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The 12th Pacific Rim Conference on Ceramic and Glass Technology

including GLASS & OPTICAL MATERIALS DIVISION MEETING (GOMD 2017)

May 21 – 26, 2017 | Hilton Waikoloa Village | Waikoloa, Hawaii, USA

PACRIM Symposium 28:
Advanced Materials and Technologies for Electrochemical Energy Storage Systems

Characterization II - 05/23/2017

Non-intrusive operando battery diagnosis and prognosis

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Motivations

Battery systems will be essential for the Hawaii Clean Energy Initiative

Hawai'i Powered
Hawai'i Clean Energy Initiative

The Hawaii Clean Energy Initiative is leading the way in relieving our dependence on oil by setting goals to achieve 100% clean energy by 2045.

Need to increase penetration of renewables
BUT Intermittency:

- Need to store the excess renewable energy
- Need to stabilize the grid

Batteries are most likely candidates:

- Fast response
- Efficiency > 95%,
- Plug and play installation
- Can be distributed at strategic locations

Reduce further oil consumption
Reduce emissions
Additional storage for the grid

Motivations

Expectations for battery systems

Long discharging time

Long life

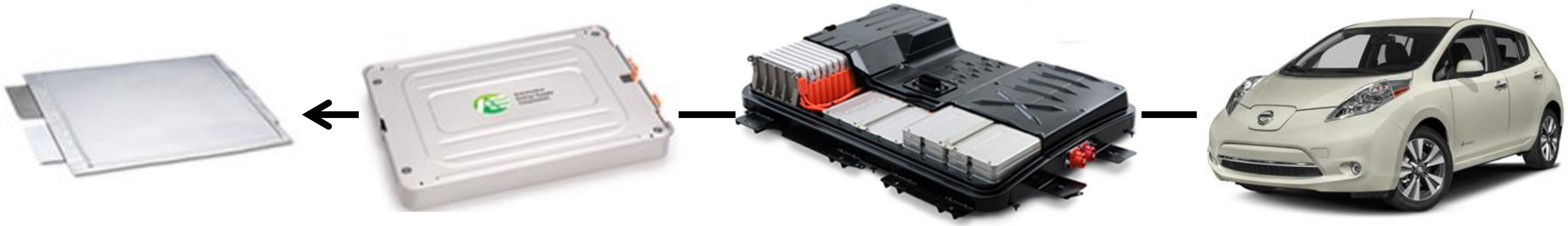
Safe operation

How to achieve that?

Need to understand batteries and battery packs better

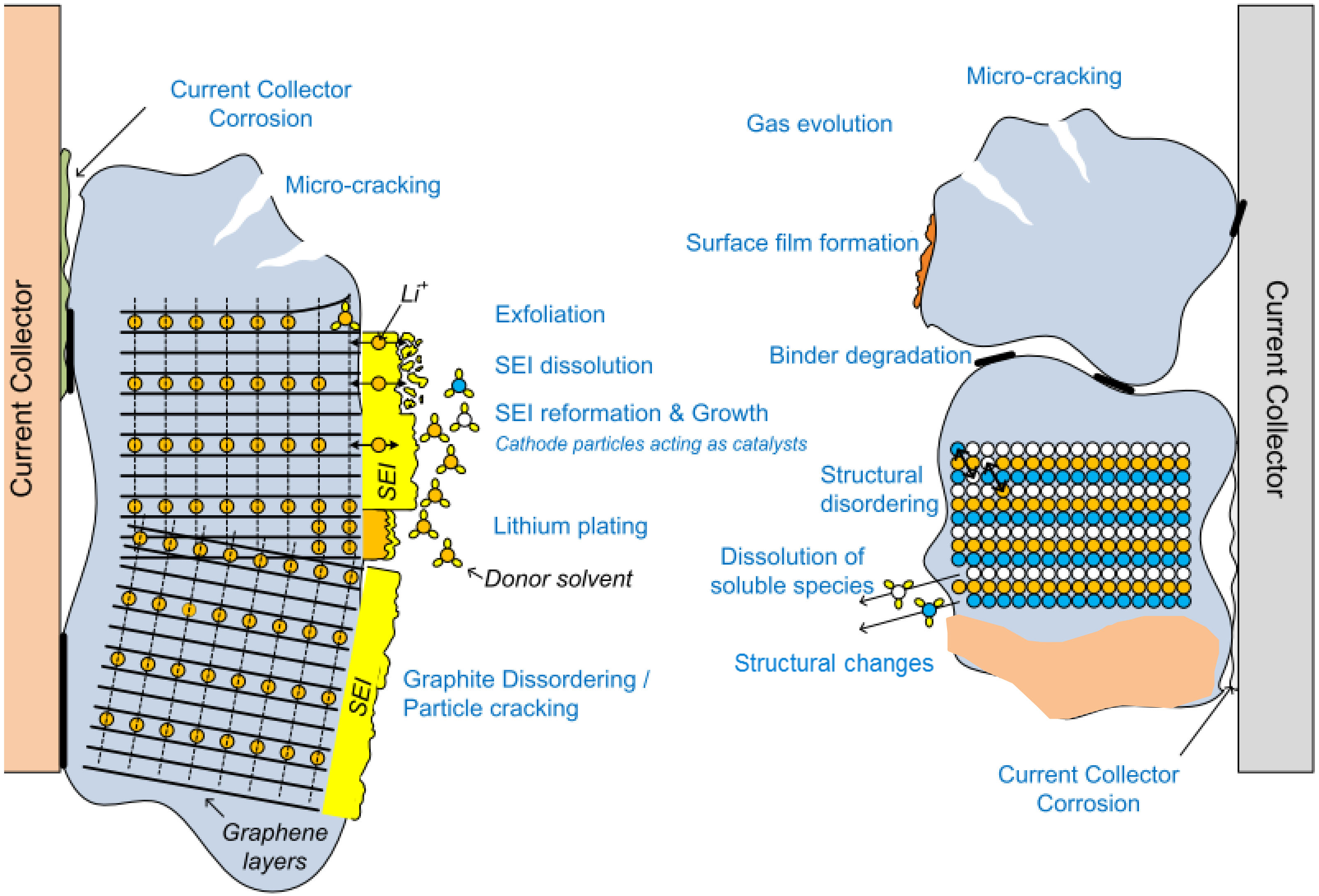
Main problem: how to efficiently diagnose batteries?

- Which one to choose?
- How do they degrade?
- Why?
- Can we prevent it?
- …



Single cell Module Pack

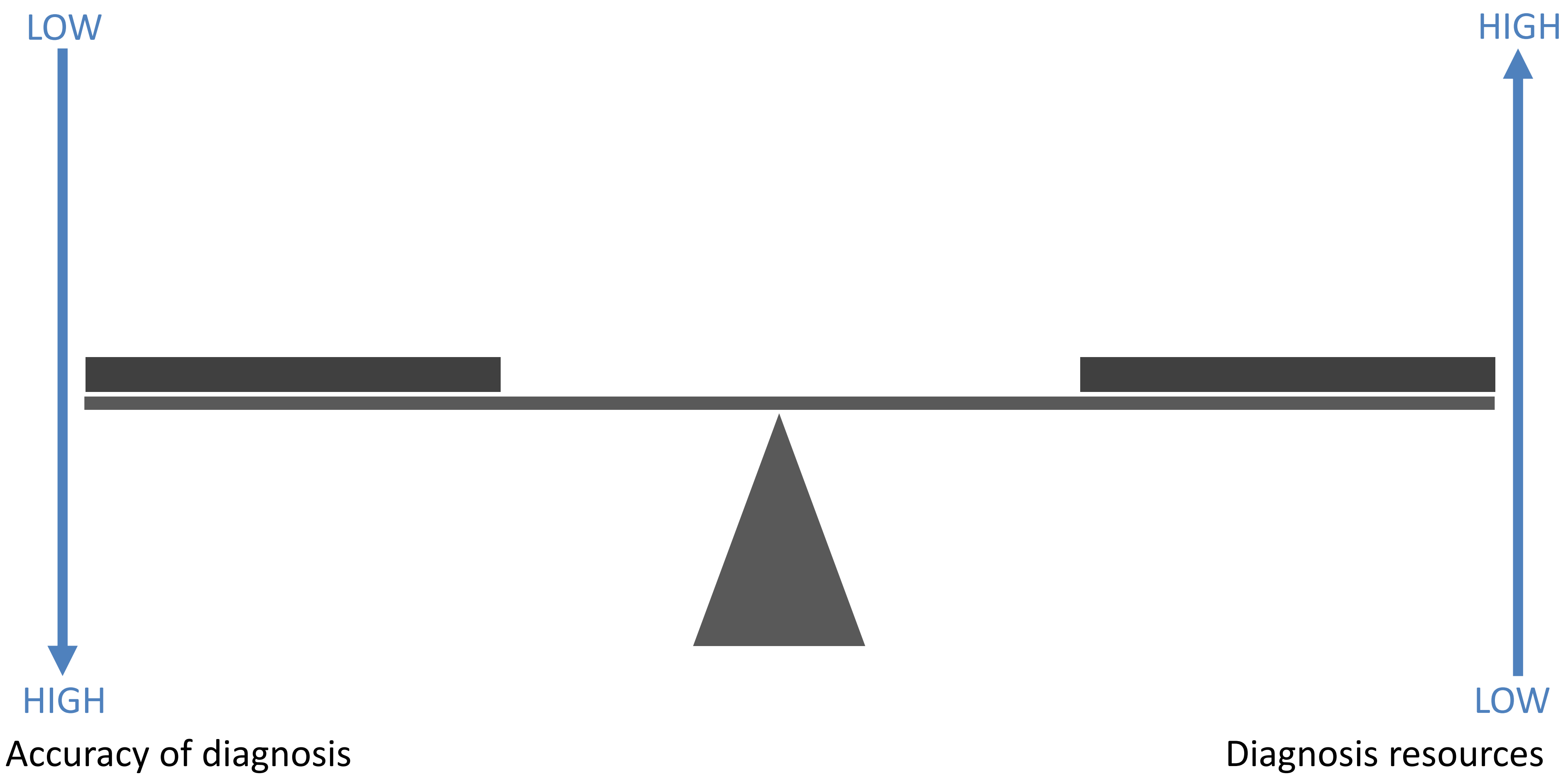
Non-exhaustive Lithium ion battery degradation mechanisms



J. Groot, State of Health Estimation of Li-ion batteries cycle life test methods

The complexity of battery diagnosis

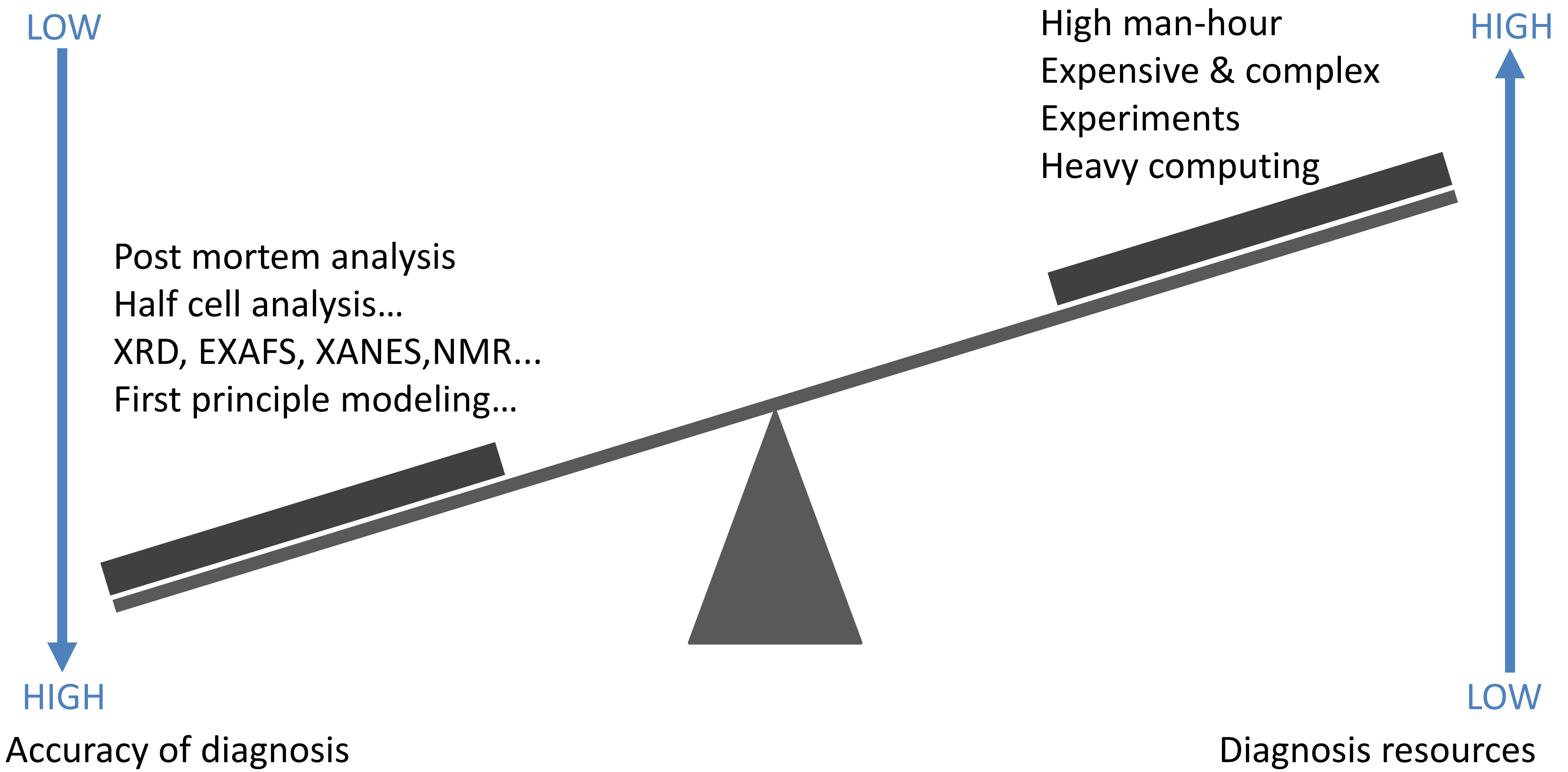
Complex balance



The complexity of battery diagnosis

Complex balance

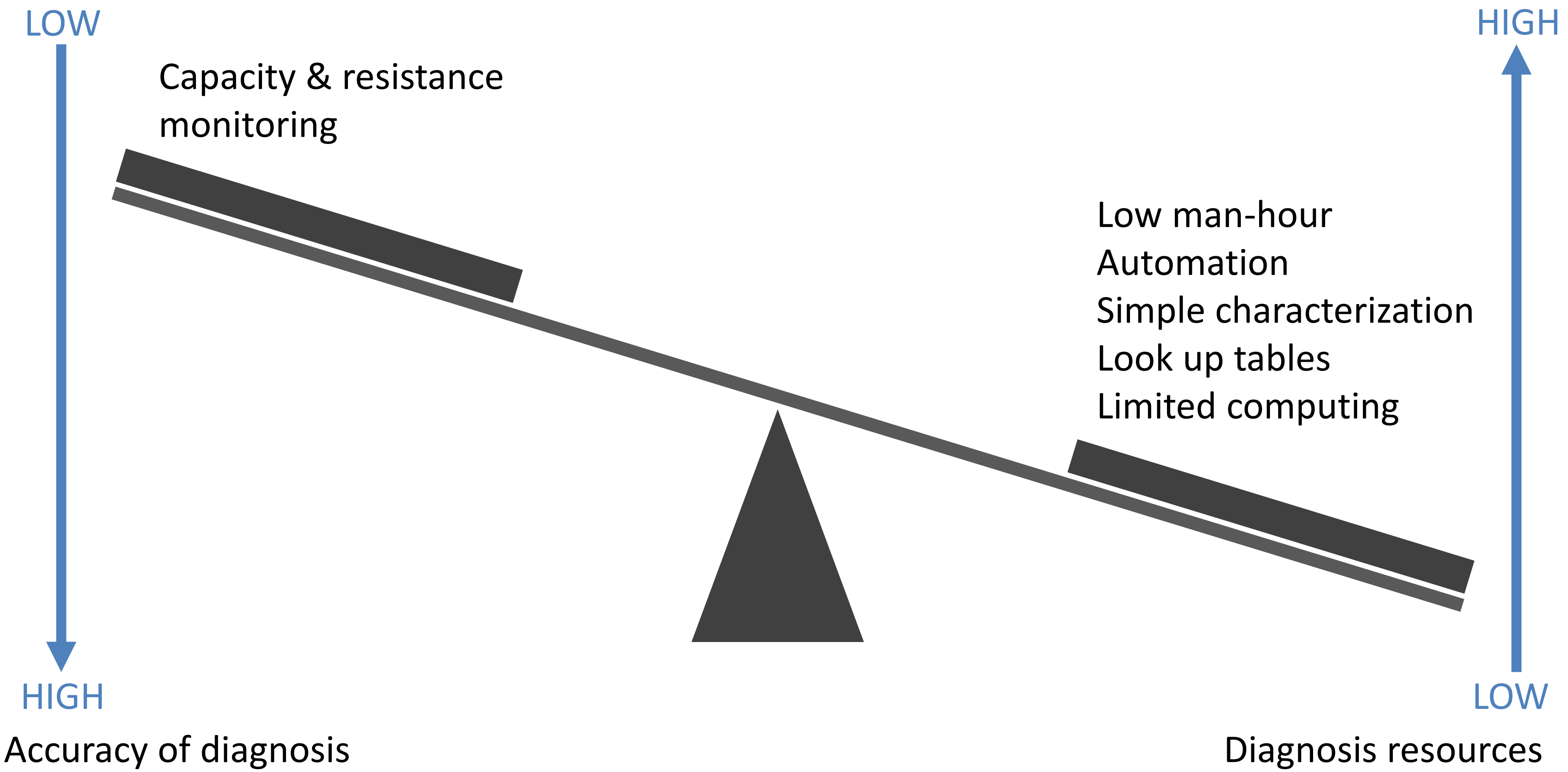
Academia, Research & Development



The complexity of battery diagnosis

Complex balance

Industry, Testing, Evaluation & Deployment



The complexity of battery diagnosis

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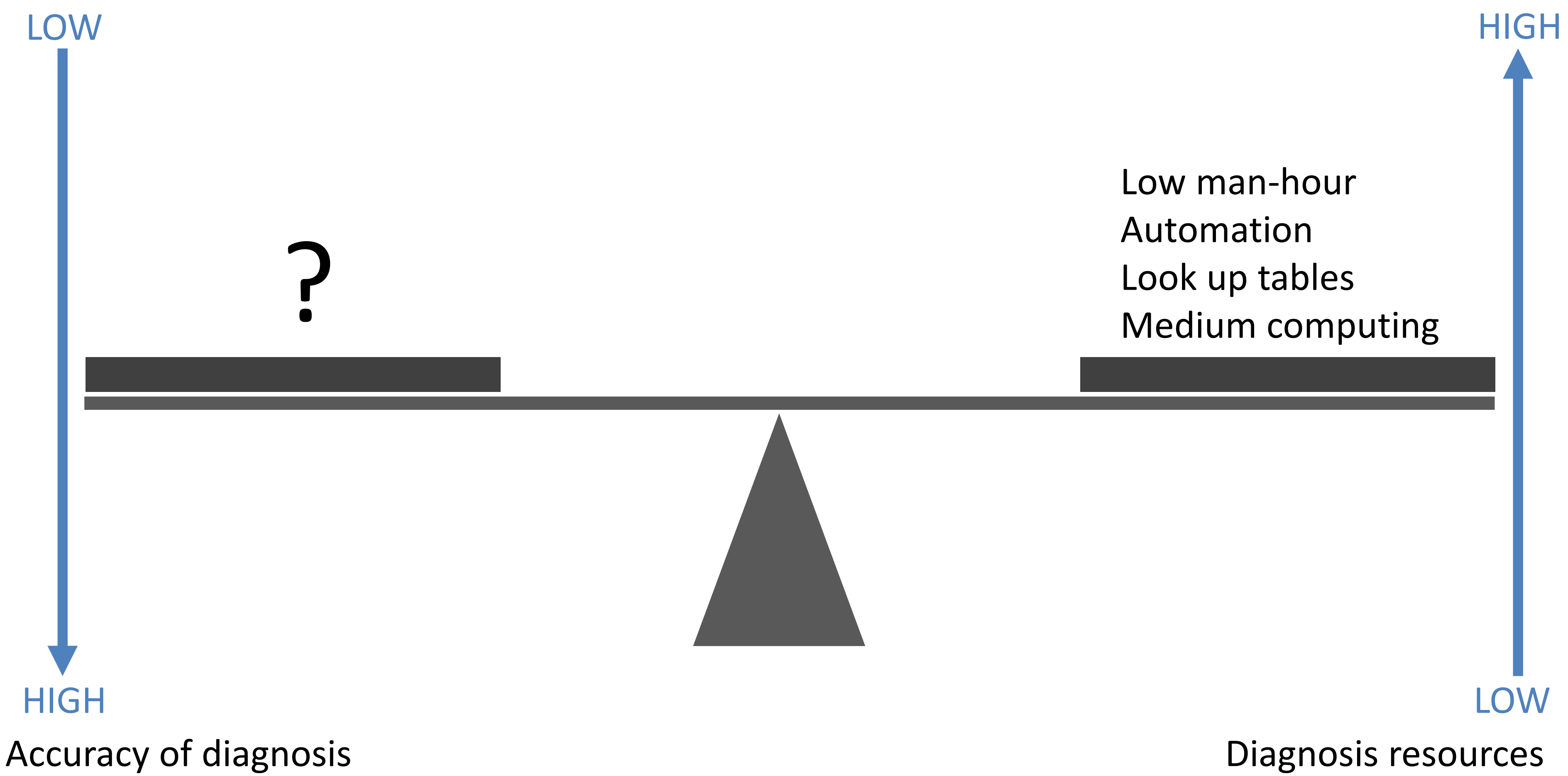
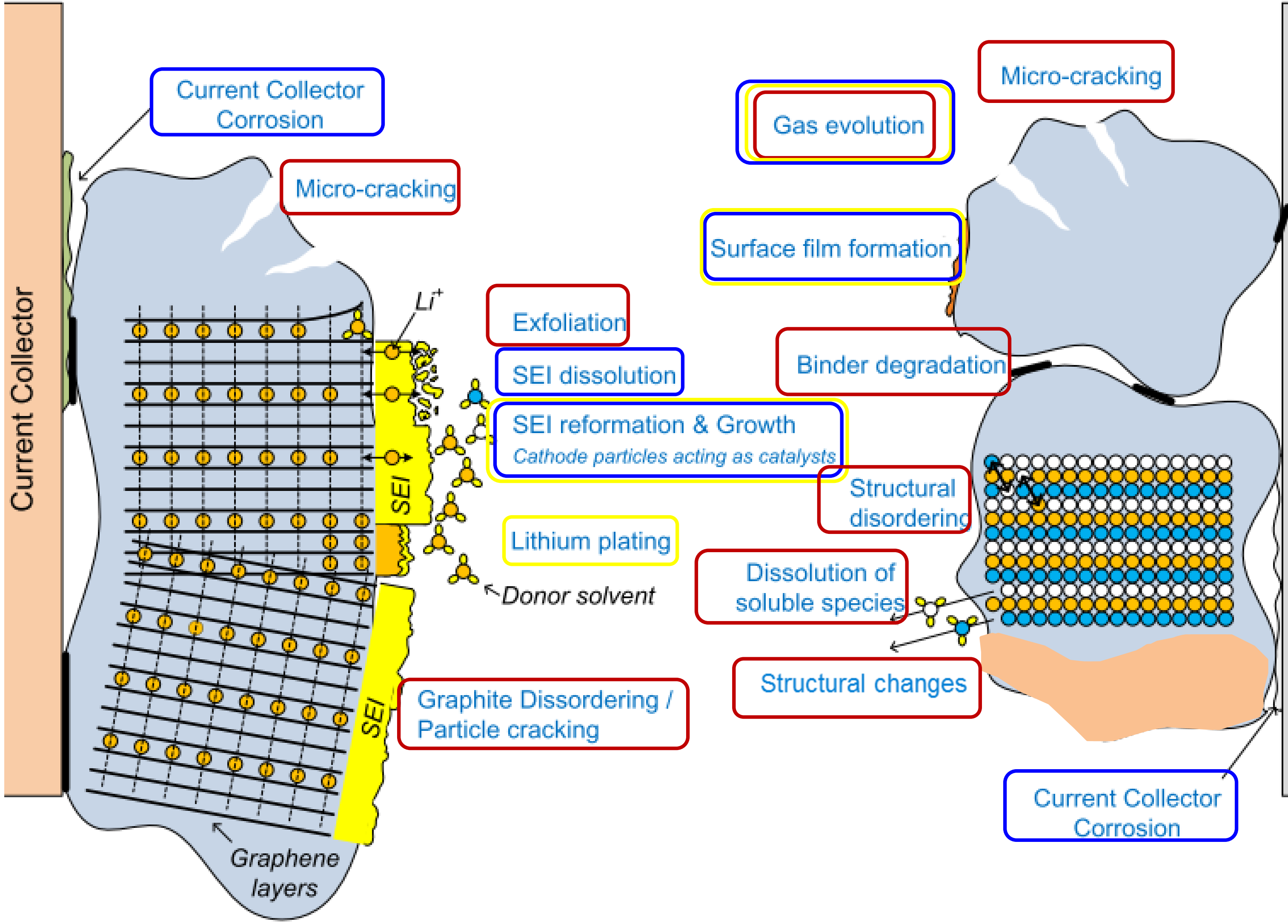


The complexity of battery diagnosis

Complex balance

Lithium ion battery degradation mechanisms



Useful categorization for diagnostics

Thermodynamics

- Change in active material
- Change in lithium inventory

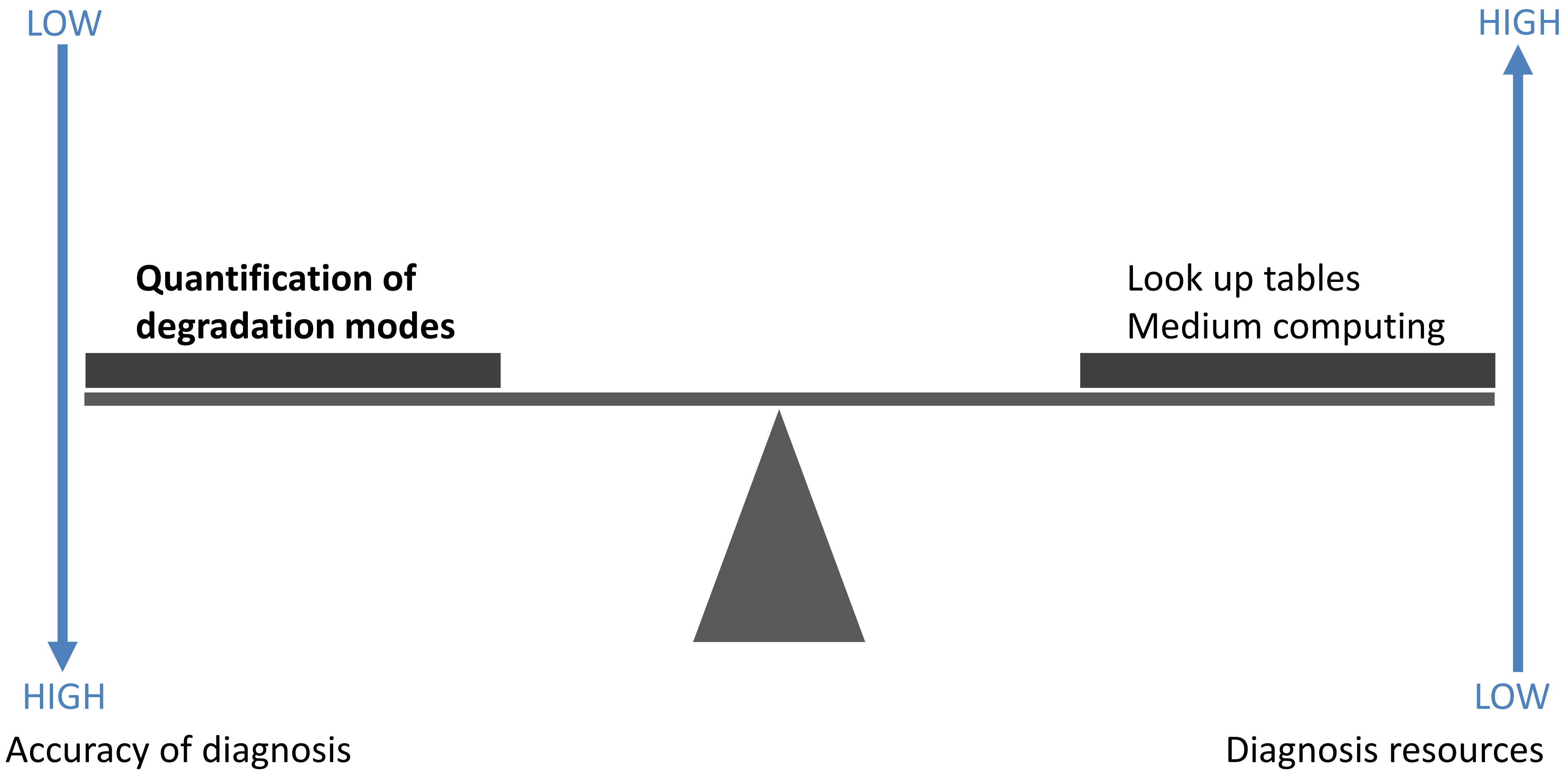
Kinetics

- Change in ohmic and faradic resistances

J. Groot, State of Health Estimation of Li-ion batteries cycle life test methods

The complexity of battery diagnosis

Complex balance

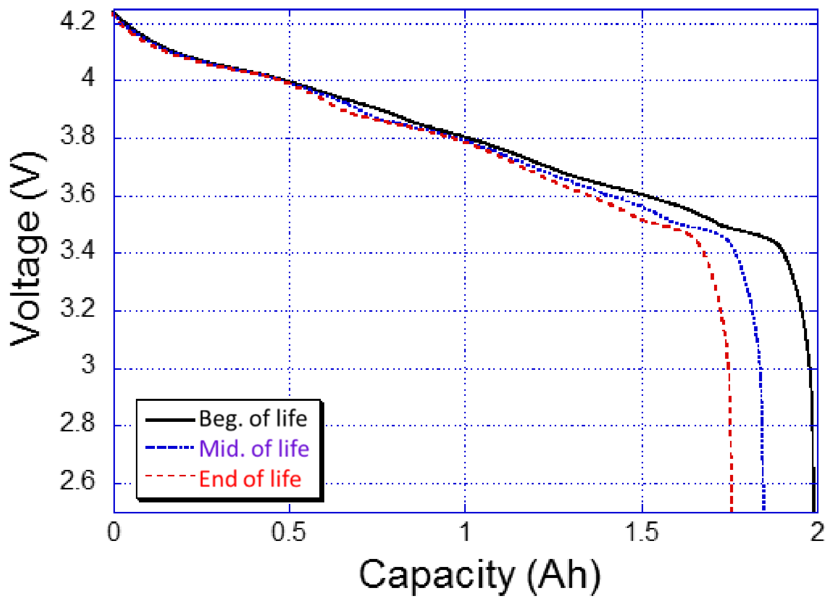


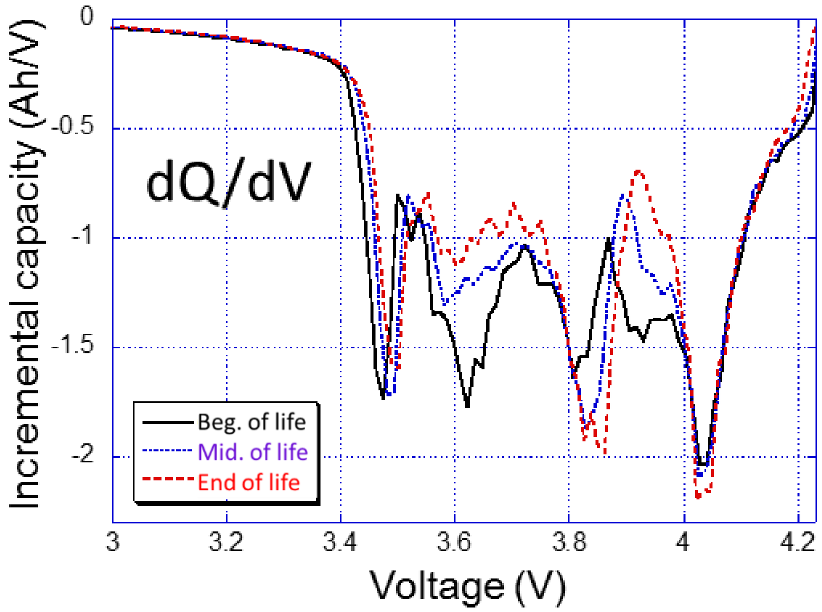
The complexity of battery diagnosis
Quantifying degradation modes

Adapt to industry requirements:

Use of available sensors: voltage, current and temperature.

Voltage carries thermodynamic information





Study evolution of voltage response

How can we extract degradation information?

How can we put it in equation for a model?

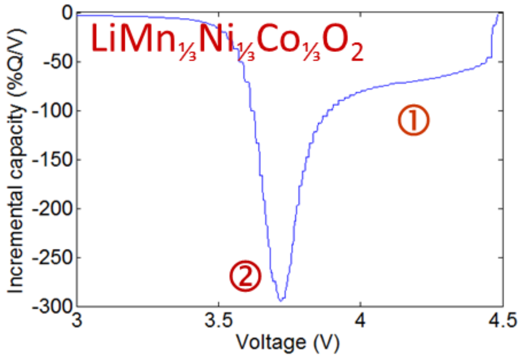
Derivatives methods will magnify the changes in the evolution of the voltage curves

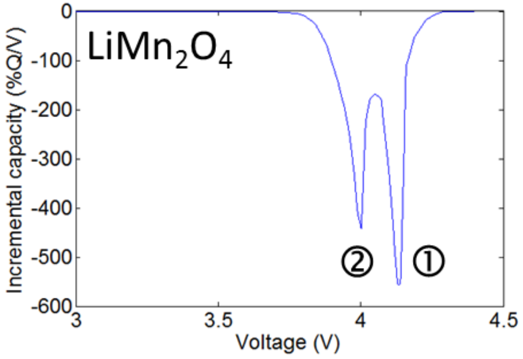
The complexity of battery diagnosis

Quantifying degradation modes

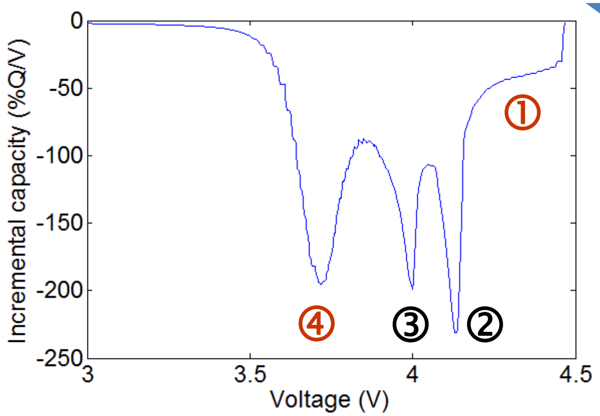
Incremental capacity analysis

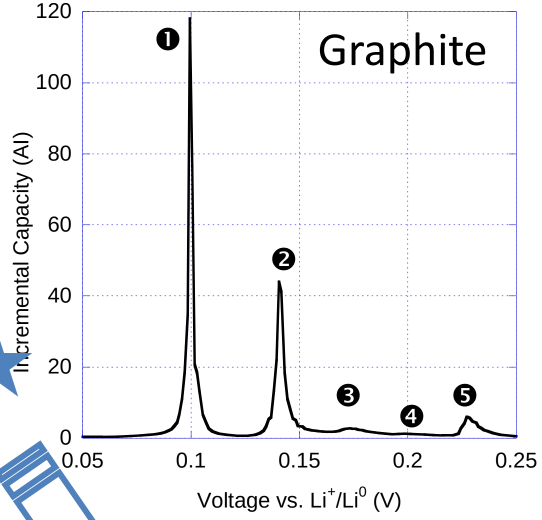
- Used in 1 WE configuration
- Much more complex in 2 WE configuration

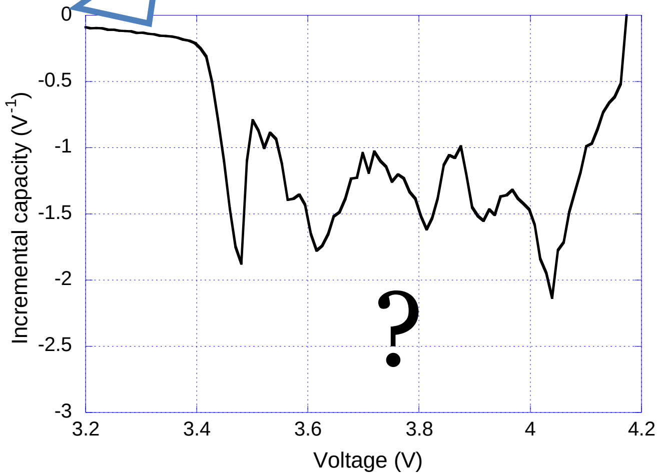




$\{LiMn_{1/3}Ni_{1/3}Co_{1/3}O_2 + LiMn_2O_4\}$







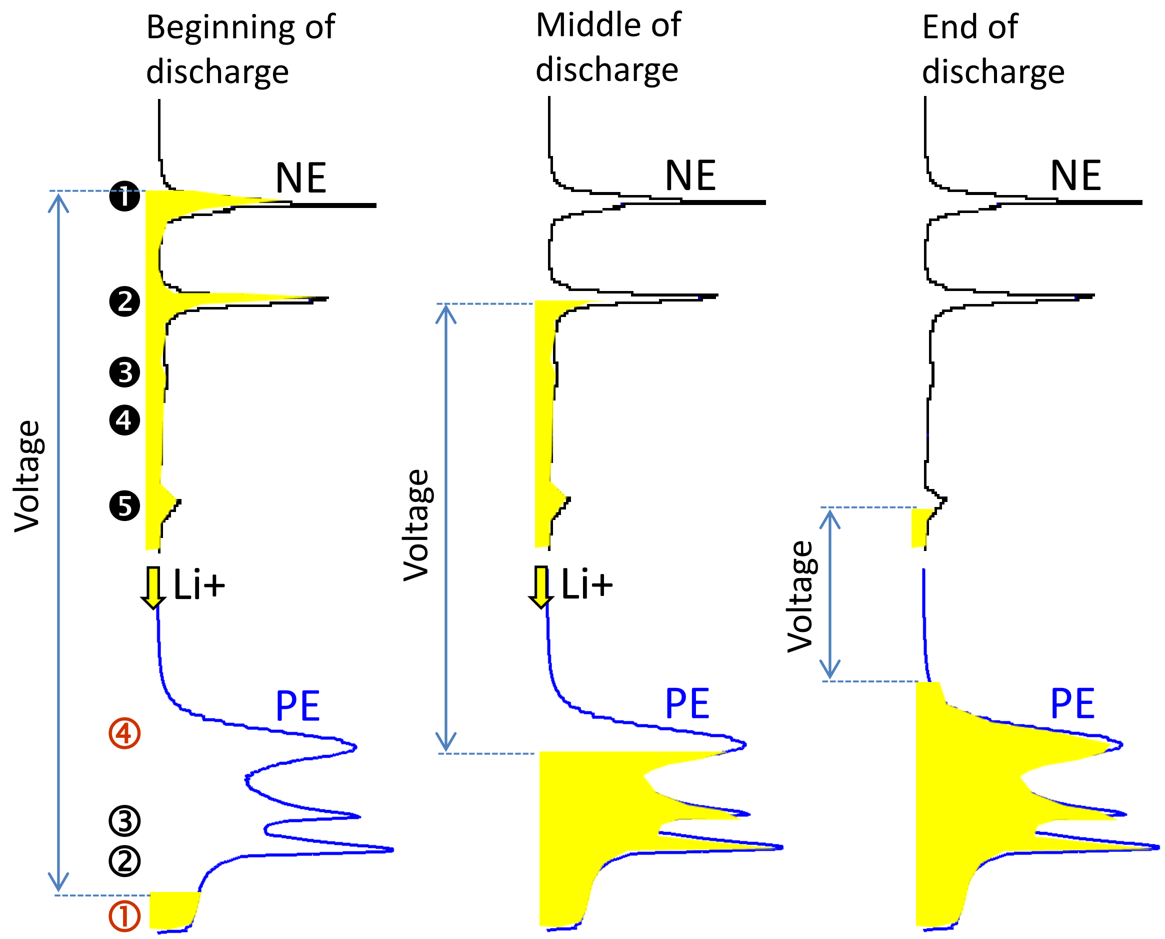
Mathematically extremely complex convolution

Different angle: communicating vessels

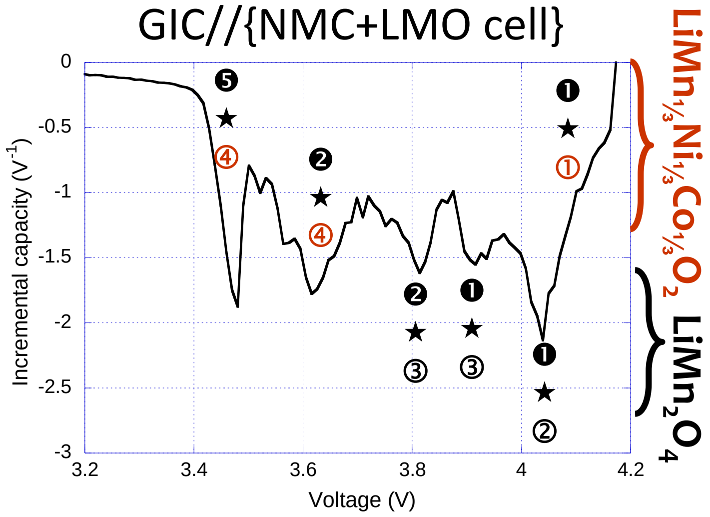
Understanding the IC signature

Peak indexation: The clepsydra analogy

Use individual electrode response



Peak ❶★①   Peak ❷★④   Peak ❺★④



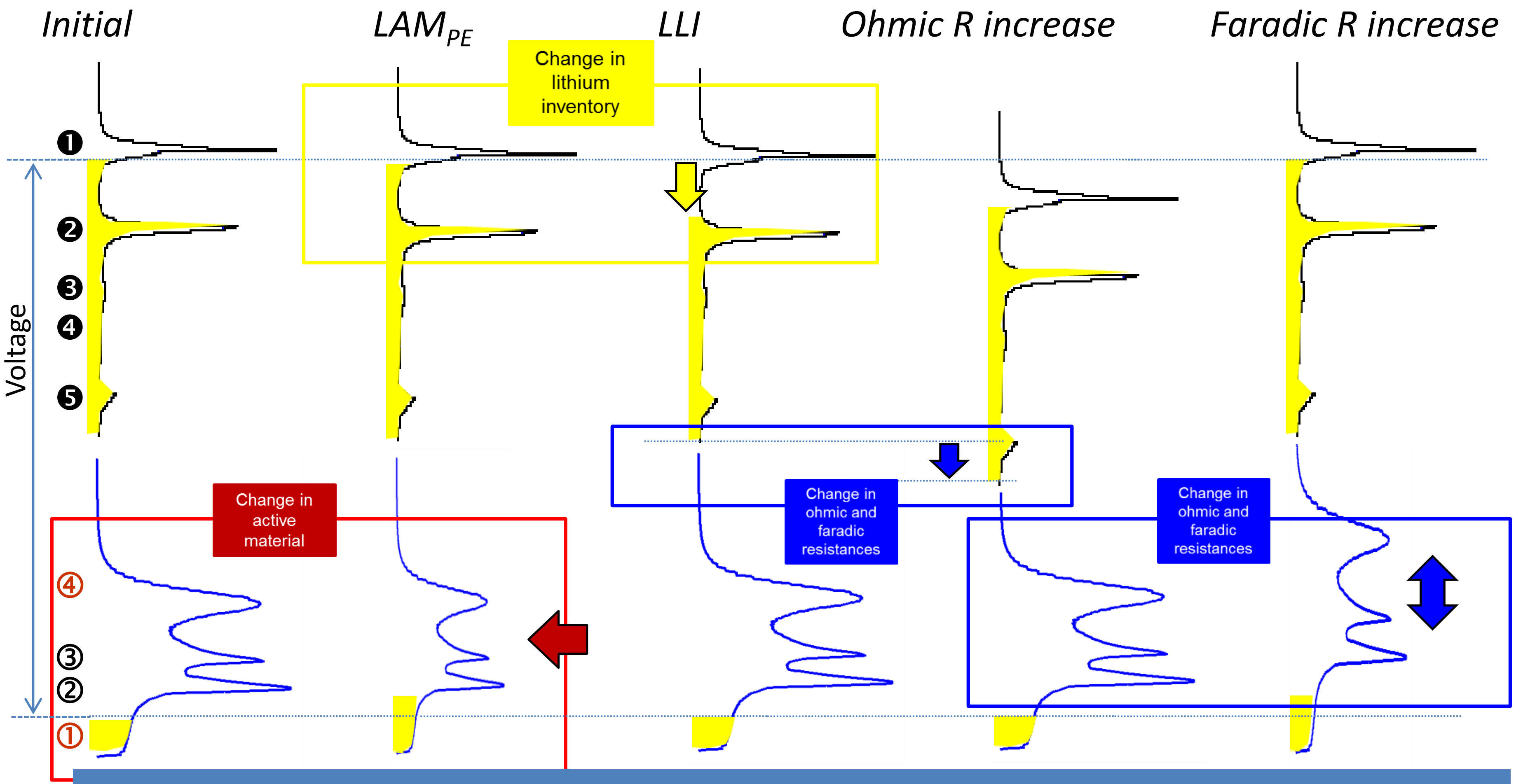
IC curves contains information on every component of the cell

The clepsydra analogy enables the indexing of IC curves

M. Dubarry *et al.*, *J. Power Sources*, **196** (2011) 10328.
M. Dubarry, A. Devie and B.Y. Liaw, *JEPS*, **1(5)** (2014), 242.
Water clock concept: M. Dubarry *et al.* *ECS222/PRIME2012* (2012) abs# 885

Understanding **changes** in the IC signature

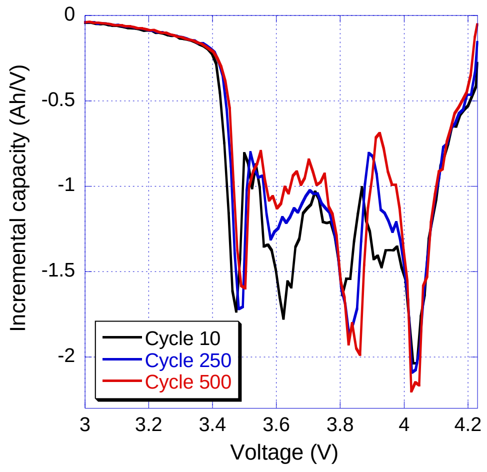
Clepsydra analogy: Visualize effect of categories of degradation

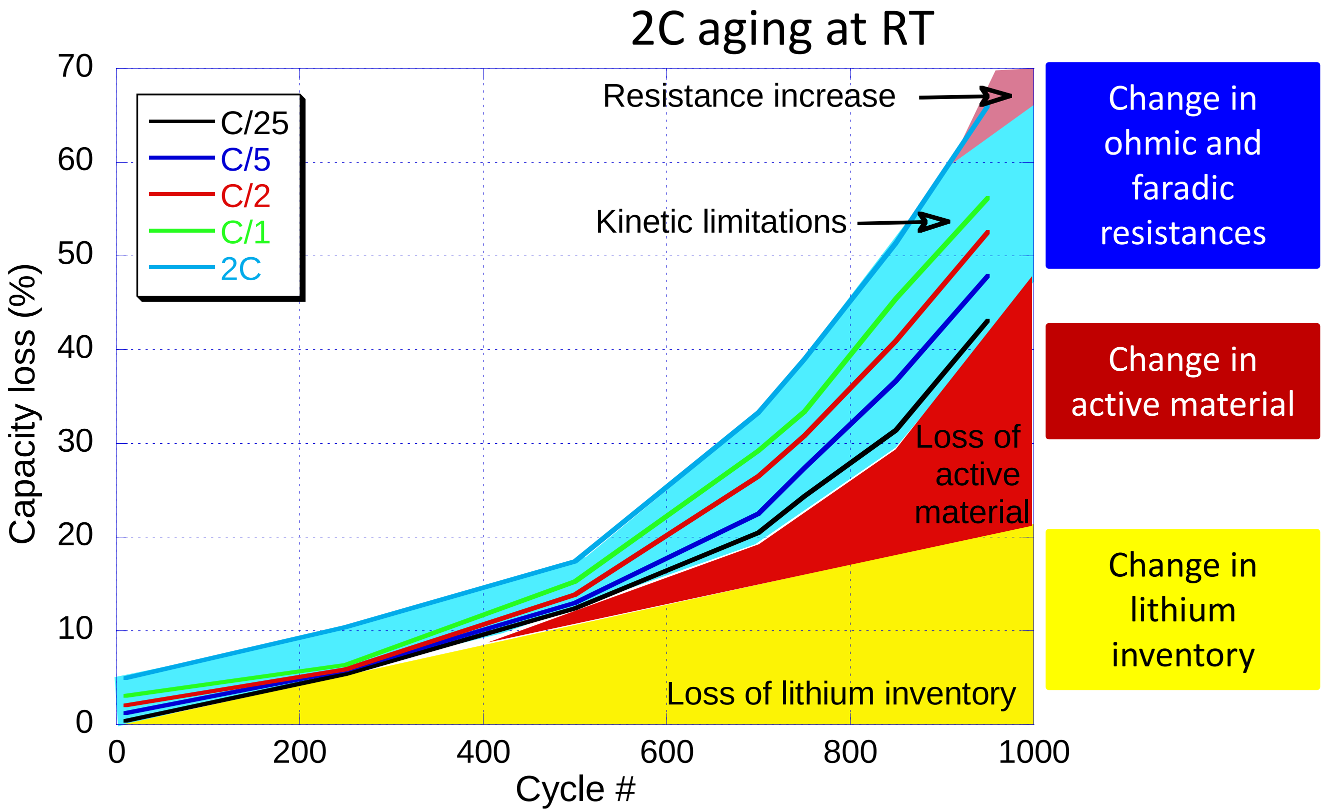


Different degradation categories will have different voltage signatures
Diagnostic possible w/o post-mortem analyses
No need to be an electrochemist

A complex balance

Experimentally: possible by coupling IC & relaxation voltage analysis

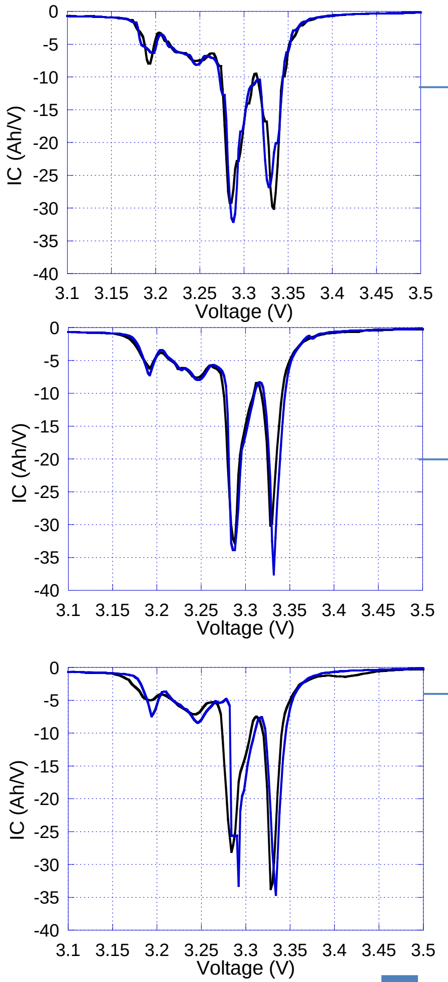


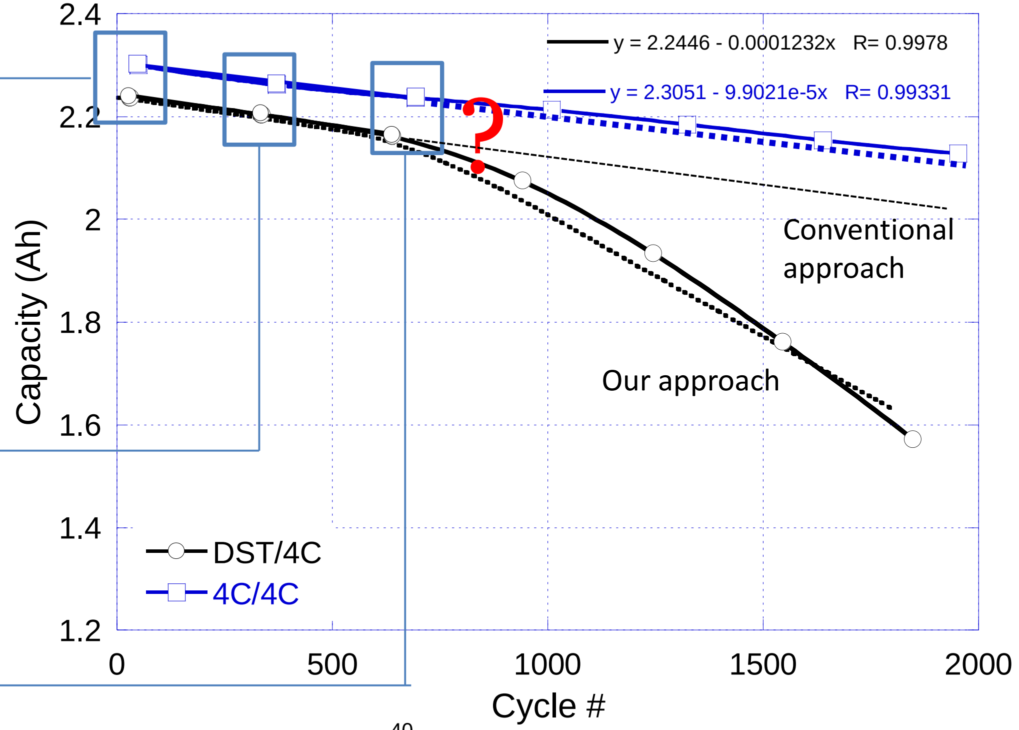


M. Dubarry et al. *J. Power Sources*, **196** (2011), 10336
M. Dubarry et al. *J. Power Sources*, **196(7)** (2011), 3420
M. Dubarry et al. *J. Power Sources*, **194** (2009), 551

Battery Diagnosis

Diagnosis to Prognosis

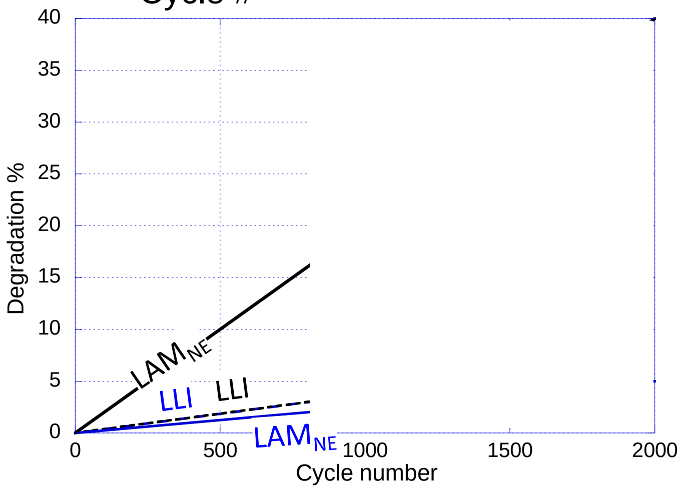




'alawa

We then use that knowledge to predict what will happen to the cell

To understand the degradation from a material stand point



We study voltage variations

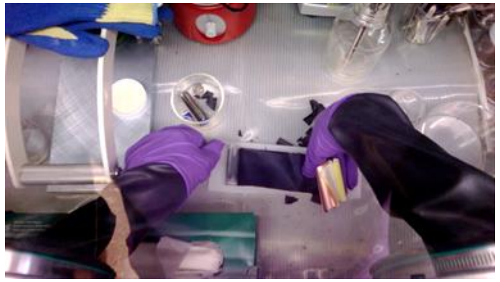
LAM_{NE}: loss of negative electrode material
LLI: Loss of lithium inventory

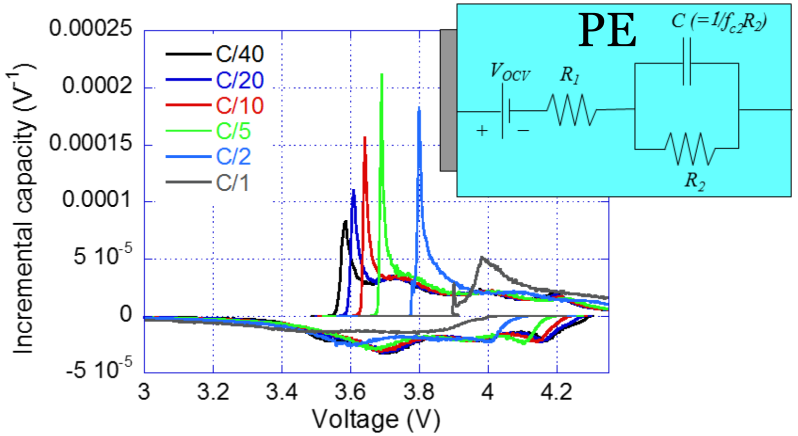
D. Ansean et al., *Journal of Power Sources*, **356** (2017), 36.

alawa - Mechanistic diagnosis and prognosis

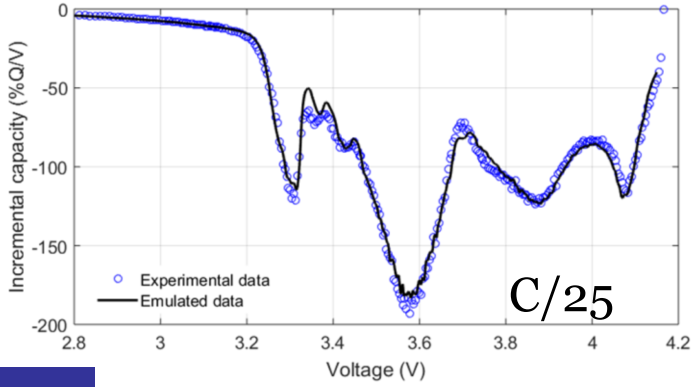
The clepsydra in equations: ‘alawa approach

Half cell data obtained from commercial electrode sheets





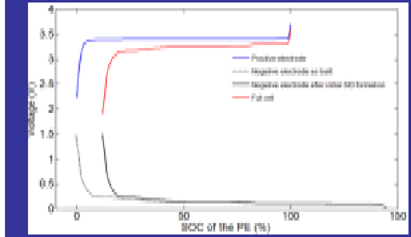
$V_{PE}\ (SOC_{PE})$



Input from degradation mechanisms

Change in active material	Change in lithium inventory	Changes in ohmic and faradic resistance

Full cell module

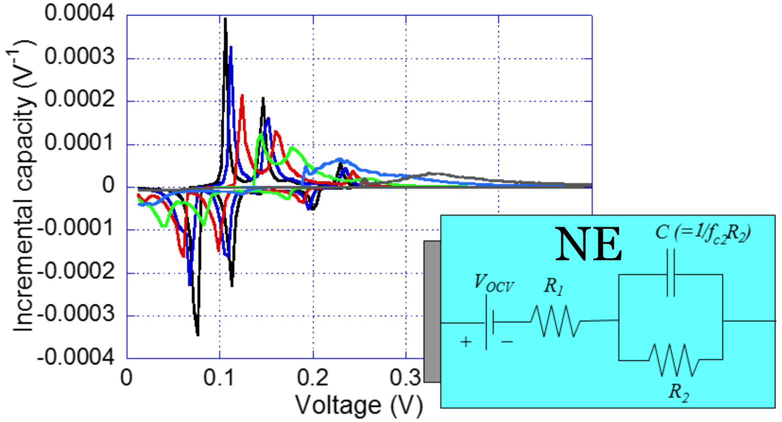


$$V_{FC} = V_{PE} - V_{NE}$$

$$V_{FC_{deg}} = V_{PE_{deg}} - V_{NE_{deg}}$$

‘alawa

Emulate every possible degradation mode and study effect on full cell (capacity and voltage)

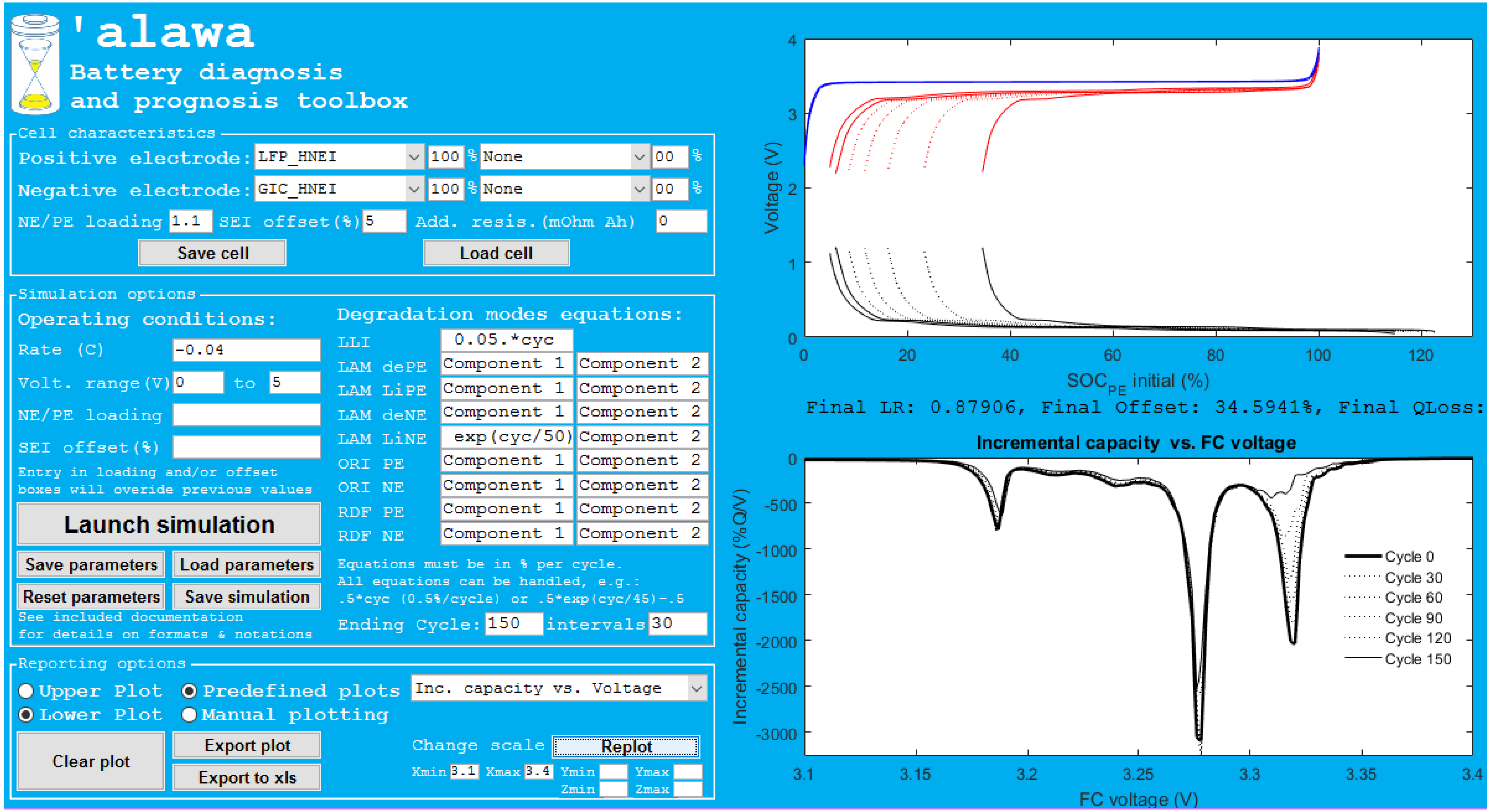


$V_{NE}\ (SOC_{NE})$

M. Dubarry et al., *J. Power Sources*, **219** (2012), 204.

Mechanistic diagnosis and prognosis
Graphical user interface: the ‘alawa toolbox

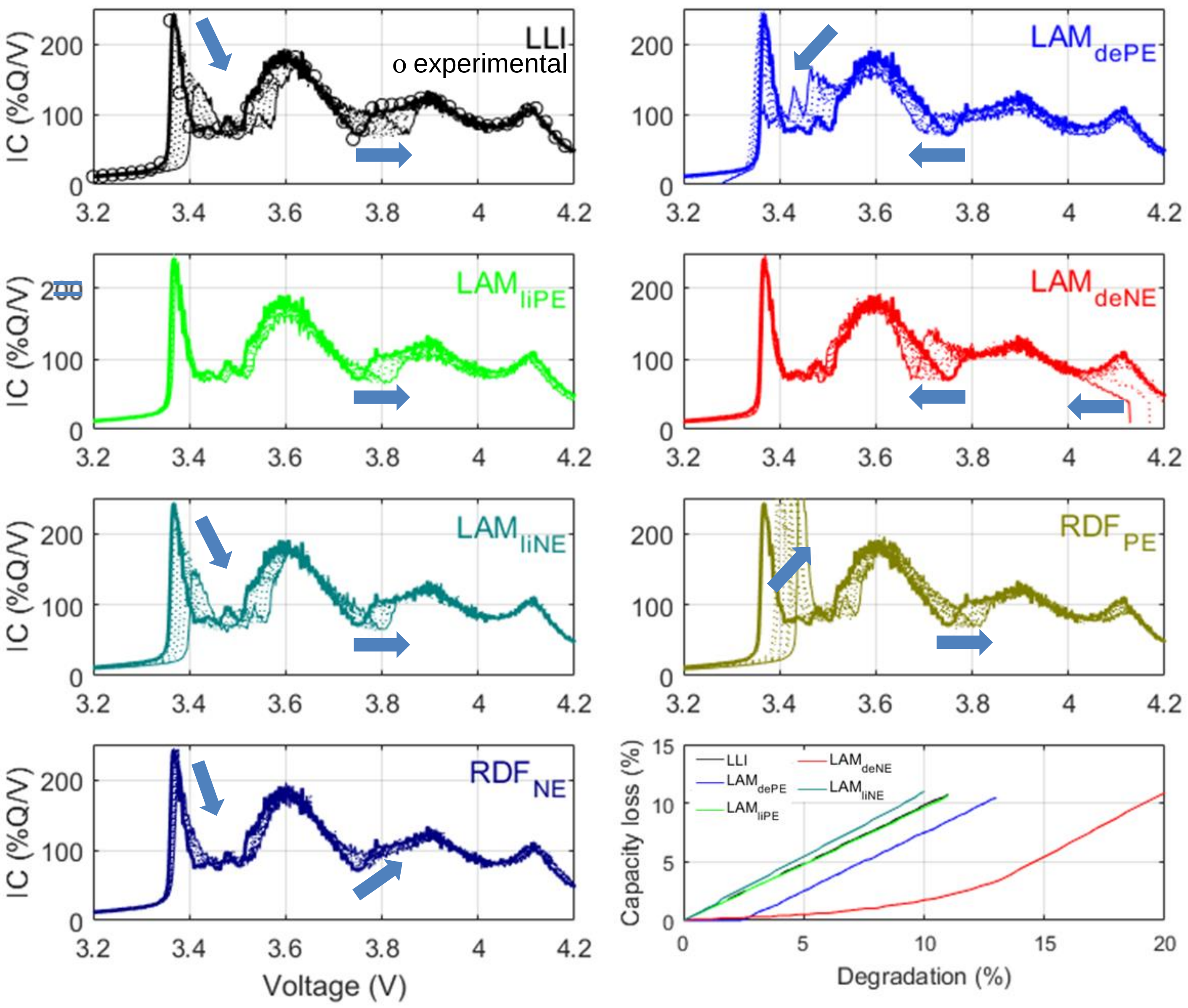
Simple, fast, powerful and accurate diagnosis and prognosis tool



Stand alone GUI available for license or collaboration

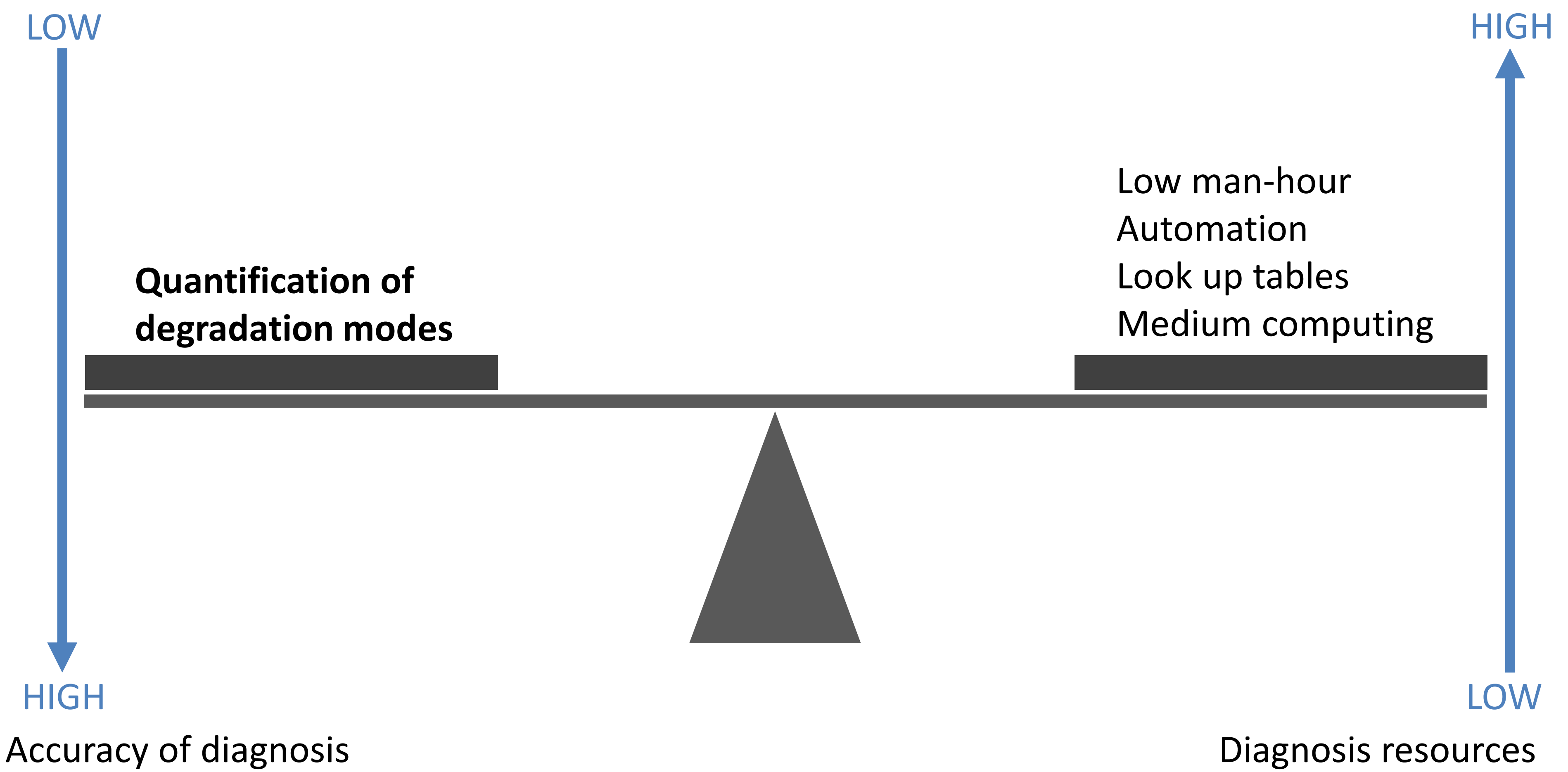
alawa - Mechanistic diagnosis and prognosis

Degradation tables



Automatic operando diagnosis and prognosis

Can we automate the diagnosis and prognosis?



Automatic operando diagnosis and prognosis

BMS implementation

Possibility 1 : Embedding the model

Millions of combinations

6 independent parameters (LLI, LAM_{PE}, LAM_{NE}, Resistance, $Kinetics_{PE}$, $Kinetics_{NE}$)

- ☒ Look up tables
- ☒ Medium computing

Possibility 2: look up table with all possible electrochemical responses

Precalculation of all responses

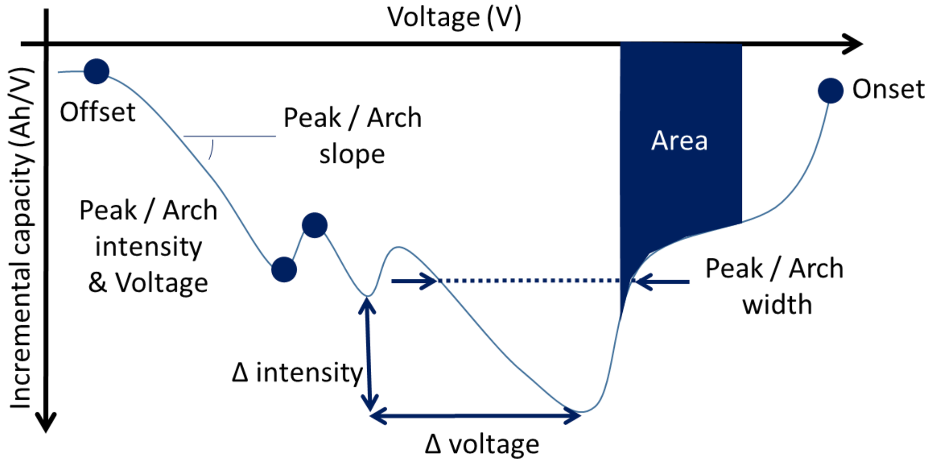
>> 100 Gb of data with 0.1% SOC accuracy

- ☑ Look up tables
- ☒ Medium computing

Possibility 3: Reduce complexity by focusing on special features

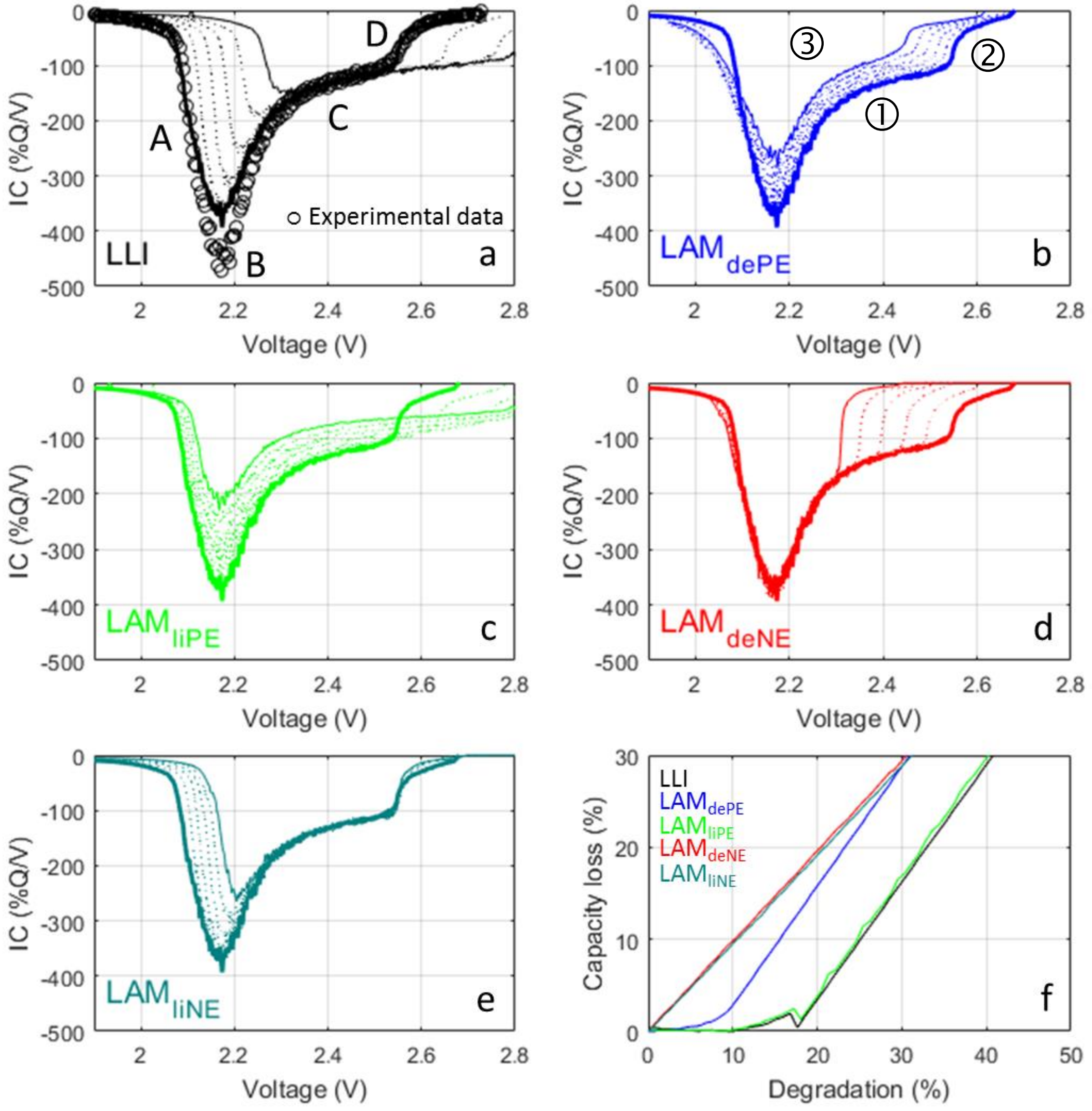
Features of interest approach

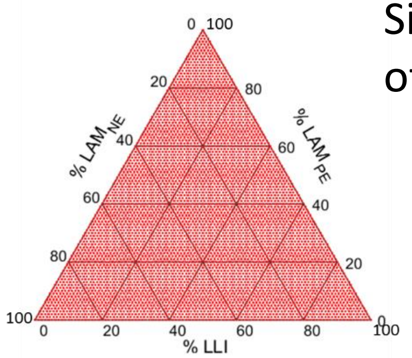
- ☑ Look up tables
- ☑ Medium computing



M. Berecibar *et al.* , *J. Power Sources*, **320** (2016), 239.
M. Dubarry *et al.* , *J. Power Sources*, in press.

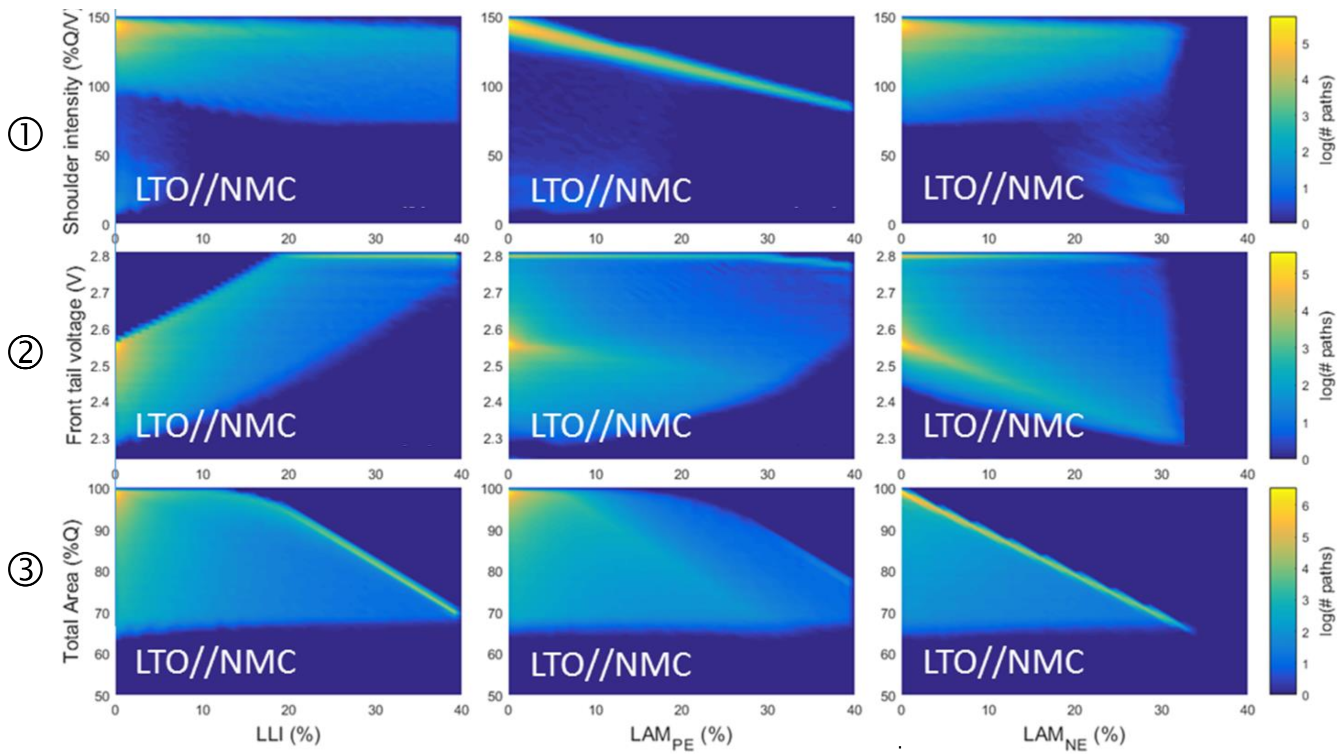
Automatic diagnosis of an overcharged LTO//NMC cell





Simulate impact of all possible combinations of LLI/LAM_{PE}/LAM_{NE} on FOIs

Individually, not good proxy to diagnose capacity loss or degradation modes

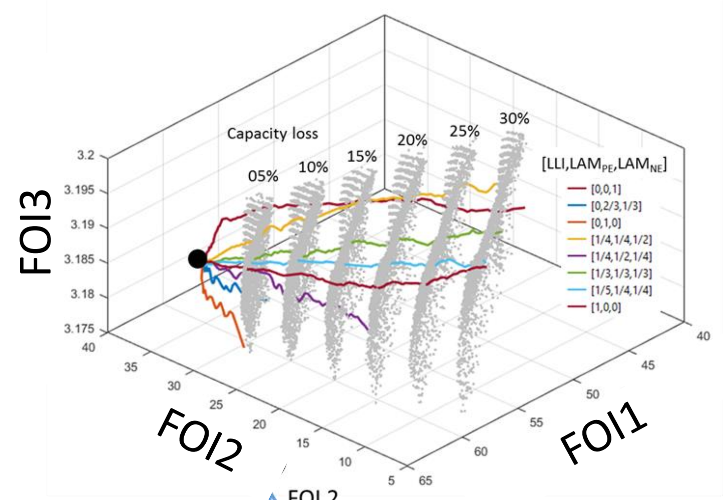


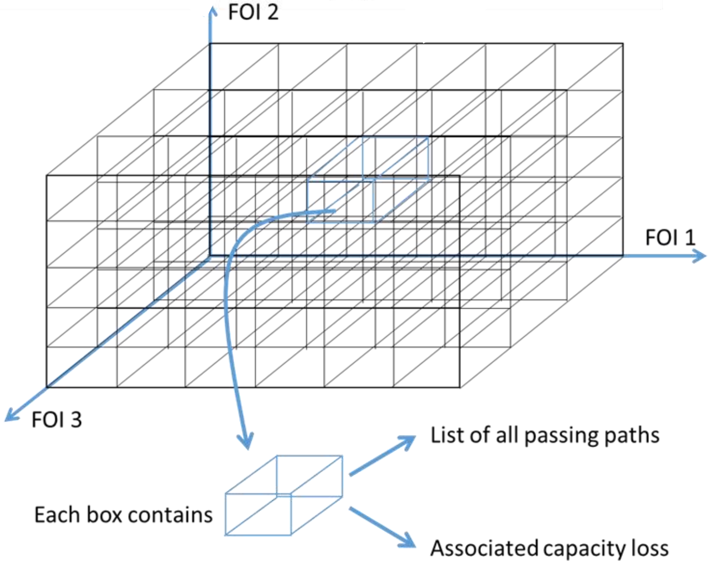
A. Devie *et al.* , *J. Electrochem. Soc.*, **162(6)** (2015), A1033. & **163(13)** (2016), A2611

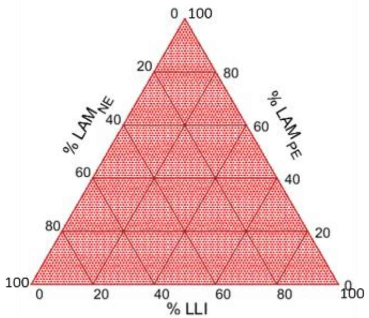
M. Dubarry *et al.* , *J. Power Sources*, in press.

Automatic diagnosis of an overcharged LTO//NMC cell

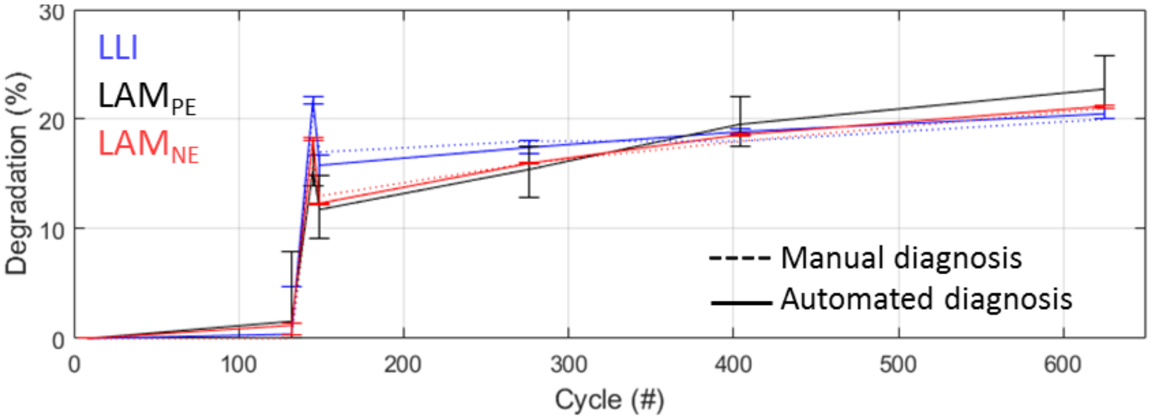
Use of **COMBINED** variations

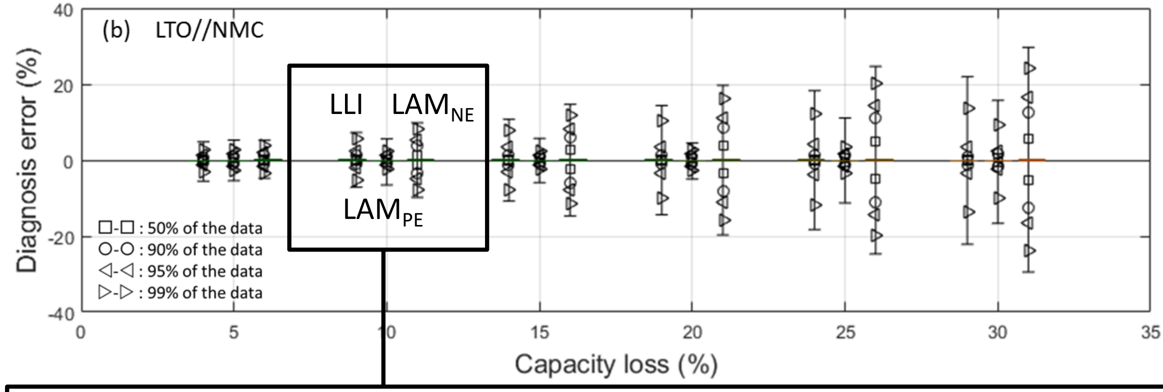


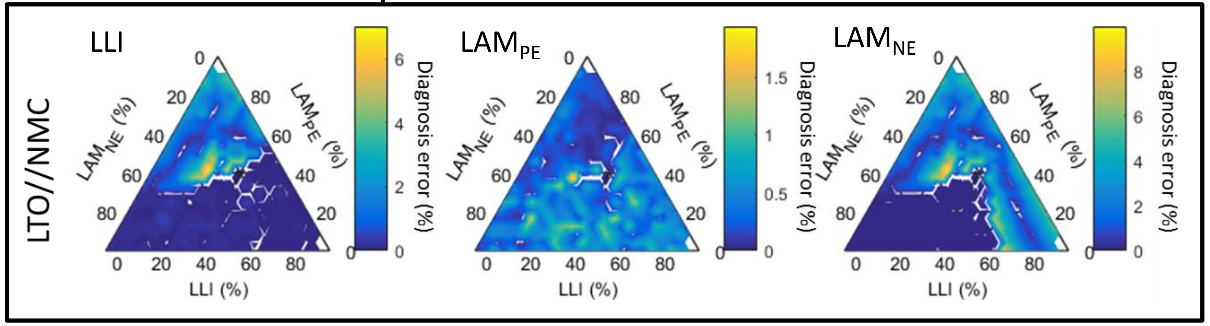




Accurate automated diagnosis is possible using look-up table and moderate computing power







.M. Dubarry *et al.* , *J. Power Sources*, in press.

Conclusions

Non-intrusive operando battery diagnosis and prognosis is possible

- Good balance accuracy/resources
- Only possible with material science insights

Degradation modes (LLI, LAMs, Kinetics) are quantifiable from the voltage response only

- Differential methods (dQ/dV, dV/dQ)
- Complex indexation but could be modeled for convenience of use
- Good starting point for other characterizations

Diagnosis and prognosis could be automated

- Features of interest approach
- Essential to test every possible degradation paths

Acknowledgements

All my students, especially Arnaud Devie and Cyril Truchot

My sponsors:

The Hawaiian Electric Company for their ongoing support to the operations of the Hawaii Sustainable Energy Research Facility (HiSERF).

Mahalo for your attention! Questions ?

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University of Hawai'i at Mānoa

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Graphical user interface: the ‘alawa toolbox

>50 registered users from >25 organizations worldwide

INL
Idaho National Laboratory

Sandia National Laboratories

BROOKHAVEN NATIONAL LABORATORY

ATL

saft

UNIVERSITY OF OXFORD

Imperial College London

AIST
NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

National Electric Vehicle Sweden

SHARP