

A Digital Twin for a Modular Second Life Battery Storage System: State-of-Health Estimation from Cell-Level to System-Level

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Motivation

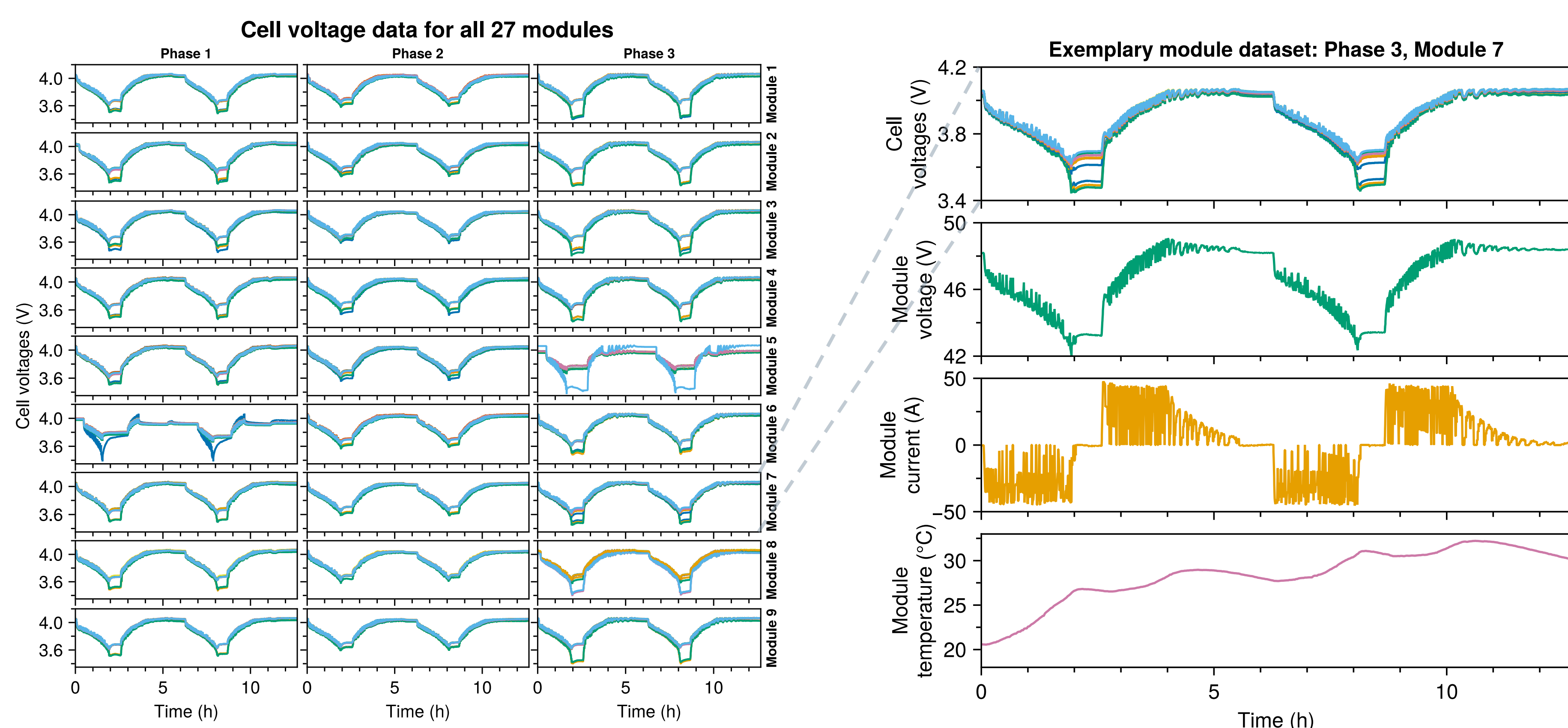
- › Limited knowledge is available when repurposing batteries for second-life: each individual cell may exhibit varying degrees of degradation.
- › Can we leverage field data to create individualized battery cell models and scale them up into a comprehensive system model?

Main Findings

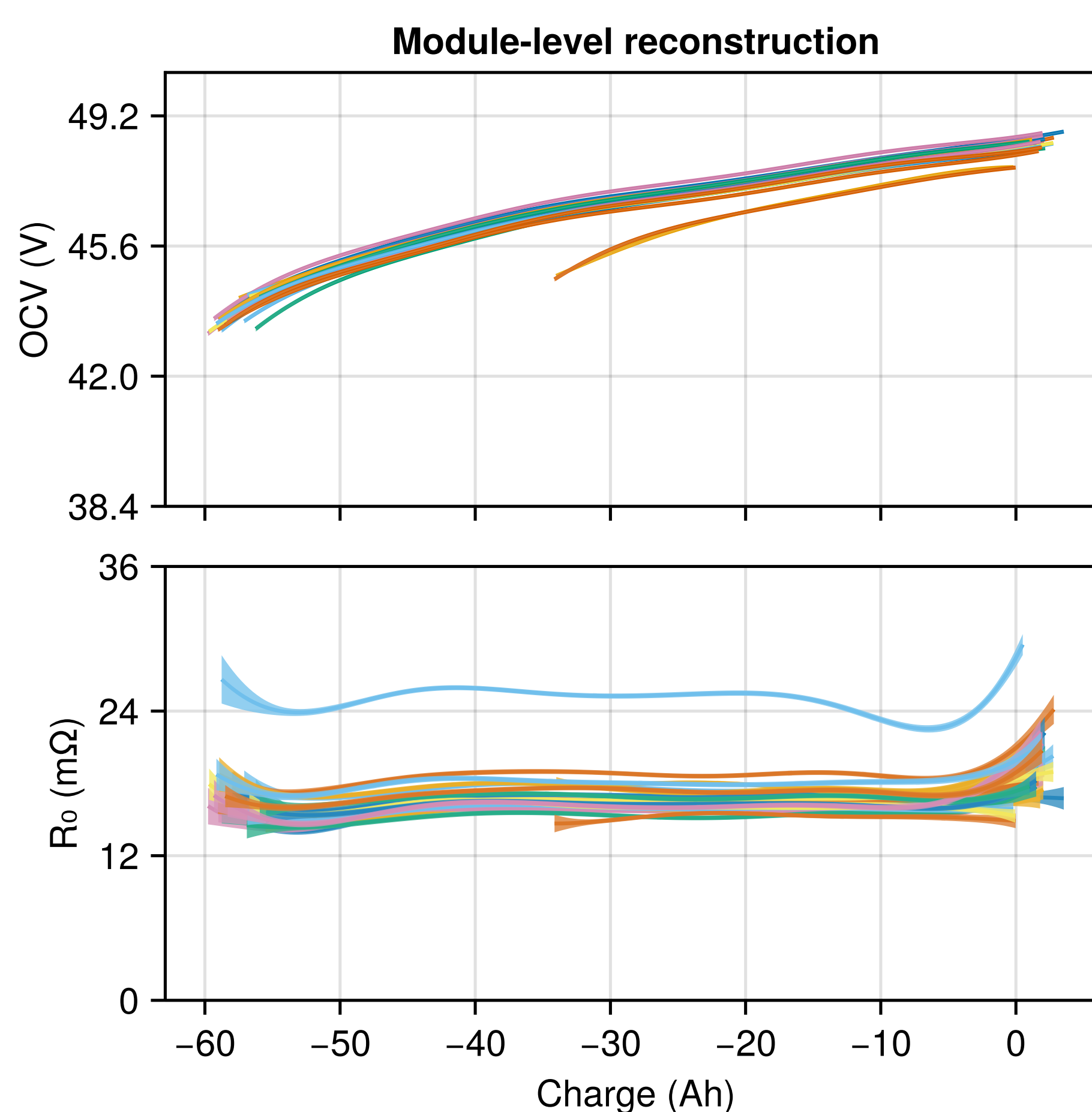
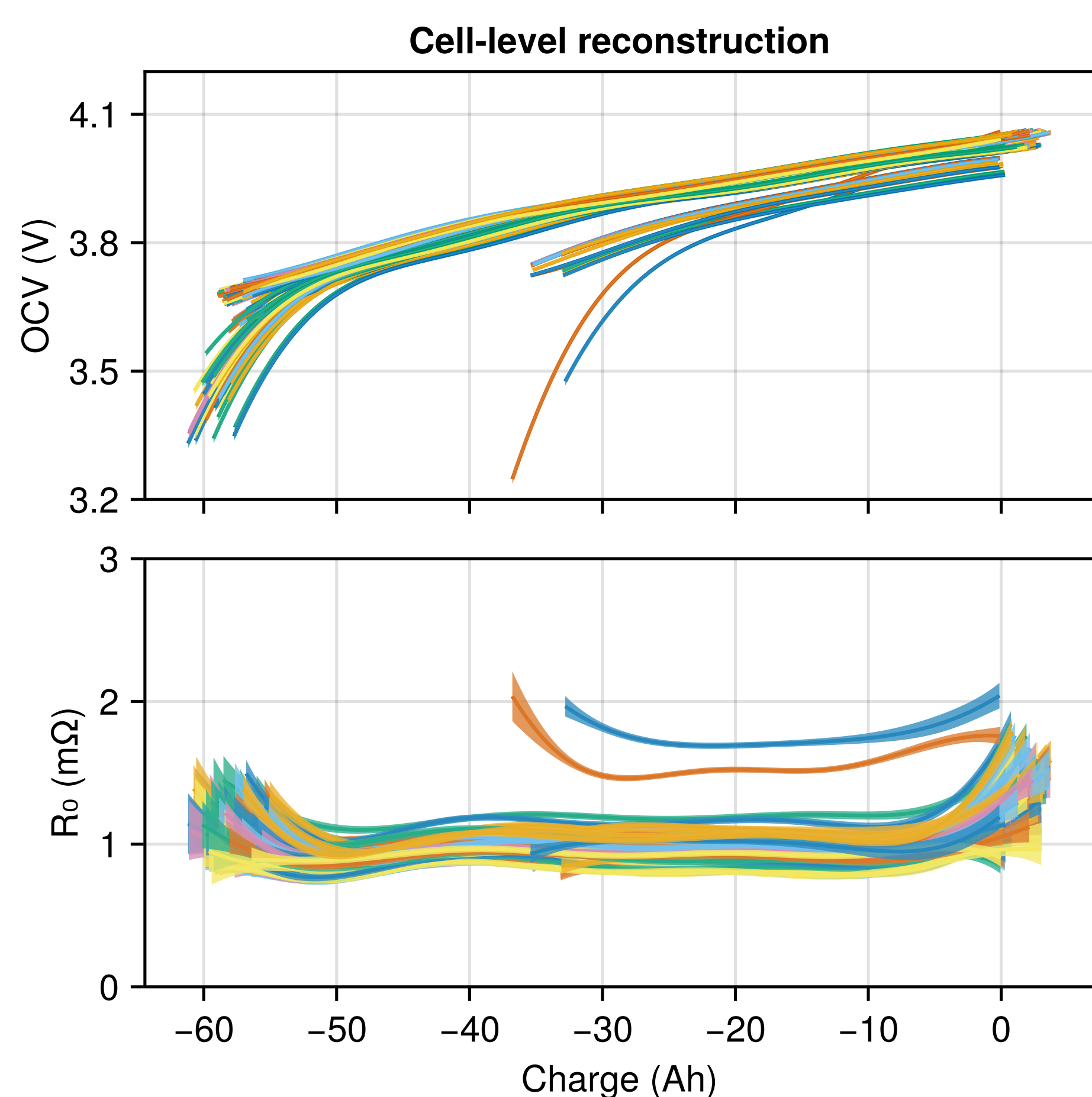
- › The capacity-based SOH of each individual cell can be accurately estimated by reconstructing its OCV curve using field data.
- › The models reveal considerable cell-to-cell variations within the second-life system.
- › Ignoring this inhomogeneity leads to an overestimation of SOH at the module level.

Methodology & Dataset

- › Case study: Second-life storage system comprising 324 highly aged cells organized into 27 modules.
- › Modules are connected to the grid via a 120 kW 3-phase modular multilevel converter (MMC).
- › Real operational data is used to fit cell-individual first-order equivalent circuit models (ECM).
- › Recursive Gaussian Process Regression extracts the aged OCV curve and SOC-dependency of the battery's internal resistance [1,2].
- › An extended Kalman filter enables simultaneous state and parameter estimation.



Battery Models



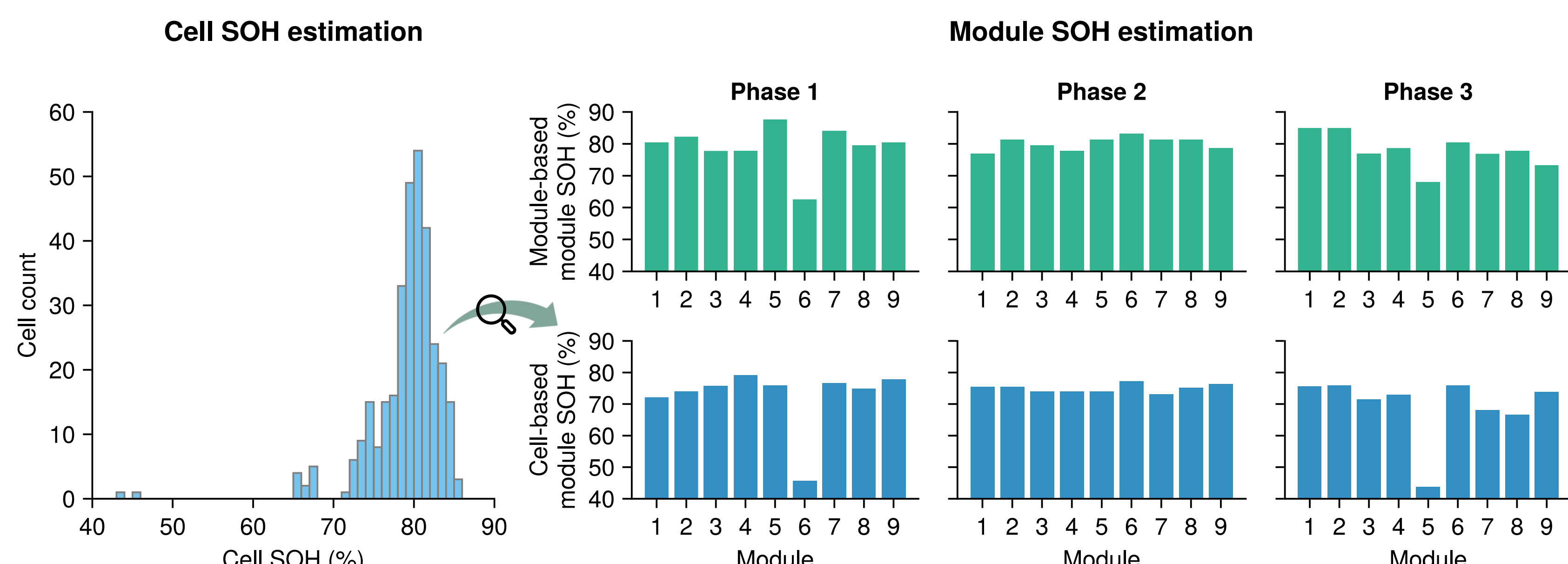
- › Two kinds of battery models are reconstructed: using cell-level and module-level voltage data.
- › Individual cells show significant capacity loss, resistance increase, and SOC imbalance.
- › Cells that reach operational limits constrain the rest of the other cells in the module, preventing their full utilization.
- › Module-level models cannot adequately capture hidden states associated with cell imbalance and weak cells.
- › These battery models can be further used for SOC estimation, predictive simulations, and optimizing operational strategies.

State-of-Health Estimation

- › The capacity-based SOH and initial SOC can be estimated from the charge under the OCV curve of the reconstructed ECM.
- › The cell SOH and SOC imbalance can be aggregated together to estimate the effective SOH of each module [3].

$$Q_{ch} = \min((1 - soc_i) \cdot Q_i) \quad Q_{dc} = \min(soc_i \cdot Q_i)$$

$$SOH_{Q,module} = \frac{Q_{ch} + Q_{dc}}{Q_{BOL}}$$



References

- [1] Huber, M.: Recursive Gaussian process: On-line regression and learning. In: Pattern Recognition Letters 45, 2014
- [2] Cornejo, M.; Jablonski, S.; Fischer, M.; Bahrke, J.; Jossen A.: Data-driven model enhancement of late-life lithium-ion batteries. In: Future Batteries 6, 2025
- [3] Ruther, M. et al.: Battery pack states, properties, and characterization techniques beyond cell level. In: Cell Reports Physical Science 6, 2025

Acknowledgements

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