GRID STORAGE LAUNCHPAD

PNNL-SA-223108

From Cell to Module: Li-ion Battery Performance under Grid Duty Cycles

Daiwon Choi, N. Shamim, E. Thomsen, A.J. Crawford, V.V. Viswanathan, Q. Huang, D.M. Reed, V.L. Sprenkle

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U.S. DEPARTMENT of ENERGY | Office of Electricity
Pacific Northwest NATIONAL LABORATORY

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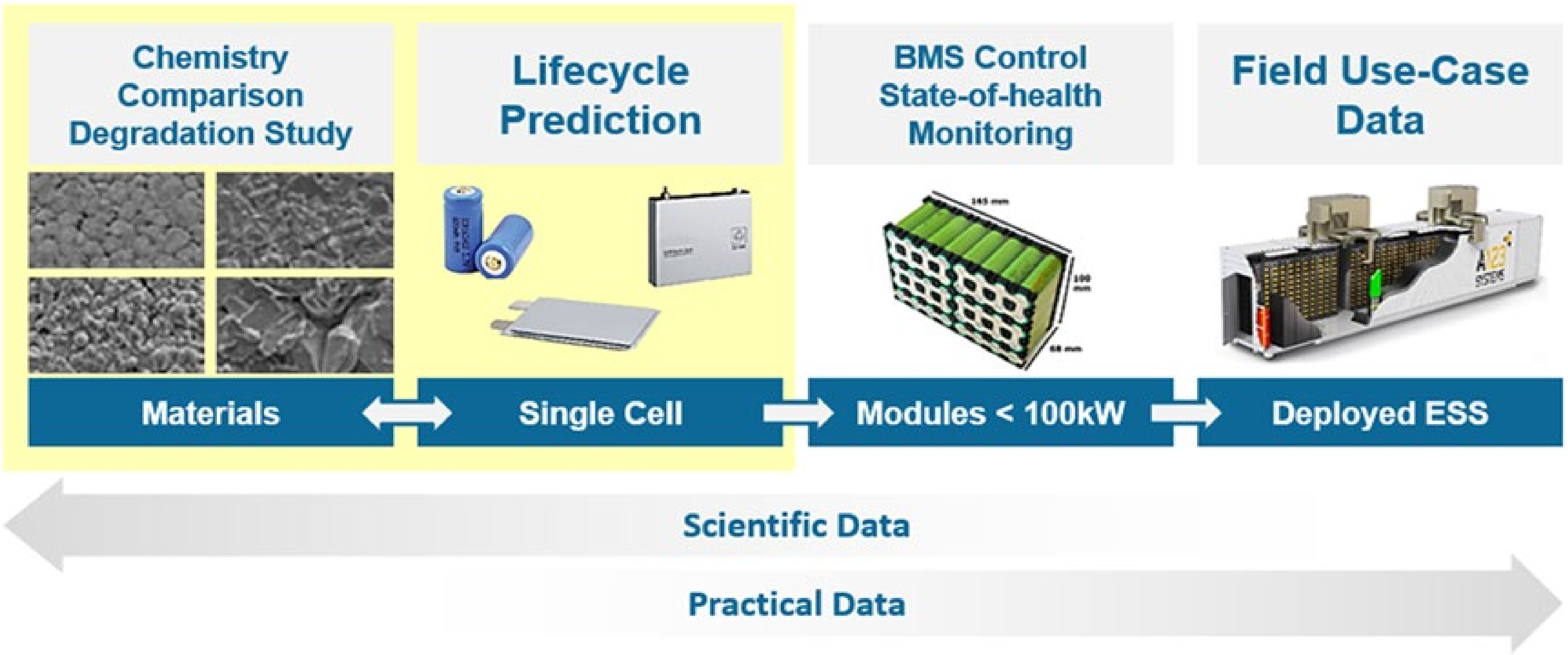
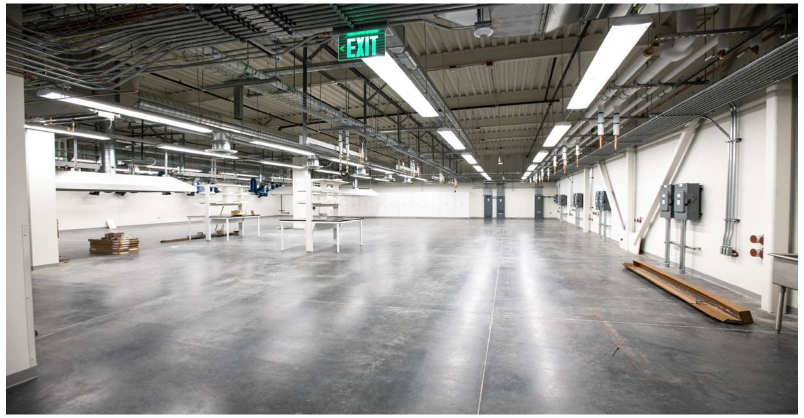
PROJECT OVERVIEW

- What is expected performance, calendar/cycle life, cost, efficiency of battery format and chemistry?
- Cell testing has been ongoing since 2020, with the transition to GSL completed last year and continued expansion of test capabilities.
- Additional chemistries under evaluation: flow, lead-acid, zinc, and sodium-beta, with plans to procure more technologies.



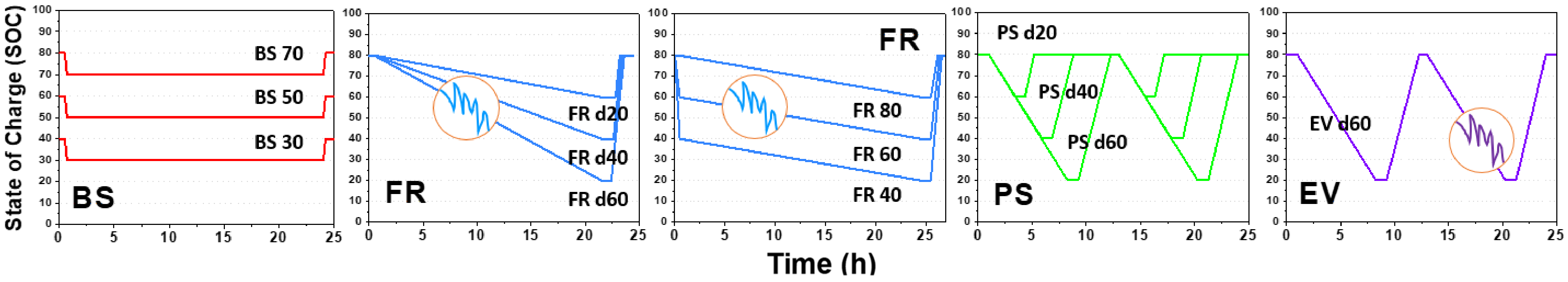


GSL GRID STORAGE LAUNCHPAD

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)

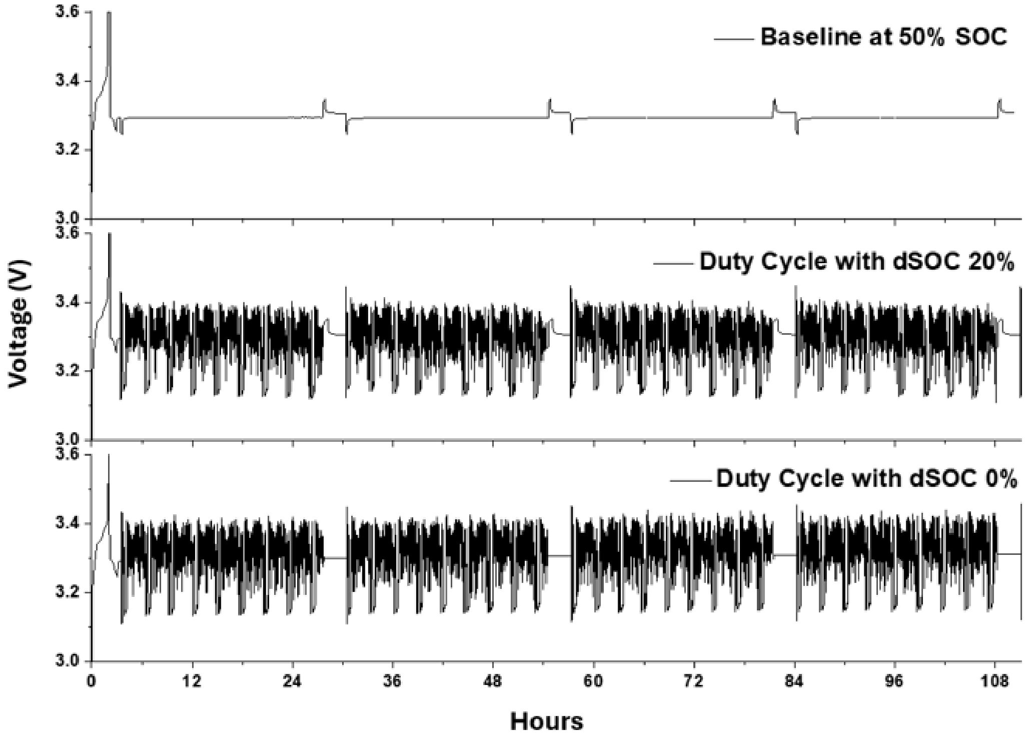
FR: Frequency Regulation

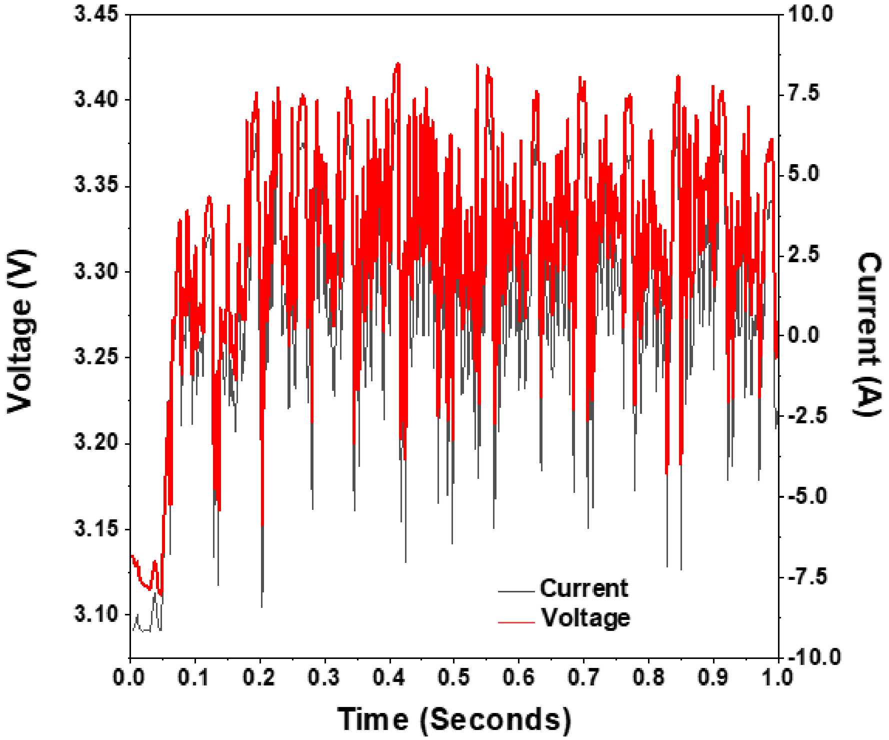
PS: Peak Shaving

EV: Electric Vehicle Drive

Ref : "Comparison of Li-ion battery chemistries under grid duty cycles", N. Kim, N. Shamim, A. Crawford, V.V. Viswanathan, B.M. Sivakumar, Q. Huang, D. Reed, V. Sprenkle, D. Choi, *J. Power Sources*, 546 (2022) p 231949

DATA CENTER DUTY CYCLES

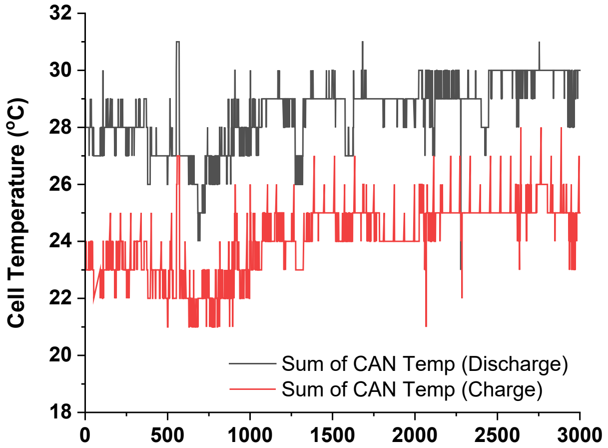


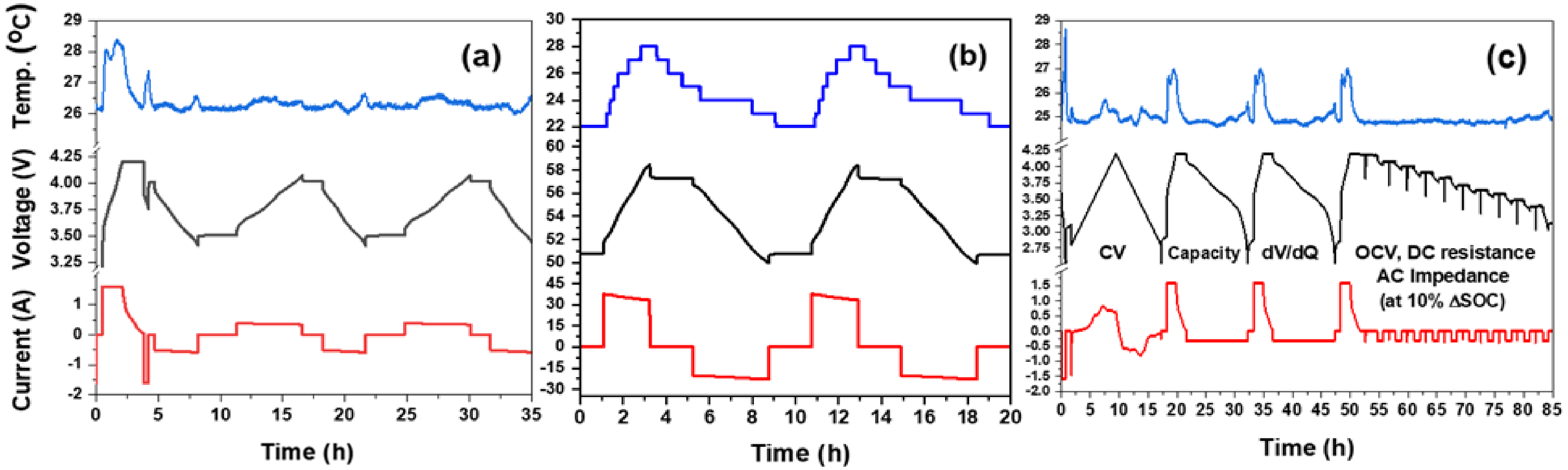


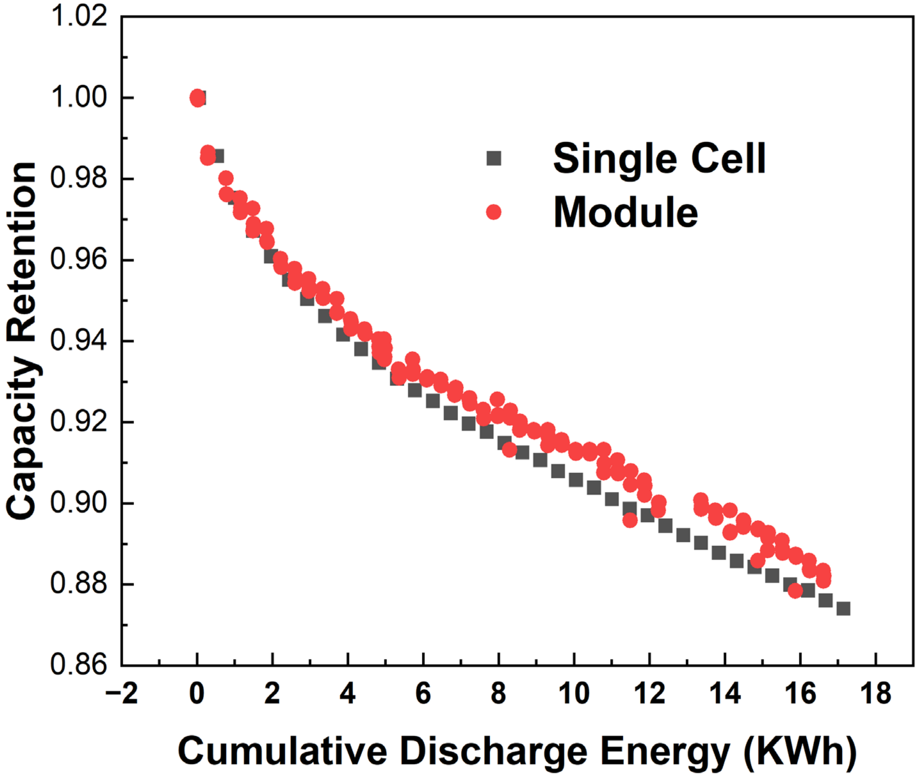
CATEGORY	PARAMETER	VALUE
NOMINAL RATINGS	Nominal Voltage	3.3 V
	Capacity (typ / min)	1.2 Ah / 1.1 Ah
	Energy	3.63 Wh
	Internal Impedance (1 kHz AC)	12.6 mΩ
	Cycle Life (100% DOD)	> 2000 cycles
DISCHARGING	Max Continuous Discharge	30 A
	Max Pulse Discharge (10 s)	50 A
	Minimum Voltage	2.0 V
	Temperature 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

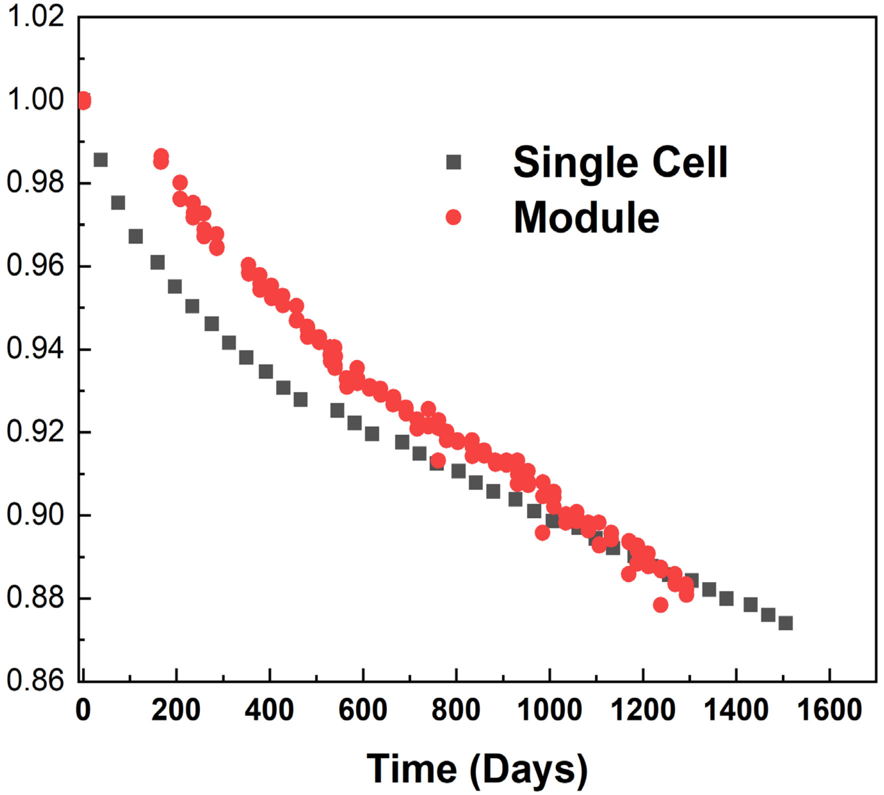
- **High power LFP cell satisfies power rating (Max. 8C rate) for the data center duty cycles but due to high pulse rate of the signal, battery tester need high resolution (millisecond) data acquisition capability (Data center duty cycle is only 2seconds)**
- **Due to large number of data point per seconds, only 2min of the 24h cycles were recorded at high resolution to reduce data size of the cell test.**

NMC MODULE TEST RESULTS









- Cell and module show similar degradation trends, indicating good scalability from cell to module level.
- Both single cells and module were tested at 25°C (chamber and fume hood).
- After ~ 4 years of peak shaving cycles (~3,000cycles), ~12% in capacity fade from both cell and module.

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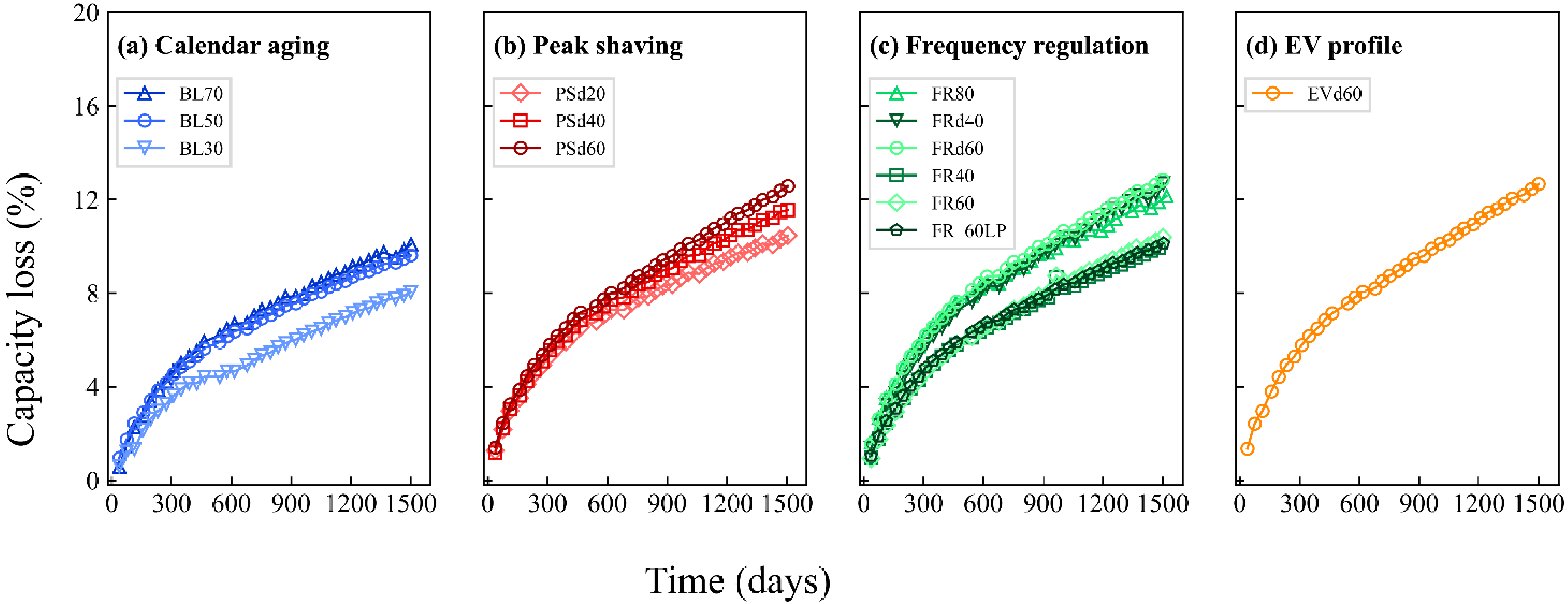
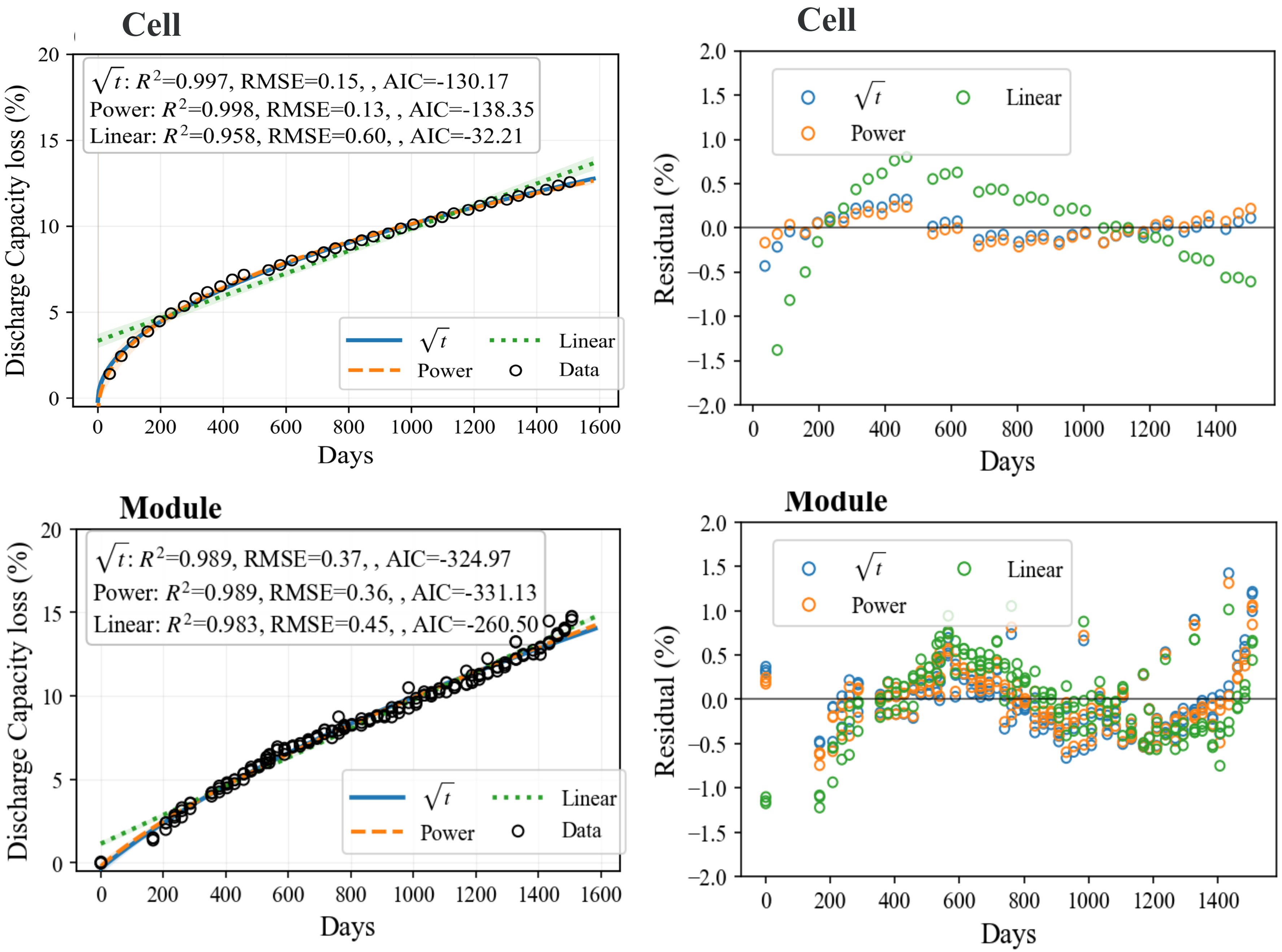
NMC CELL **PERFORMANCE**



- **Li-ion NMC cells tested across 13 different duty cycles show that even after 4 years of continuous cycling, spanning a total of 6 calendar years including downtime for rest, power outages, repairs, and lab work, their capacity degradation remains under 12%.**
- **Lower SOC and narrower ΔSOC level cycling degraded the cell less.**

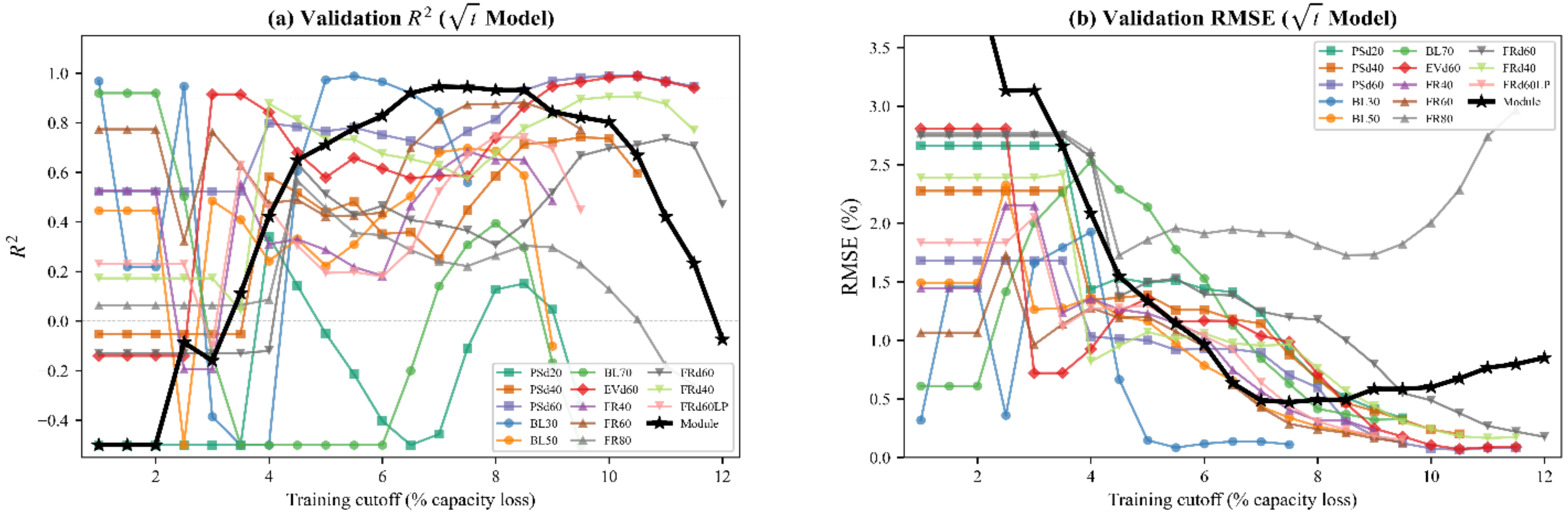
CELL & MODULE TEST RESULTS



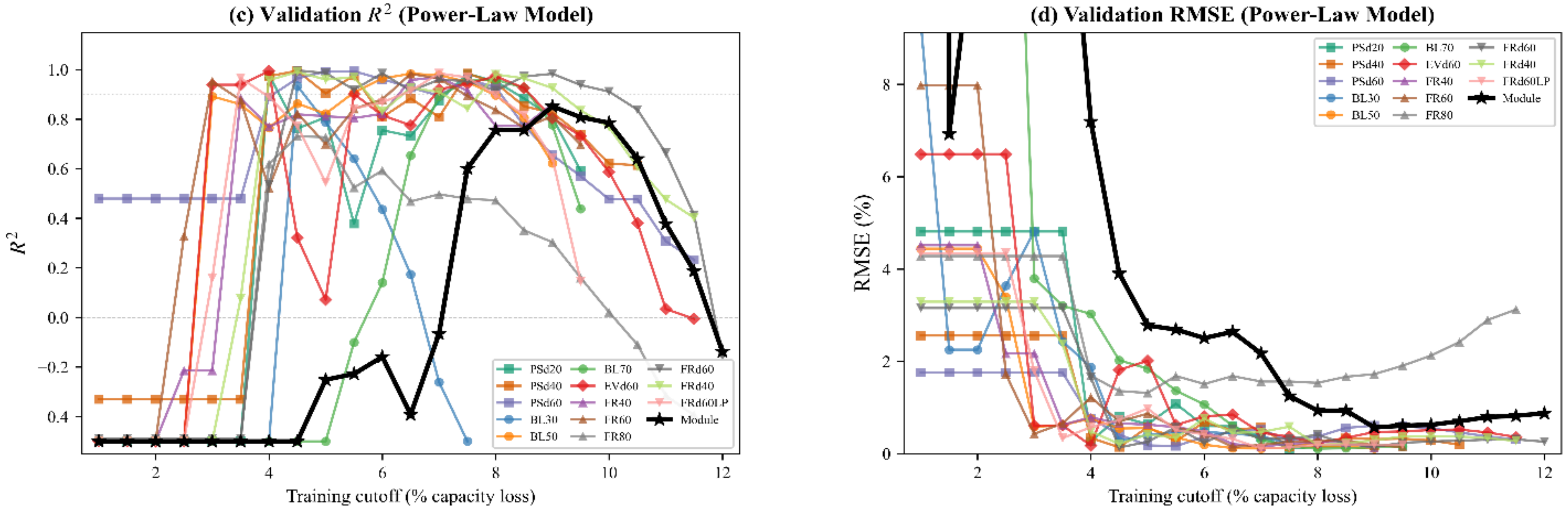
- Power-law provides the best overall fit, with lowest RMSE and most favorable AIC.
- √t model performs comparably in R^2 but shows slightly higher error.
- Linear model underperforms, especially in long-term trend capture.
- Residuals for power-law and √t are randomly distributed, indicating good model adequacy.
- Linear model shows systematic residual trends, confirming model bias and poor fit.

CELL & MODULE TEST RESULTS

√t Model Performance vs Training Data Size

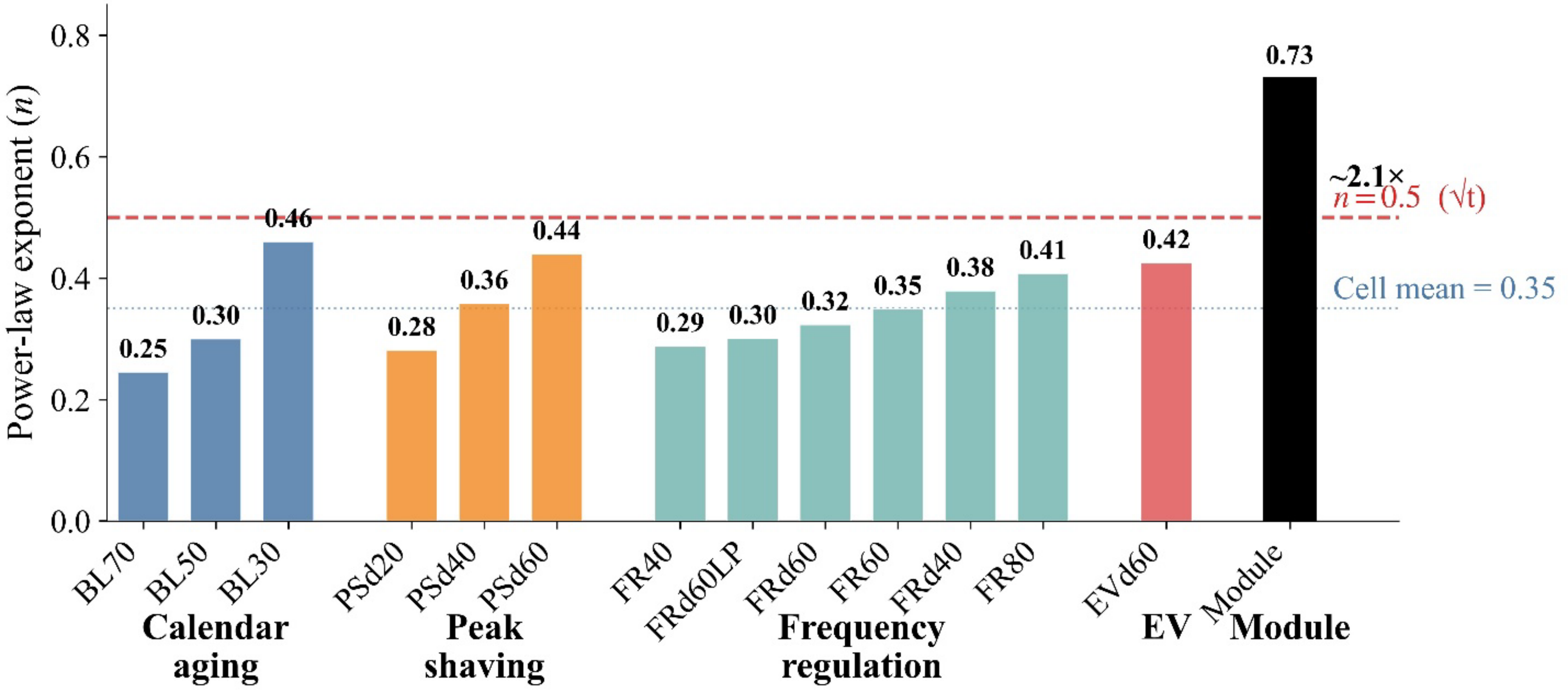


Power–Law Model Performance vs Training Data Size



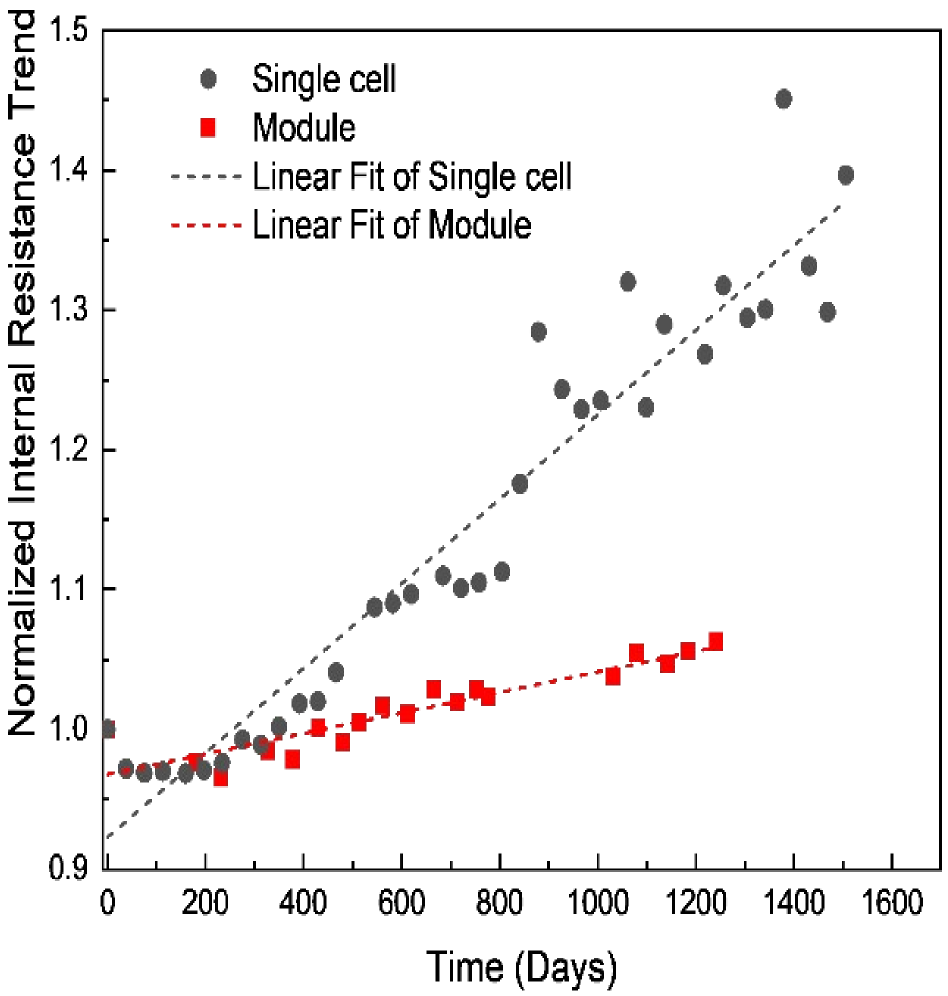
- ❑ Power-law model outperforms √t and linear, with higher R^2 and lower RMSE.
- ❑ √t model works early but degrades at longer times.
- ❑ Reliable fits require ~4–8% capacity loss; early data is unstable.
- ❑ Module-level fits are less accurate due to system-level variability.
- ❑ Linear model is least accurate overall.

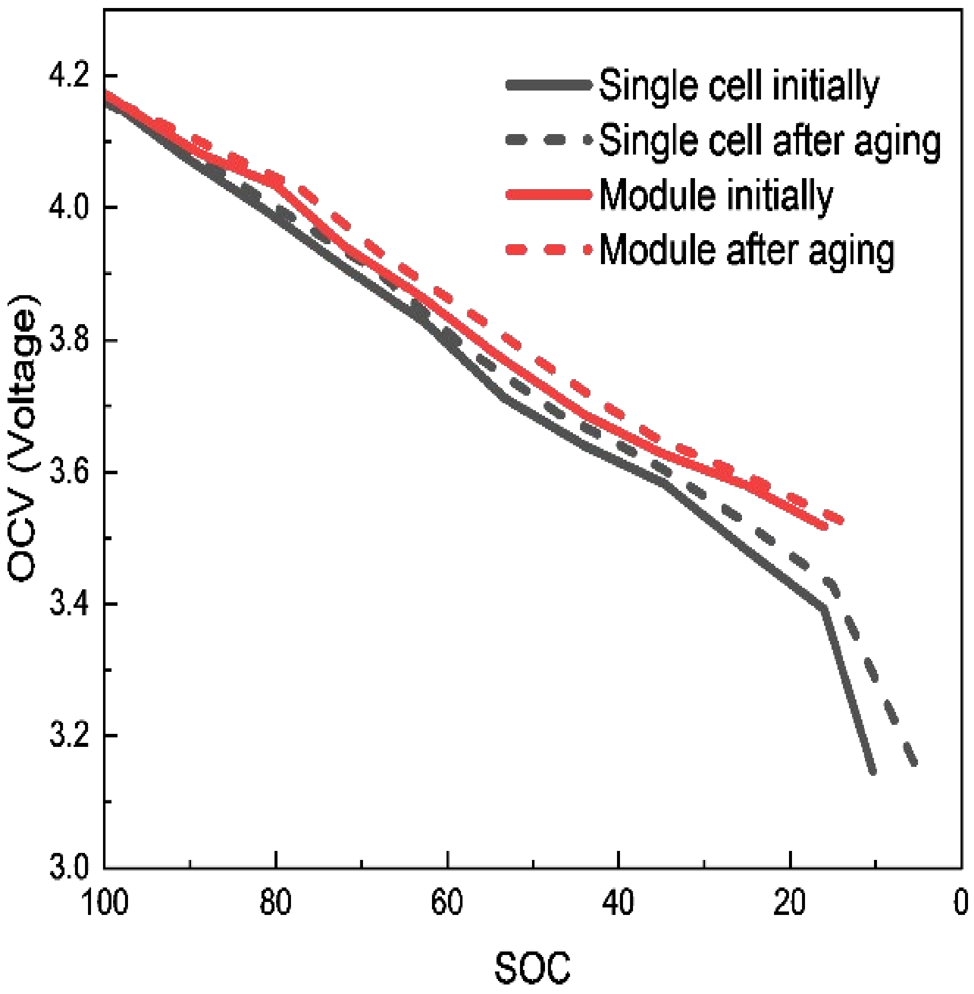
CELL & MODULE TEST RESULTS



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)

CELL & MODULE TEST RESULTS





- **Resistance change show linear behavior but slope is different between cell and module. Module has XP14S configuration. If only one of the 14 series connected "cells" has higher resistance, it contributes less in percent increase for the module**
- **OCV before and after 4 years, show slight increase in both cell and modules**

CELL & MODULE TEST RESULTS

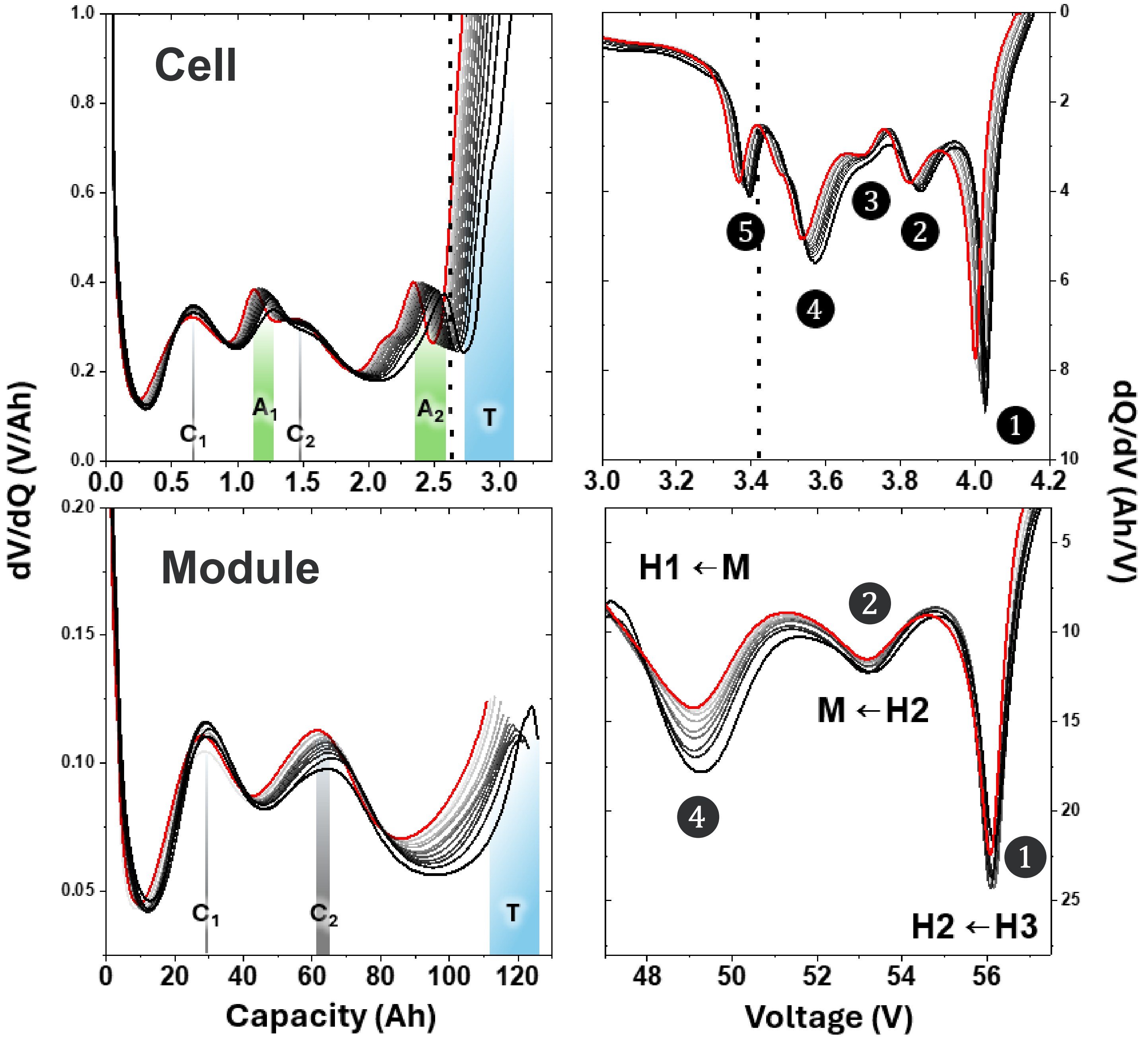


Table 1. Calculated capacity loss of graphite anode based on full cell dV/dQ curves.

	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 lose of lithium inventory (LLI) and loss of active negative material (LAM_{NE}).

CONCLUSION

- Cell-to-module degradation trends are consistent under peak-shaving duty cycles
- ~12% capacity fade after ~4 years (~3,000 cycles) at 25 °C
- Power-law model provides the most robust lifetime prediction across datasets
- Reliable prediction requires ≥ ~4–8% capacity loss (early data is insufficient)
- Degradation is dominated by LLI with minor LAM contribution
- Thermal and material characterizations on degraded cells will be performed in the future.

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SUMMARY

- Unique long-term dataset: 6 years, multiple chemistries, real grid duty cycles
- Na-ion chemistries are now included in grid duty cycle testing.
- Data center duty cycles are being developed, with cell candidates under evaluation.
- Cell and module show strong scalability in degradation behavior
- Power-law framework enables both prediction and mechanism insight (n-value)
- Realistic ESS operation (peak shaving) shows moderate, predictable aging
- Future work: module-level diagnostics, thermal effects, and larger formats

ACKNOWLEDGEMENTS

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Thank you.