GRID STORAGE LAUNCHPAD

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Predicting Long-Term Grid Battery Performance from Cell to Module Scale

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U.S. DEPARTMENT of ENERGY | Office of Electricity

Pacific Northwest NATIONAL LABORATORY

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PROJECT OVERVIEW

❑ Goal

- ✓ Develop predictive models for long-term stationary battery performance under realistic grid duty cycles.
- ✓ Quantify lifetime, efficiency, and degradation across battery chemistries and formats.[1-3]

❑ Current Practice

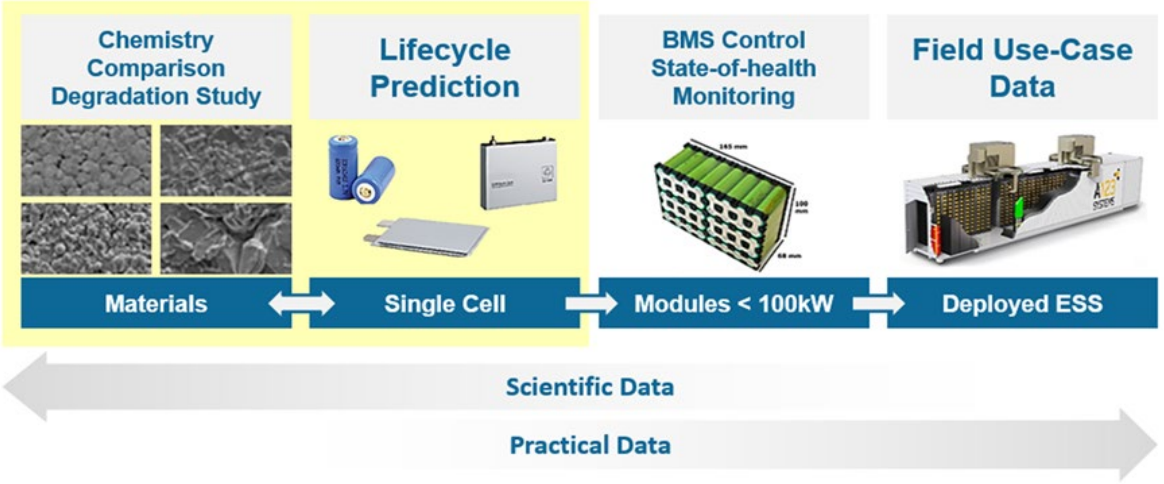
- ✓ Current lifetime projections rely on accelerated testing or simplified duty cycles.
- ✓ Limited long-term data exist linking cell and module degradation under realistic grid operation.

❑ Why PNNL?

- ✓ PNNL provides long-duration battery testing, grid-duty-cycle validation, and advanced electrochemical diagnostics, and post-mortem material characterization.
- ✓ GSL enables integrated cell-to-system testing and material/thermal characterization.

❑ Innovation

- ✓ Multi-year grid performance comparison.
- ✓ Integrated modeling, diagnostics, and material characterization.
- ✓ Improved lifetime prediction and mechanistic insight for grid storage deployment.



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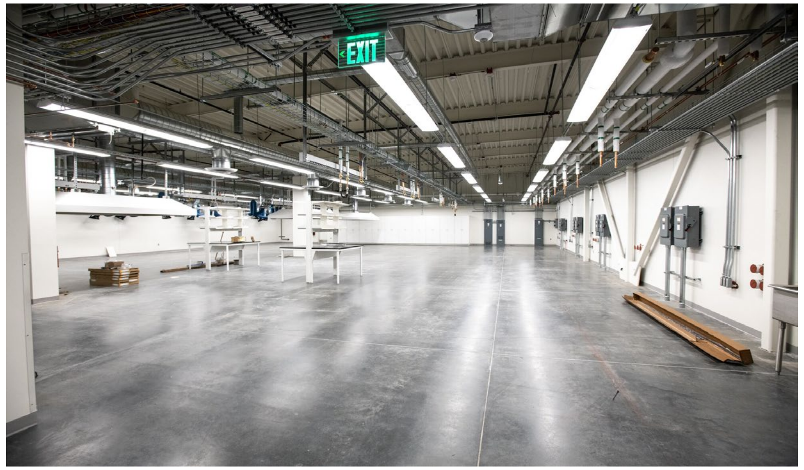
IMPACT & ALIGNMENT

❑ Duration (FY20–Present)

- ✓ Generated ~6 years of long-term cycling data across multiple Li-ion chemistries and duty cycles
- ✓ Expanded from cell-level testing to module-scale validation at GSL

❑ Impact

- ✓ Improves confidence in battery lifetime prediction and grid-storage reliability
- ✓ Supports utilities, data centers, manufacturers, and grid operators
- ✓ Reduces lifetime uncertainty and deployment cost
- ✓ Enables safer, optimized, and more reliable grid-scale storage systems



❑ Vertical / Investment Area

- ✓ Analytics, Safety & Reliability

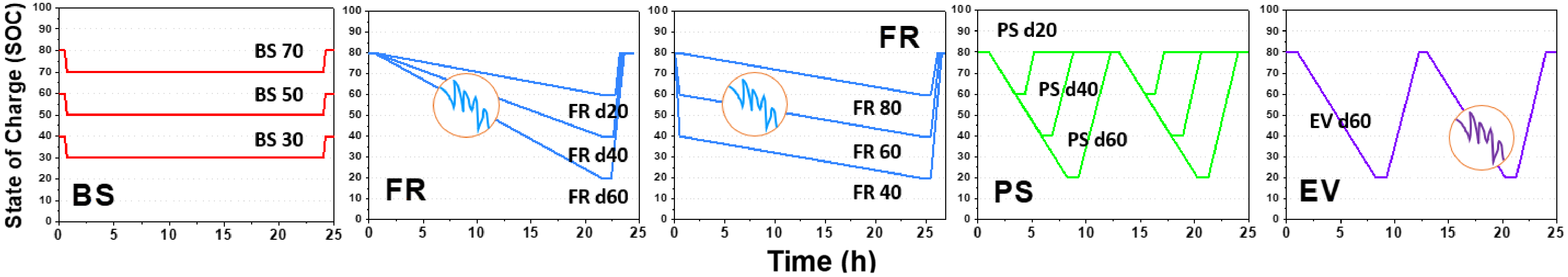
❑ Alignment / Supports Strategic Pathway

- ✓ Supports grid reliability through improved storage lifetime understanding
- ✓ Enables optimized grid services using realistic duty-cycle prediction
- ✓ Reduces uncertainty for large-scale storage deployment
- ✓ Advances safe and reliable long-duration energy storage systems

CELL TEST INFORMATION

Type	Format	Test Duration (years)	Capacity (mAh)		Max. Charge Rate	Cathode	Anode
			Nominal	Measured			
LFP1	26650	6	2.5	2.54 ± 0.03	1C	$LiFePO_4$	Graphite
LFP2		3	3.7	3.77 ± 0.01			
LFP3		3	2.9	2.90 ± 0.01			
LFP4	18650	<1	1.2	1.20 ± 0.01			
NCA1		6	3.4	3.31 ± 0.02	C/2	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	
NCA2		3	3.4	3.40 ± 0.02			
NMC1		6	3.5	3.42 ± 0.02		$LiNi_{0.82}Co_{0.12}Mn_{0.06}O_2$	
NMC2		3	3.0	3.12 ± 0.02			
NC		6	3.0	3.04 ± 0.02		$LiNi_{0.9}Co_{0.1}O_2$	
LTO		3	1.5	1.55 ± 0.03	3C	$LiNi_{0.5}Co_{0.19}Mn_{0.31}O_2$	$Li_4Ti_5O_{12}$
NaION1		<1	1.15		2C	Oxides	Hard Carbon
NaION2	32700	<1	4.0		1C	Oxides	

* Chemical composition analyzed by ICP-OES, XPS and EDX.



BS: Baseline (Calendar Aging)

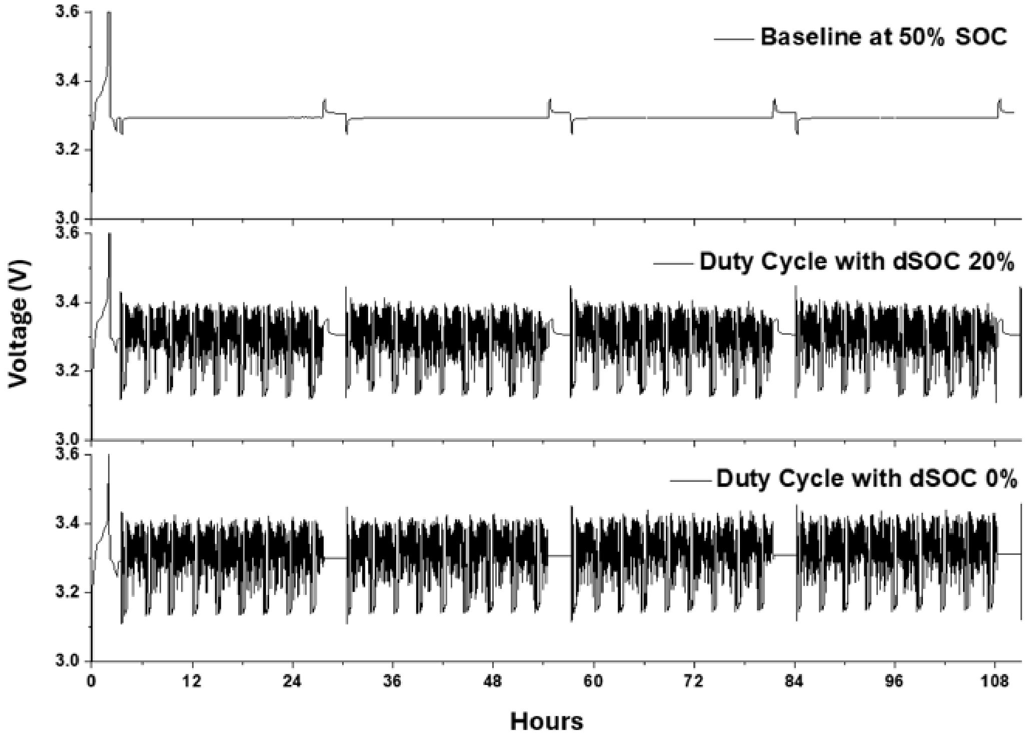
FR: Frequency Regulation

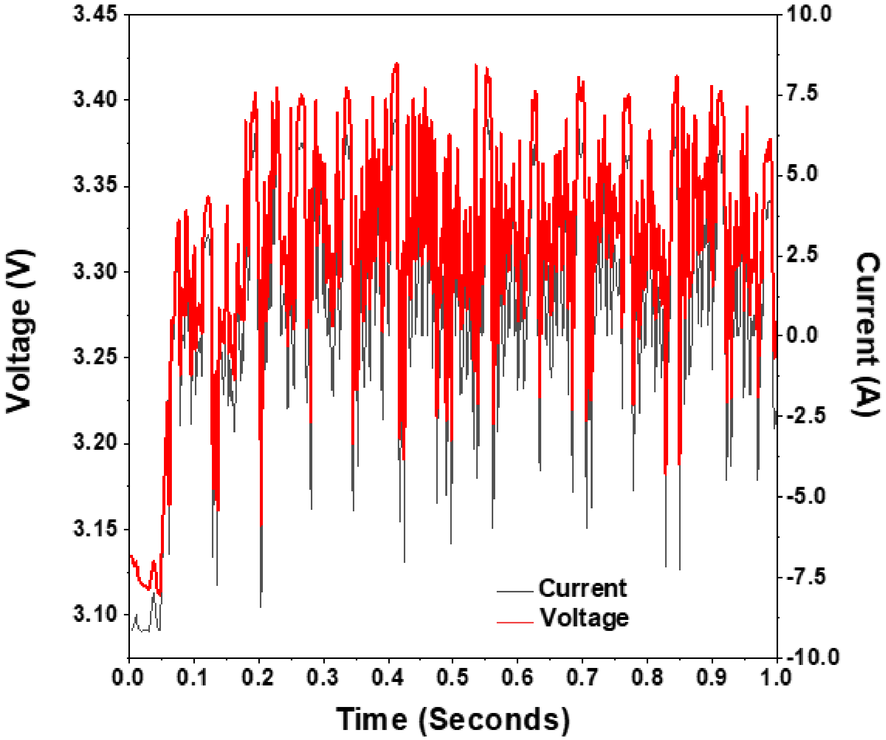
PS: Peak Shaving

EV: Electric Vehicle Drive

Fig. 1. Various grid service test cycles [4-6]

DATA CENTER DUTY CYCLES





CATEGORY	PARAMETER	VALUE
NOMINAL RATINGS	Nominal Voltage	3.3 V
	Capacity (typ / min)	1.2 Ah / 1.1 Ah
	Energy	3.63 Wh
	Internal Impedance (1 kHz AC)	12.6 mΩ
	Cycle Life (100% DOD)	> 2000 cycles
DISCHARGING	Max Continuous Discharge	30 A
	Max Pulse Discharge (10 s)	50 A
	Minimum Voltage	2.0 V
	Temperature Range	-30 °C to 55 °C
CHARGING	Recommended Charge Current	1.5 A
	Max Continuous Charge	4 A
	Max Pulse Charge (10 s)	10 A
	Charge Voltage	3.6 V

- High power LFP cell satisfies power rating for the data center duty cycles but due to high pulse rate of the signal, battery tester need high resolution (millisecond) data acquisition capability (Data center duty cycle is only 2seconds)
- Due to large number of data point per seconds, only 2min of the 24h cycles were recorded at high resolution to reduce data size of the cell test.

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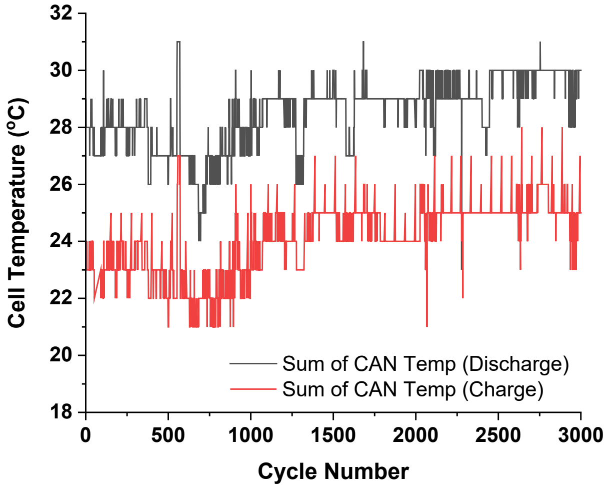
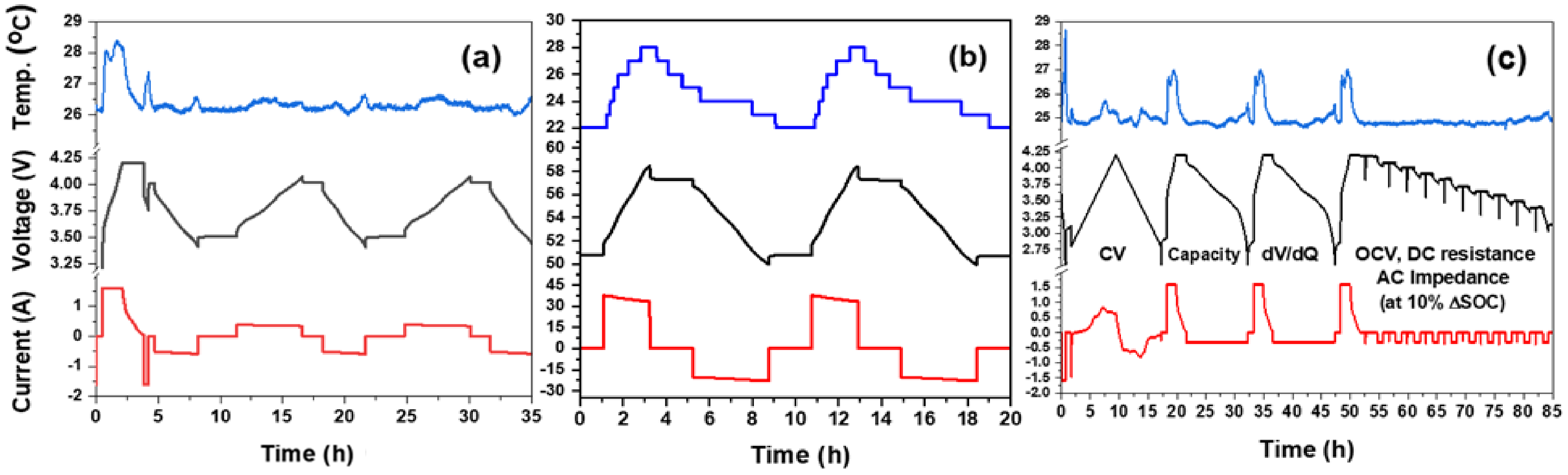
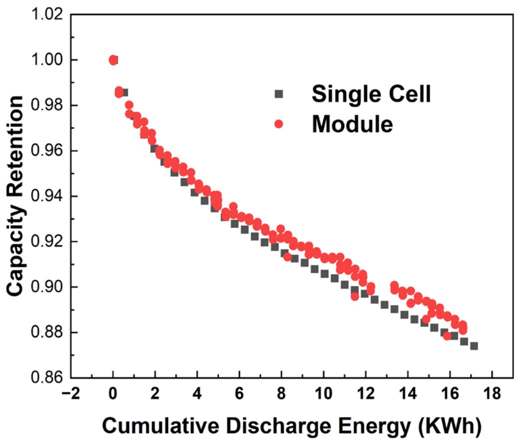
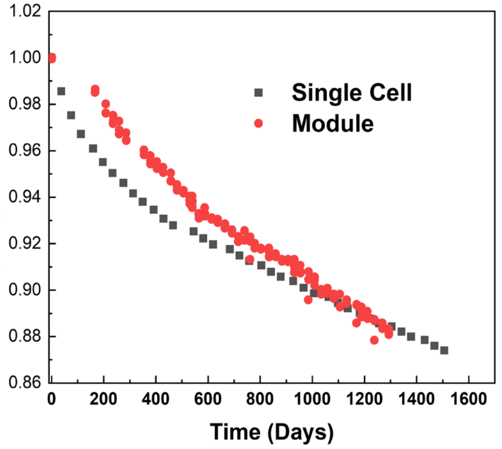
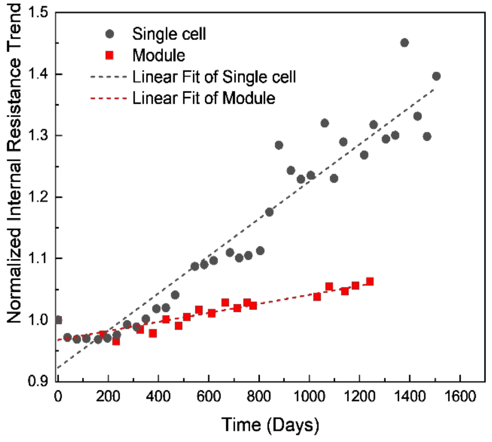
CELL/MODULE **TEST RESULTS**

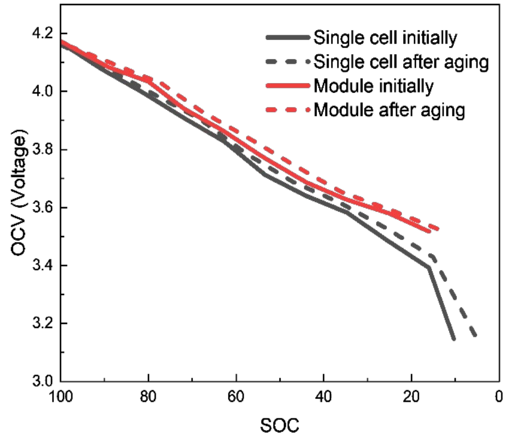






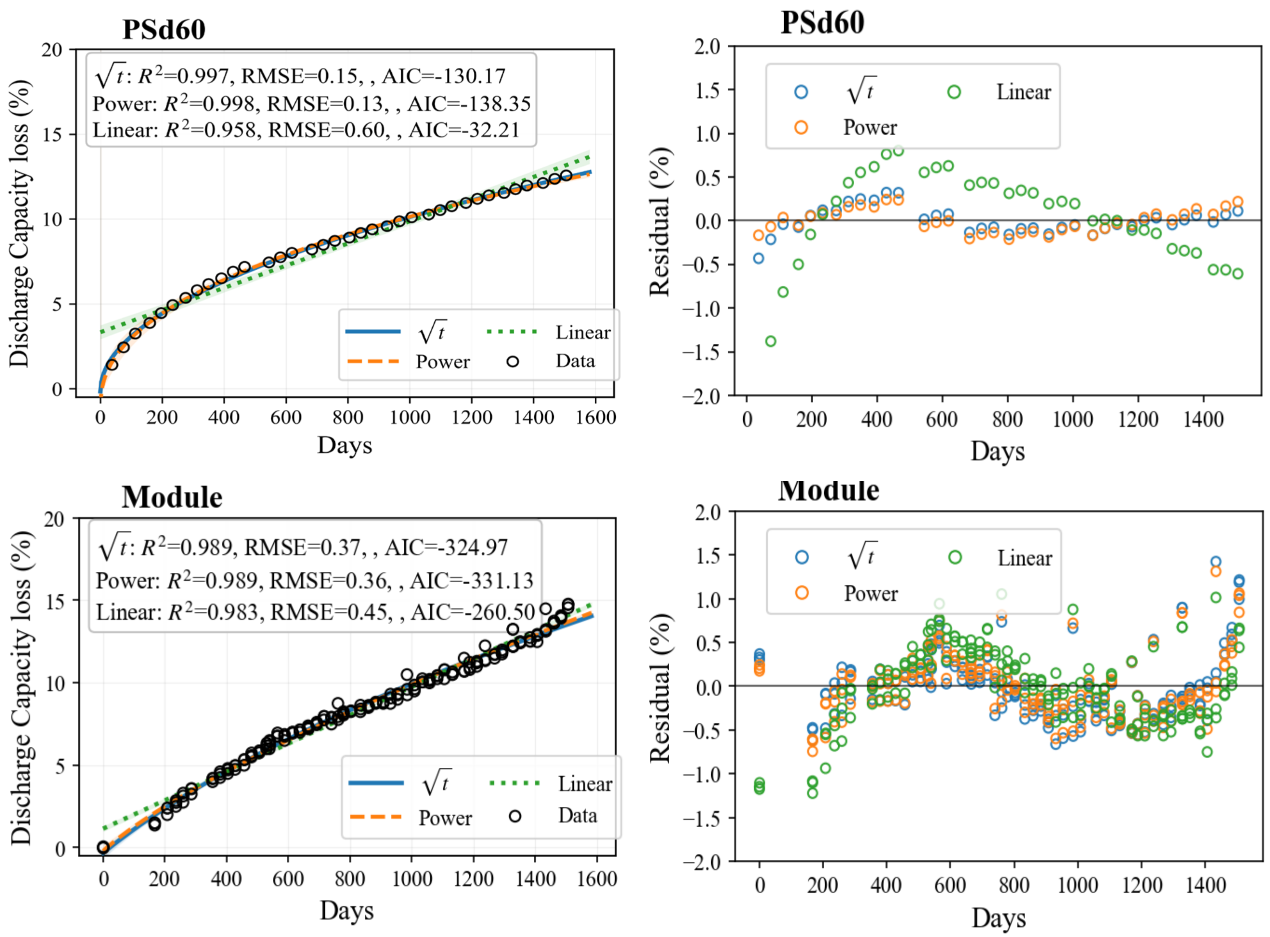


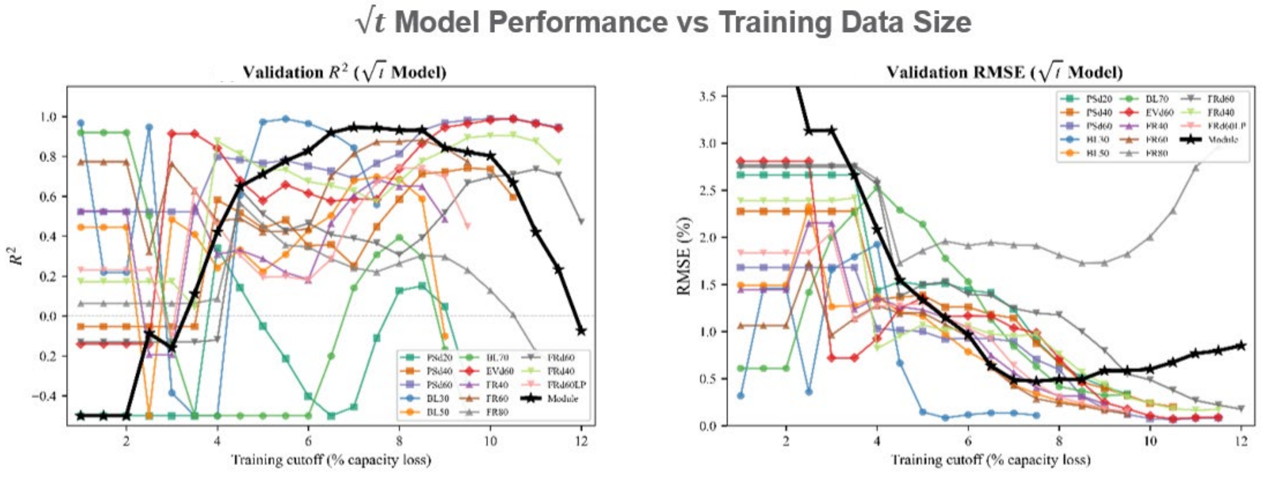


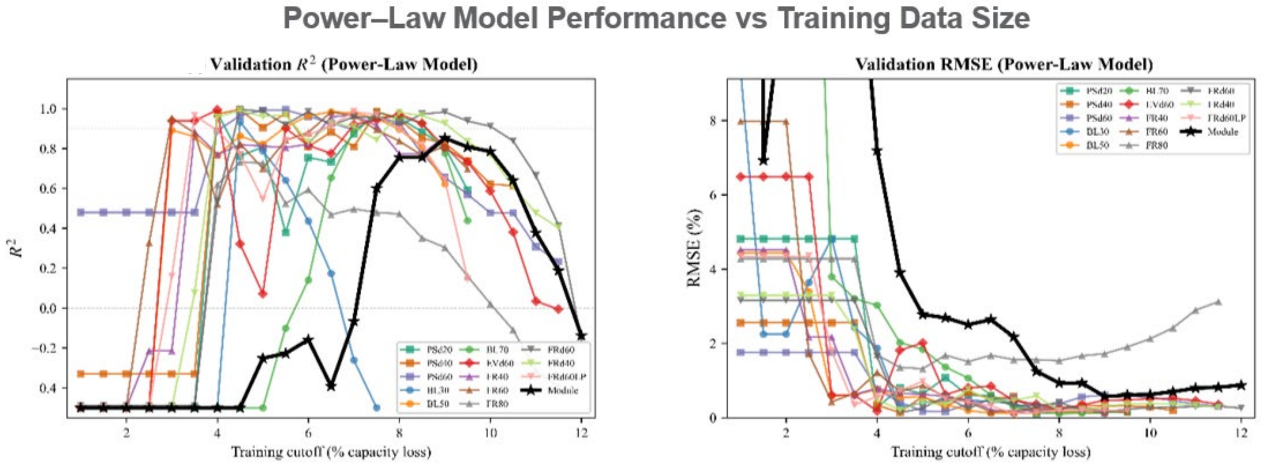


- **Cell and module show similar degradation trends, demonstrating good scalability from cell to module level.[7]**
- **Both single-cell and module tests were conducted at 25°C under controlled conditions.**
- **Resistance increase is approximately linear, but the XP14S module configuration reduces the impact of individual high-resistance cells at the module level.**
- **OCV shows a slight increase after ~4 years for both cells and modules.**

CELL/MODULE TEST RESULTS

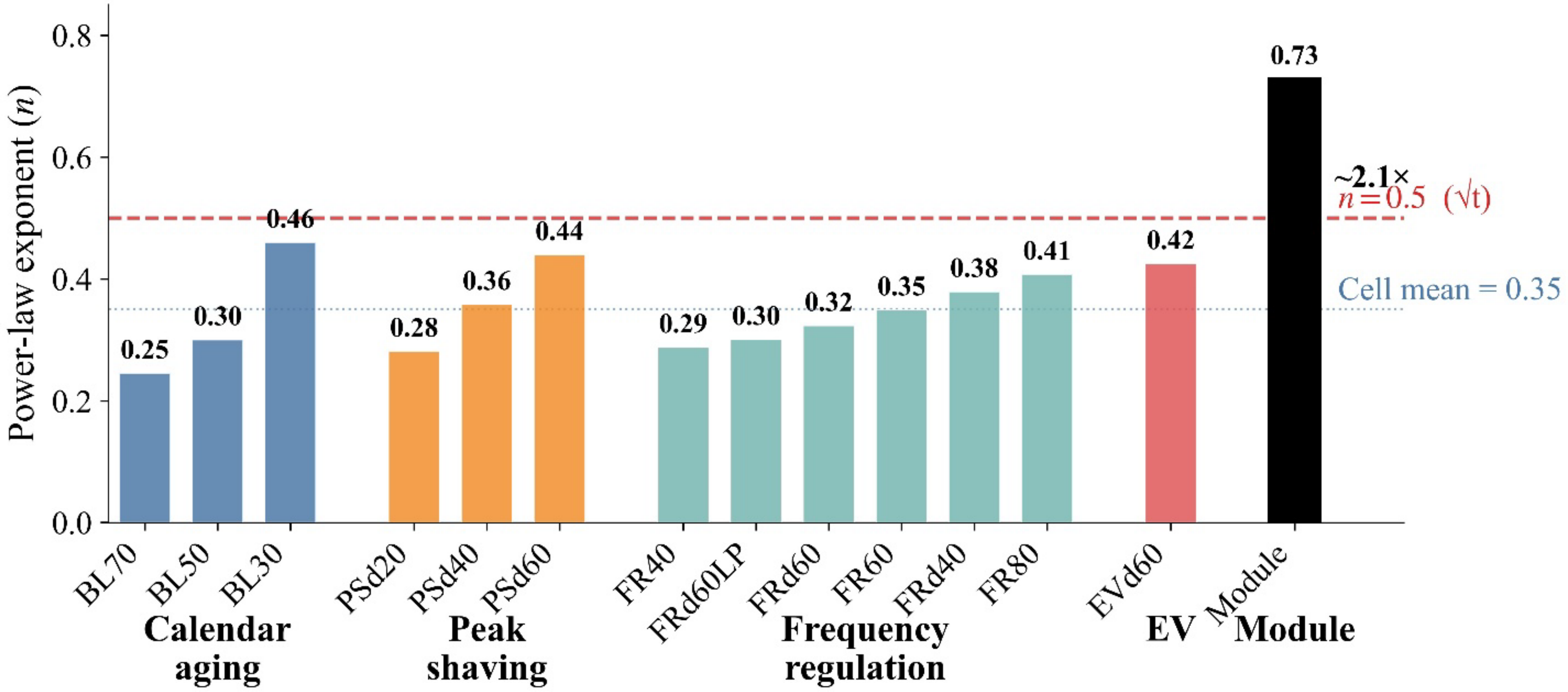






- Power-law model provides the best overall fit, with lowest RMSE and best AIC; √t performs similarly but with slightly higher error.
- Linear fitting underperforms, particularly for long-term degradation, and shows systematic residual bias.
- Reliable prediction requires ~4–8% capacity loss, while module-level fits show greater variability than cell-level results.

CELL/MODULE TEST RESULTS



Fitted (n)	Interpretation	Likely mechanism
0.20 – 0.30	Strongly slowing degradation	Stable/passivating SEI, calendar-aging dominated, low stress
0.30 – 0.45	Moderate sub-diffusive aging	SEI growth plus mild cycling effects
≈ 0.50	Classical √t behavior	Ideal diffusion-limited SEI
> 0.50	Accelerating degradation	Additional mechanisms: impedance growth, LAM, thermal/current non-uniformity, cell-to-cell imbalance, module effects (contact resistance, interconnect degradation)

dV/dQ & dQ/dV ANALYSES

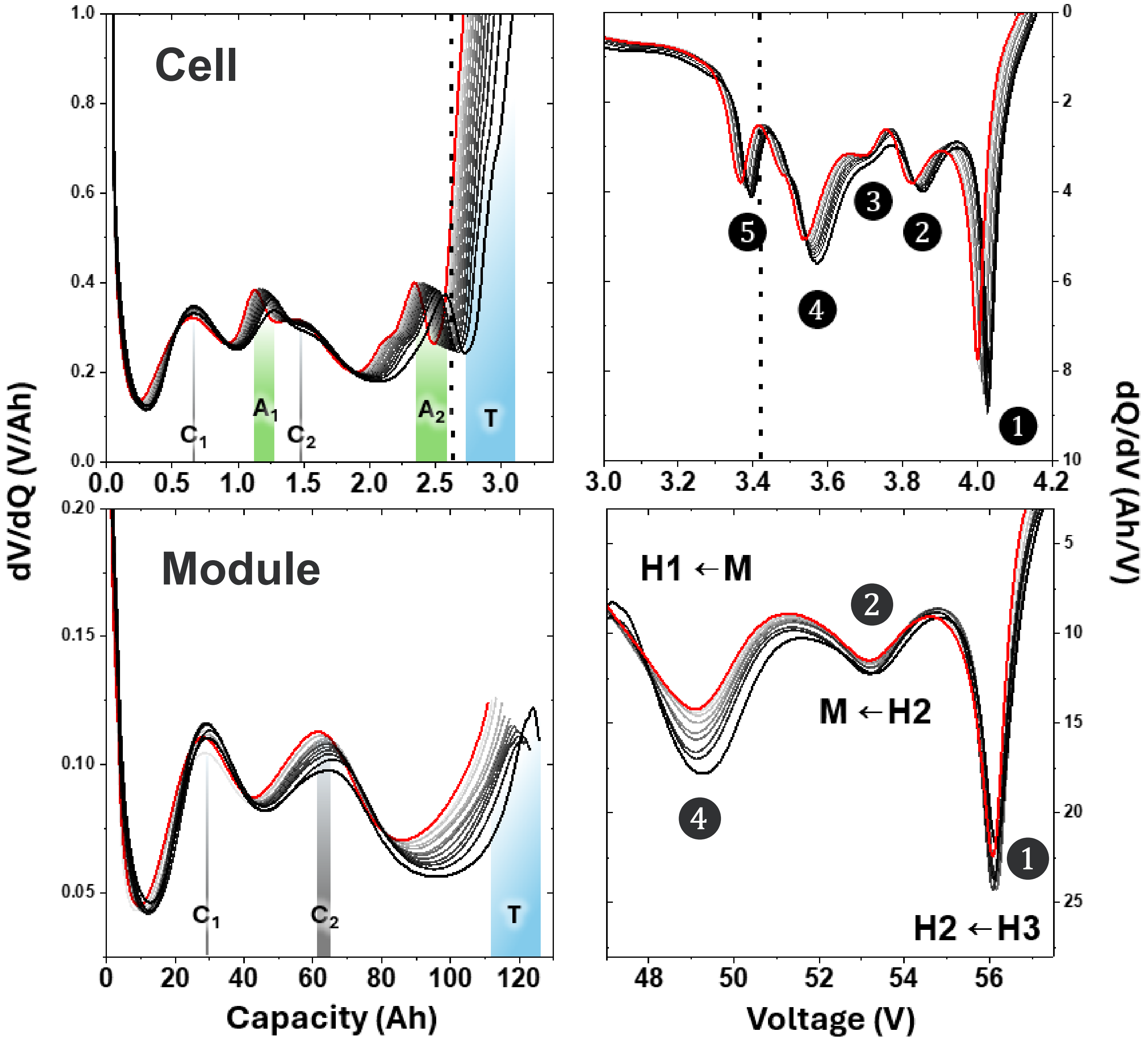


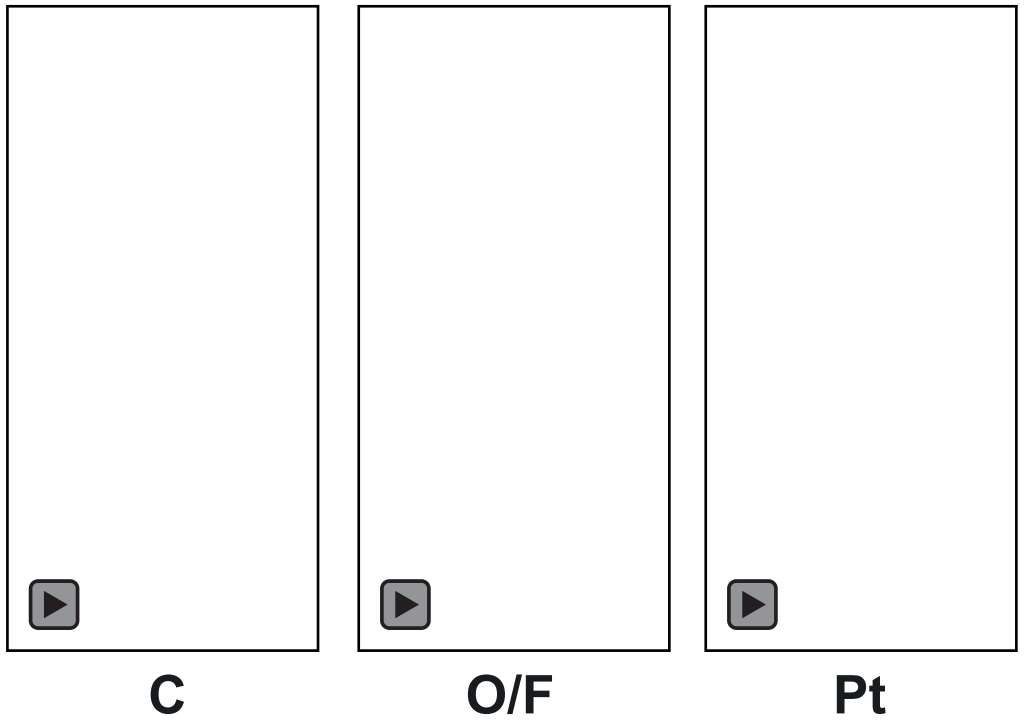
Table 1. Calculated capacity loss of graphite anode based on full cell dV/dQ curves.[7]

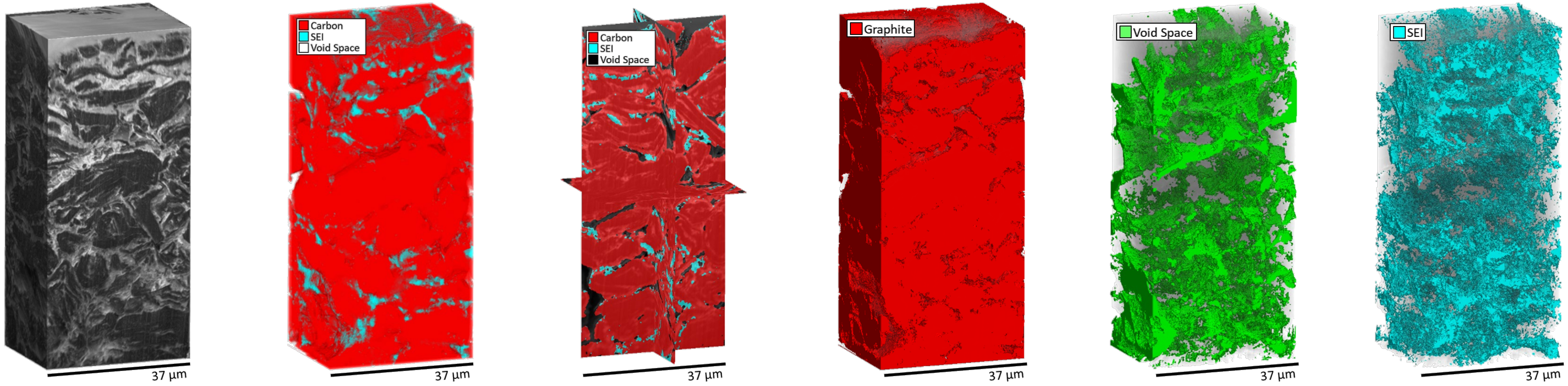
	LAM_{PE}	LAM_{NE}	LLI	Total Capacity Loss
Cell	~ 0 %	2.86 %	8.79 %	11.65%
Module	~ 0 %	Unknown	Unknown	10.58 %

- Single cell dV/dQ plot show two distinctive peaks from both cathode and anode but anode peaks are not observable from module data.
- Capacity loss is mostly from loss of lithium inventory (LLI) and loss of active negative material (LAM_{NE}).

MATERIAL CHARACTERIZATIONS

- SEM and EDS analyses were used to reconstruct electrode microstructures and phase distributions.
- Carbon, O/F-rich SEI species, and Pt deposition were identified as the primary detected components.
- Dark regions and low EDS signal areas correspond to pore-space distribution within the electrode structure.
- Reconstructed phase maps enable quantitative analysis for future degradation and transport modeling studies.





CONCLUSION

- Cell and module show consistent degradation behavior under peak-shaving duty cycles, demonstrating strong scalability from cell to module level.
- Both cell and module exhibited only ~12% capacity fade after ~4 years (~3,000 cycles) at 25°C.
- The power-law framework provided the best long-term fit, enabling both lifetime prediction and mechanistic insight through the fitted n-value.
- Reliable prediction requires ~4–8% capacity loss; very early-life data alone is insufficient.
- Degradation is dominated by LLI with minor LAM contribution.

FUTURE DIRECTION

- Expand grid duty cycle testing to additional and emerging battery chemistries.
- Develop data-center duty cycles and evaluate candidate cell technologies.
- Extend module-level studies to thermal effects, diagnostics, and larger-format systems as GSL capabilities expand.
- Correlate material/component characterization with long-term degradation behavior.
- Perform thermal diagnostics and post-mortem characterization of aged cells and modules.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Z. Yang *et al.*, *Chemical Reviews,* vol. 111, no. 5, pp. 3577–3613, 2011/05/11, doi: 10.1021/cr100290v.

[2] D. Choi *et al., Journal of Power Sources,* vol. 511, p. 230419, 2021/11/01, doi: https://doi.org/10.1016/j.jpowsour.2021.230419.

[3] X. Li *et al.*, *Batteries & Supercaps,* vol. 9, no. 3, p. e202500746, 2026/03/01, doi: https://doi.org/10.1002/batt.202500746.

[4] A. J. Crawford *et al.*, *Journal of Power Sources,* vol. 380, pp. 185–193, 2018/03/15, doi: https://doi.org/10.1016/j.jpowsour.2018.01.080.

[5] D. R. Conover, A. J. Crawford, V. V. Viswanathan, S. Ferreira, and D. Schoenwald, United States, 2014–06–01. [Online]. Available: https://www.osti.gov/biblio/1136613

[6] N. Kim *et al.*, *Journal of Power Sources,* vol. 546, p. 231949, 2022/10/30, doi: https://doi.org/10.1016/j.jpowsour.2022.231949.

[7] D. Choi *et al.*, in *2025 IEEE Electrical Energy Storage Applications and Technologies Conference (EESAT)*, 20–21 Jan. 2025, pp. 1–5, doi: 10.1109/EESAT62935.2025.10891238.

[8] Q. Huang *et al.*, *Journal of Power Sources,* vol. 608, p. 234628, 2024/07/15, doi:https://doi.org/10.1016/j.jpowsour.2024.234628.

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Thank you.