A Mechanistic Investigation of the Relationship Between Battery Energy and Capacity

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Are capacity and energy loss equivalent?

"Capacity" is one of the most critical metrics in energy storage system standards.

However, there is inconsistency in the definition of capacity across documents.

Some standards refer to an energy capacity with units of Wh and a coulombic capacity with units of Ah

Other standards simply use the term 'capacity' without defining the units and use it on a normalized base.

Can the Wh and Ah definitions be used interchangeably?

Faraday number
Charge on 1 e^-

$$Capacity_i(\mathrm{Ah}) = \underbrace{n}_{\#\text{ of } e^-} . F . \underbrace{N}_{\#\text{ of moles}} = \int_0^t Current.\mathrm{dt}$$

Definition: Total amount of electrons a battery can store, independent of its voltage.

Units: Ampere-hours (Ah)

What it means: A 10 Ah phone battery can theoretically hold 10 A of current for 1 hour

Preger et al., J. Electrochem. En. Conv. Stor., 23(2): 021109 (2026).
Dubarry et al., Joule, Accepted

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# of e⁻ # of moles

$$Energy_i\ (\mathrm{Wh}) = \int_0^t Voltage.Current.\mathrm{dt}$$

$$= \overline{Voltage}.Capacity$$

Definition: Actual electrical work the battery can deliver.

Units: Watt-hours (Wh)

What it means: A 10Ah 12V battery holds 120Wh of energy.

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Relating Capacity and Energy Losses
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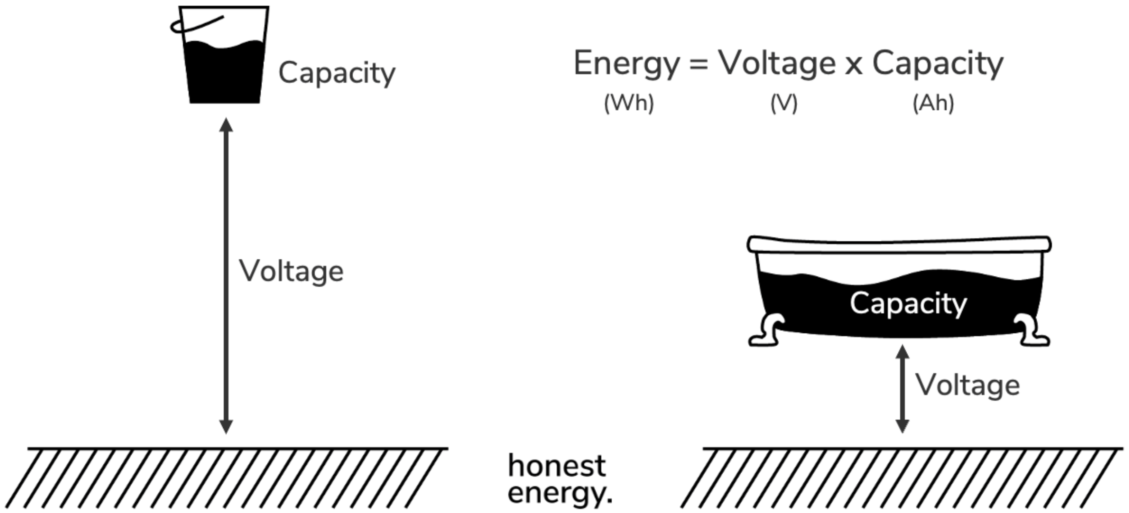

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$$Capacity\ Retention_i\ (\%) = \frac{Capacity_i\ (Ah)}{Capacity_0\ (Ah)} \times 100\%$$

$$Energy\ Retention_i\ (\%) = \frac{Energy_i\ (Wh)}{Energy_0\ (Wh)} \times 100\% = \frac{Capacity_i\ (Ah) \times \overline{Voltage_i}\ (V)}{Capacity_0\ (Ah) \times \overline{Voltage_0}\ (V)} \times 100\%$$

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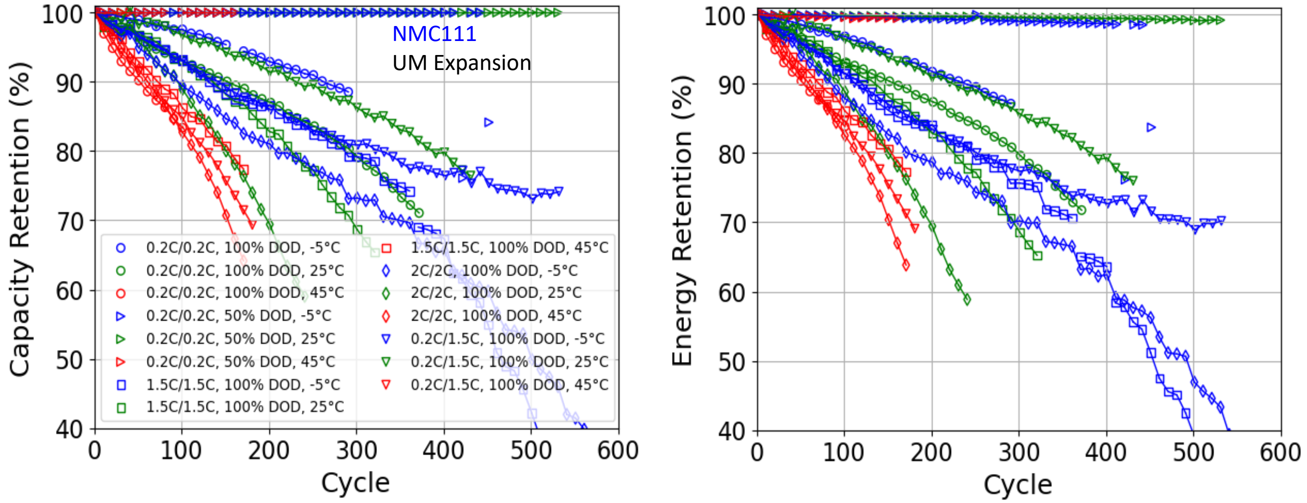
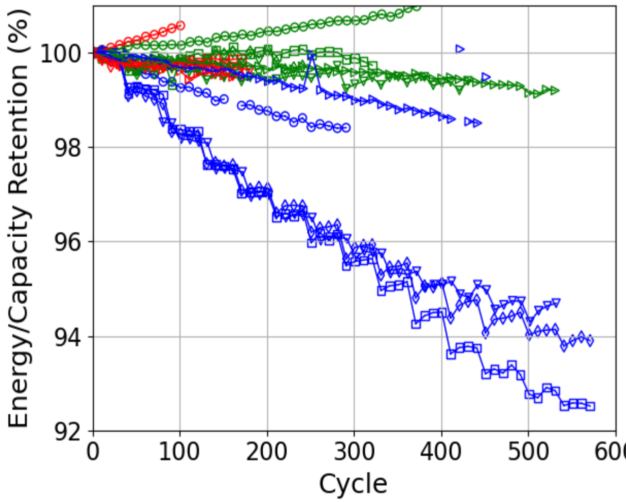
Relating Capacity and Energy Losses
Are capacity and energy loss equivalent?

Experimental observations from available battery databases





Both seem to follow similar trends

Clearly not that simple…

$$\frac{E}{Q} = \frac{Energy\ Retention_i\ (\%)}{Capacity\ Retention_i (\%)}$$

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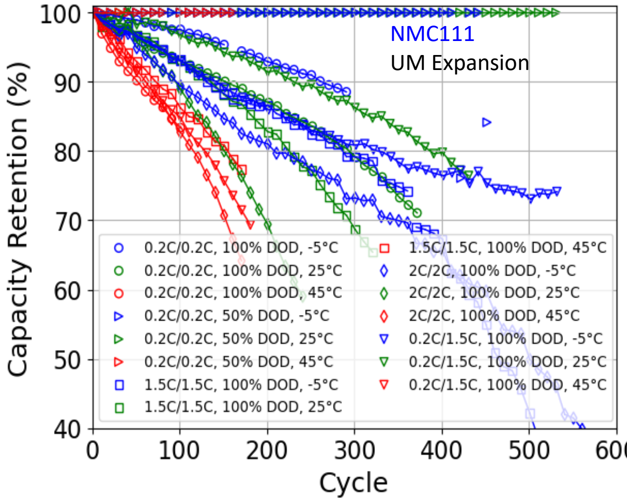
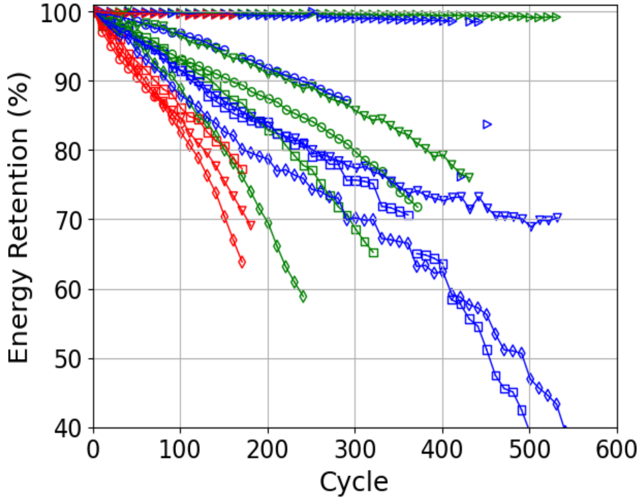
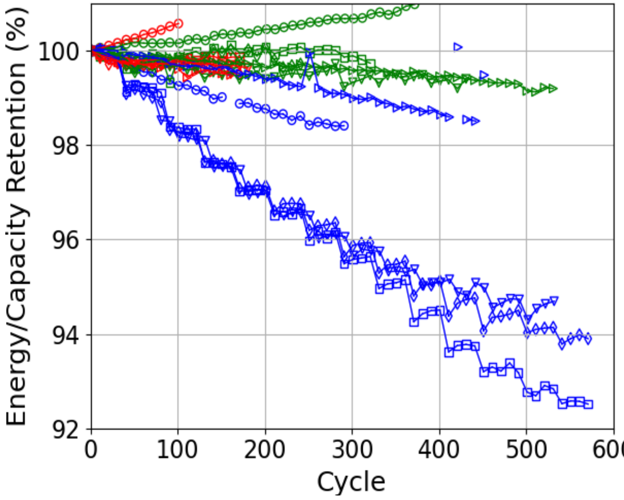
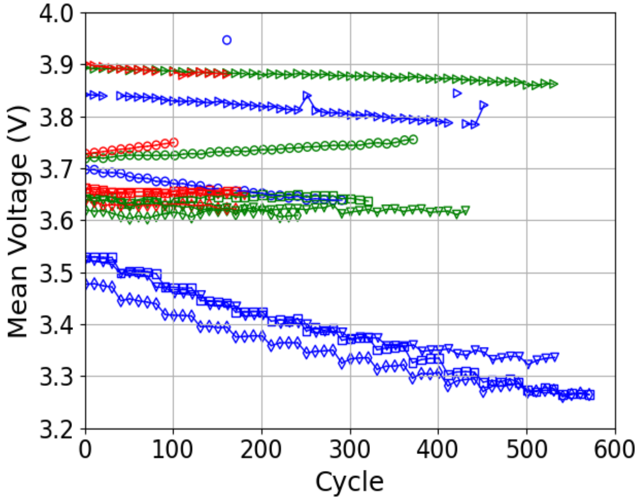
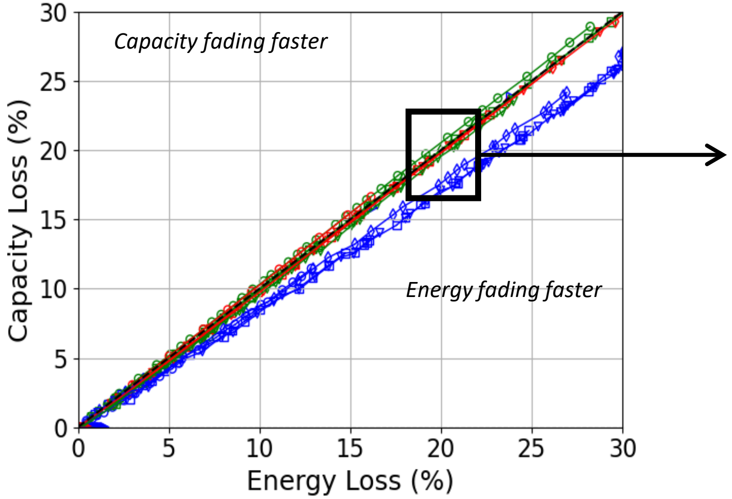


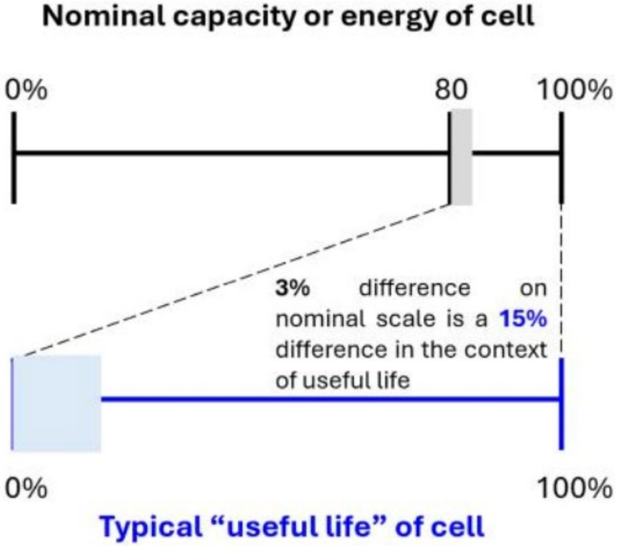




Why?







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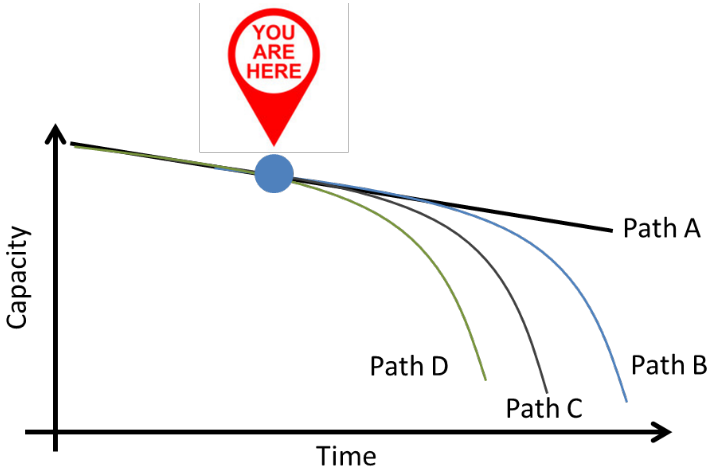
The complexity of battery degradation

Path dependence of the degradation



Charging

Temperature

Discharging

Different paths will lead to different degradations

Every battery is different → Different voltage variations

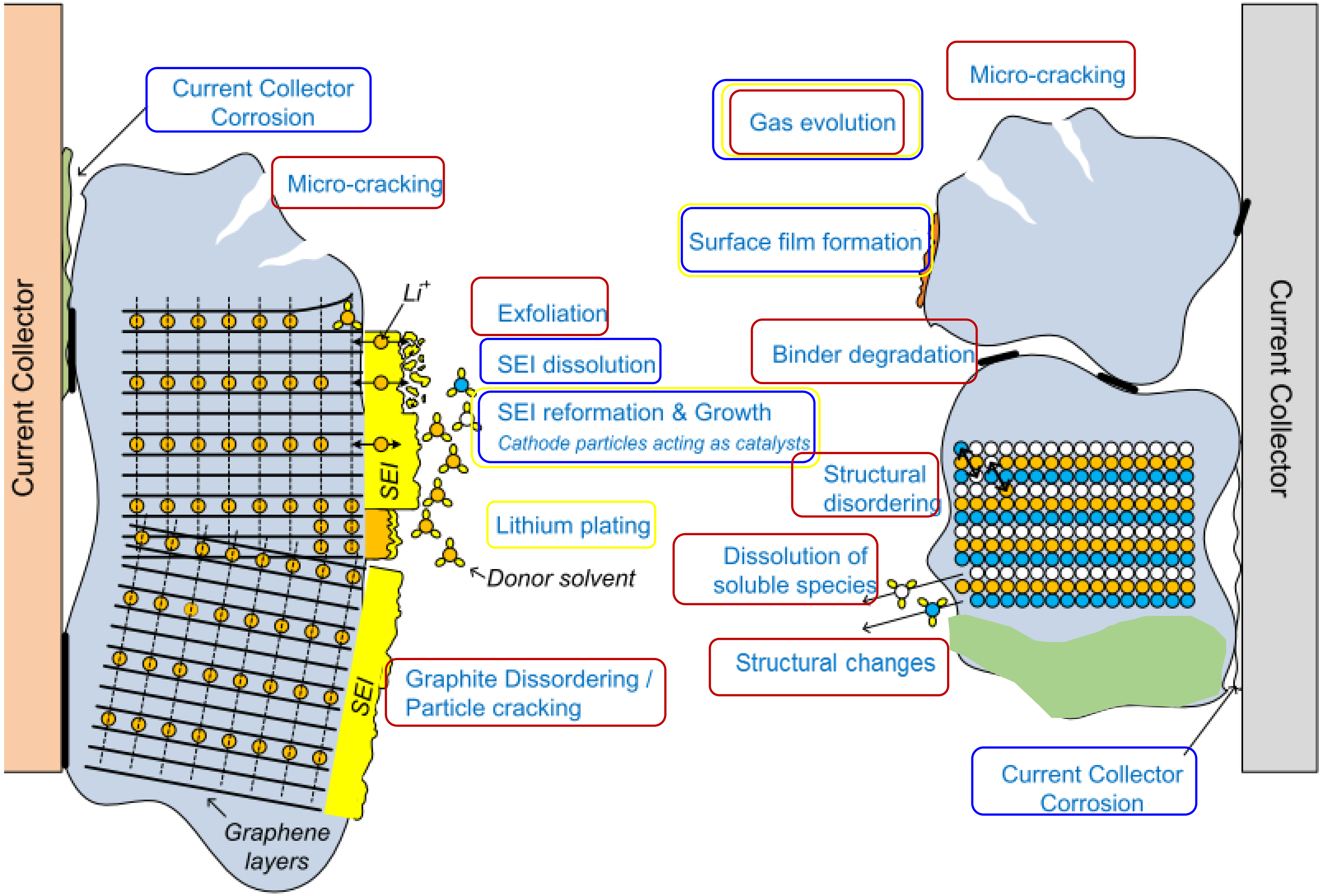
The complexity of battery degradation
A million ways to fail…

Lithium-ion battery degradation mechanisms

20+ possible mechanisms
- Positive Electrode
- Negative Electrode
- Separator
- Electrolyte
- Current collectors

Complex mix

Degradation modes refer to **the impact of a mechanism rather than its root cause.**



Degradation modes

Thermodynamics
- Change in active material
- Change in lithium inventory

Kinetics
- Change in ohmic and faradic resistances

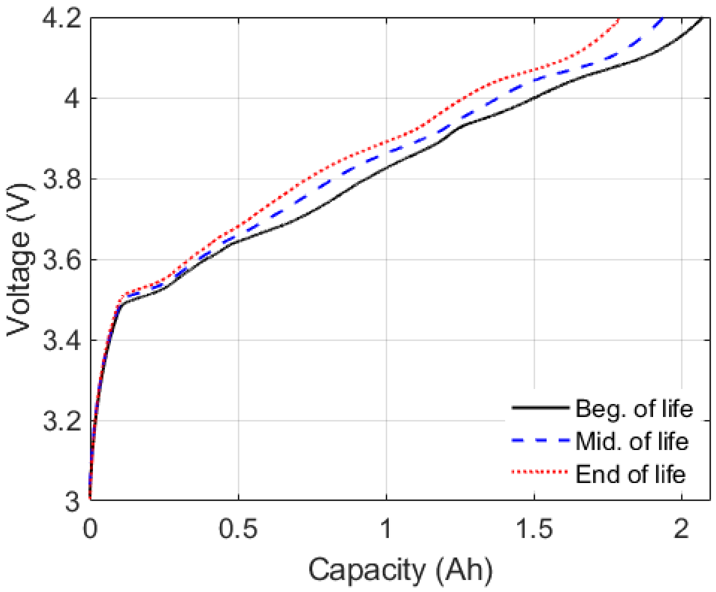
The complexity of battery degradation

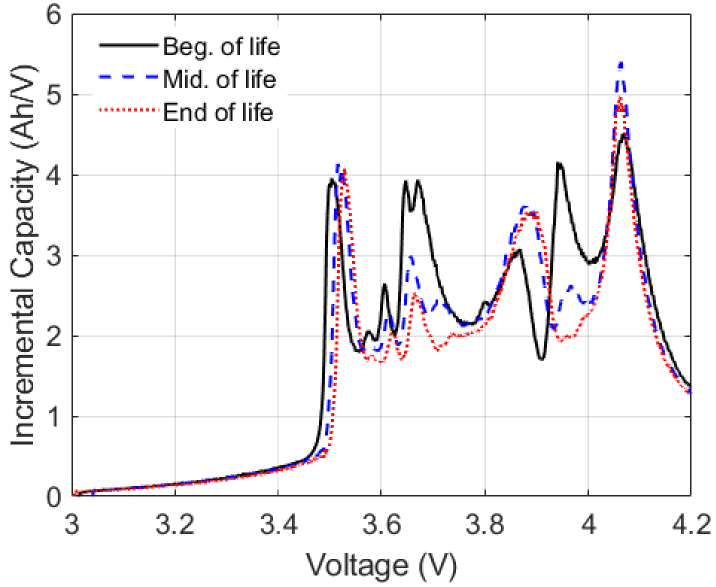
How to visualize minute voltage changes?

Evolution of the voltage response

Degradations will affect voltage differently

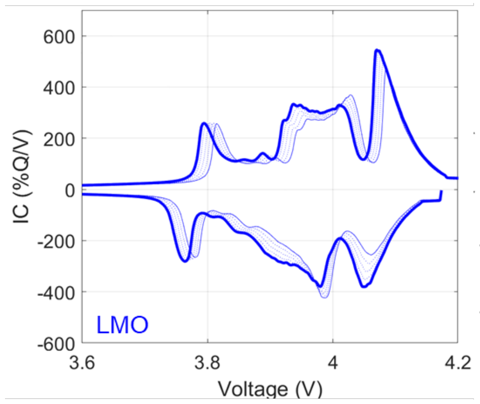
Use of derivative curves to enhance changes

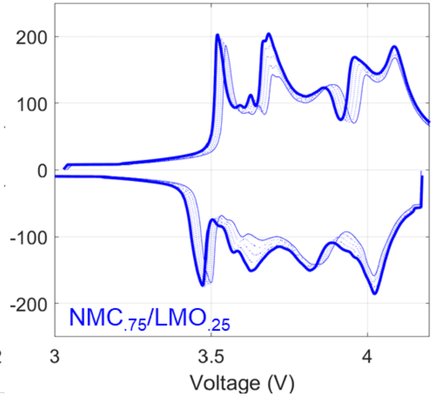


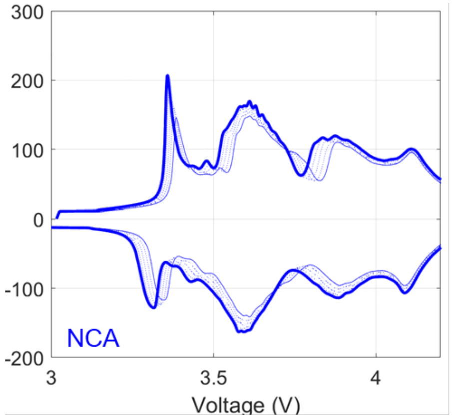


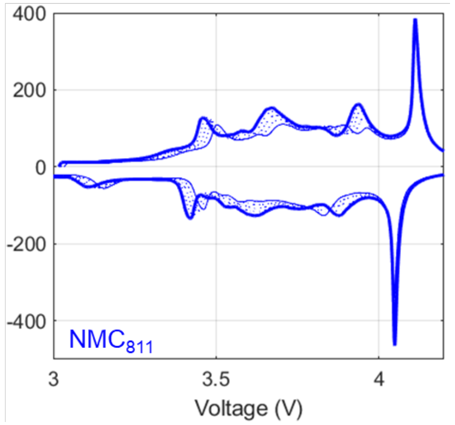
Response is chemistry dependent

Li-ion or Na-ion







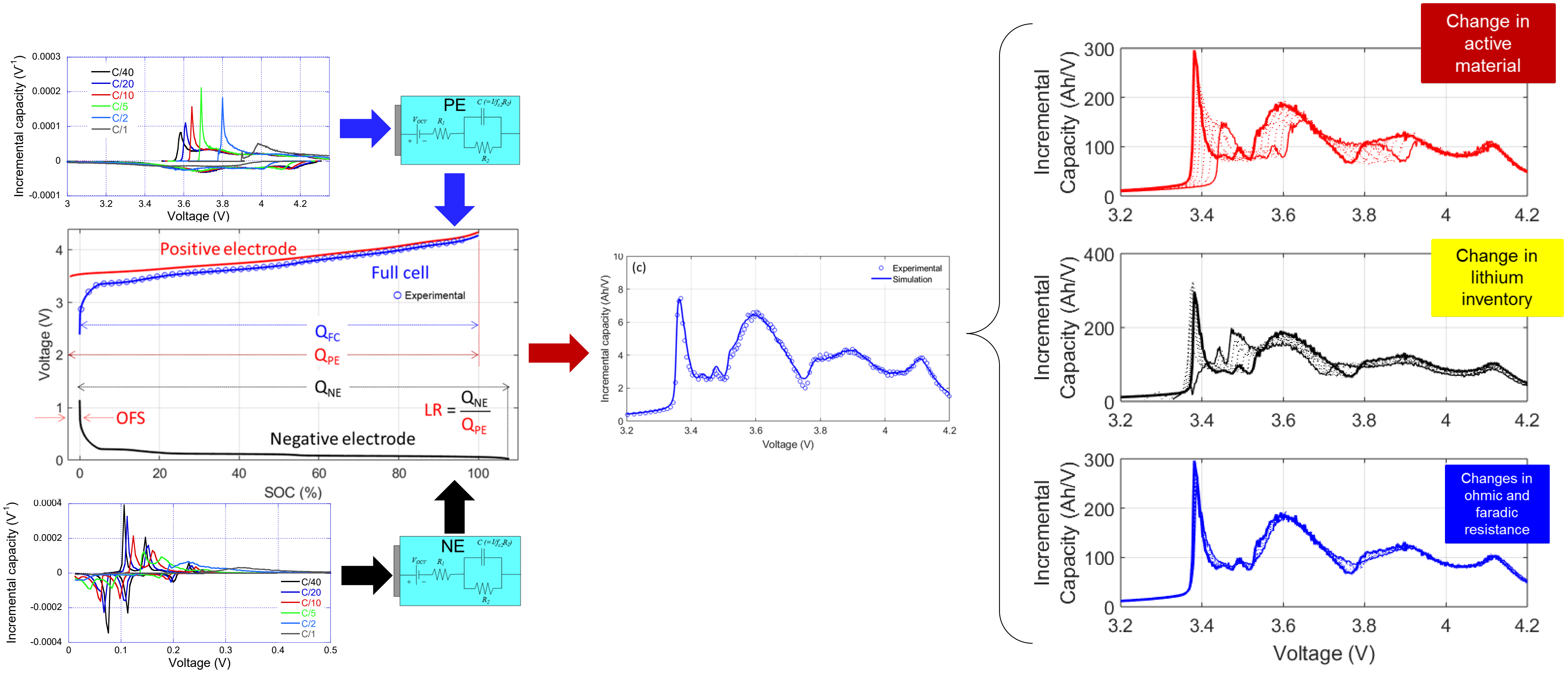


Need a model to relate voltage changes to degradation modes and to track their evolution

A. Barai, K. Uddin and M. Dubarry et al., *Progress in Energy and Combustion Science* **72** (2019) 1–31
M. Dubarry and D. Anseán, *Frontiers in Energy Research* **10** 1023555 (2022)

Individual Electrode Performance

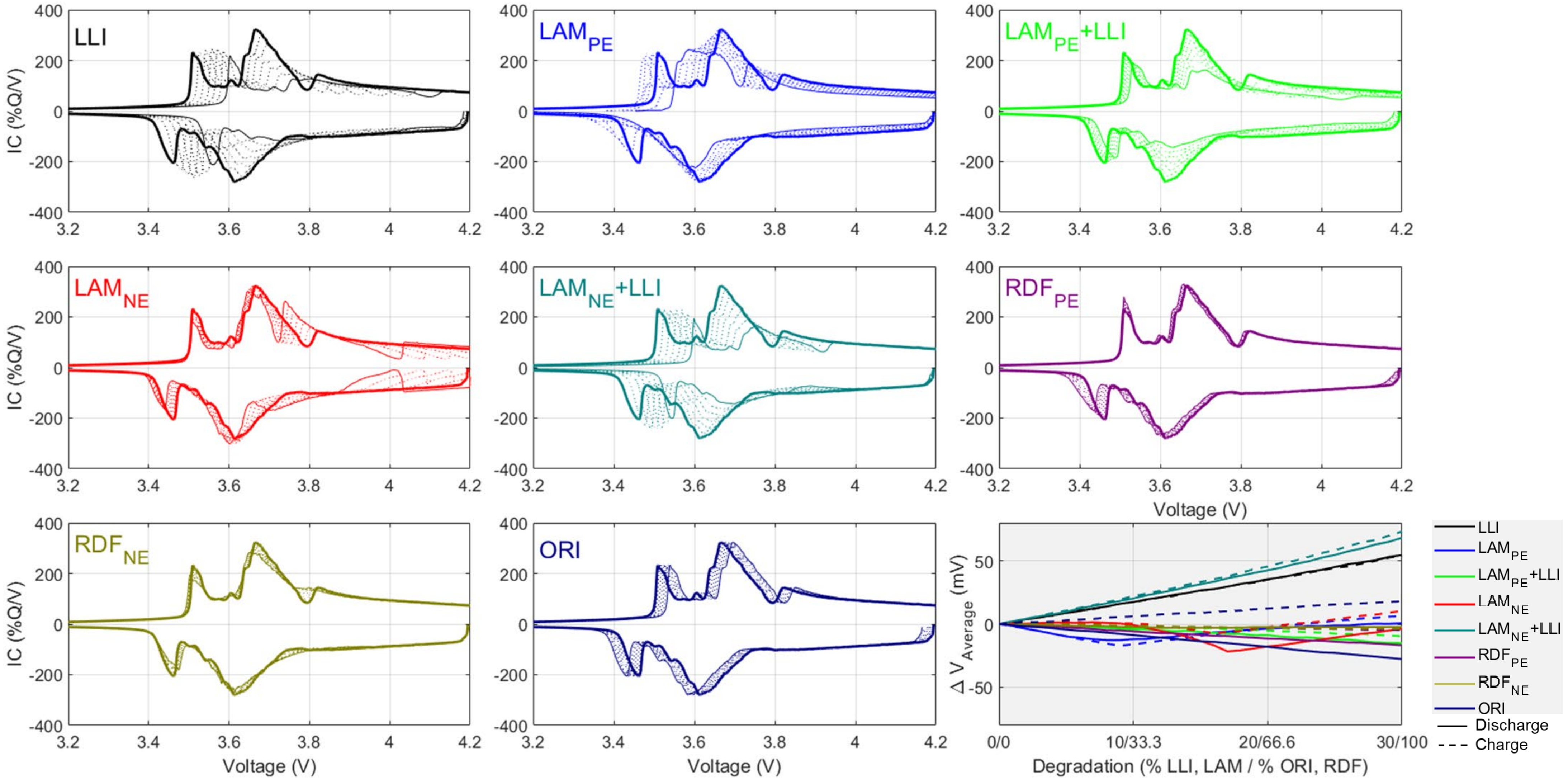
Emulation of the full-cell response from half-cell data



Dubarry M. et al. JPS 219 (2012) 204-216

Individual Electrode Performance

NMC_{111}, Emulation of the full-cell response from half-cell data @ C/5



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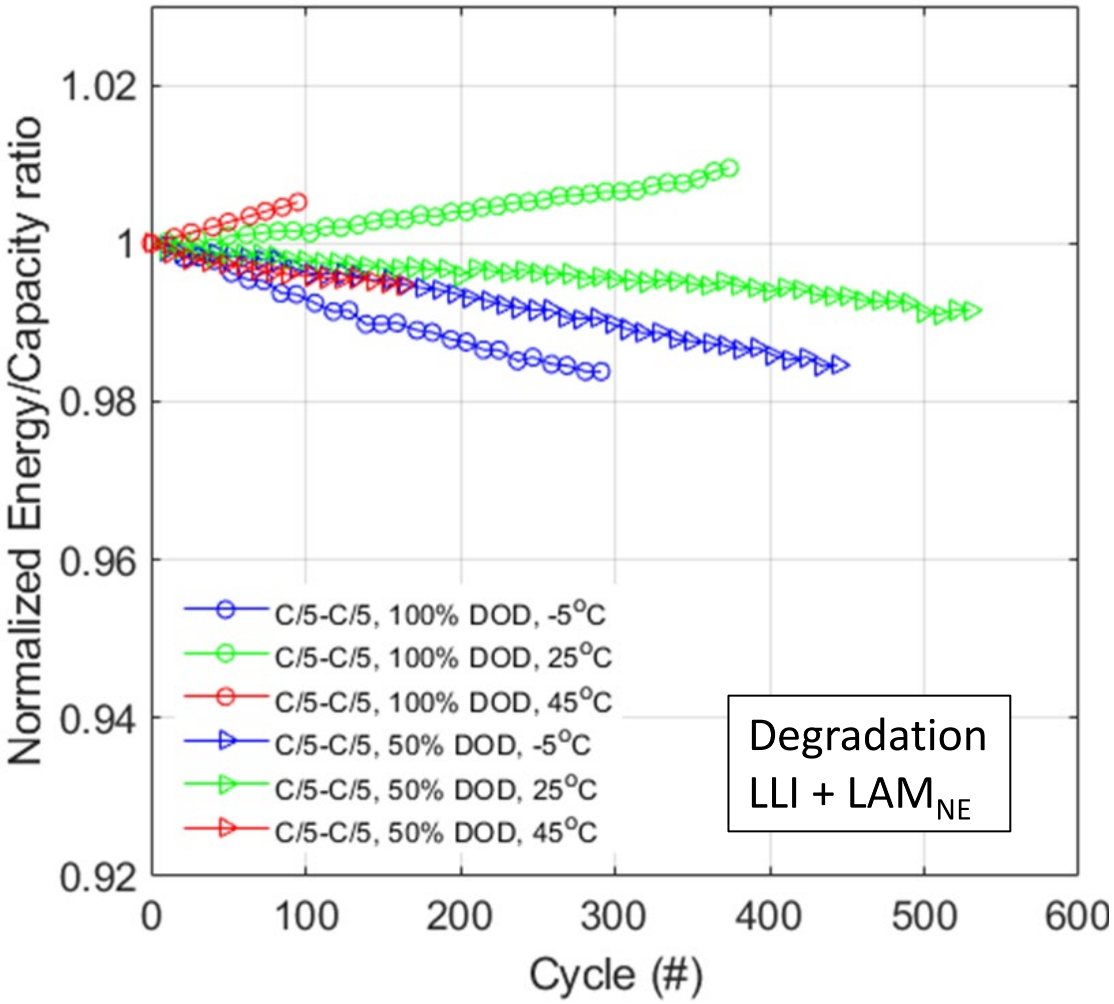

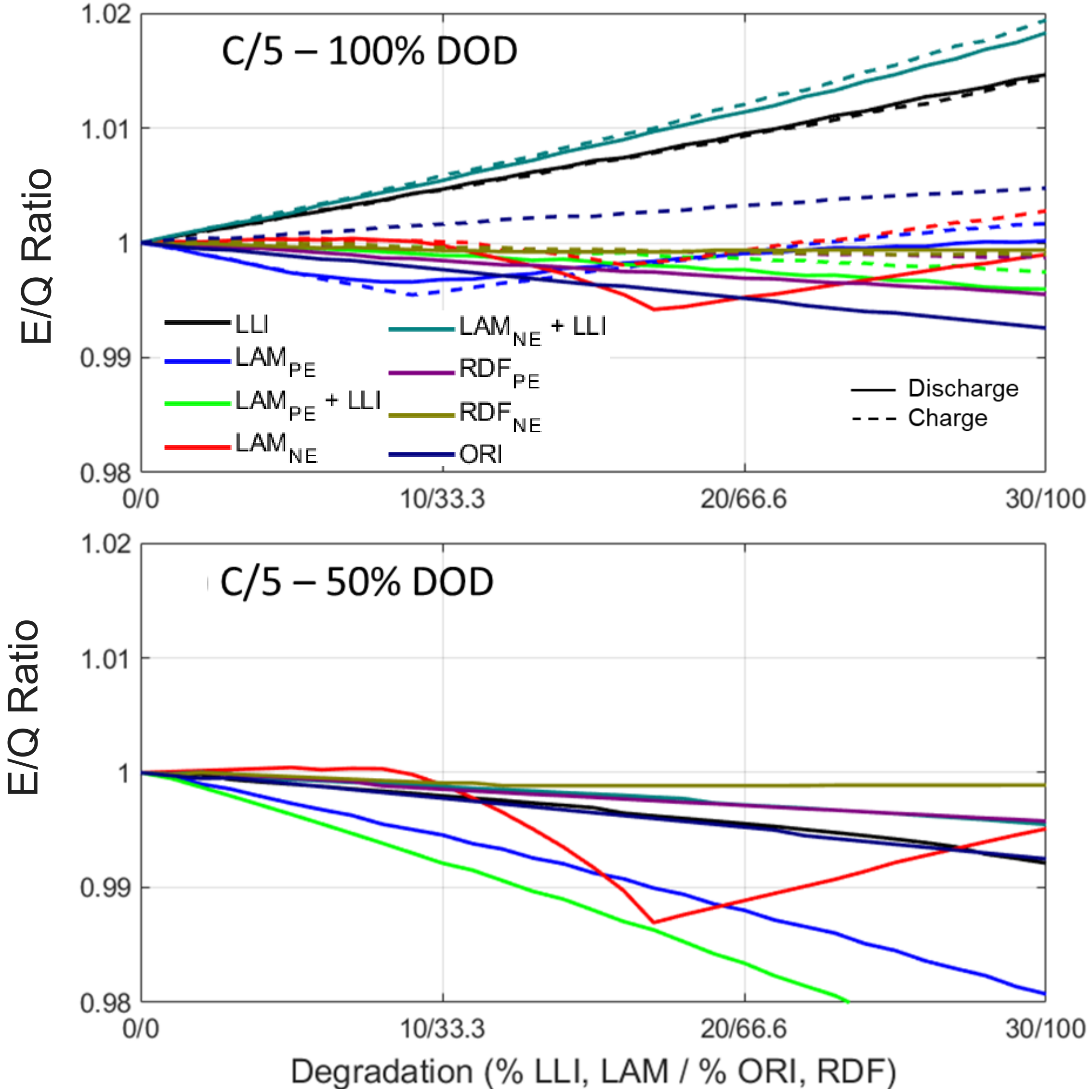

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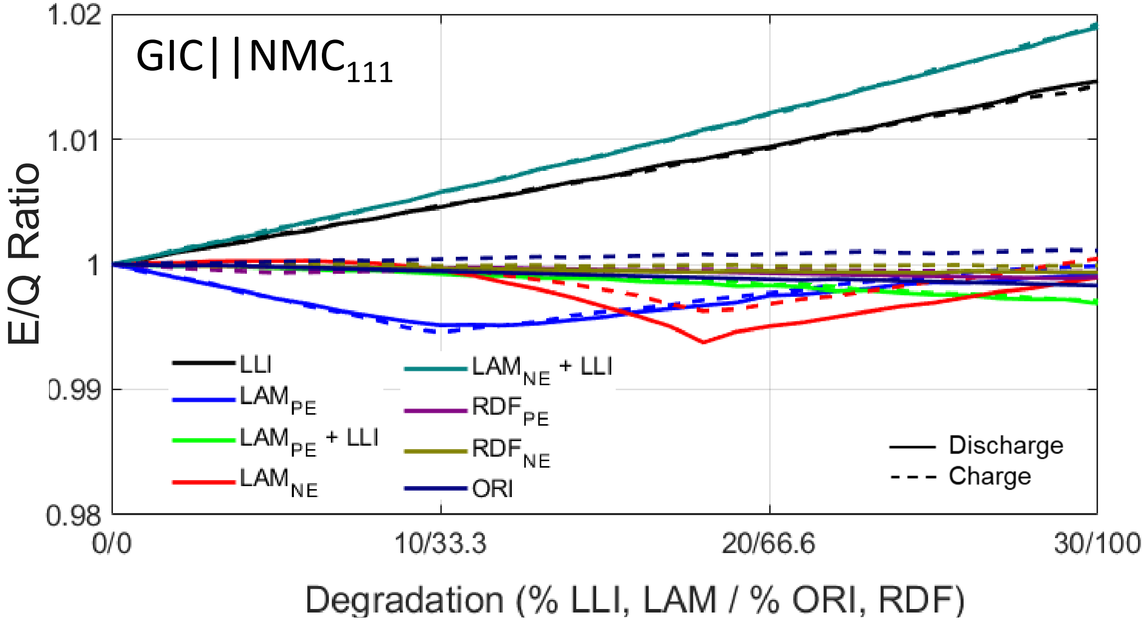
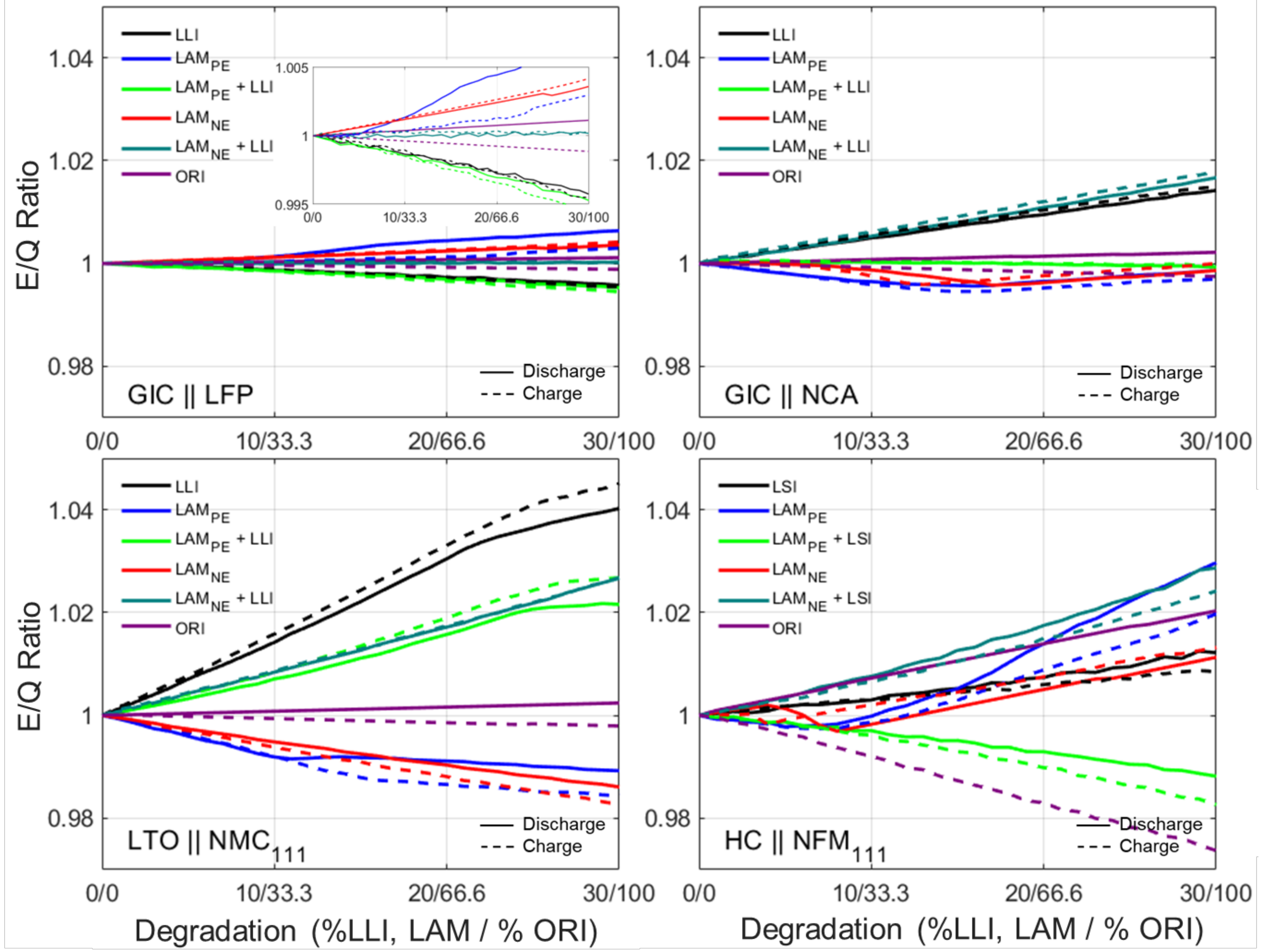
Individual Electrode Performance

Can it be generalized to other chemistries?

Yes for NCA and NMC_{811}

No for LFP,LTO, or Naion based cells





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Conclusions

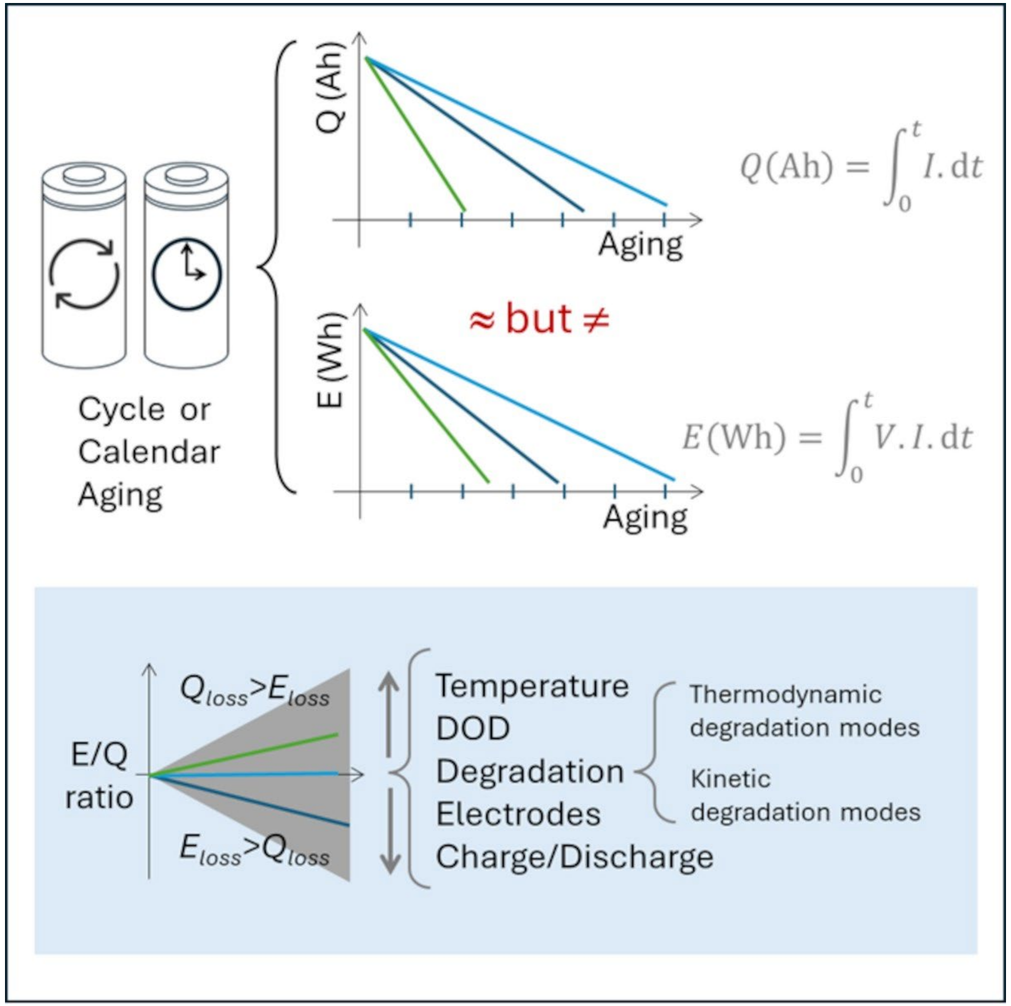
This work defined and validated a mechanistic framework for the evolution of the energy-to-capacity ratio:

- Highly sensitive to the cell degradation path.
- Evolution not straightforward

  Net result of multiple competing factors.
- Impact of each degradation mode is also chemistry dependent.

  LLI increased along ratio layered oxides but decreased for LFP

  RUL underestimation for layered oxides, overestimation for LFP
- Predominantly dominated by kinetics at higher rates
- Strongly DOD dependent.



Tracking the E/Q ratio alongside capacity measurements appears crucial for more accurate monitoring and management across the battery lifecycle.

In addition, it might also better reflect the cell power fade than the resistance variations because it encompasses both thermodynamic and kinetic components.

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Acknowledgments

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Thank you!

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