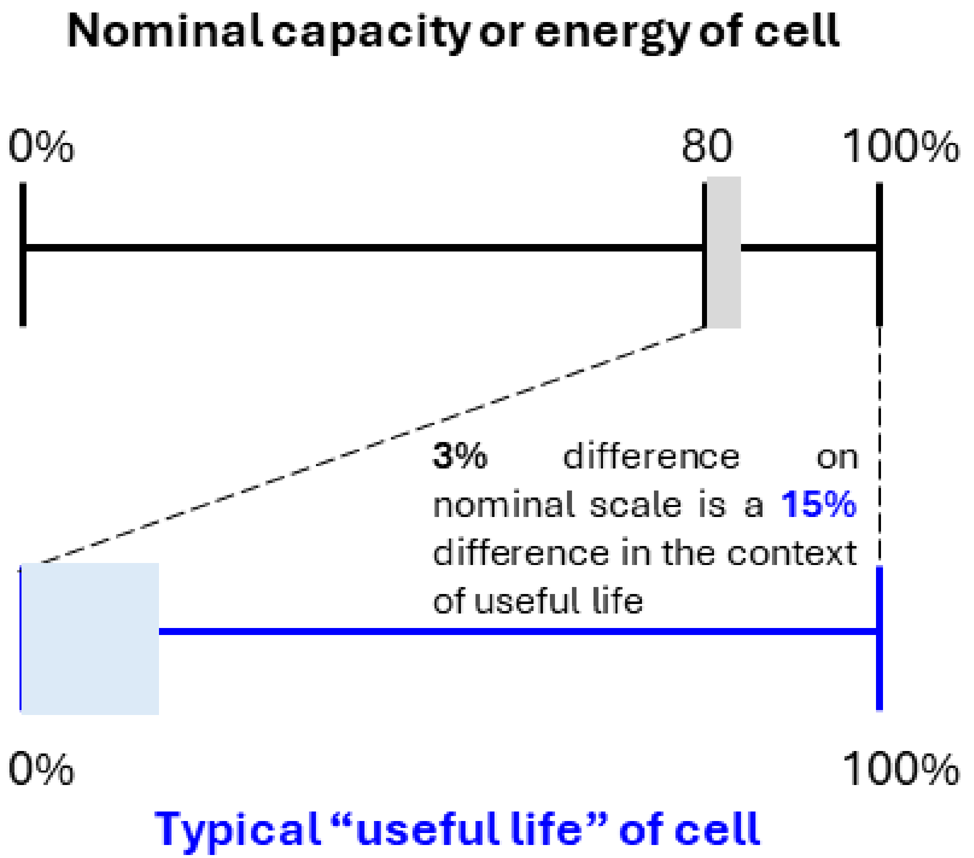
Extra


Nominal capacity or energy of cell
0%
80
100%
3% difference on nominal scale is a 15% difference in the context of useful life
0%
100%
Typical "useful life" of cell