SEPTEMBER 03TH 2024

Perspectives on Commercial Sodium-Ion Batteries

Dr. Minglong He, ABB Switzerland

ECCE Europe 2024

ABB

Content

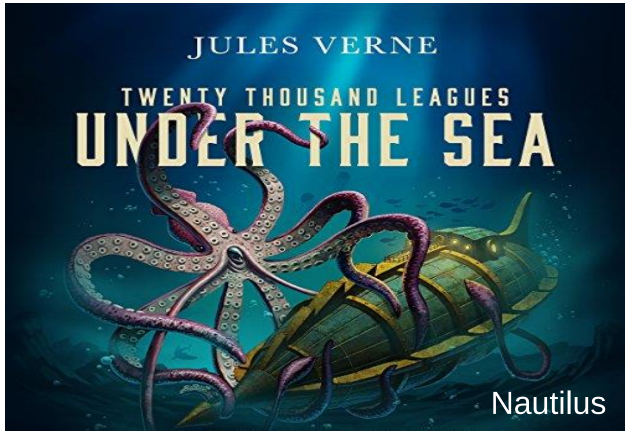
1. Landscape of commercial sodium-ion battery development
2. ABB’s engagement and position
3. Results of commercial sodium-ion battery assessments
4. Summary and perspectives

Motivation of Sodium-ion Battery

Sodium resource ~ 1000 times of Li resource

Sodium Battery from Science Fiction in 1870

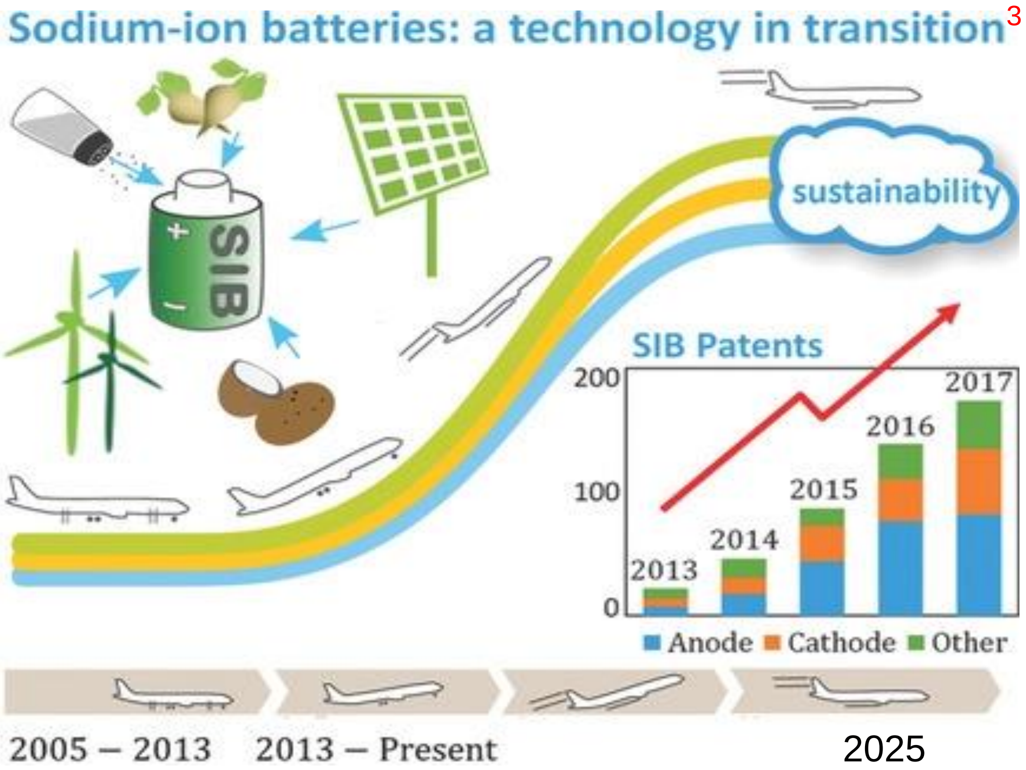
Jules Verne (1828 – 1905)[1]



Twenty Thousand Leagues Under the Sea (1869 – 1870)[2]

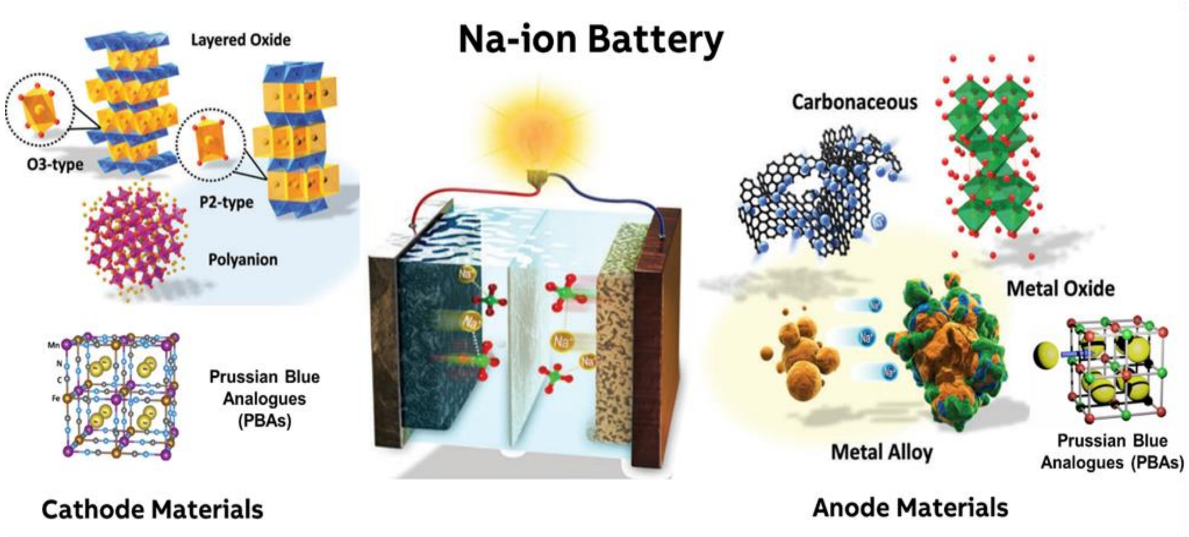
Captain Nemo: I'll mention that sodium batteries have been found to generate the greater energy, and their electro-motor strength is twice that of zinc batteries. Only the sodium is consumed, and the sea itself gives me that.

Trend of sodium-ion technology



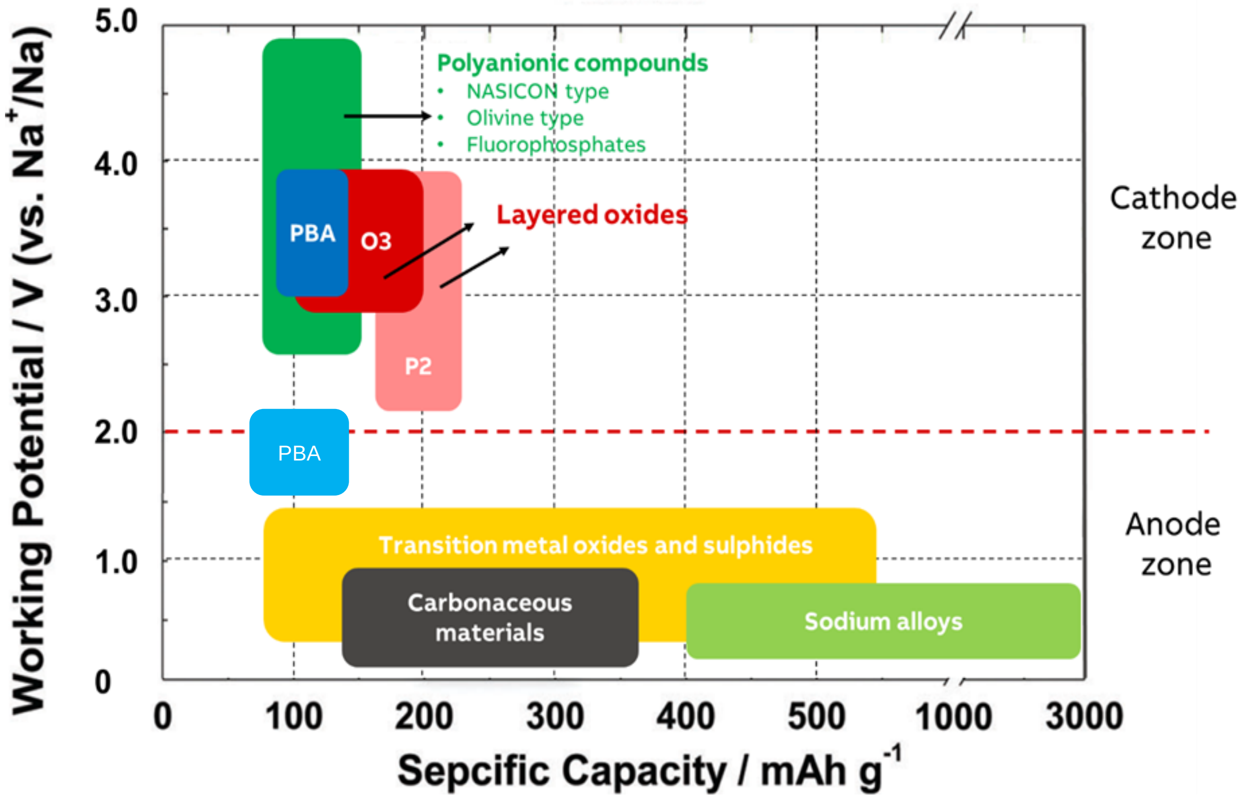
1 https://en.wikipedia.org/wiki/Jules_Verne
2 https://www.storytel.com/in/en/books/20-000-leagues-under-the-sea-185335
3 Chayambuka, K., Mulder, G., Danilov, D. L., Notten, P. H. L., Adv. Energy Mater. 2018, 8, 1800079. https://doi.org/10.1002/aenm.201800079

Sodium-ion Cell Chemistry

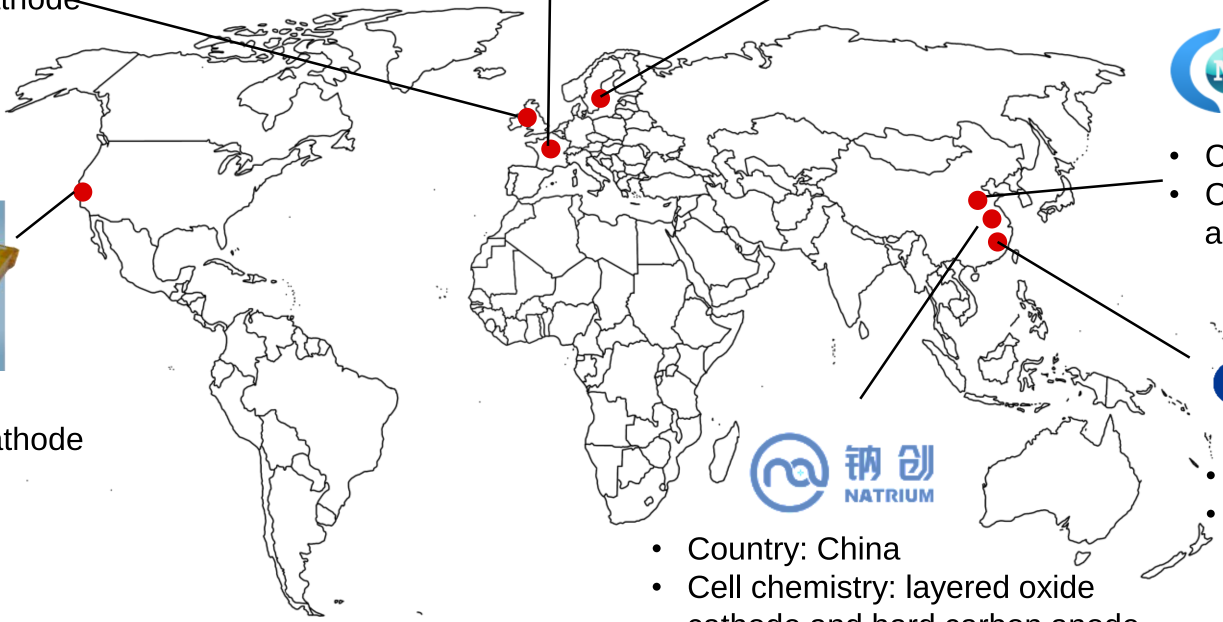


Cathode:
- Layered oxides (example: $NaFe_{0.33}Ni_{0.33}Mn_{0.33}O_2$)
- Polyanionic compounds (example: Na-$FePO_4$)
- Prusisan blue analogues (example: $Na_xMn_yFe(CN)_6{\cdot}nH_2O$)

Anode:
- Hard carbon/soft carbon
- Metal oxide (example: LTO)
- Prusisan blue analogues (example: $Na_xMn_yMn(CN)_6{\cdot}nH_2O$)
- Metal alloy (example: Sn)



Representative Sodium-ion Startups and Companies

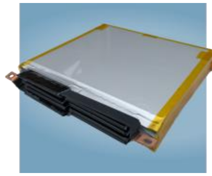


- Country: UK
- Cell chemistry: layered oxide cathode and hard carbon anode

- Country: France
- Cell chemistry: NVPF cathode and hard carbon anode

- Country: Sweden
- Cell chemistry: Prussian White cathode and hard carbon anode

- Country: China
- Cell chemistry: layered oxide cathode and soft carbon anode



- Country: USA
- Cell chemistry: Prussian Blue cathode and Prussian Blue anode

- Country: China
- Cell chemistry: layered oxide cathode and hard carbon anode

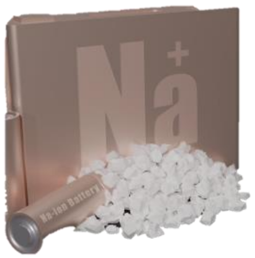
- Country: China
- Cell chemistry: Prussian White and layered oxide cathode and carbon anode

Sodium-ion Batteries Become Important Alternatives to Lithium-ion Batteries

BYD breaks ground on new 30GWh sodium-ion battery facility in China

BYD is building the new sodium-ion battery facility in Xuzhou with an investment of nearly 10bn yuan ($1.4bn).

January 8, 2024



Natron Energy starts manufacturing '50,000+ cycle-life' sodium-ion batteries at Michigan factory

By Cameron Murray

April 30, 2024

Sineng Electric launches world's largest sodium-ion battery storage project

Sineng Electric's 50 MW/100 MWh sodium-ion battery energy storage system (BESS) project in China's Hubei province is the first phase of a larger plan that will eventually reach 100 MW/200 MWh. The initial capacity has already been connected to the grid and can power around 12,000 households for an entire day.

AUGUST 8, 2024 CARRIE HAMPEL

MARKETS | MARKETS & POLICY | ASIA | CHINA

Tiamat to build a 5 GWh factory for sodium-ion batteries in France

The French company Tiamat Energy is planning a factory for sodium-ion battery cells with an annual capacity of 5 GWh in northern France - and is receiving financial support from Stellantis, among others. (UPDATE BELOW)

First sodium-ion battery EVs go into serial production in China

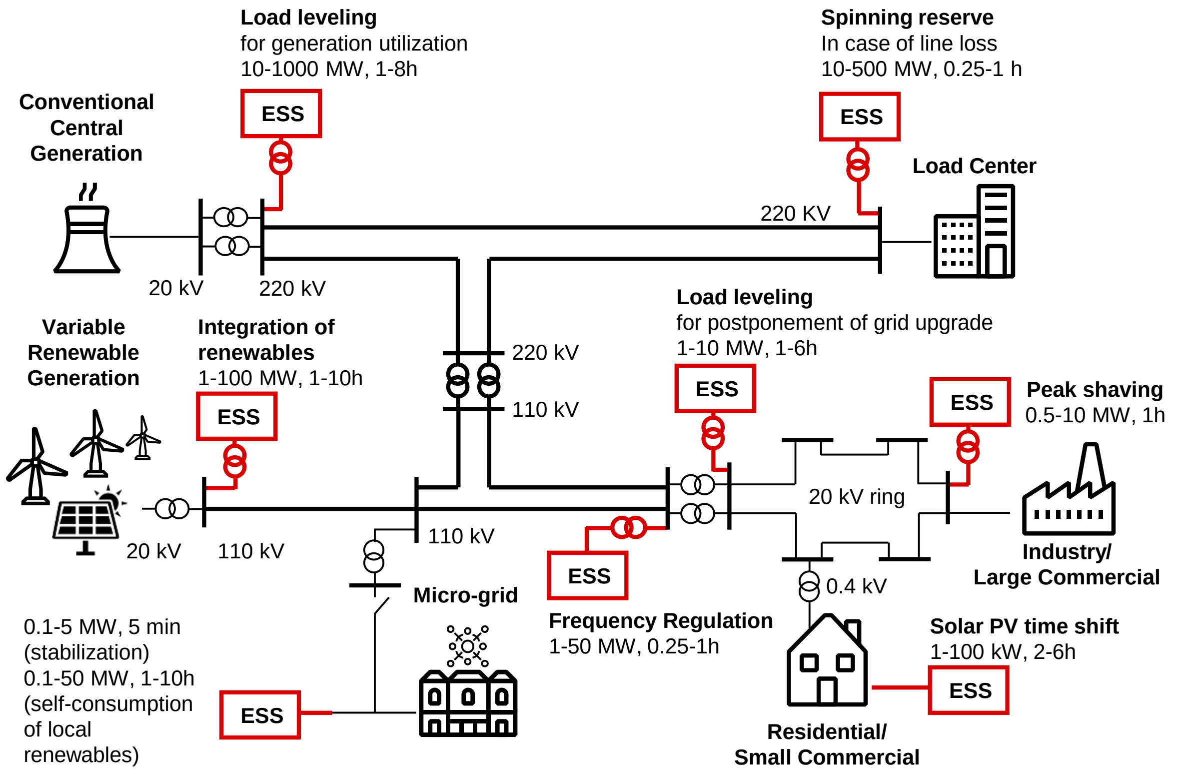
The first electric cars with sodium-ion batteries have gone into production in China. The two small electric car models are being manufactured by Yiwei and JMEV.

1. https://www.electrive.com/2024/01/12/tiamat-to-build-a-5-gwh-factory-for-na-ion-batteries-in-france/
2. https://www.energy-storage.news/natron-energy-starts-manufacturing-50000-cycle-life-sodium-ion-batteries-at-michigan-factory/
3. https://www.power-technology.com/newsletters/byd-sodium-battery-facility-china/?ref=ctvc.co
4. https://www.electrive.com/2024/01/02/first-sodium-ion-battery-evs-go-into-serial-production-in-china/
5. https://www.pv-magazine.com/2024/08/08/sineng-electric-launches-worlds-largest-sodium-ion-battery-storage-project/

ABB’s Engagement and Position

Energy Storage Applications

Stationary



Transportation

Rolling stock / Marine

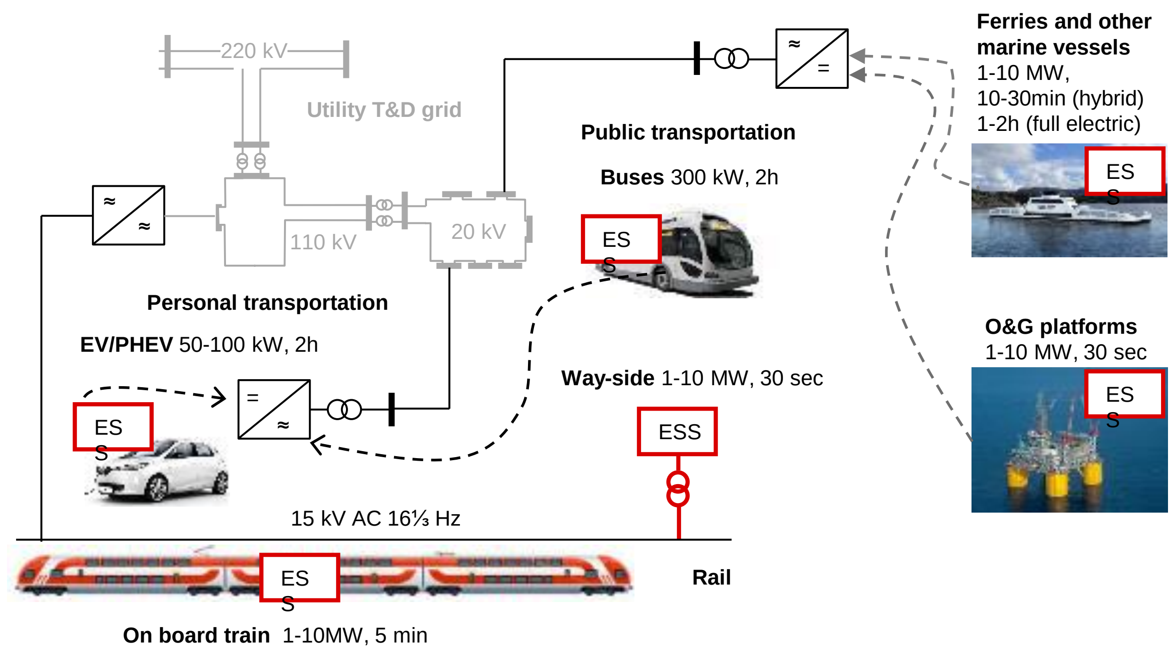
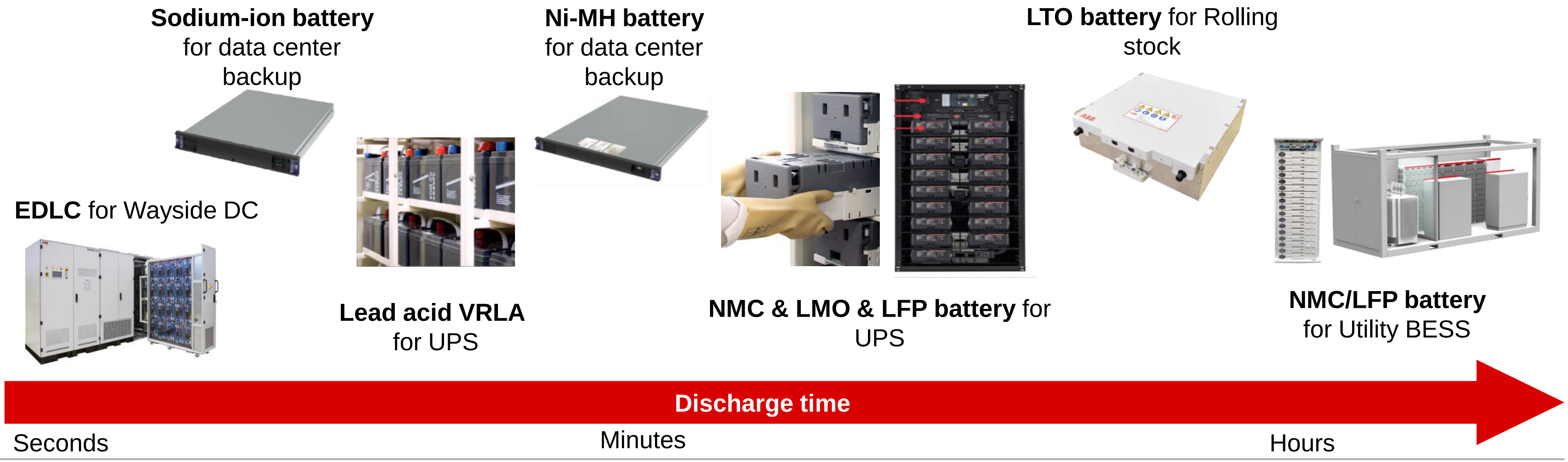


ABB offers solutions in most of the given examples

Remark: Typical values and some examples for the purpose of illustration are given.
In reality, the values can vary considerably, depending on the specific cases.

ABB's Positioning on Storage

- ABB does not manufacture battery cells
- ABB selects the optimal technology for the application (examples below)
- ABB acts as product supplier and system integrator



ABB’s Engagement – Sodium-ion Battery Technology

ABB selects the optimal technology for the application

Natron Prussian blue-based Na-ion battery

Journal of Power Sources
Volume 548, 15 November 2022, 232036

Assessment of the first commercial Prussian blue based sodium-ion battery

Minglong He [a], Roy Davis [b], Daniel Chartouni [a], Mark Johnson [b], Markus Abplanalp [a], Pirmin Troendle [a], Ralf-Patrick Suetterlin [a]

Tiamat NVPF/HC-based Na-ion battery

Journal of Power Sources
Volume 588, 30 December 2023, 233741

High power NVPF/HC-based sodium-ion batteries

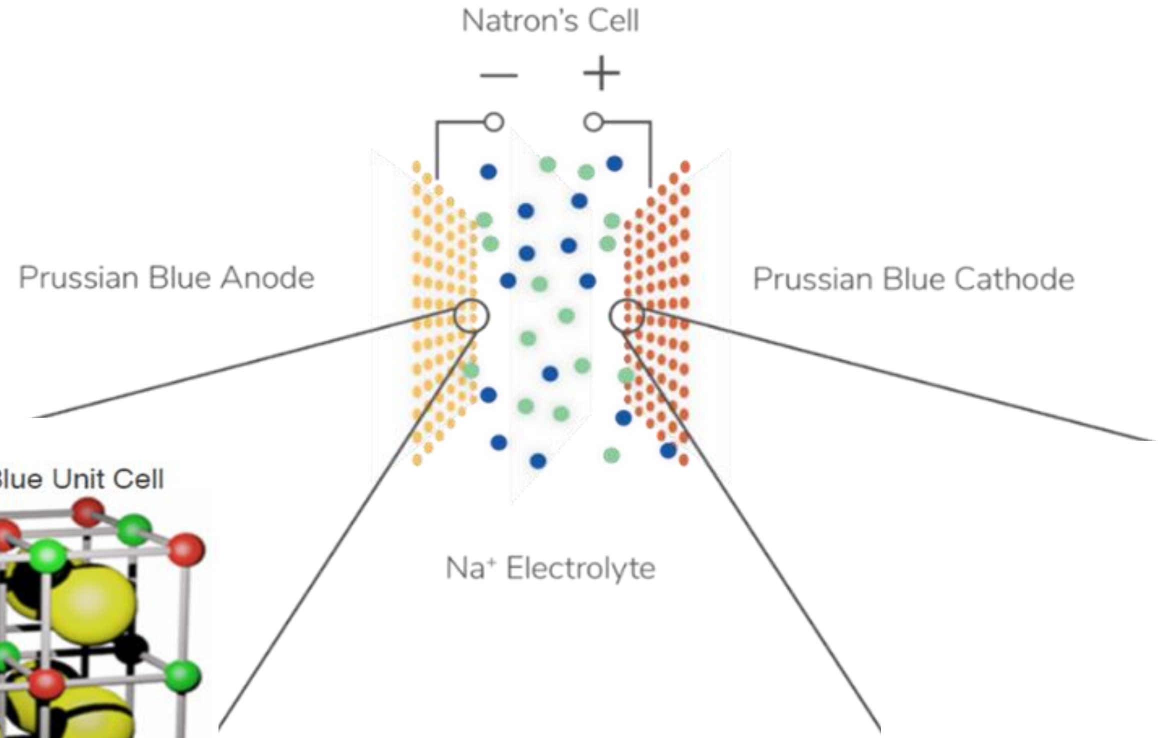
Minglong He [a], Asmae EL. Mejdoubi [b], Daniel Chartouni [a], Mathieu Morcrette [b], Pirmin Troendle [a], Roberto Castiglioni [a]

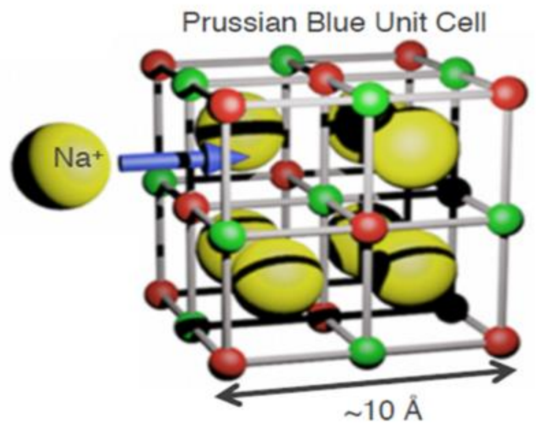
1. https://doi.org/10.1016/j.jpowsour.2022.232036
2. https://doi.org/10.1016/j.jpowsour.2023.233741

Results of commercial sodium-ion battery assessments

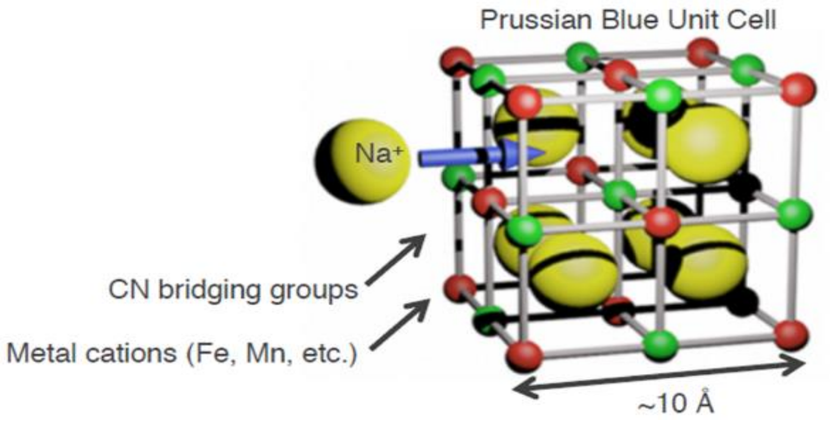
Cell Chemistry of Natron Na-ion battery

Prussian Blue cell chemistry





Sodium manganese hexacyanomanganate



Sodium manganese-iron hexacyanoferrate


45
Wissen
Verwaistes Grünzeug
Mit Pflanzen wie Cassava lässt sich die Welt künftig besser ernähren 47
Verlorener Kanton
Warum Napoleon dem Bündnerland das Veltlin weggenommen hat 48
Das blaue Energiewunder

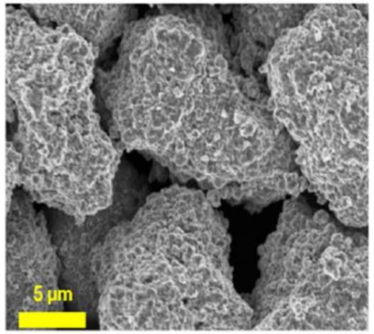
Prussian Blue

Reference: NZZ amSonntag 8. Januar 2023

Fundamentals of Natron Na-ion battery

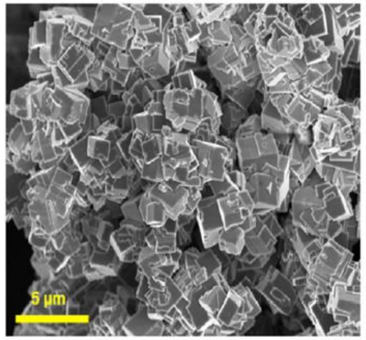
Battery materials and electrochemistry

Electrode materials



Cathode

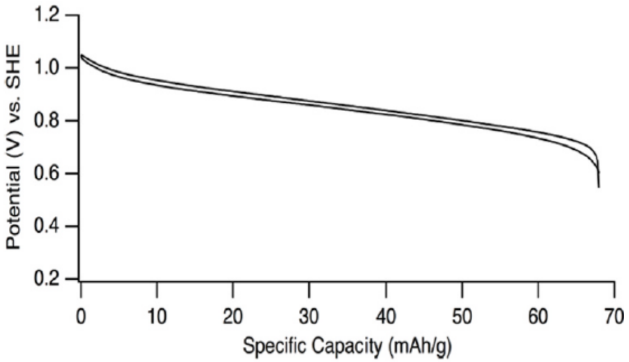
$Na_xMn_yFe(CN)_6 \cdot nH_2O$
(Sodium manganese-iron hexacyanoferrate)
200-500 nm primary particles
10-20 µm secondary particles



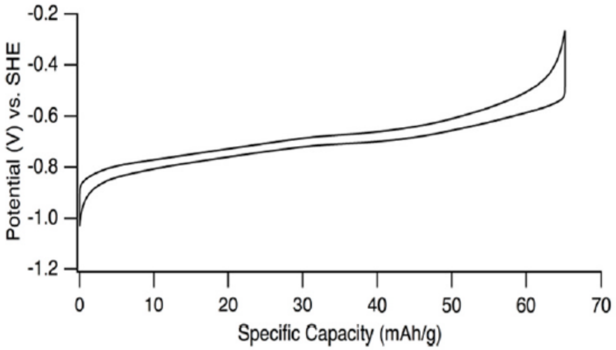
Anode

$Na_xMn_yMn(CN)_6 \cdot nH_2O$
(Sodium manganese hexacyanomanganate)
2-3 µm particles

Cell voltage and capacity



- Cathode specific capacity: 67 mAh/g
- Cathode average potential: 0.9V vs. SHE



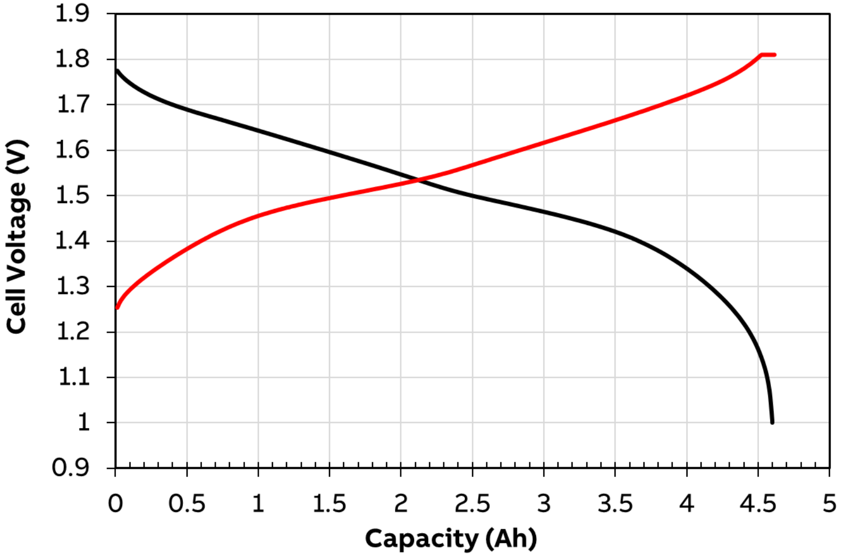
- Anode specific capacity: 68mAh/g
- Anode average potential: -0.7V vs. SHE

Reference: Journal of Power Sources 548 (2022) 232036.

Natron Prussian Blue-based Sodium-ion Battery Cell

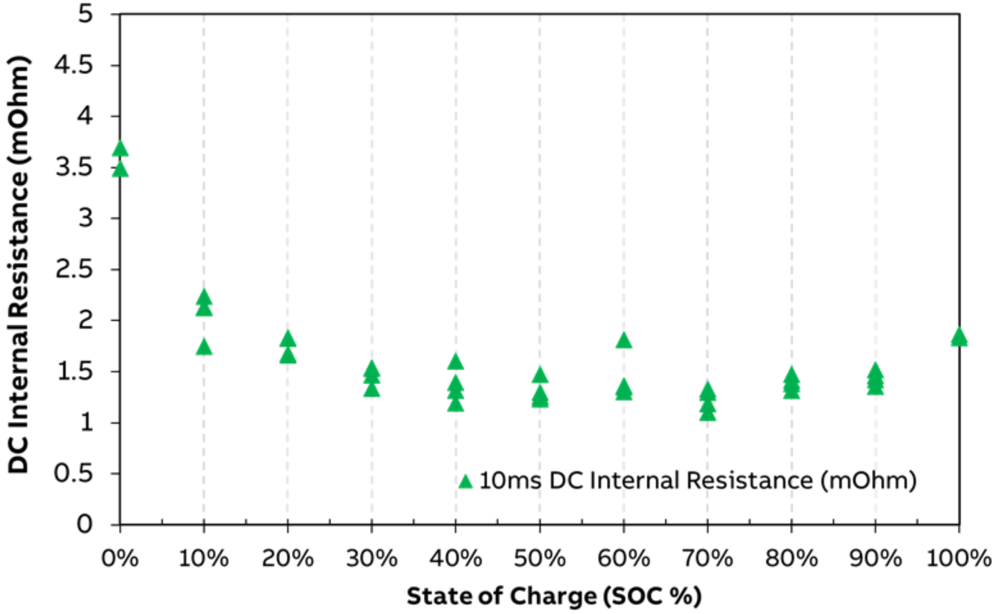
Basic cell information

Cell information



- Cell weight: 300 g
- Cell volume: 0.19 L
- Nominal cell voltage: 1.56 V
- Cell capacity: 4.6 Ah
- Specific energy of 23 Wh/kg

DC internal resistance - DCIR



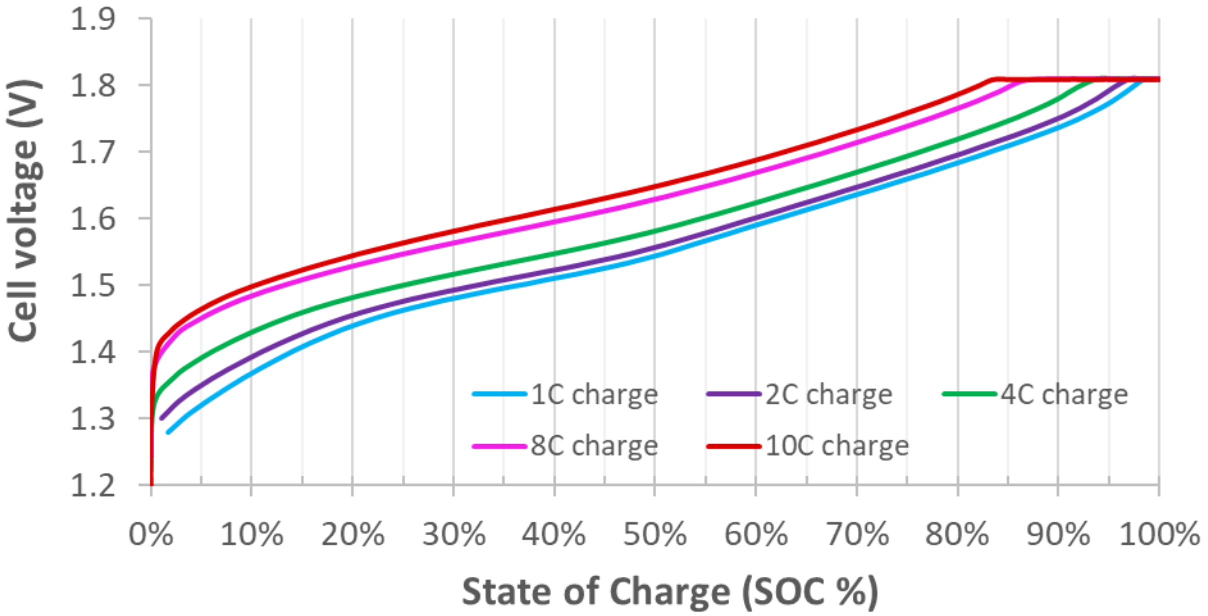
- Cell internal resistance of 1.4 mOhm (10ms, 50% SOC)
- Rough estimation of the short circuit current on cell level at 50% SOC is 1086 A derived by applying Ohm's Law (the OCV at 50% SOC is 1.52 V).

Reference 1: Journal of Power Sources 548 (2022) 232036.
Reference 2: Natron Energy

Natron Prussian Blue-based Sodium-ion Battery Cell

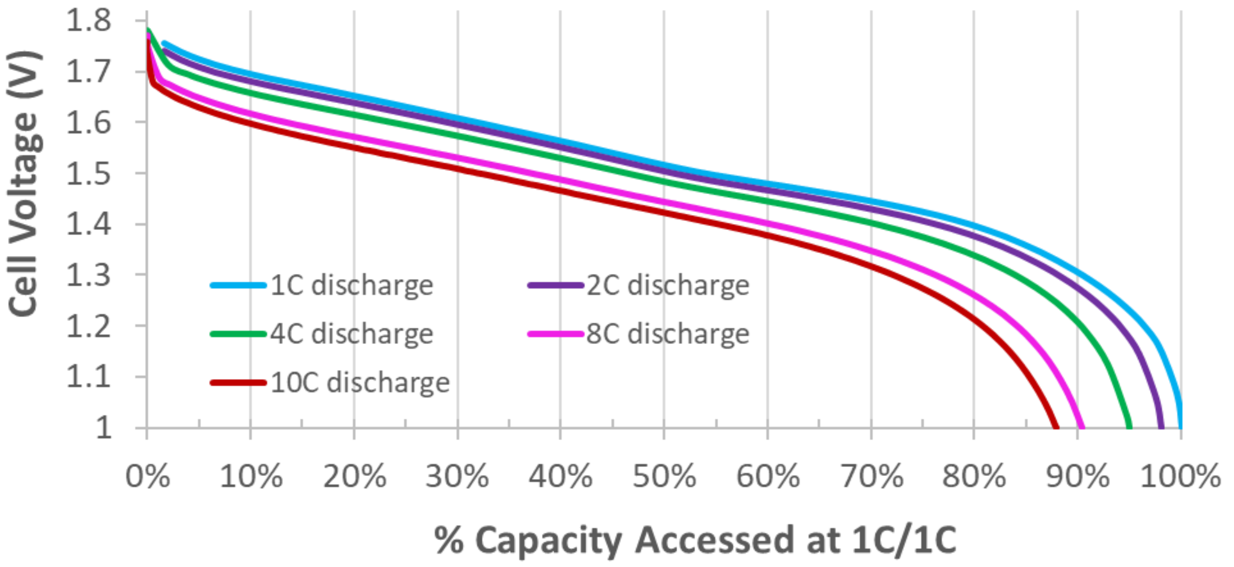
Rated performance

Rated Charge performance



- Charged from 0% SOC to 80% SOC in < 5 minutes and to 99% SOC in < 10 minutes.

Rated discharge performance



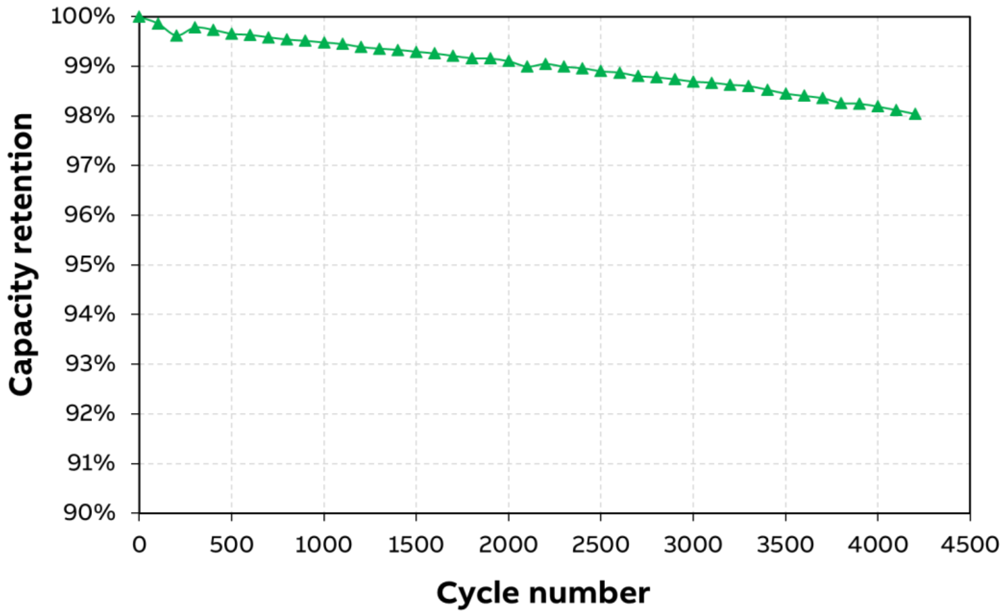
- 88% discharge capacity at a 10C rate in comparison to 1C discharge.
- Natron: a maximum continuous charge C rate of 17C and a maximum continues discharge C rate of 54C are allowed at the cell level.

Reference: Journal of Power Sources 548 (2022) 232036.

Natron Prussian Blue-based Sodium-ion Battery Cell

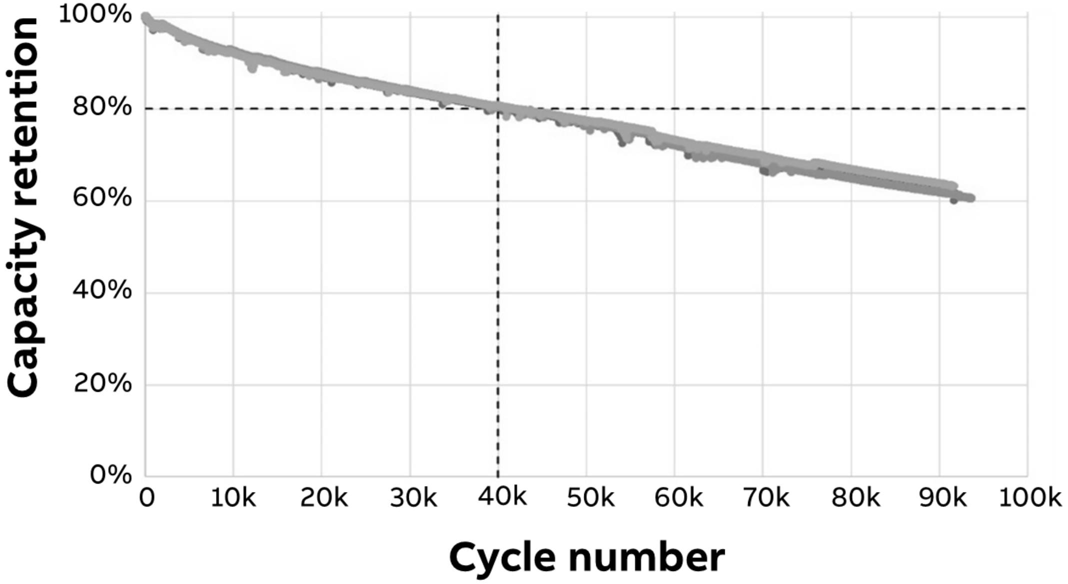
Cycle life performance

Ageing tests performed in ABB's battery lab



- Capacity loss of about 2% after 4200 cycles with 10C charge and 10C discharge
- Cycle life of >40,000 cycles is estimated if a linear extrapolation is applied

Ageing tests performed in Natron's battery lab

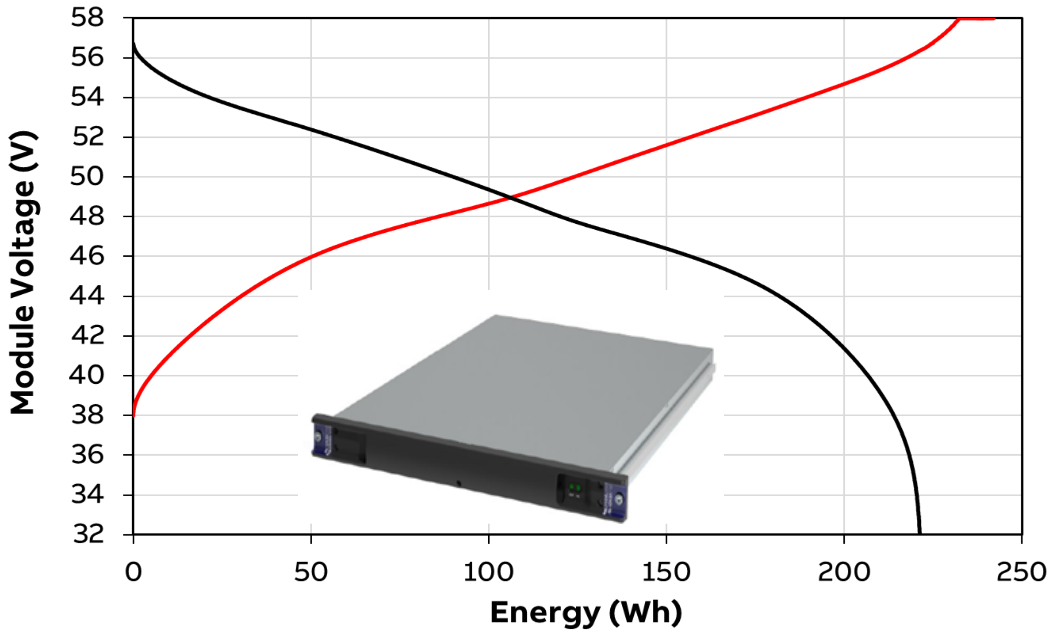


- Cycle life of >40,000 cycles to 80% initial capacity
- Cycle life >90,000 cycles to 60% initial capacity

Natron Prussian Blue-based Sodium-ion Battery Module

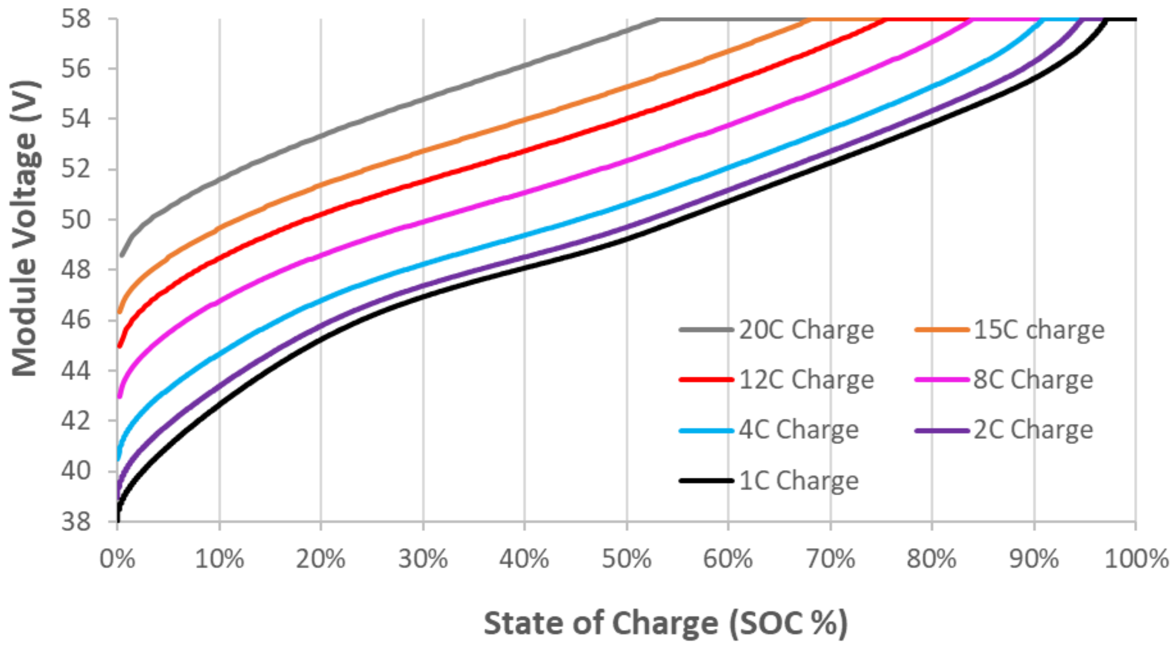
Battery module performance

Battery module information



- Capacity of 4.6 Ah, energy of 0.22 kWh, and energy density of 10.3 Wh/kg
- Voltage range of 32 V–58 V, an average voltage of 50.3 V at 50% SOC.

Battery module rated charge performance

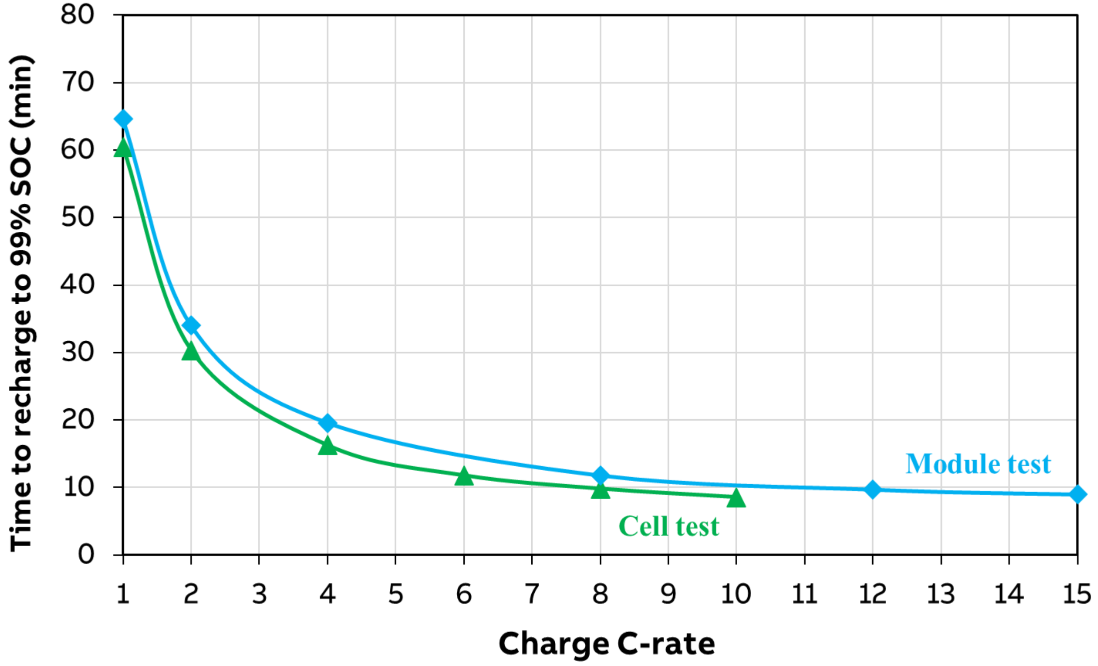


- Excellent fast-charge capability up to 20C
- A maximum temperature increase of 8 °C was detected with 20C charge

Natron Prussian Blue-based Sodium-ion Battery Module

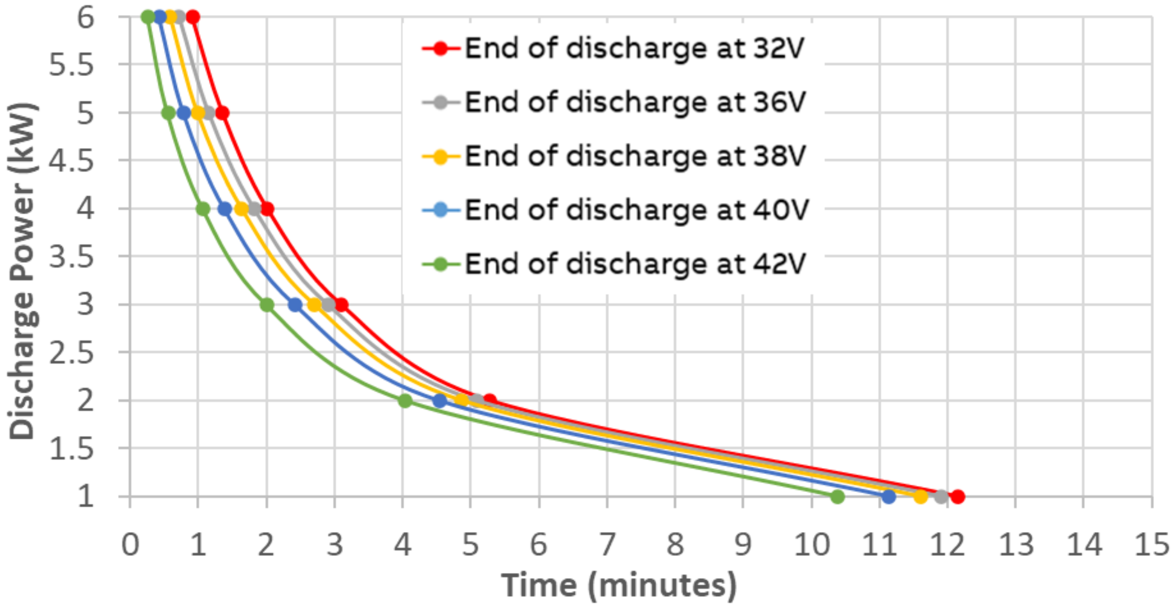
Battery module performance

Battery module rated charge performance



The module (32 cells) can be charged from 0% SOC to 80% SOC in <5 min and to 99% SOC in <10 min.

Module constant power dischage performance



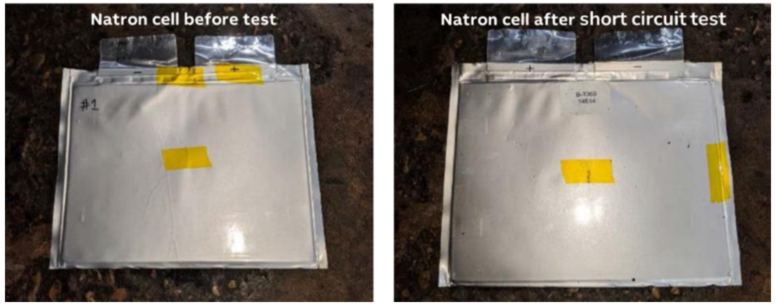
- Up to 6 kW of battery backup for 1 min discharges and up to 1 kW for 12 min, with end of discharge voltage of 32 V
- A discharge power of 4 kW for 2 min (350 W/Liter for those 2 min)

Reference: Journal of Power Sources 548 (2022) 232036.

Safety Evaluation

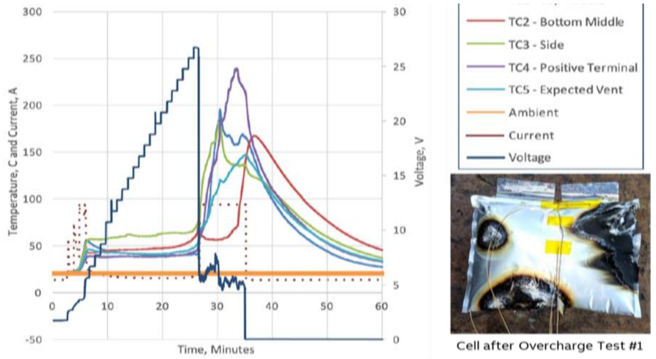
Abuse tests based on UL9540A methods

Short circuit test



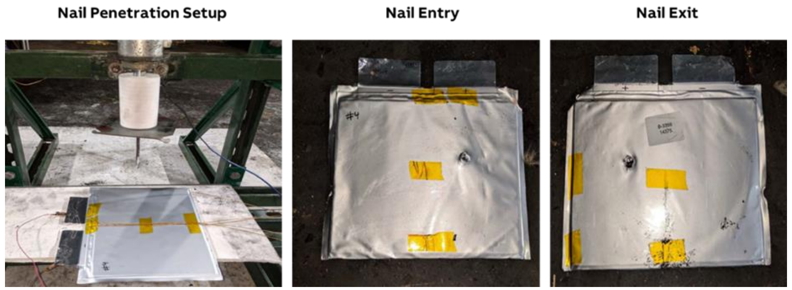
- The current at the initial short circuit was about 796 A
- No venting and no thermal runway were observed
- A minor extent of cell swelling was observed in the center

Overcharge test



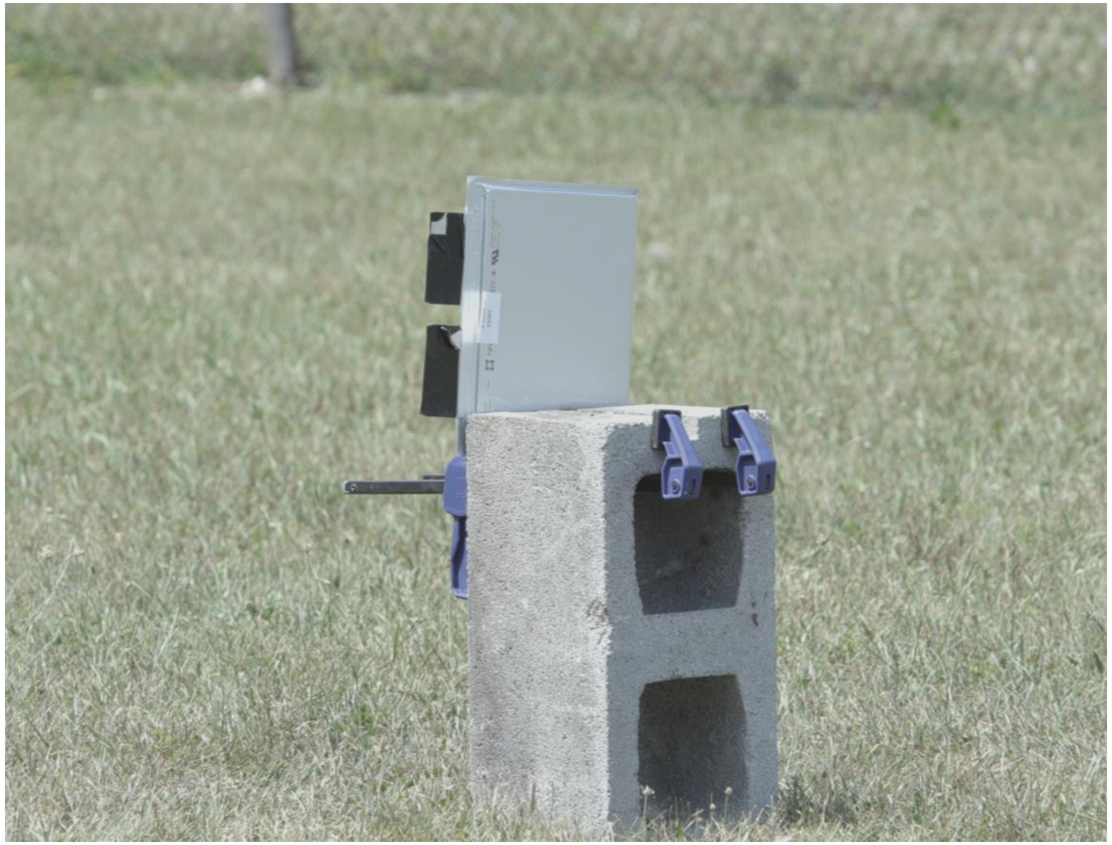
- Constant current, voltage from 1.73 V to 26 V at a rate of 1 V/min
- At 26 minutes, flame was observed at voltage of 26 V, temperature increase to 150-200 °C
- When the power supply turned off, the flames self-extinguished.

Nail penetration test

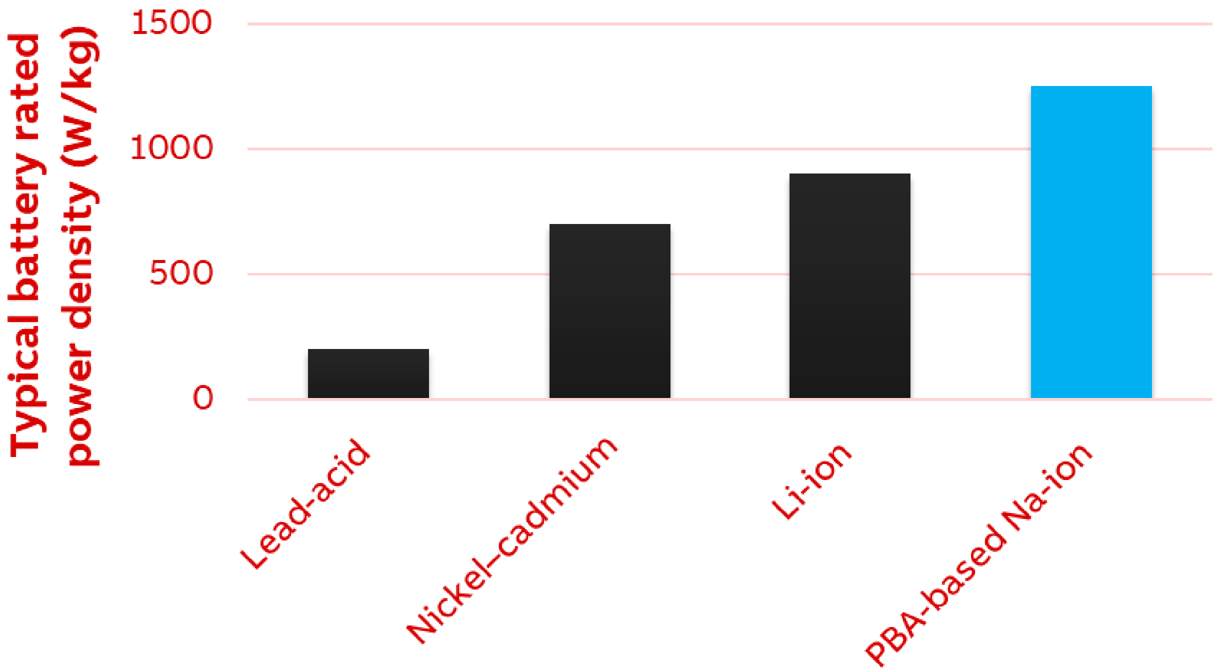


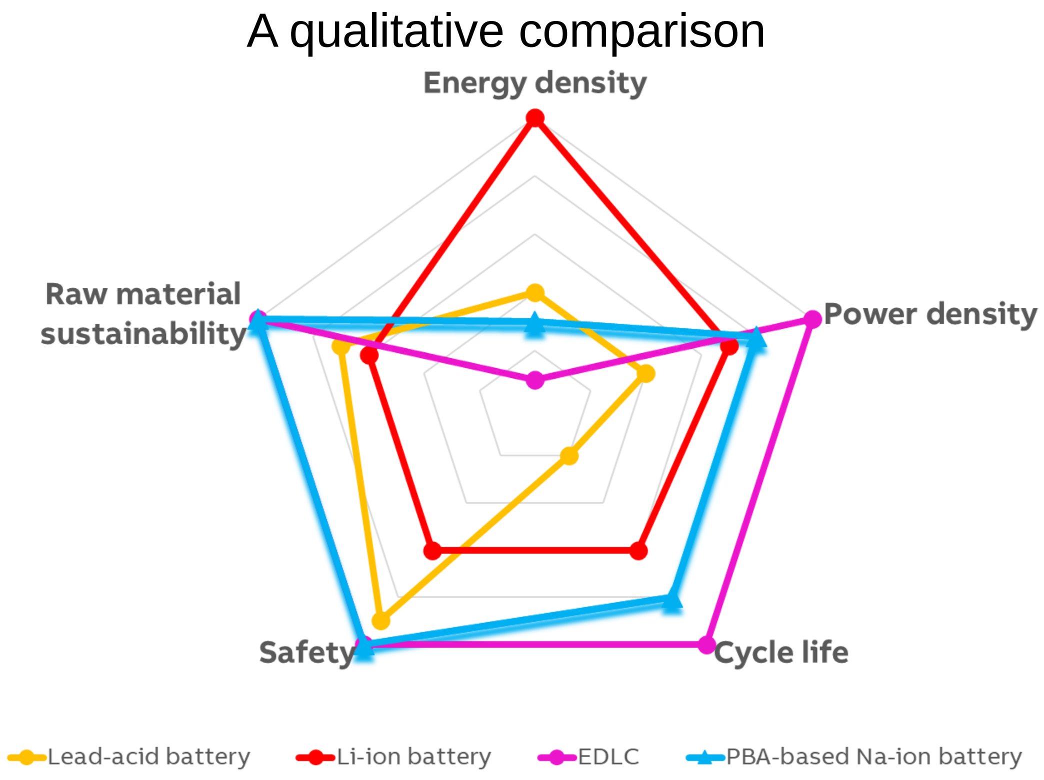
- 8 mm diameter, 125 mm long nail used
- The nail increased in temperature slightly (ca. 2°C)
- No venting and no thermal runway

Natron Battery Shooting Test



Comparison to Other Energy Storage Devices





- A rated power density of up to 1250 W/kg
- Performance characteristics between batteries and supercapacitors in terms of power, energy density, and cycle life
- The Prussian Blue-based sodium-ion technology could be applicable for high-power applications (e.g., uninterruptible power supply), providing alternatives to the existing battery solutions.

Reference: Journal of Power Sources 548 (2022) 232036.

ABB Engagement - Sodium-ion Battery Technology

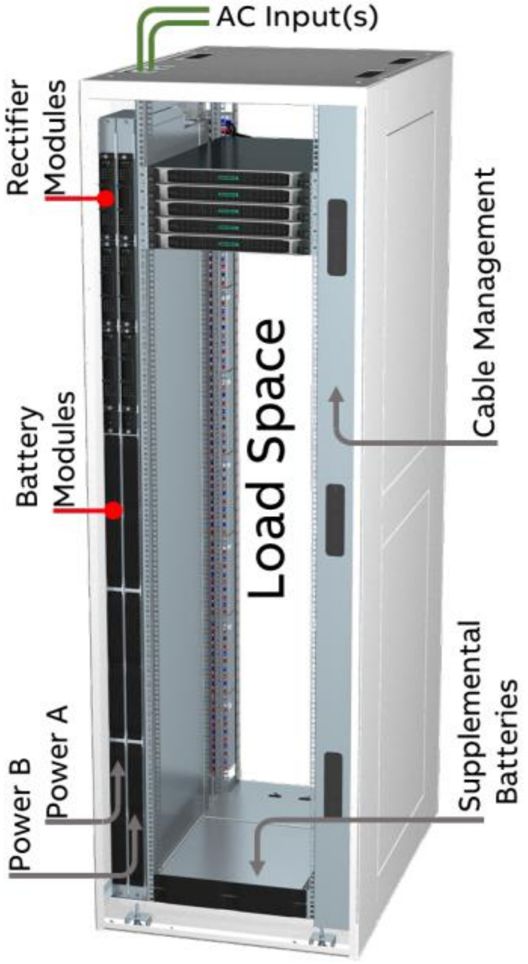
Natron Energy

Natron Energy, California, USA

ABB TECHNOLOGY VENTURES

In 2020, Natron Energy announced they have raised $35 million in Series D funding. ABB Technology Ventures, NanoDimension Capital and Volta Energy Technologies co-led the round, with existing investors Chevron, Khosla Ventures and Prelude continuing their participation in funding.

HDR Sodium Ion/Prussian Blue – BME2500/220NAION48



Edge Datacenter Cabinet
(ABB Power Conversion division*)

* ABB completed sale of Power Conversion division to AcBel in 2023.

Summary and Perspectives

Summary and Perspectives

- **Energy density:** The state-of-the-art Na-ion batteries typically have energy densities of 20-160 Wh/kg, which is targeted to reach more than 200 Wh/kg for the next-generation cells. Na-ion batteries can achieve a comparable energy density to LFP batteries.
- **Power density:** The layered oxide-based sodium-ion batteries have a comparable power density to lithium-ion batteries, while PBA and polyanionic based sodium-ion batteries exhibit attractive performance features of ultra-high-power density.
- **Cycle life:** PBA/PBA sodium-ion batteries from Natron Energy have the highest cycle number (up to 40’000 cycles) among all batteries. The other Na-ion batteries have cycle life of 1000-4500 cycles.
- **Safety:** Different sodium-ion batteries have shown superior thermal stability and abuse tolerance in comparison to LFP and NMC batteries.
- **Maturity:** Multiple prototypes of sodium-ion cells and modules have been developed and deliver promising results. The sodium-ion technology starts ramping up mass production.
- **R&D focus:** The main R&D direction for sodium-ion battery technology lies in improving energy density (target of 200 Wh/kg) and cycle life.
- **Cost:** The frequently discussed cost advantage of Na-ion batteries highly depends on the prices of Li-ion raw materials. Sodium-ion batteries become cost-competitive in the case of high prices of lithium, cobalt, and nickel.

ABB

ECCE ENERGY CONVERSION CONGRESS & EXPO Europe 2024
2-6 September, Darmstadt

Electrochemical Impedance Spectroscopy and Prognostics in Battery Systems

Prasanth Venugopal, Ning Zhansheng, Reza Azizighalehsari, Gert Rietveld & Thiago Batista Soeiro





1. Introduction to Battery Degradation

2. Introduction to EIS (Electrochemical Impedance Spectroscopy)

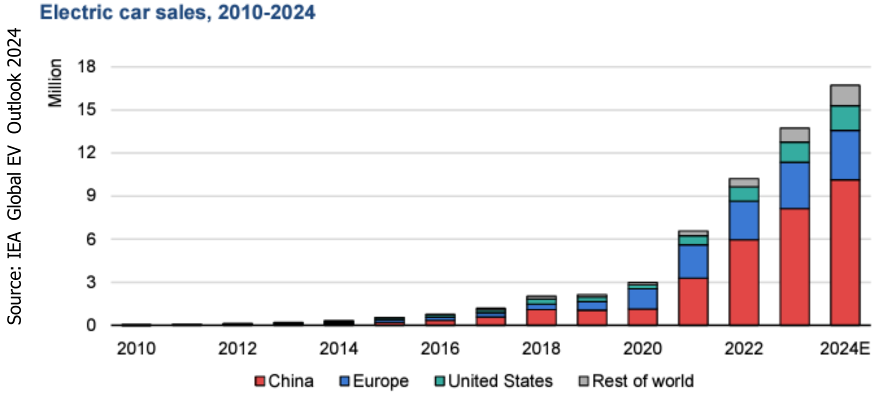
3. EIS and its connection to ECM

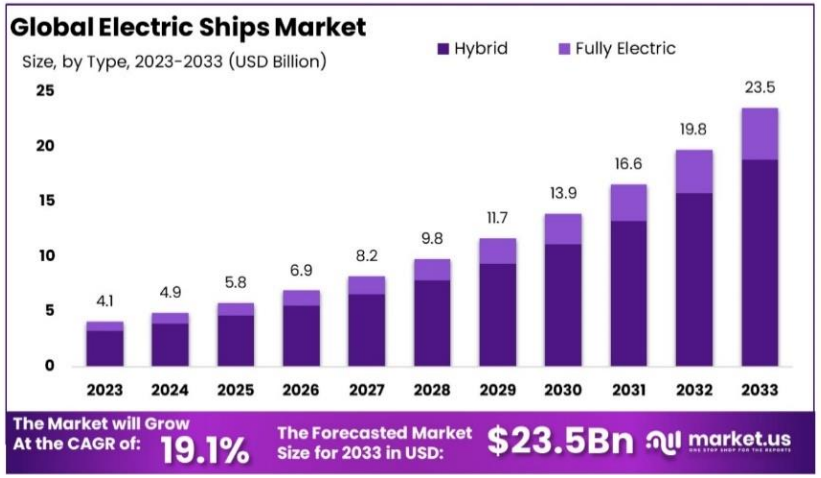
4. Factors influencing good EIS

5. Capacity Predictions using ML/AI Tools

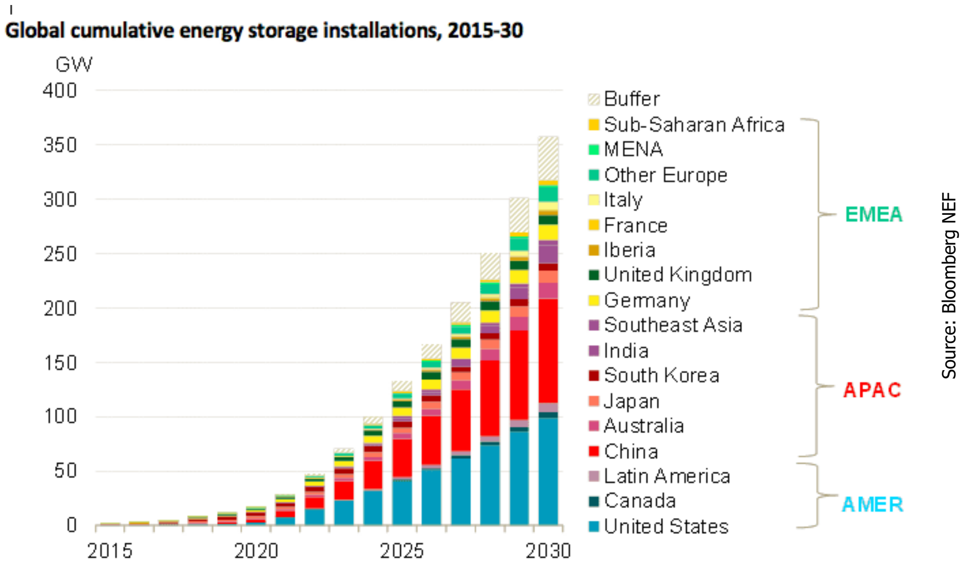
GLOBAL MARKETS AND BATTERIES GROWTH

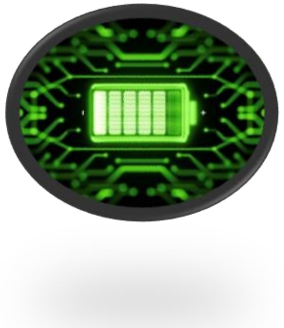
EV: 35% year-on-year increase 23/22



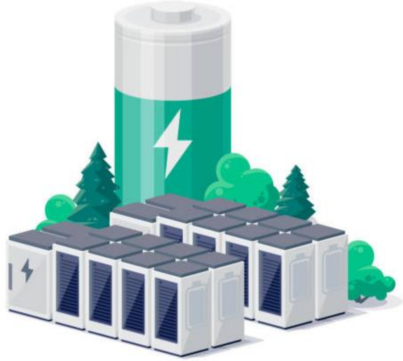


E Ships: Valued at USD 4.1 Billion (2023)



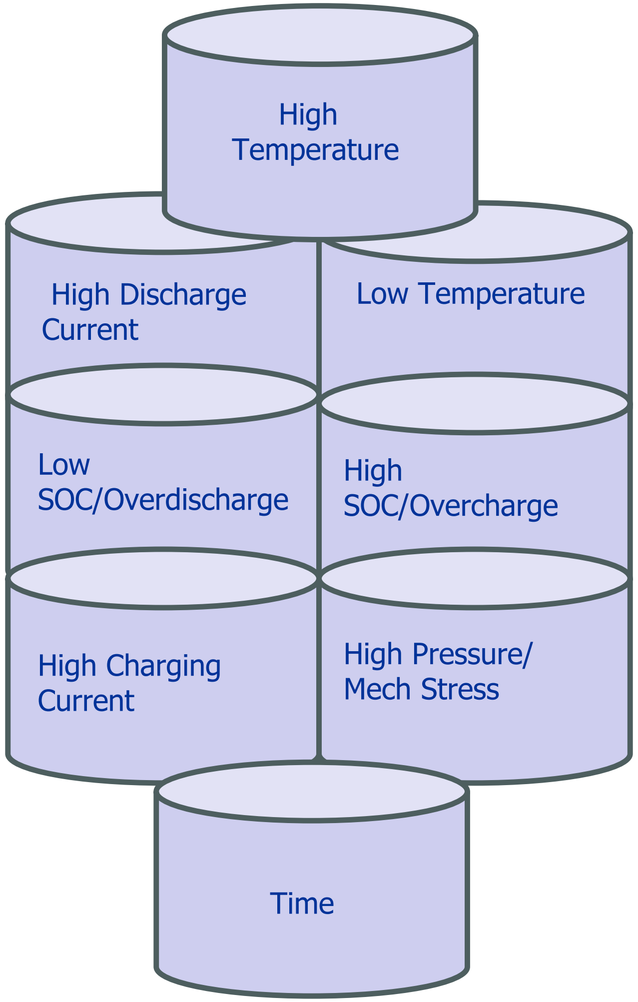


Energy Storage Market Set to Grow 20x by 2030



DEGRADATION MODES IN BATTERIES

Conditions



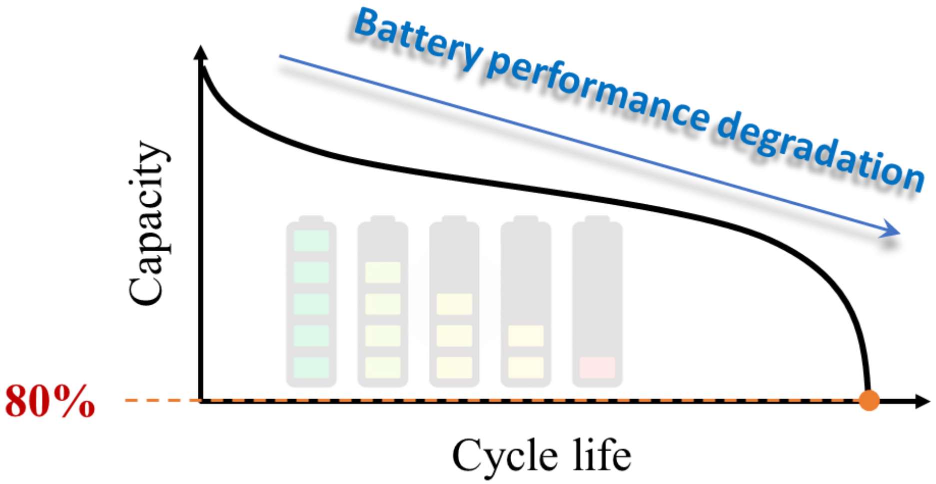
Degradation

Mechanisms

Loss of Lithium Inventory (LLI)

Loss of Active Materials (LAM)

Increase in Internal Impedance (III)



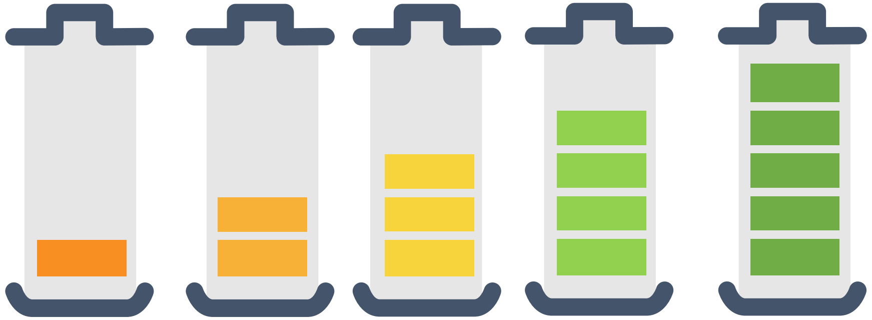
SOC AND SOH ESTIMATION TECHNIQUES

Battery Diagnostic

- Battery SOC
  - Open Circuit Voltage
  - Impedance Measurement
  - Coulomb-Counting
  - Model Based
  - Machine Learning
- Battery SOH
  - Physics-based
  - Empirical
  - Data-driven
  - Incremental Capacity Analysis

Voltage,
Current,
Temperature,
Operation time,

SOC

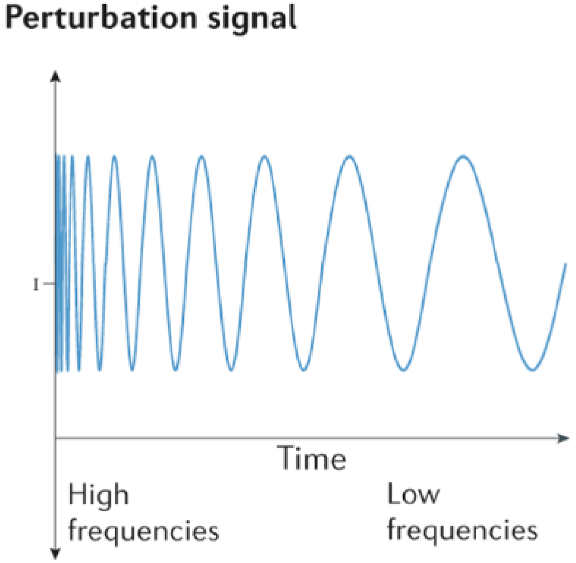


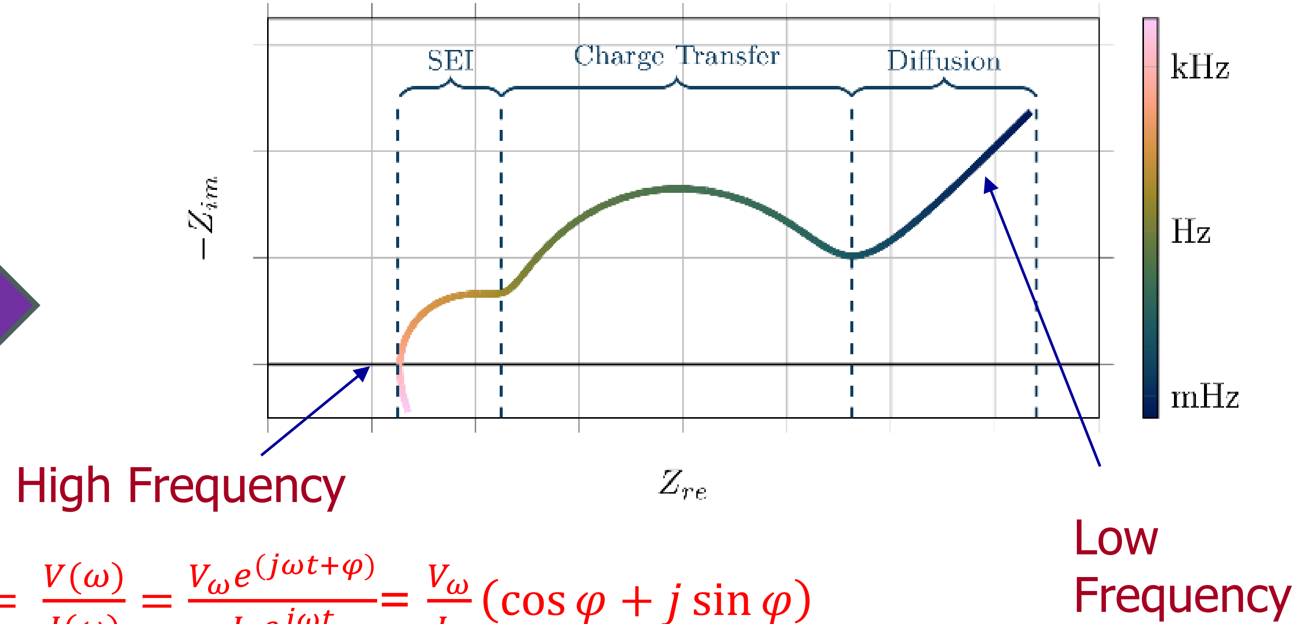
SOH

Aging process,
Temperature,
Over voltage,
Under Voltage,
Over current,
Under current,
Cell unbalance

ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY

- ✓ Electrochemical system is probed with an ac current (**Galvanostatic**), the voltage response recorded, and impedance interpreted
- ✓ For other systems, the probing technique can be **Potentiostatic** (high impedance systems)

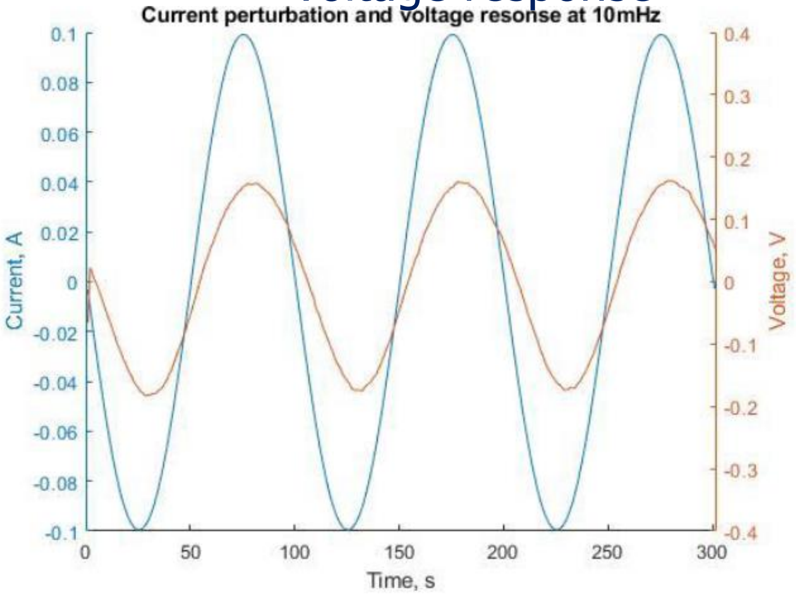




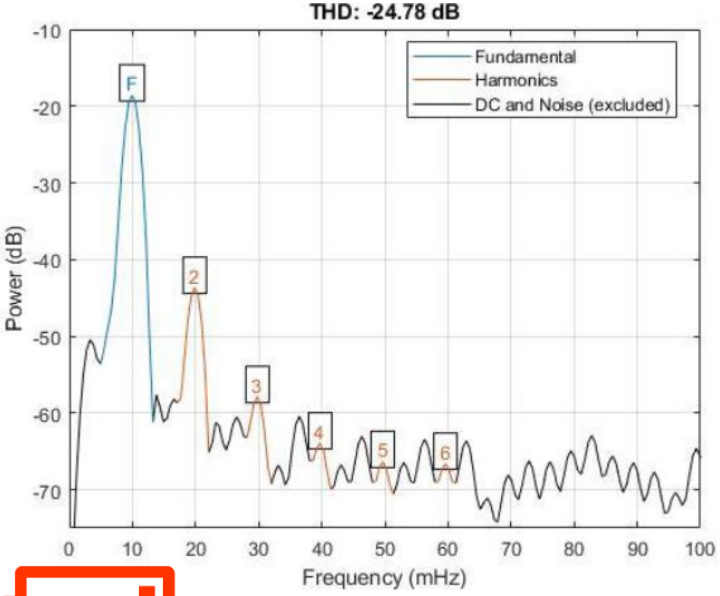
Galvanostatic Formulation: $Z(\omega) = \frac{V(\omega)}{I(\omega)} = \frac{V_\omega e^{(j\omega t+\varphi)}}{I_0 e^{j\omega t}} = \frac{V_\omega}{I_0}(\cos\varphi + j\sin\varphi)$

ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY

Voltage response



FFT, THD



100 mA → 6S LiB module @ 10 mHz

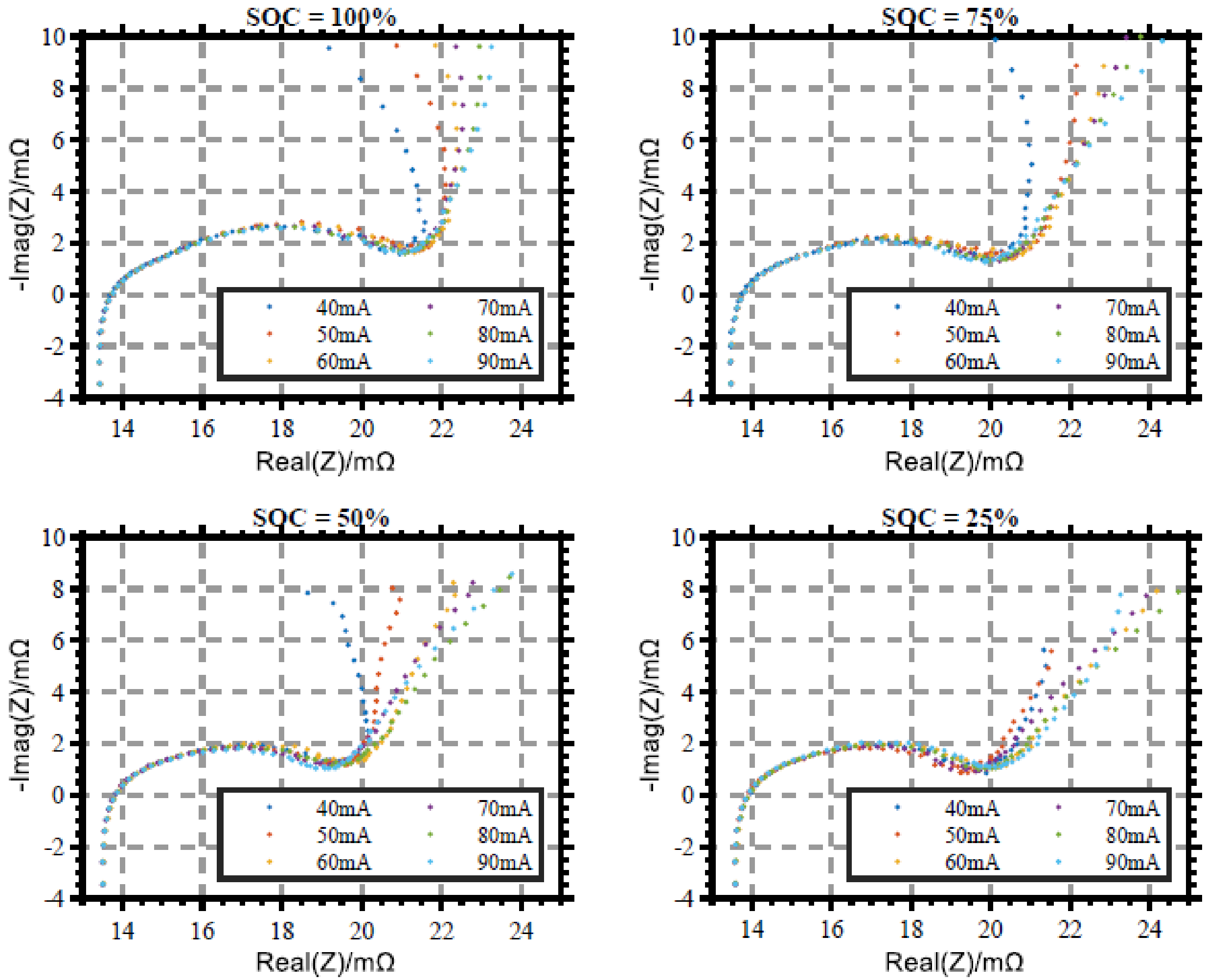
Features:

- Small signal injection → quasi-LTI system and models battery dynamics
- System in thermodynamic equilibrium (or 'steady state')
- Measurement is small perturbation (approximately linear)
- Different processes have different time constants
- Large frequency range, µHz to GHz (and up)

Disadvantages:

- Expensive equipment esp. with high accuracy
- Low frequencies are difficult to measure

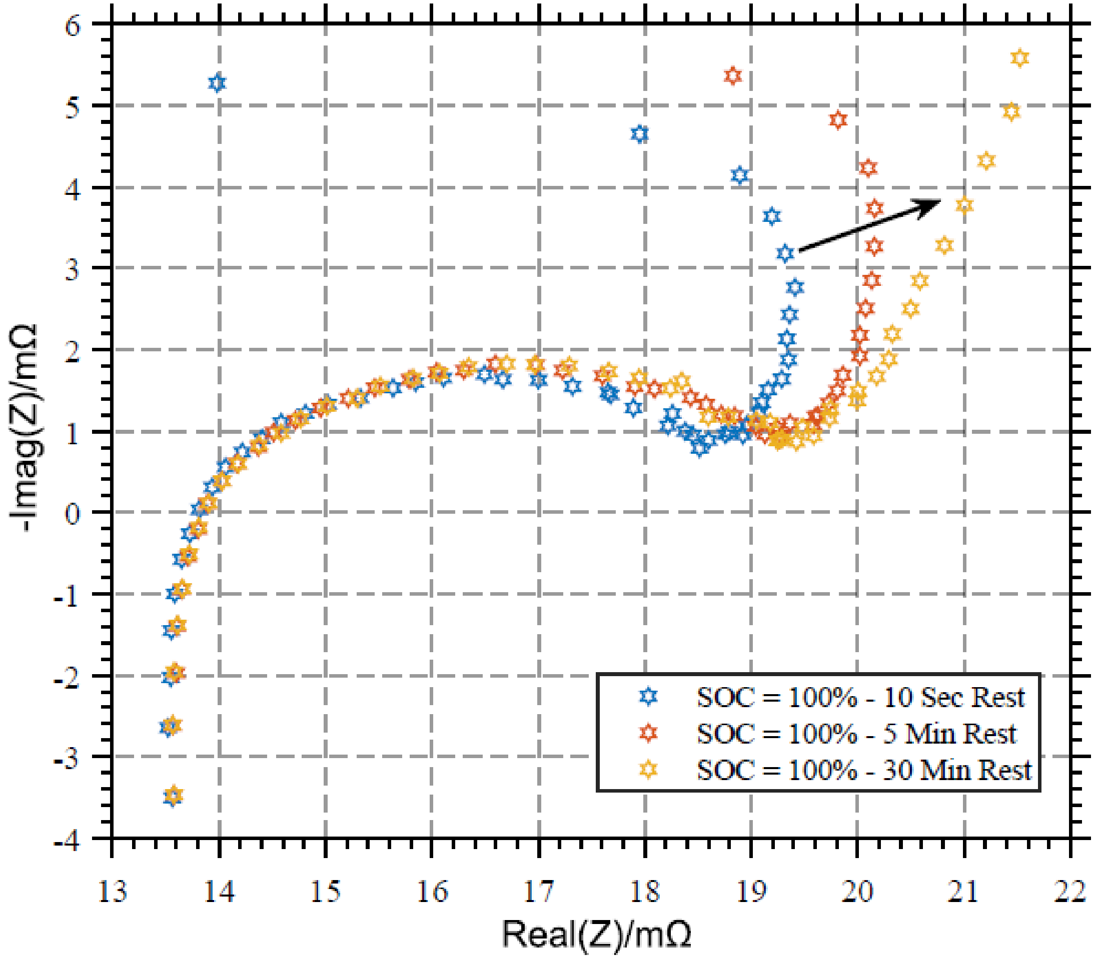
IMPACT OF SIGNAL AMPLITUDE



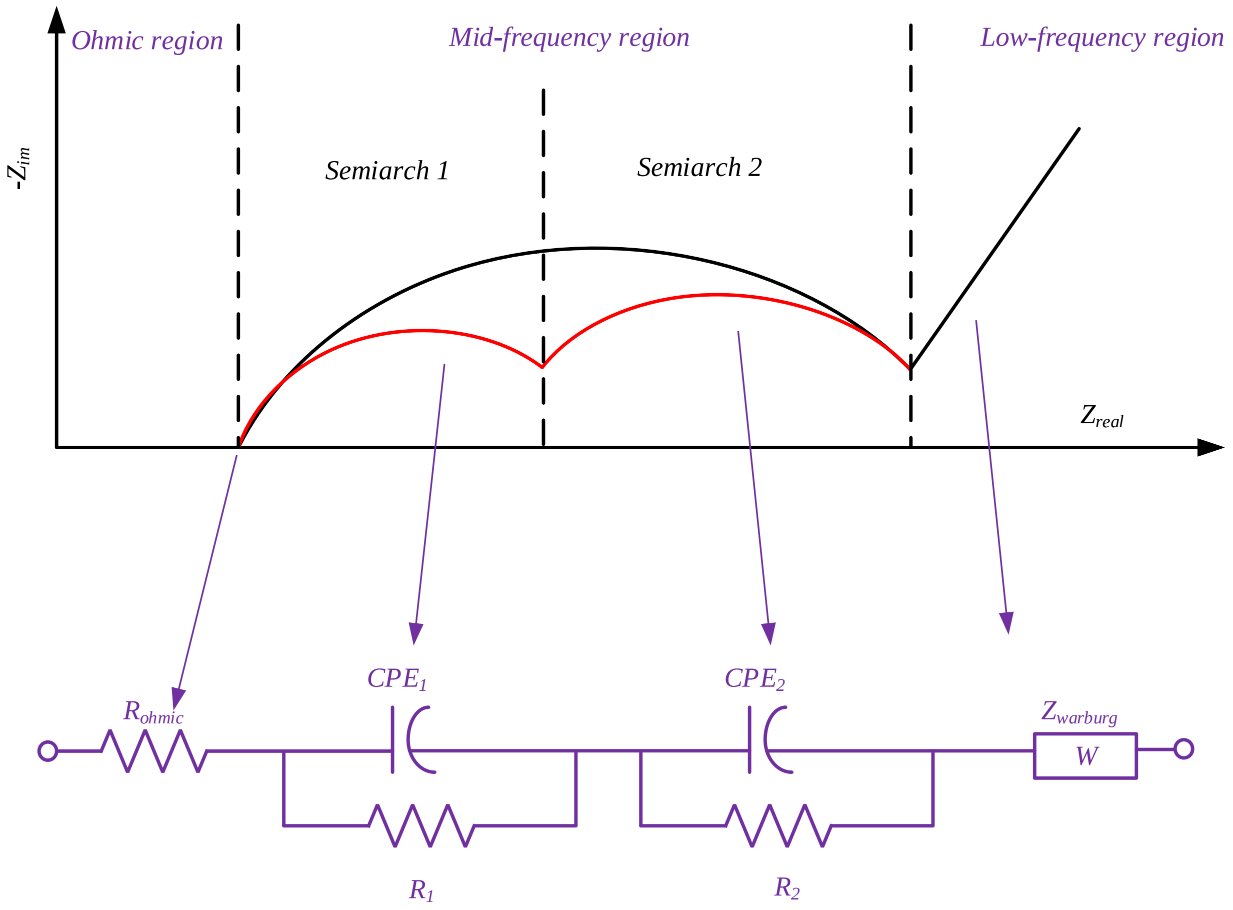
- Injected current amplitude directly influences impedance spectra quality, notably at low frequencies.
- Small amplitude preserves battery state, maintains linearity, reflects actual operating conditions, and minimizes system perturbation for accurate interpretation.
- Balance needed between linearity/stability and sensitivity for precise impedance analysis.
- Selection based on the battery's characteristics and acceptable accuracy range in EIS spectra.

S. Azizighalehsari, Z. Ning, B. Breazu, P. Venugopal, G. Rietveld and T. B. Soeiro, "Battery Dynamics Exploration: Insights and Implications of Relaxation Time in Electrochemical Impedance Spectroscopy," *2023 IEEE 8th Southern Power Electronics Conference and 17th Brazilian Power Electronics Conference (SPEC/COBEP)*, Florianopolis, Brazil, 2023, pp. 1-6, doi: 10.1109/SPEC56436.2023.10407778.

- Adequate rest period is crucial for accurate representation of electrochemical behavior.
- Allows dissipation of transient effects, ensuring impedance measurements reflect actual cell behavior.



S. Azizighalehsari, Z. Ning, B. Breazu, P. Venugopal, G. Rietveld and T. B. Soeiro, "Battery Dynamics Exploration: Insights and Implications of Relaxation Time in Electrochemical Impedance Spectroscopy," *2023 IEEE 8th Southern Power Electronics Conference and 17th Brazilian Power Electronics Conference (SPEC/COBEP)*, Florianopolis, Brazil, 2023, pp. 1-6, doi: 10.1109/SPEC56436.2023.10407778.

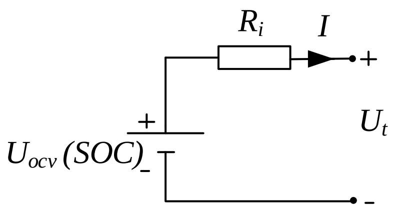


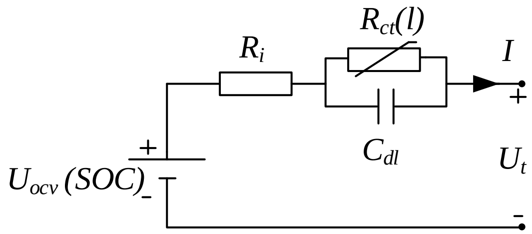
1) f > 1 kHz and τ < 10ms: Contact resistance corresponding to particle-particle or particle current.
2) 1 kHz < f < 100 Hz and 1 ms < τ < 10 ms: Transport of Li-ions in the Solid-Electrolyte Interface (SEI).
3) 10 mHz < f < 100 Hz and 10 ms < τ < 10 s: Dual electrode-related charge transfer resulting in two or more peaks.
4) f < 100 mHz and τ > 10s: Diffusion related slow electrochemical process

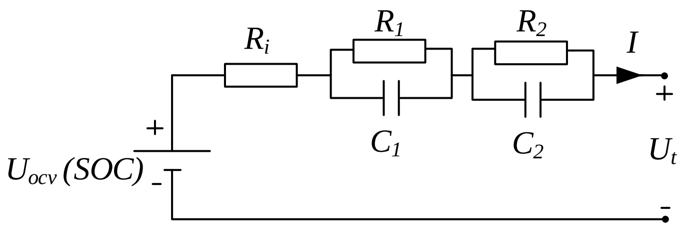
- Ideal ECM must model the electrode dependent, battery dynamics (non-linearity) completely
  - → Low frequency diffusion process
  - → Charge transfer electrochemistry
  - → Double layer capacitance effect (voltage dependent)
- The high frequency region is often neglected for individual cells (but has significance for modules and packs, online EIS)

S. Azizighalehsari, E. A. Boj, P. Venugopal, T. B. Soeiro and G. Rietveld, "A Distribution of Relaxation Time Approach on Equivalent Circuit Model Parameterization to Analyse Li-ion Battery Degradation," in *IEEE Transactions on Industry Applications*, doi: 10.1109/TIA.2024.3430268.

ECM EVOLUTION FOR BATTERY MODELS



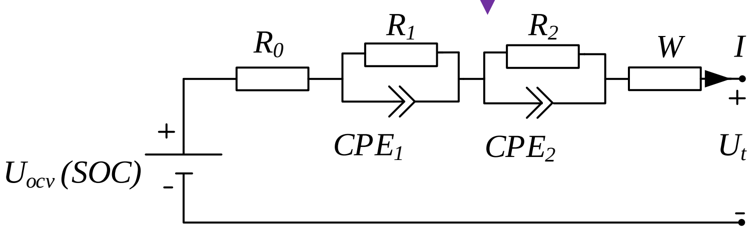


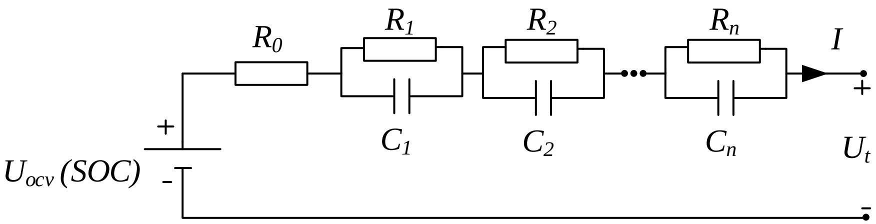


R_{int} circuit:
- Models' internal resistance

1^{st} Order RC circuit:
- Separation of time constant
- No model for diffusion

2^{nd} Order RC circuit:
Ideal capacitors can't model charge transfer process

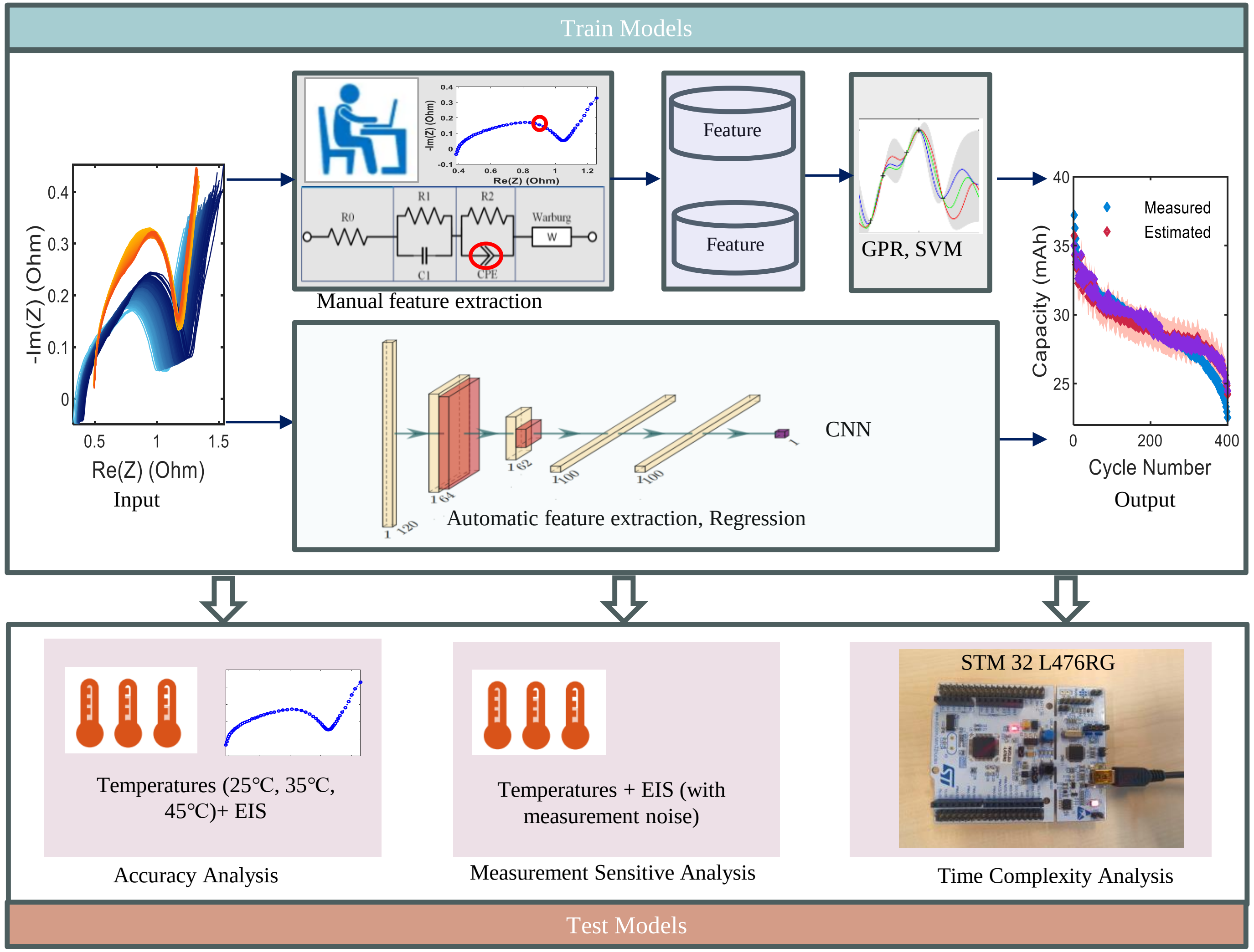




Fractional-order model:
- Models CT with CPE (Volberg element).
- Diffusion modelled with Warburg element

Higher-order model:
- Separation of anode/cathode electrochemistr

EIS FOR BATTERY CAPACITY ESTIMATION USING ML/AI

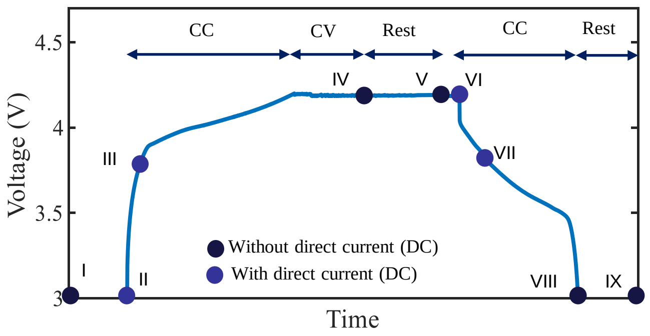


Input: Impedance

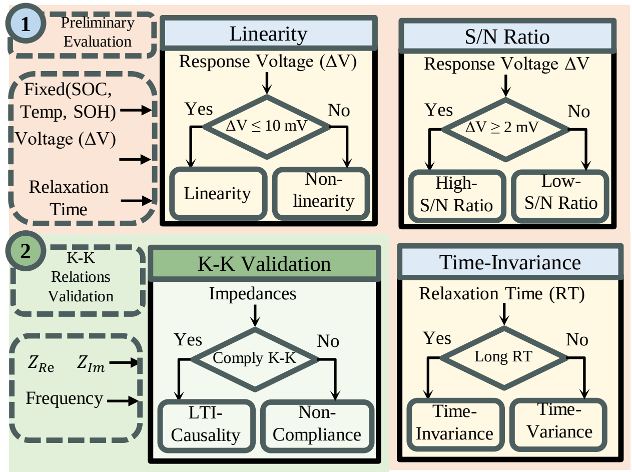
Output: Capacity

Ning, Zhansheng, et al. "Computation-light AI models for Robust Battery Capacity Estimation based on Electrochemical Impedance Spectroscopy." *IEEE Transactions on Transportation Electrification* (2024).

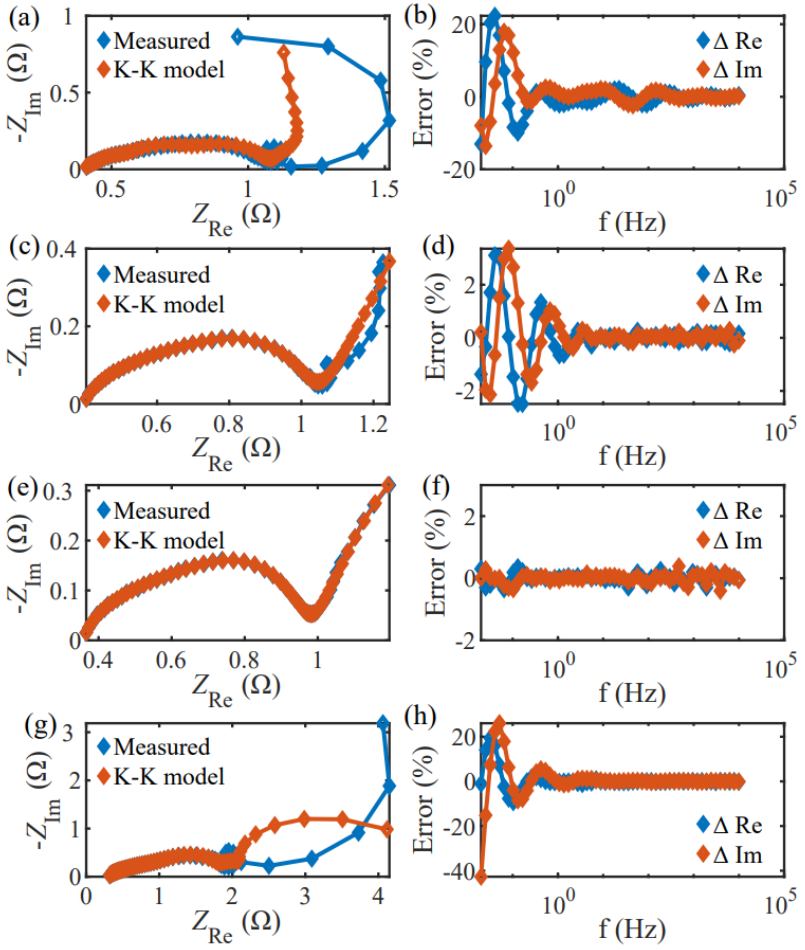
EIS FOR BATTERY CAPACITY ESTIMATION



EIS Measurement Conditions



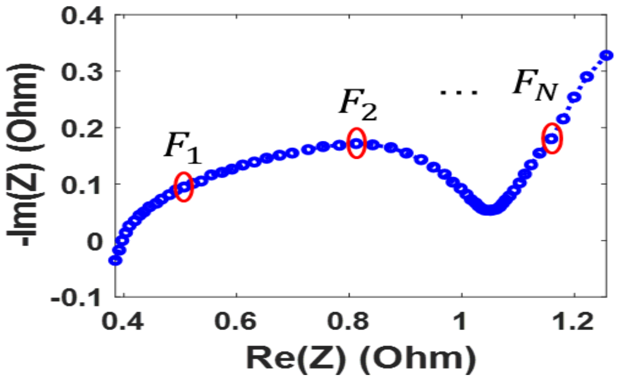
Two approaches for evaluating the characteristics of the battery system



Evaluation results based on Kramers-Kronig relations

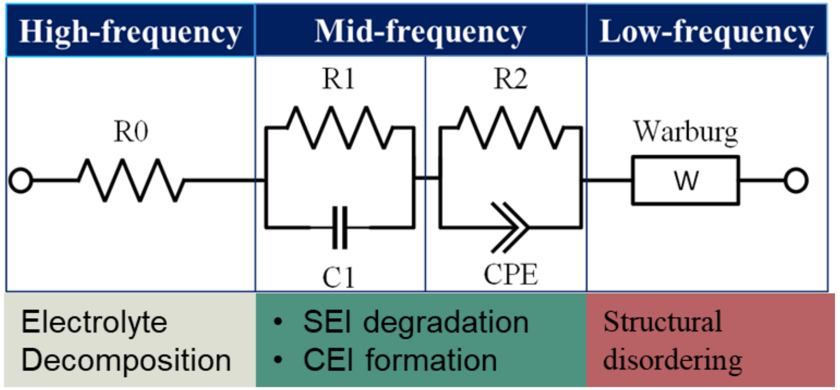
- Battery Aging Features Extraction Methods

1



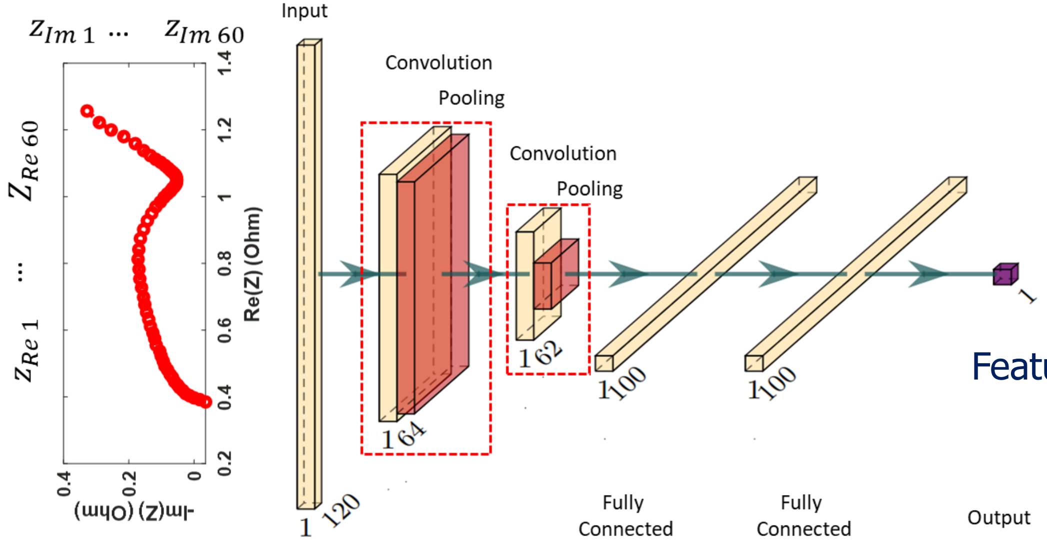
Feature directly from EIS data

2



Feature from ECM

3

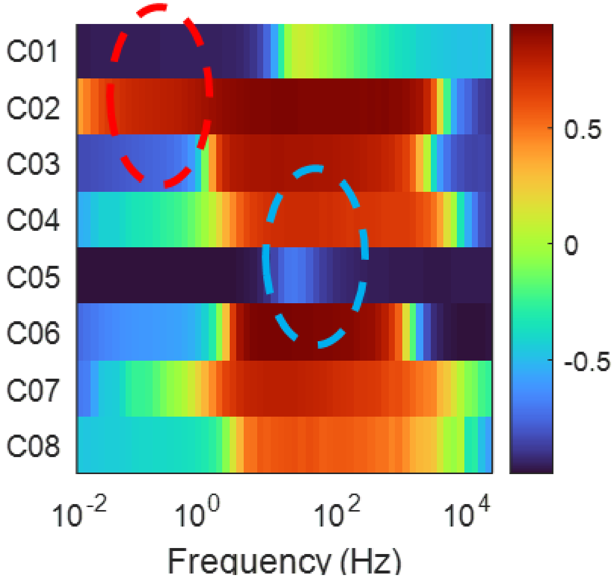


Feature from CNN methods

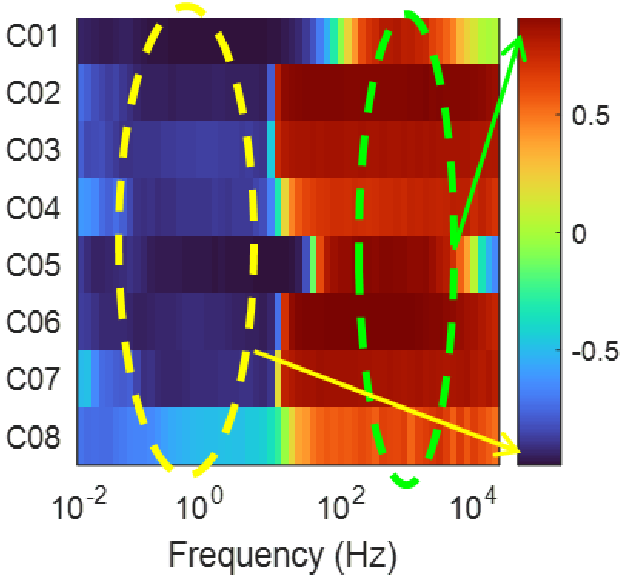
CORRELATION ANALYSIS FOR BATTERY CELLS

Correlation Analysis for All Cells

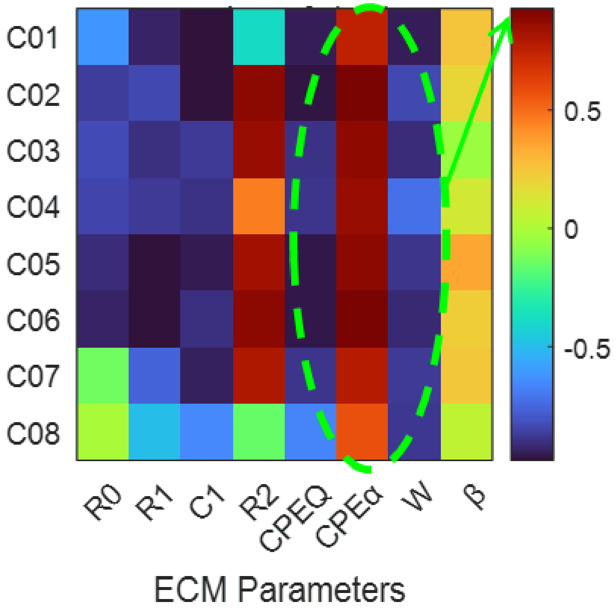
Pearson correlation coefficient (ρ)



ρ of real-part of Impedance (Z_{Re})



ρ of imaginary-part of Impedance (Z_{Im})

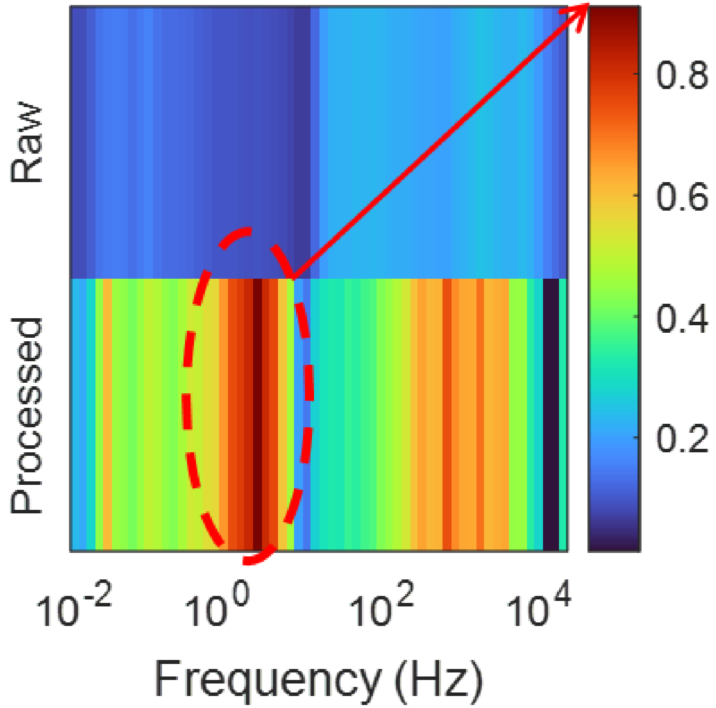


ρ of ECM parameters

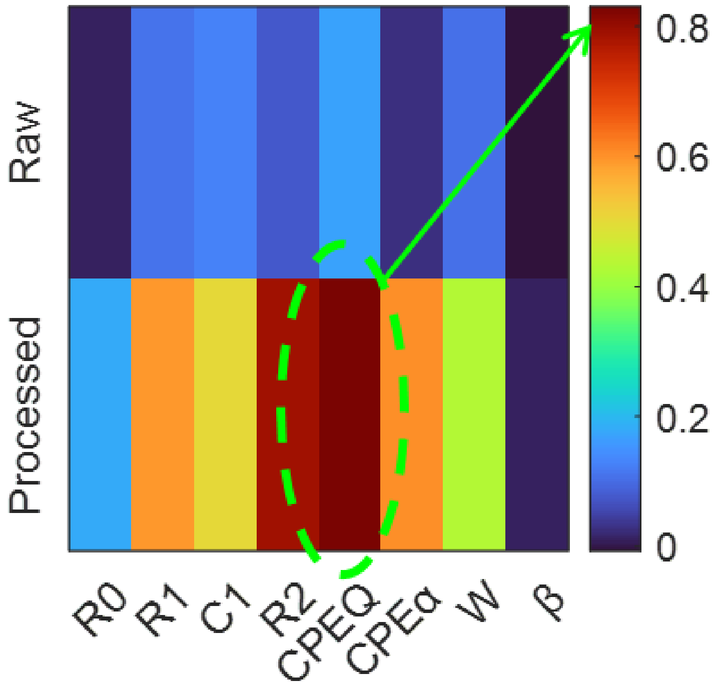
- The **imaginary** part of impedance, the **CPE**, and the **Warburg** element have a high correlation with the battery capacity for all cells

- Consistency Analysis for All Cells

Feature consistency coefficient (FC)



Feature consistency analysis of Z_{Im}

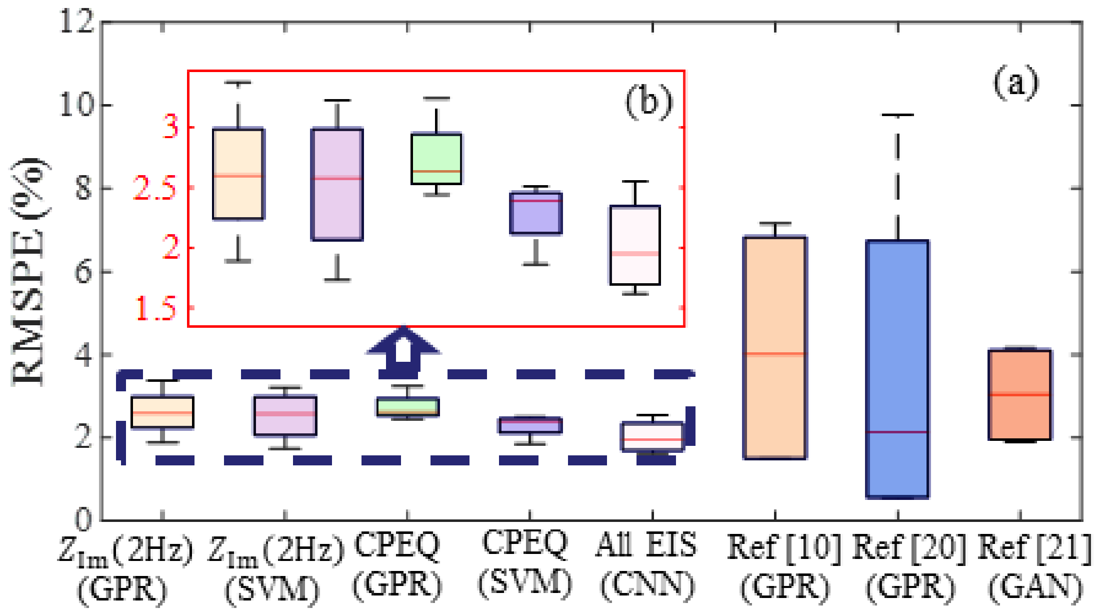


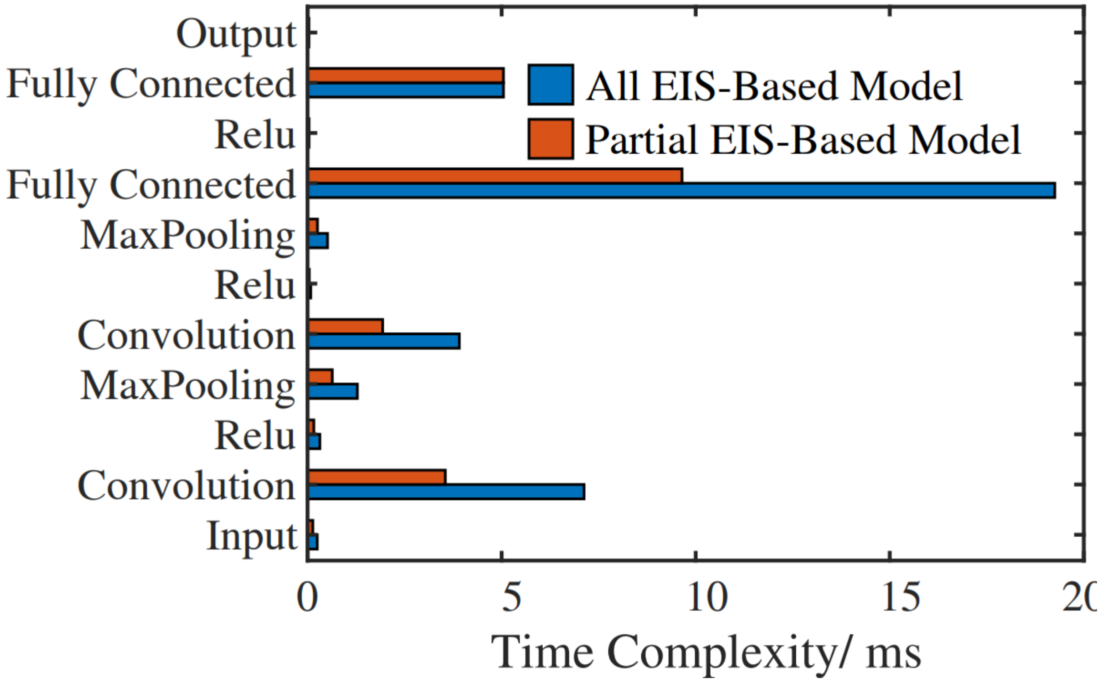
Feature consistency analysis of parameters of ECM

The pre-processed Z_{Im} at a frequency of **2 Hz (Z_{Im} (2Hz)),** and the **CPEQ** of ECM have the highest feature consistency

EIS FOR BATTERY CAPACITY ESTIMATION

- Results, Accuracy & Time Complexity





Robustness Analysis
- RMSE: Worst Case: 2.5%
- RMSE: Best Case: 1.4%

Time Complexity Analysis
- All-EIS-based CNN: 37.85 ms
- Partial-EIS-based CNN : 21.48 ms

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2. Z. Ning, P. Venugopal, T. B. Soeiro and G. Rietveld, "Computation-light AI models for Robust Battery Capacity Estimation based on Electrochemical Impedance Spectroscopy," in *IEEE Transactions on Transportation Electrification*, doi: 10.1109/TTE.2024.3435455.
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10. E. A. Boj, S. Azizighalehsari, P. Venugopal, G. Rietveld and T. Batista Soeiro, "A Distribution of Relaxation Time Approach on Equivalent Circuit Model Parameterization to Analyse Li-ion Battery Degradation," 2023 11th International Conference on Power Electronics and ECCE Asia (ICPE 2023 - ECCE Asia), Jeju Island, Korea, Republic of, 2023, pp. 1403-1409, doi: 10.23919/ICPE2023-ECCEAsia54778.2023.10213476.
11. M. Appelman, P. Venugopal and G. Rietveld, "Impact of Discharge Current Profiles on Li-ion Battery Pack Degradation," 2022 IEEE 20th International Power Electronics and Motion Control Conference (PEMC), Brasov, Romania, 2022, pp. 474-480, doi: 10.1109/PEMC51159.2022.9962917.
12. R. Eskandari, P. Venugopal and G. Rietveld, "Advanced Battery Management Systems with Integrated Battery Electronics," *2022 IEEE 20th International Power Electronics and Motion Control Conference (PEMC)*, Brasov, Romania, 2022, pp. 55-61, doi: 10.1109/PEMC51159.2022.9962868.
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Q&A

Battery Ageing • Battery Models • Battery Diagnostics • Battery Pack Design • Electromobility • Stationary Energy Storage • Energy System Analysis

AI-Powered Data Analysis for Battery Aging and Safety Assessment

ECCE Europe 2024

9/3/2024
Dr.-Ing. Weihan Li

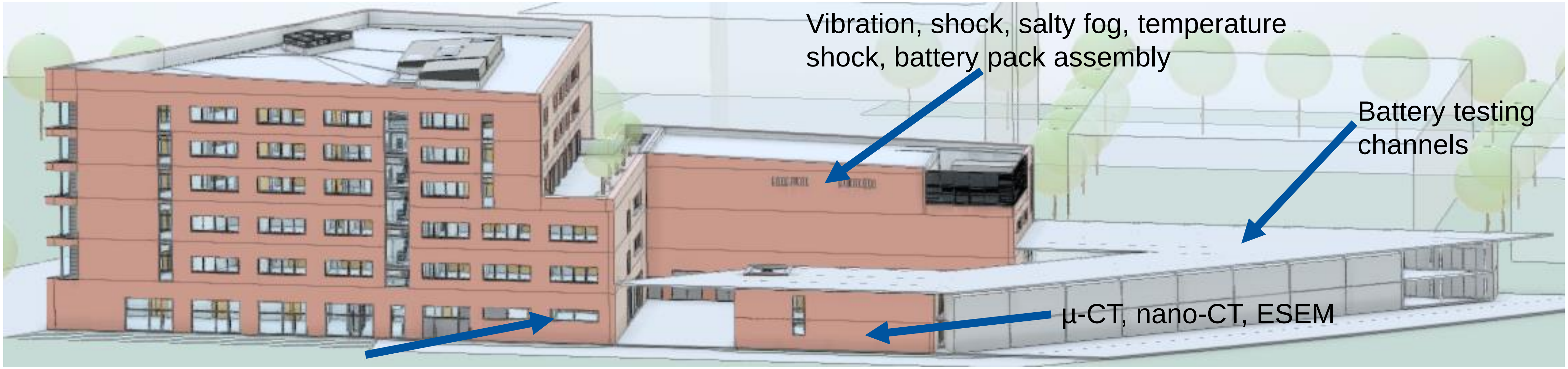
Center for Ageing, Reliability and Lifetime Prediction of Electrochemical and Power Electronic Systems (CARL)

CARL Center for Ageing, Reliability and Lifetime Prediction of Electrochemical and Power Electronic Systems | RWTH AACHEN UNIVERSITY

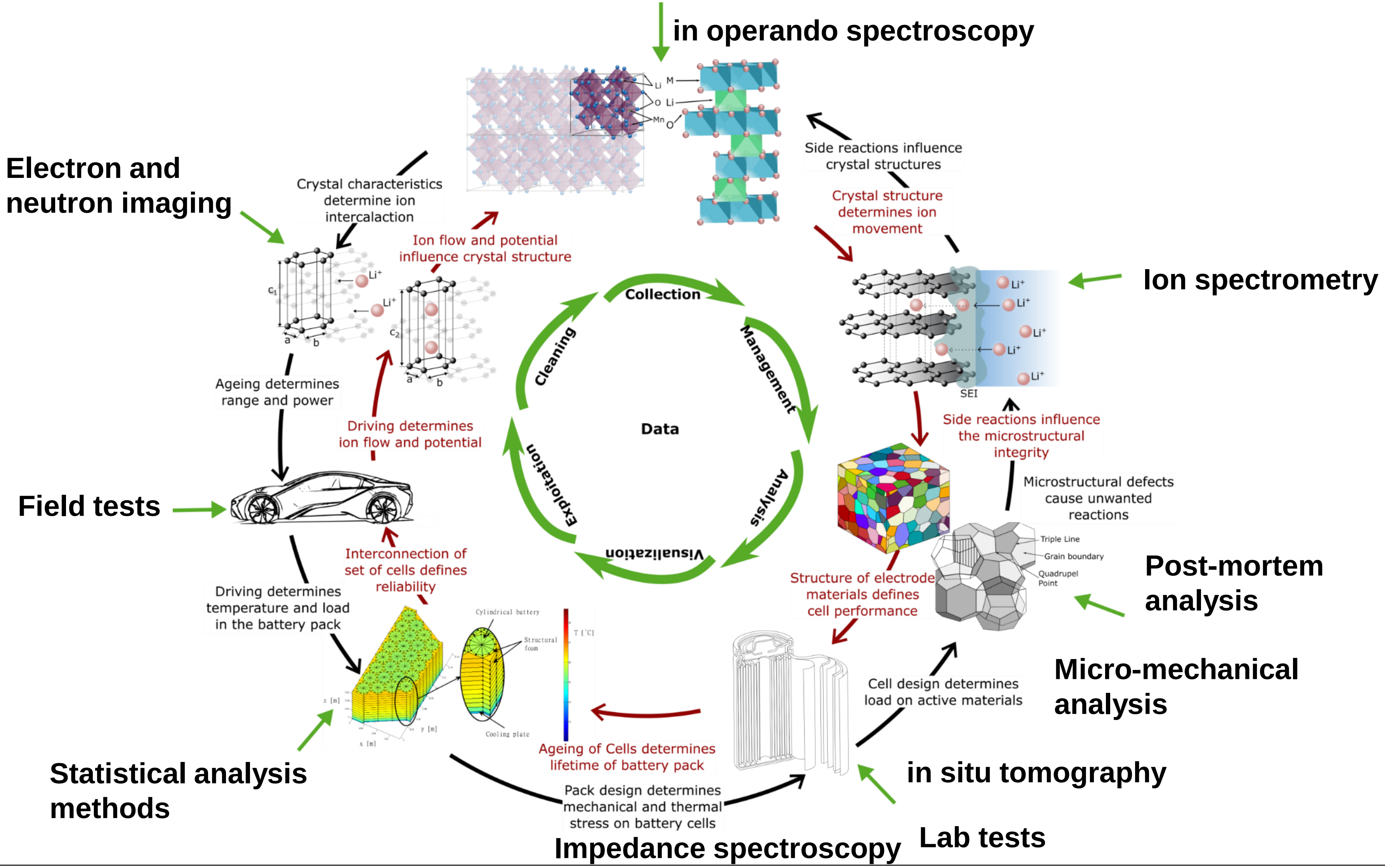
Center for Ageing, Reliability and Lifetime Prediction for Electrochemical and Electronics systems – Supporting battery applications and battery production

- $2150 m^2$ office area
- $2750 m^2$ laboratory area
- >150 researchers
- 120 Mio. € investment

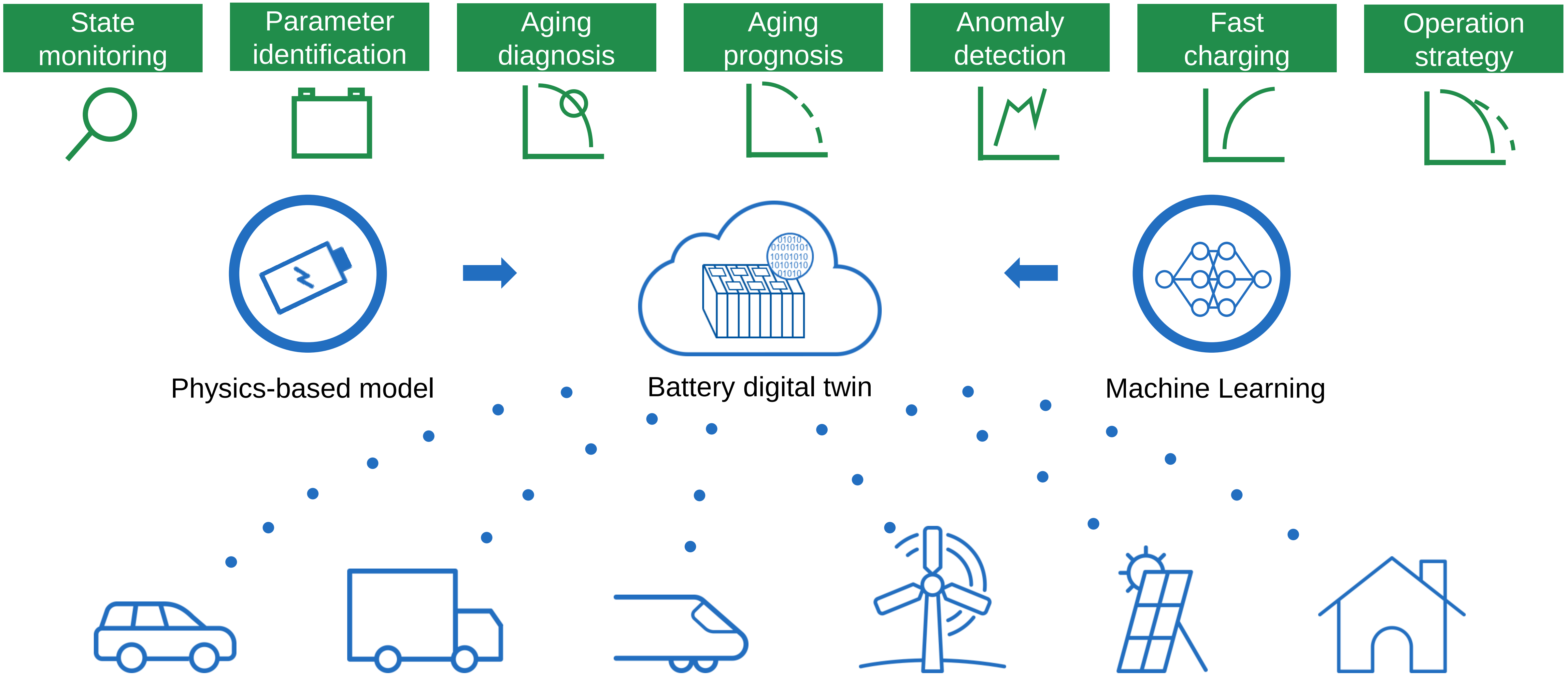
- >4000 battery testing channels
- Environmental stress lab
- Chemistry lab
- Clean room & Drying room
- CT & Microscopy



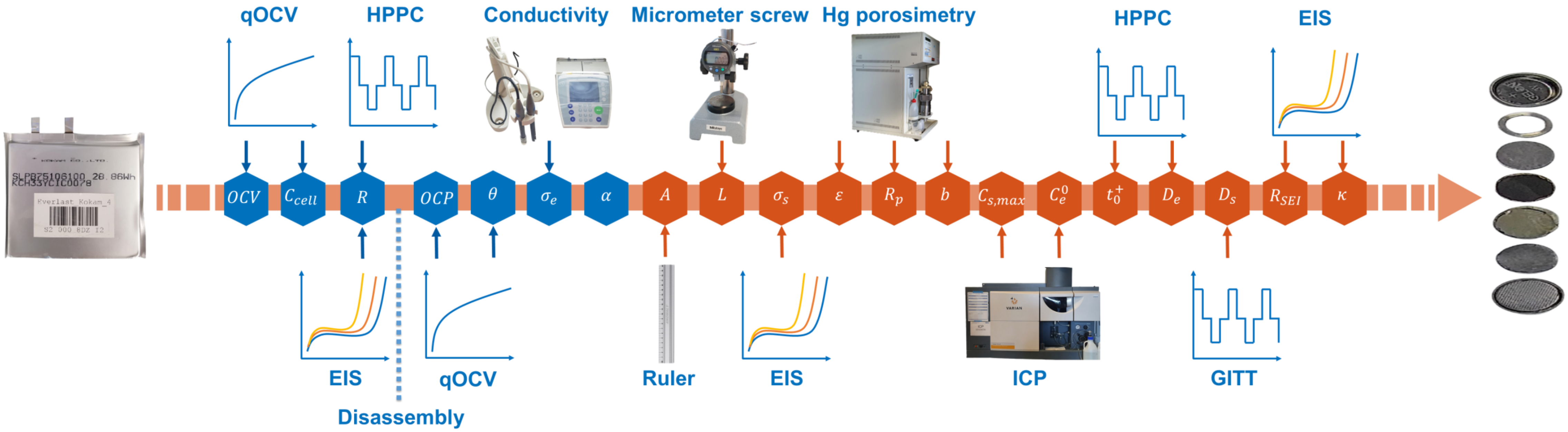
Circle of Innovation



Machine learning for safe, efficient and sustainable battery use

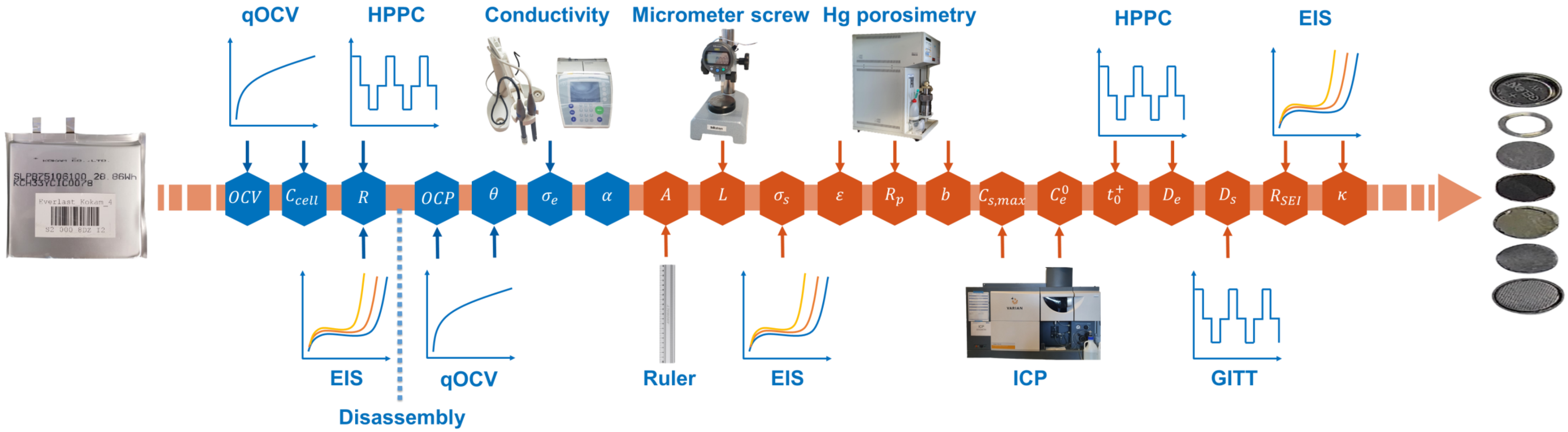


State-of-the-art experimental parameter measurements



Li W, et al., Energy Storage Materials, **2022** (44): 557-570.

State-of-the-art experimental parameter measurements



Li W, et al., Energy Storage Materials, **2022** (44): 557-570.

Results: Experimental vs. Data-driven

- Lower RMSE under constant-current discharging

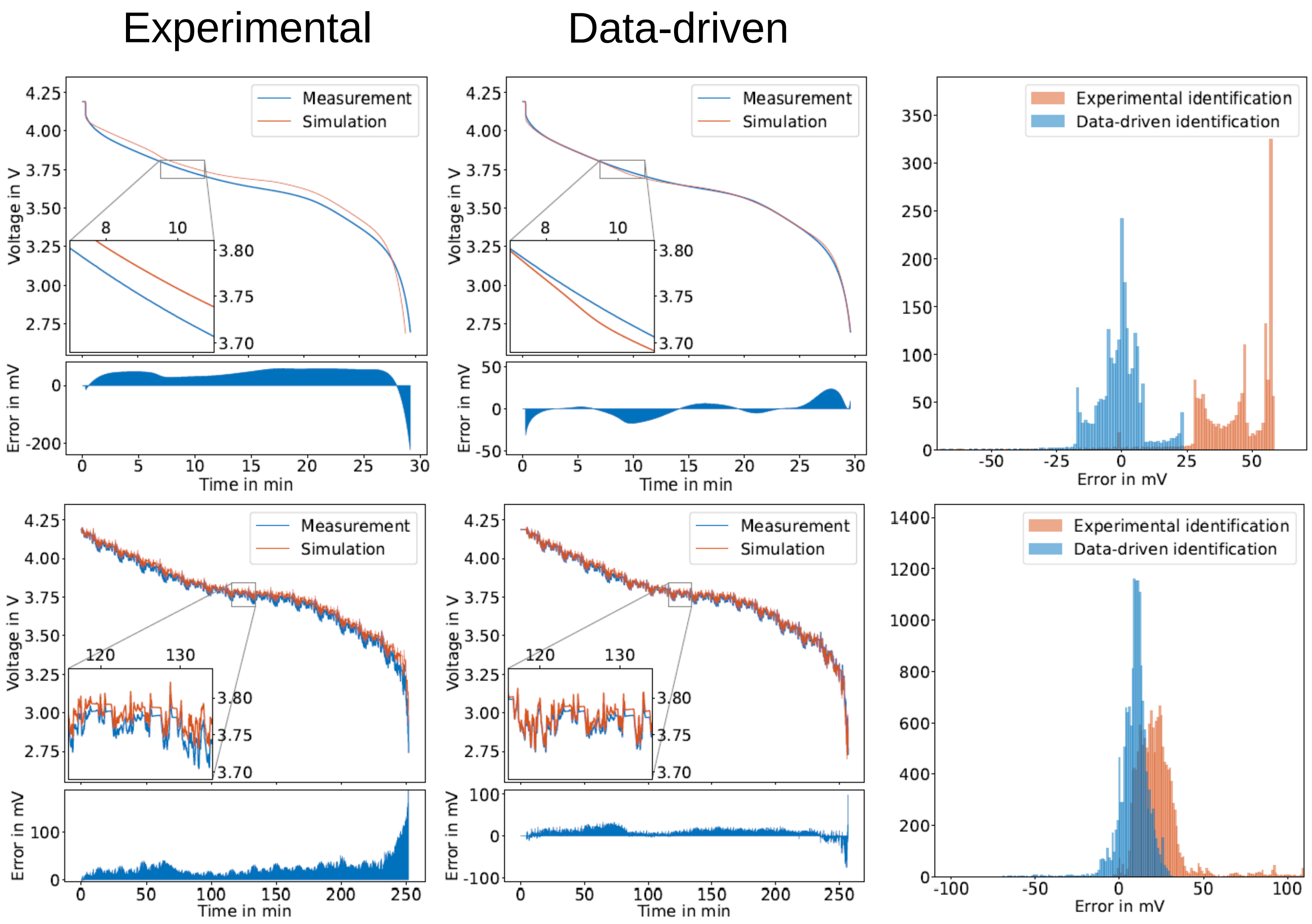
18.0%

- Lower RMSE under driving cycles

67.1%

- Lower electrode capacity errors

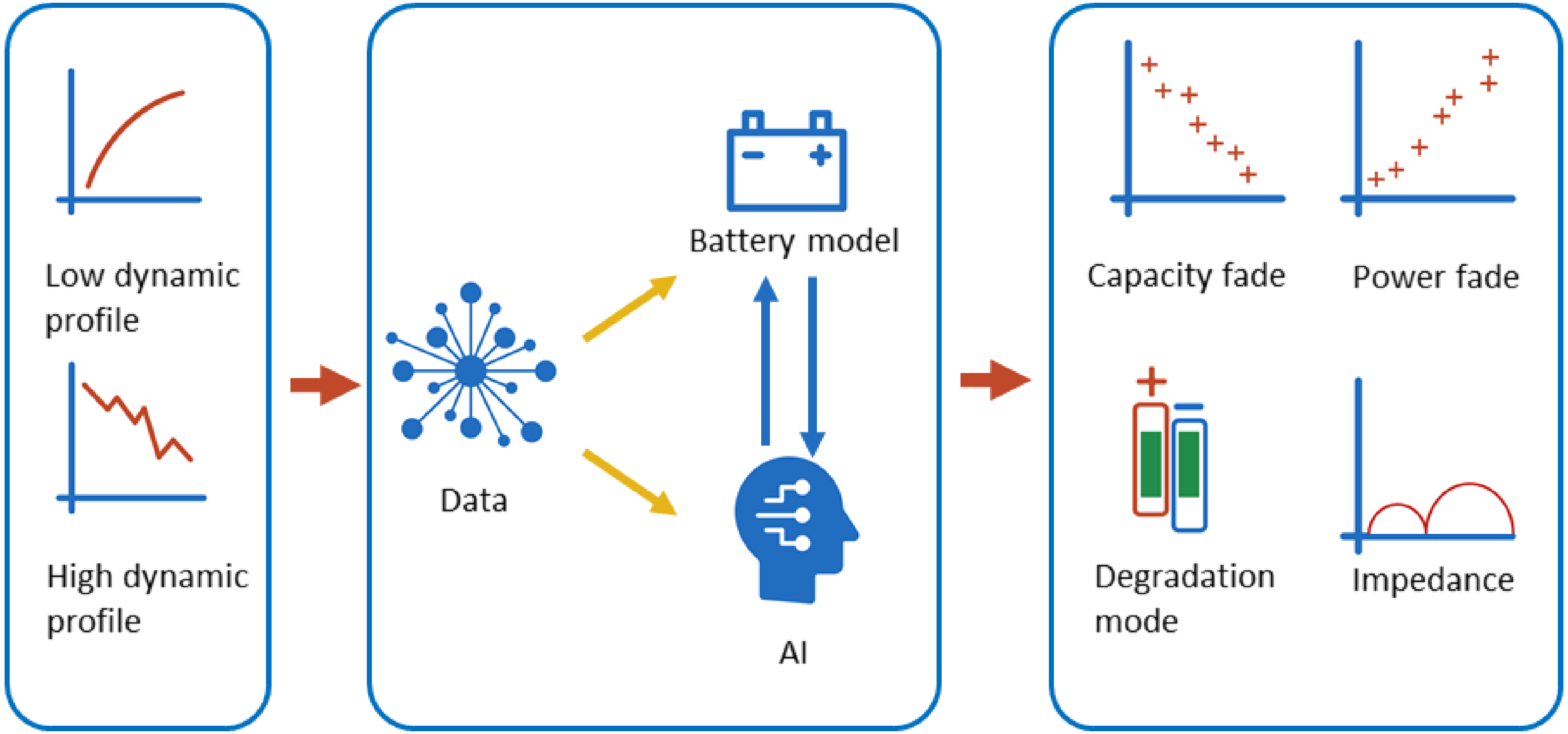
4.6%



Li W, et al., Energy Storage Materials, **2022** (44): 557-570.

Online aging diagnosis by integrating physics and AI

- Data
  - Low-dynamic profile
  - High-dynamic profile
- Battery model
  - Impedance-based model
  - OCV model
- Artificial Intelligence
  - Cuckoo search algorithm



Li W, et al. **2022,** Energy Storage Materials, 53, 391-403.

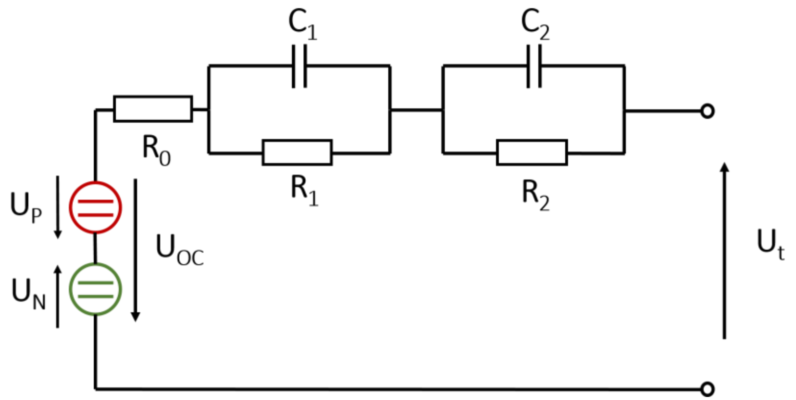
Combining the impedance-based model and OCV reconstruction model

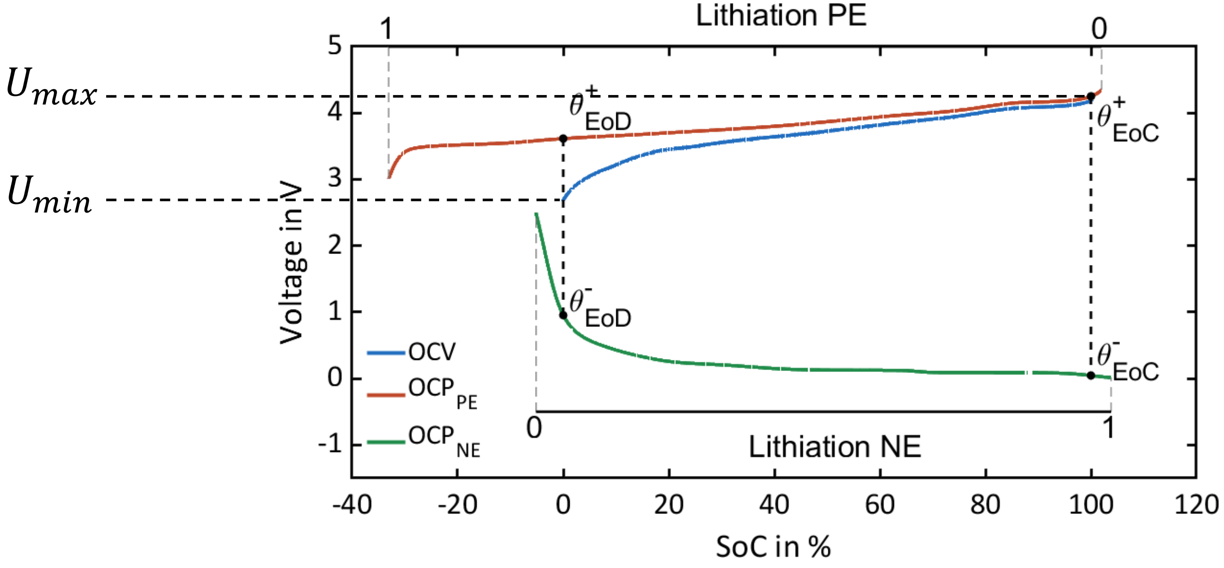
- Equivalent-circuit model
  - Ohmic resistance
  - Charge transfer
  - Diffusion
- OCV reconstruction model
  - Electrode OCP
  - OCV balancing parameters
  - Cut-off voltages: U_{max}, U_{min}

$\theta^{+}_{EOD}, \theta^{+}_{EOC}, \theta^{-}_{EOD}, \theta^{-}_{EOC}$ → OCV

U_{max}, U_{min}

$\theta^{+}_{EOD}, \theta^{-}_{EOD}$ → OCV

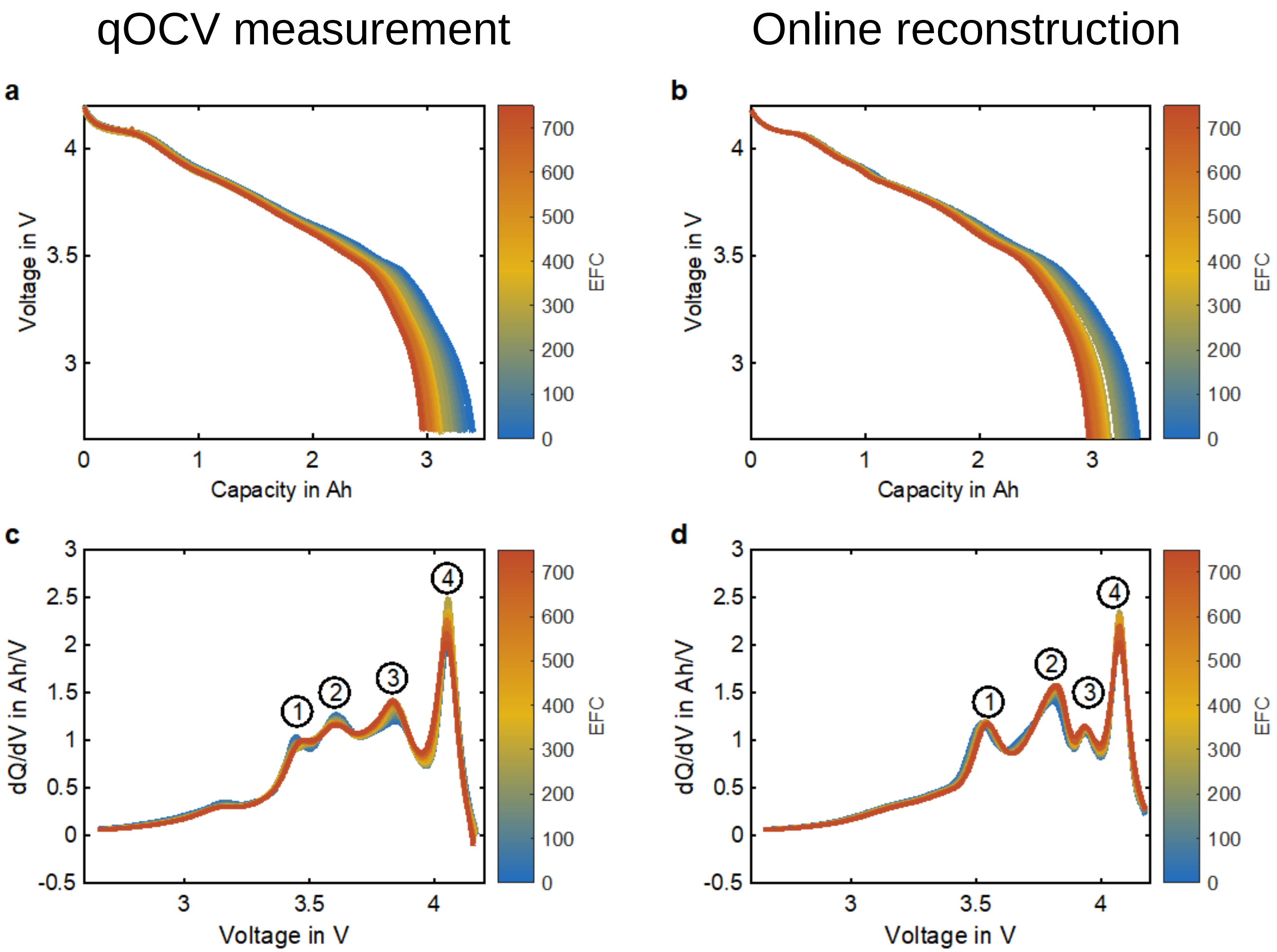




Li W, et al. **2022,** Energy Storage Materials, 53, 391-403.

Online OCV reconstruction

- OCV reconstruction
  - Benchmark: qOCV test
- Incremental capacity analysis
  - Qualitative evaluation of the degradation modes



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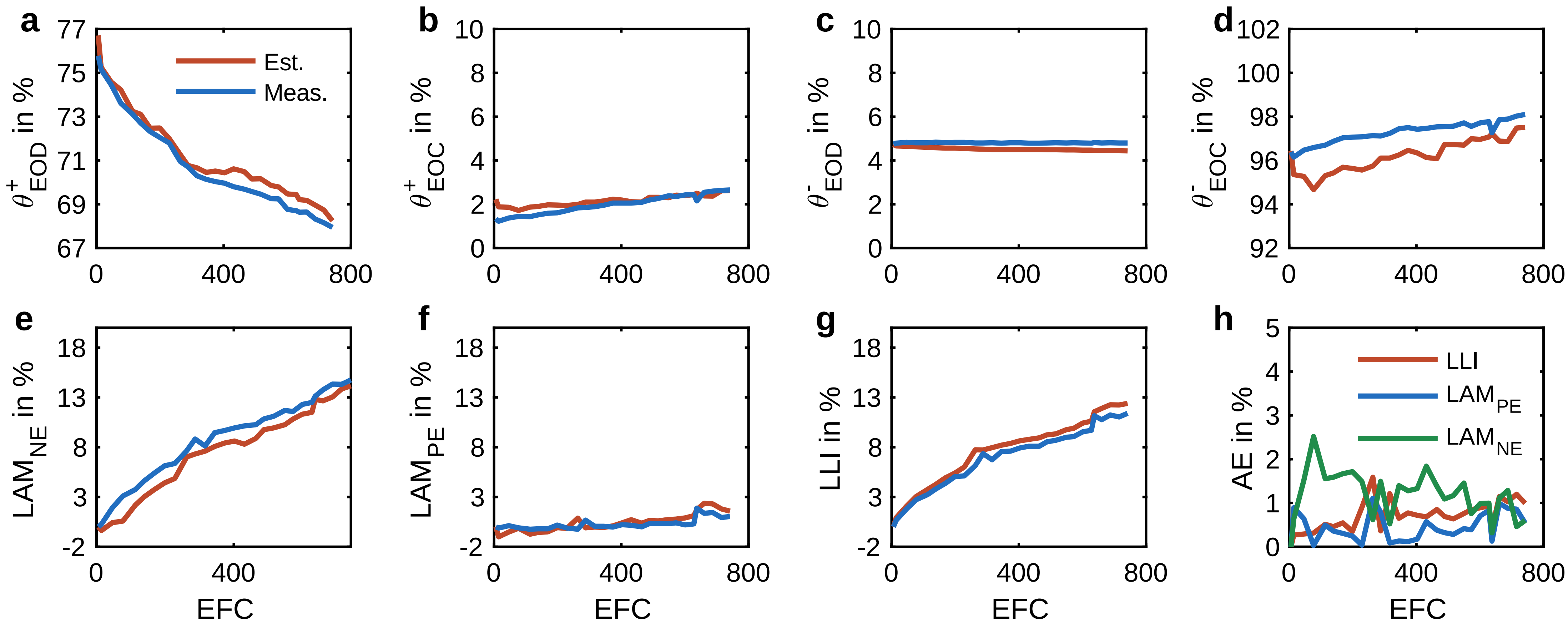
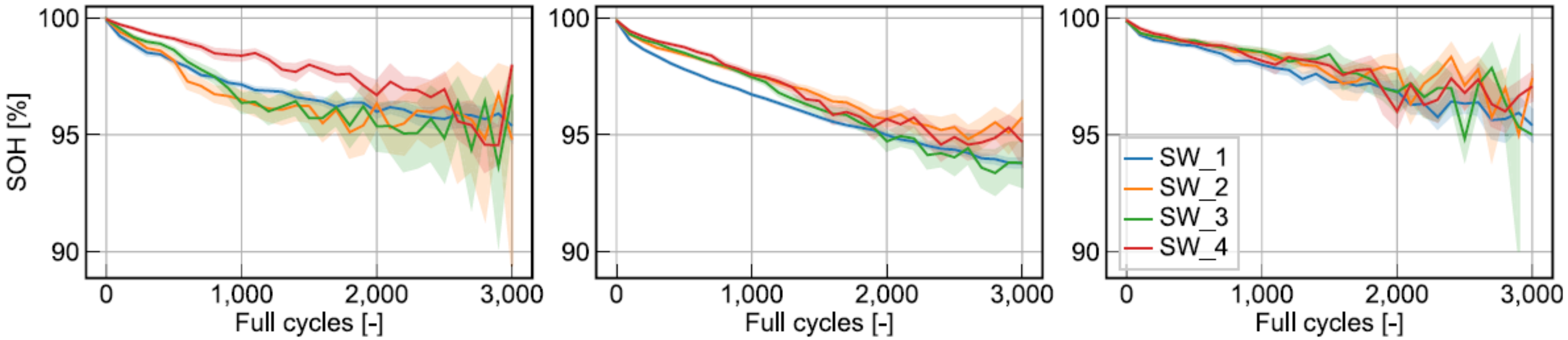
Online aging mode identification

- Identification results of stoichiometric parameters and degradation modes



Li W, et al. **2022,** Energy Storage Materials, 53, 391-403.

Overview of the variables in field data



Name	Description	Value range
Single values		
SOH	state of health at readout	[0, 100] (%)
SOC	state of charge at readout	[0, 100] (%)
energy_throughput	total battery energy throughput until readout	[0, 8,000] (kWh)
voltage	battery voltage at readout	[0, 70] (V)
current	battery current at readout	[−1,500, 1,500] (A)
temperature	battery temperature at readout	[−126, 126] (°C)
Histogram values		
$time\_soc\_x, x \in [1, 10]$	time spent in SOC range [0, 10, 20, …, 100] (%)	$[0, 2^{32} - 1]$ (s)
$time\_temperature\_x, x \in [1, 6]$	time spent in temperature range [0, 0, 20, …, >70] (°C)	$[0, 2^{32} - 1]$ (s)
$(dis)charge\_temperature\_x, x \in [1, 6]$	(dis)charge in temperature range [0, 0, 20, …, >70] (°C)	$[0, 2^{32} - 1]$ (Ah)
$number\_dod\_x, x \in [1, 7]$	number of DODs in range [0, 1.1, 2.2, …, >9.9] (Ah)	$[0, 2^{32} - 1]$ (counts

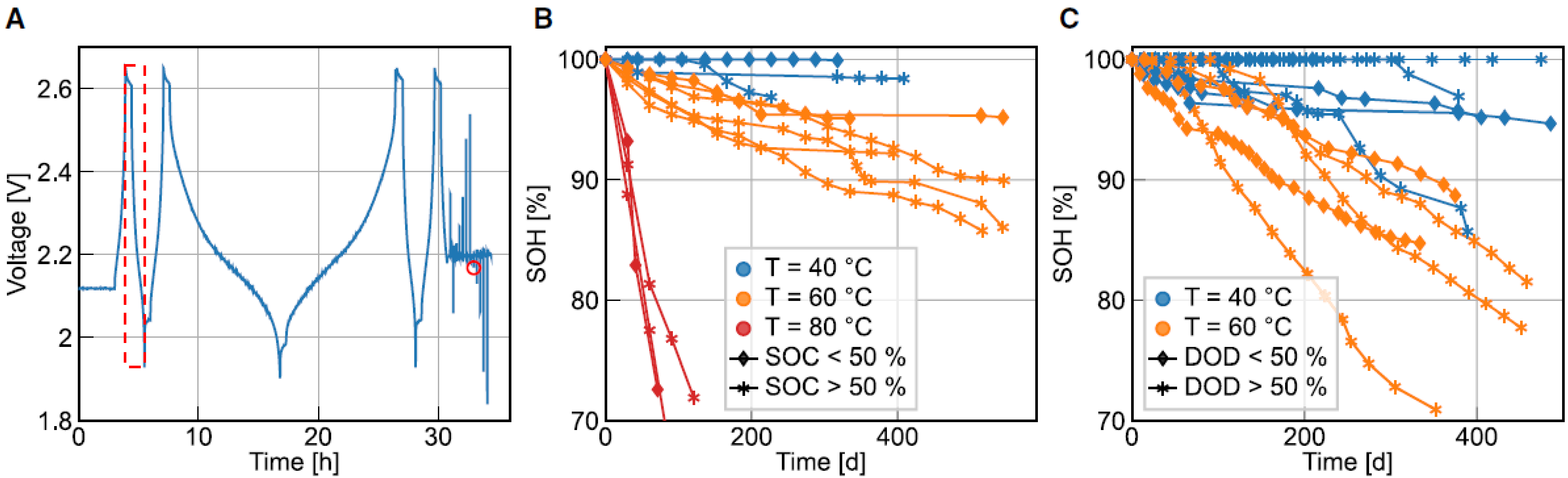
V. Steininger, et al., Cell Reports Physical Science 4, 101596, 2023.

Laboratory data for both calendar and cyclic aging

Checkup test

Calendar aging test

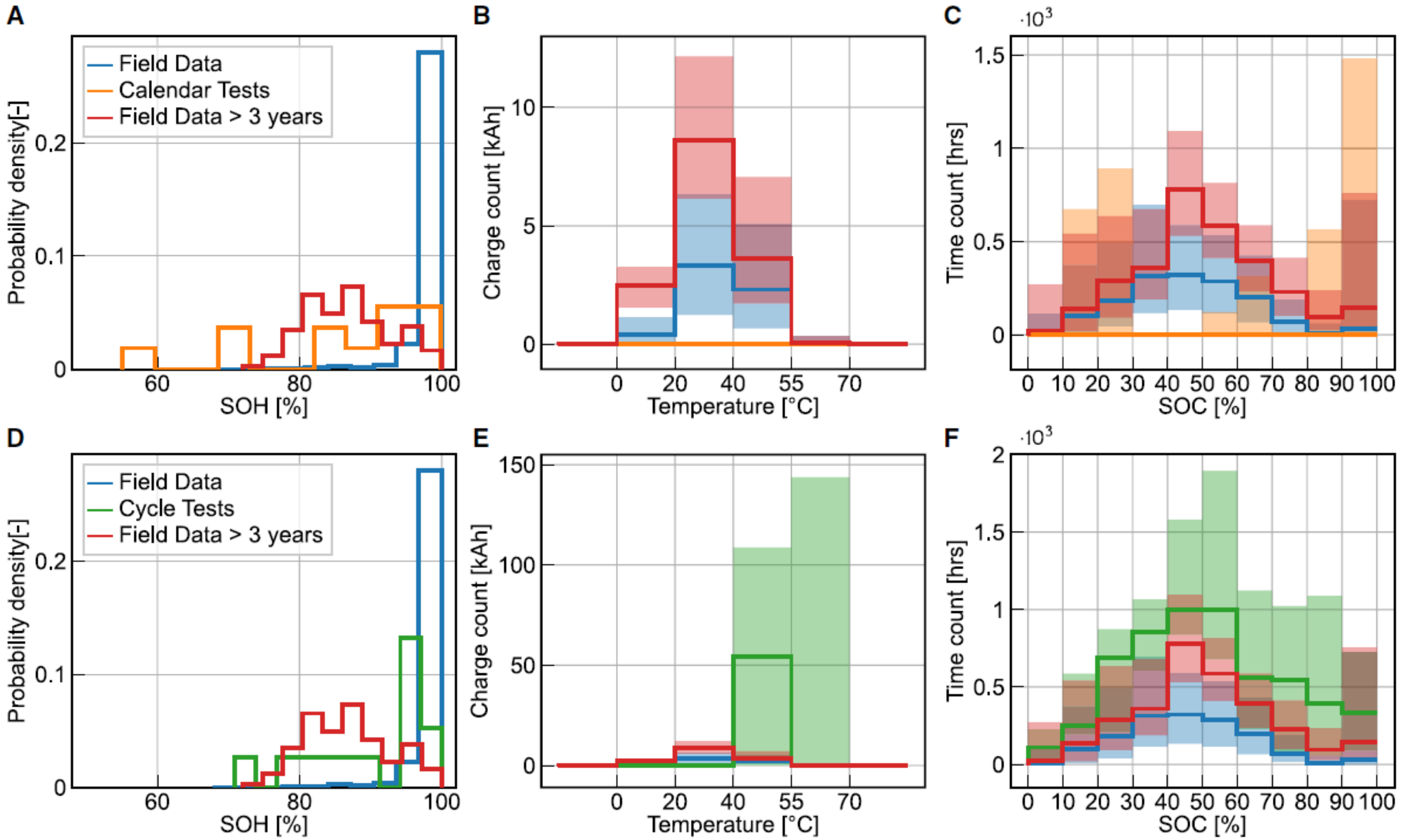
Cyclic aging test



V. Steininger, et al., Cell Reports Physical Science 4, 101596, 2023.

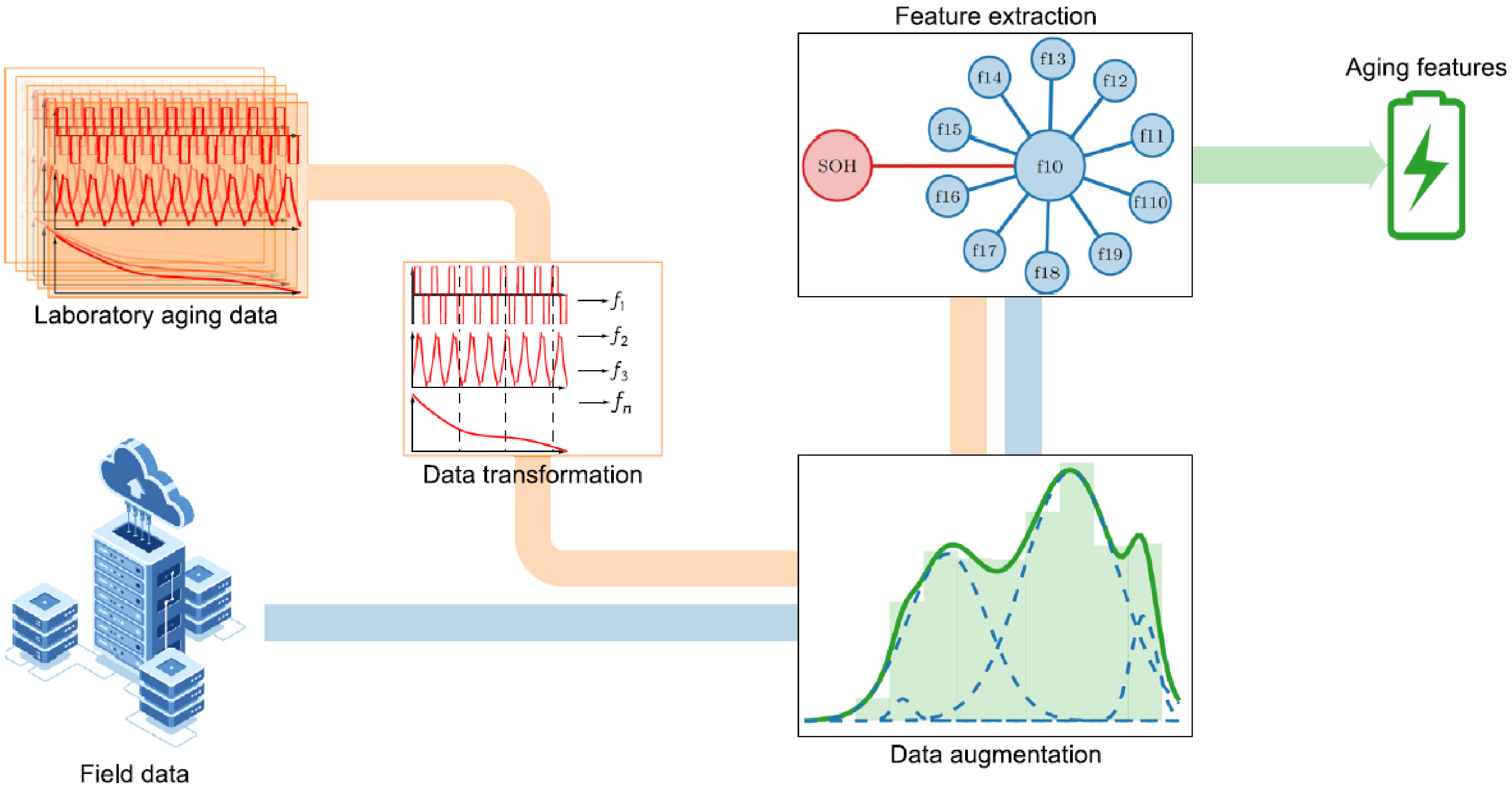
Field data vs. laboratory data for aging diagnosis

- Field data from 600.000 vehicles
- Laboratory data from both calendar and cyclic ageing tests



V. Steininger, et al., Cell Reports Physical Science 4, 101596, 2023.

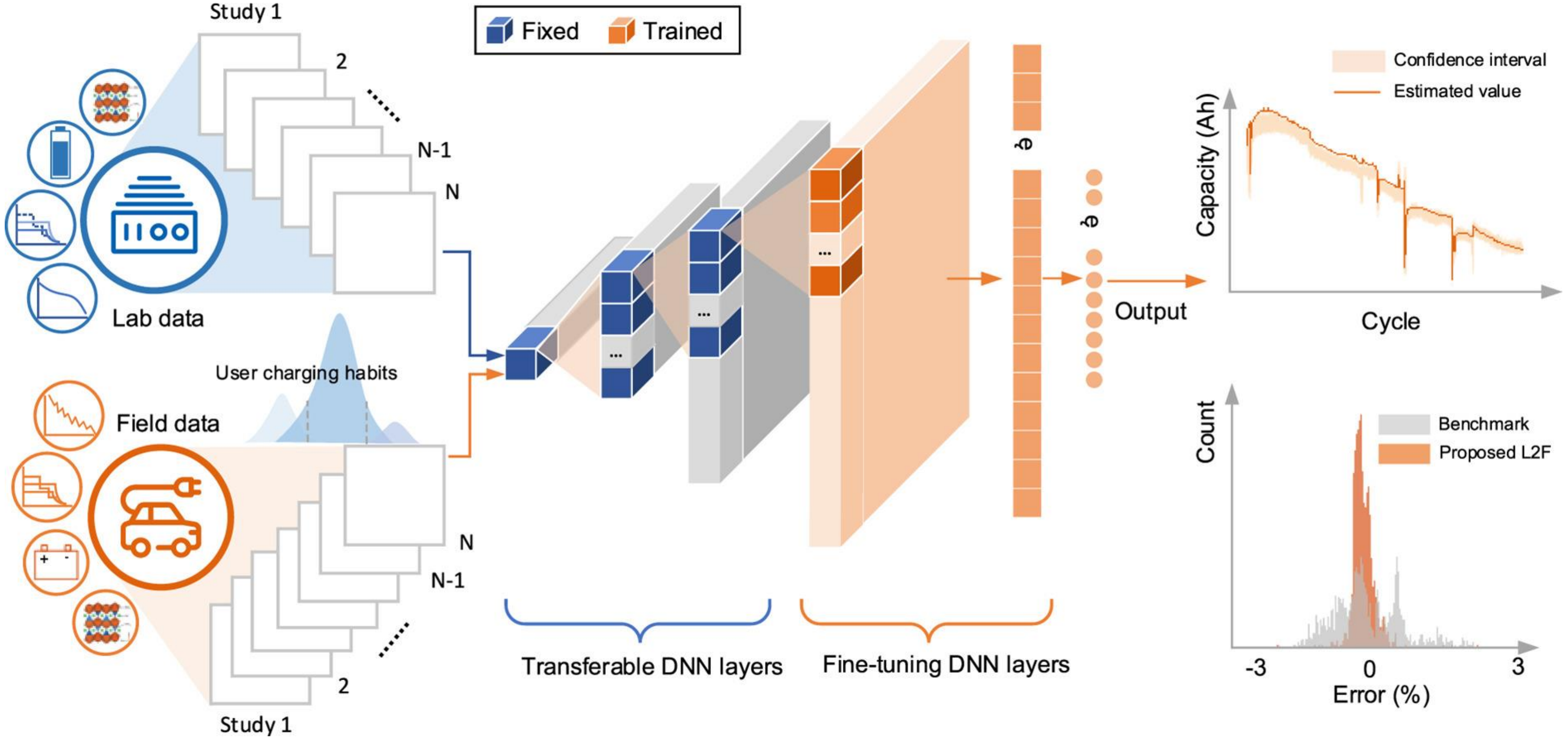
Feature extraction framework to integrate laboratory and field data



V. Steininger, et al., Cell Reports Physical Science 4, 101596, 2023.

Transferable capacity estimation from laboratory to field

- Automatic feature extraction and dimension increasing with physical interpretation.
- Uncertainty awareness of charging protocols, charging habits and production quality.
- Only using 100 s charging data in the determined voltage window.



Q. Wang, et al., Applied Energy, 350, 121747, 2023.

Challenges in battery aging prediction

Manufacturing | Depth of Discharge | Temperature | Time | State of Charge | Current load | Mechanical stress

Capacity fade | Power fade

First life

https://www.zdnet.com/article/electric-vehicles-are-the-future/

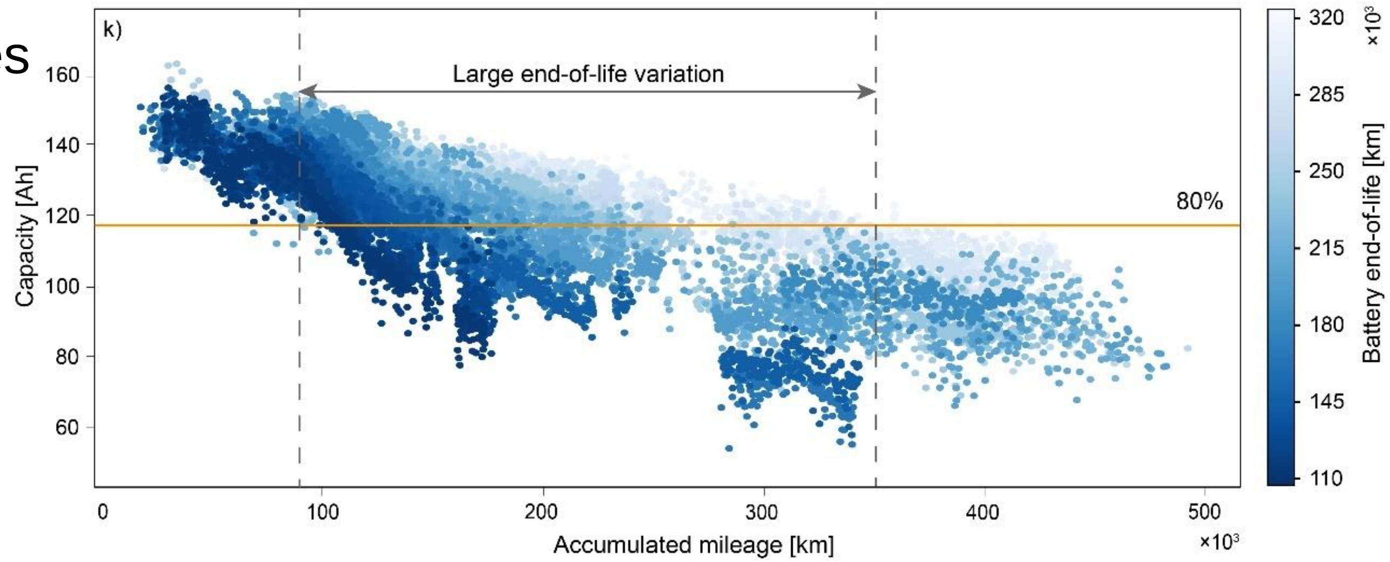
- How long is the 1st life?
- What is the residue value after 1st life?
- How long is the 2nd life?
- How reliable is the battery in 2nd life?
- Which 2nd life use case is more suitable?

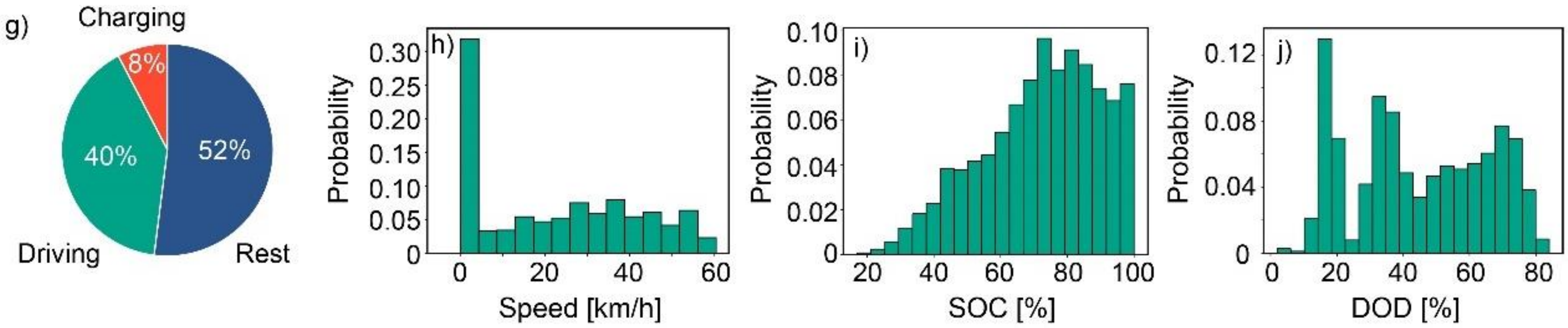
Second life

https://institutional.bnpparibas-am.com/what-you-need-to-know-about-polysilicon-and-its-role-in-solar-modules/

Lifetime prediction from large-scale field data

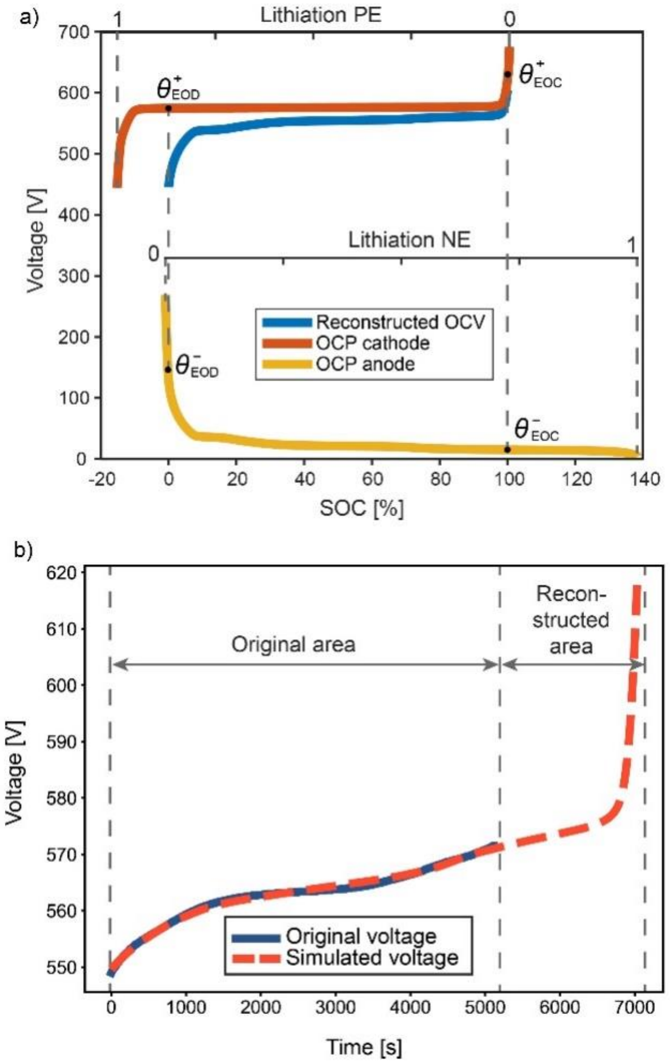
- Real-world operating data of electric buses
  - 60 EVs
  - Over 3 years of time, 400k km of mileage
  - 48 GB data, 240 million rows
  - Over 100 raw features





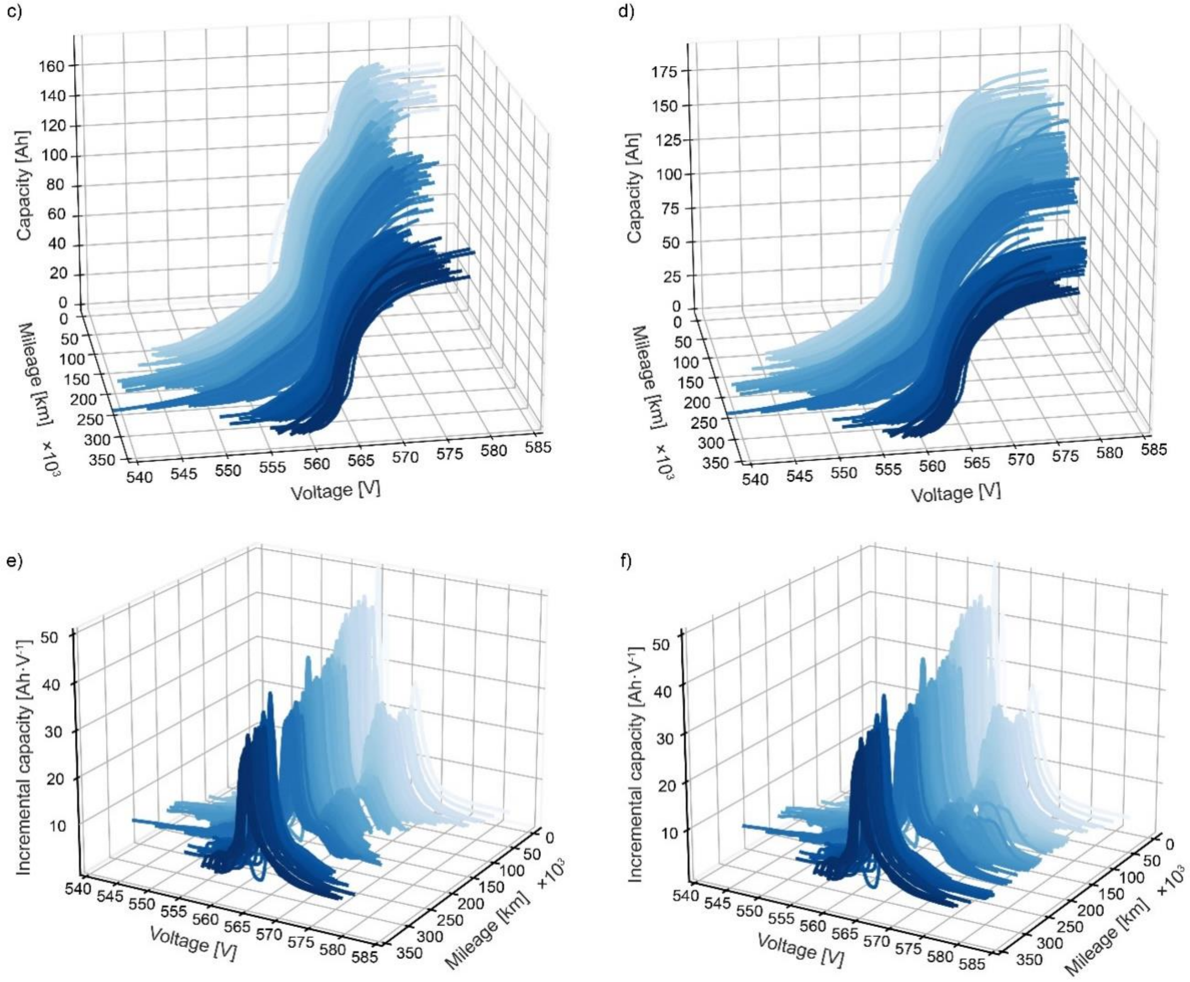
Q. Wang, et al., Cell Reports Physical Science, 2023.

Data preprocessing and charging curve reconstruction



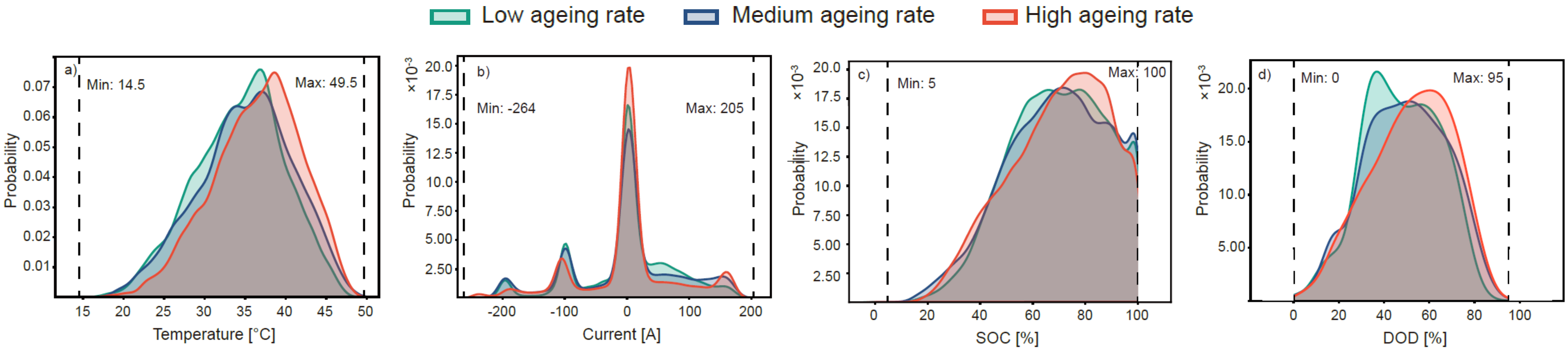
Raw data

Reconstructed data



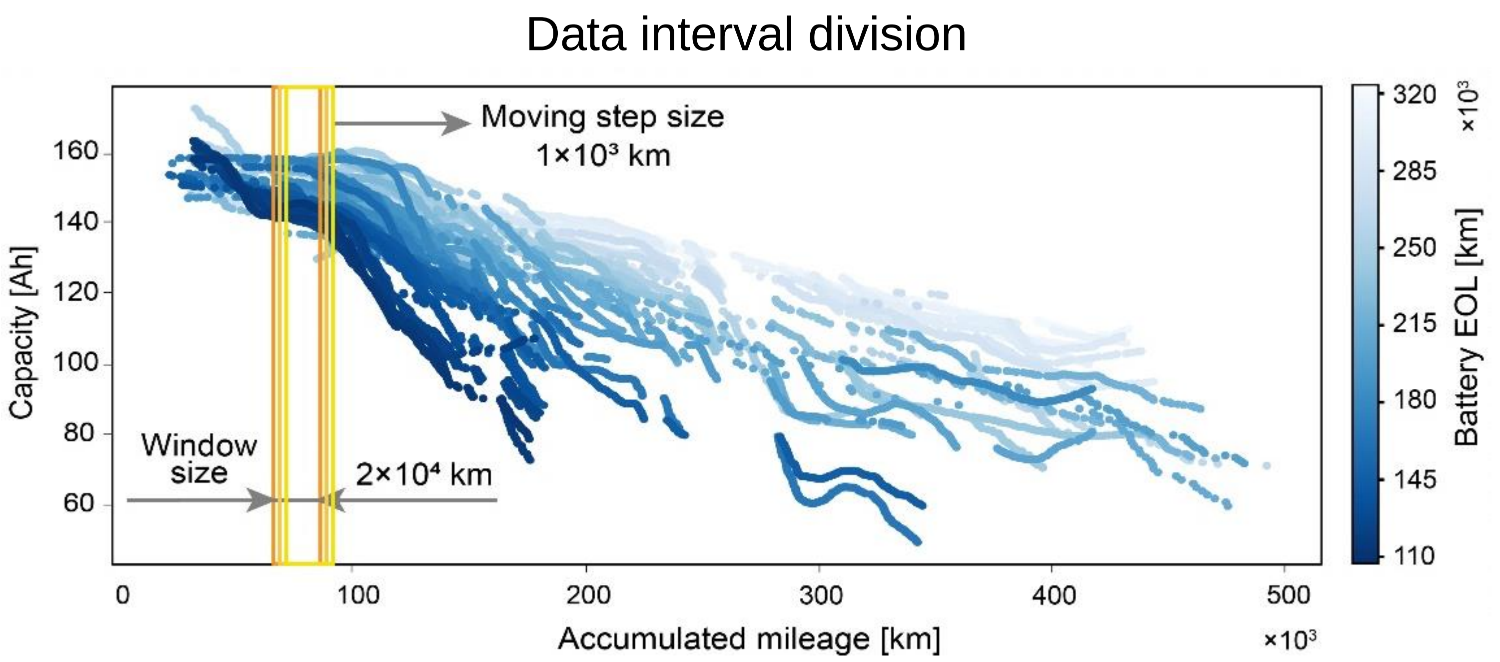
Q. Wang, et al., Cell Reports Physical Science, 2023.

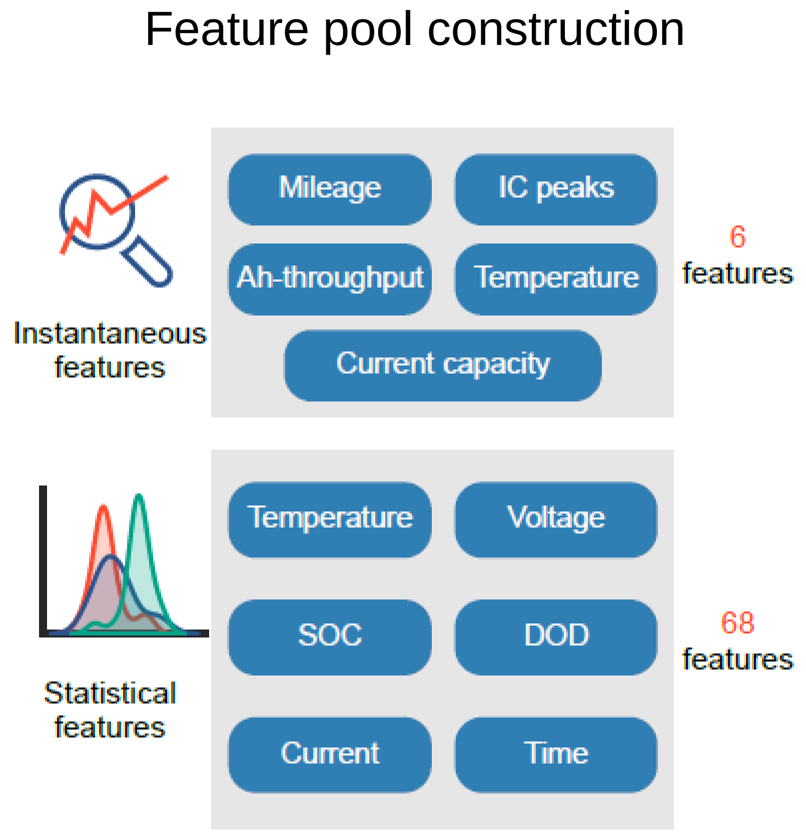
Statistical distributions of stress factors of vehicles with different ageing rates



Q. Wang, et al., Cell Reports Physical Science, 2023.

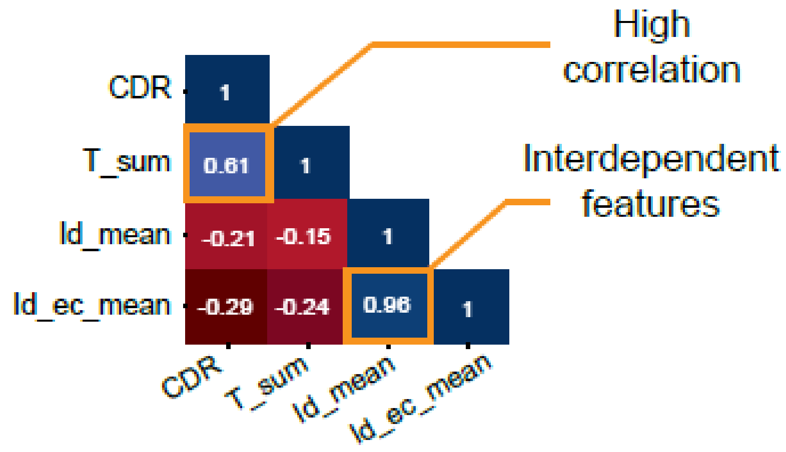
Statistical feature engineering with multi-level strategy



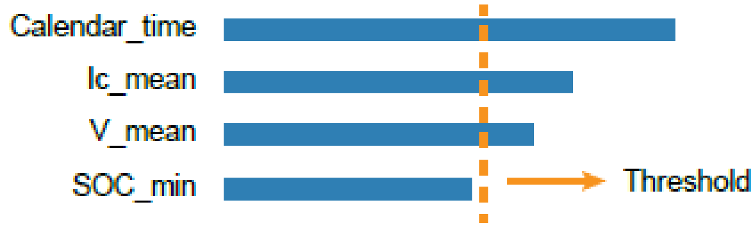


Q. Wang, et al., Cell Reports Physical Science, 2023.

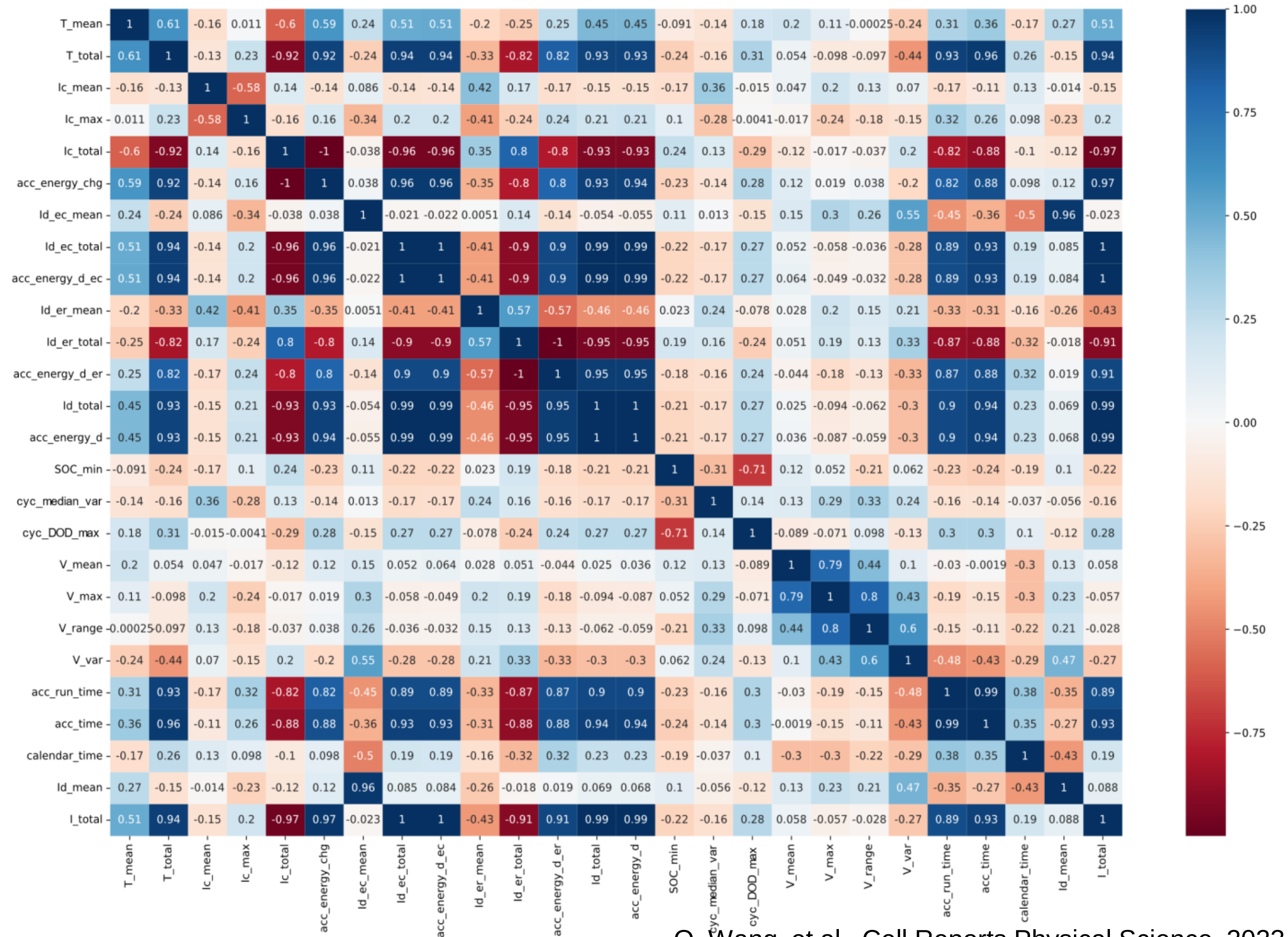
Feature selection with correlation analysis



Correlation analysis

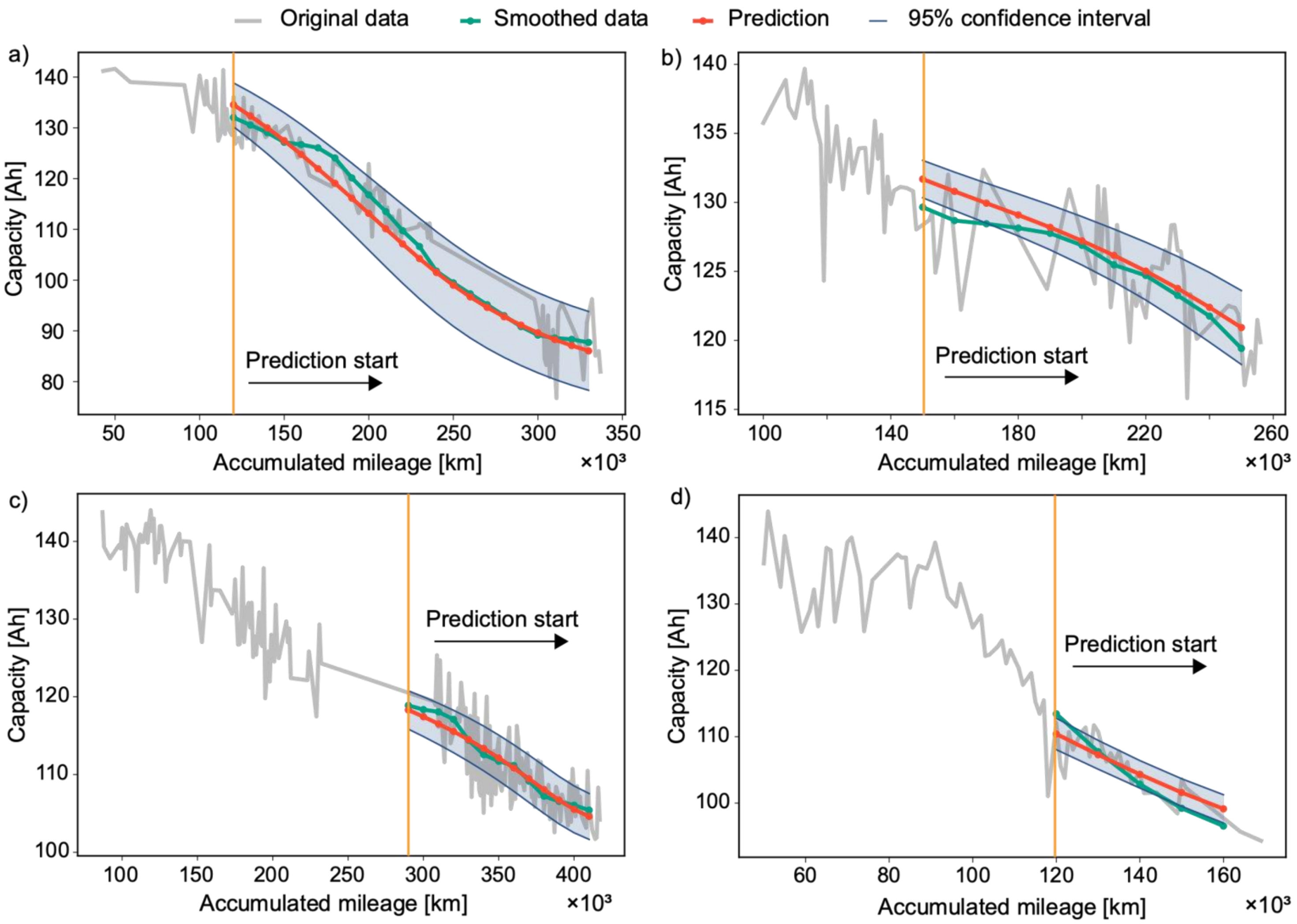


LightGBM feature importance



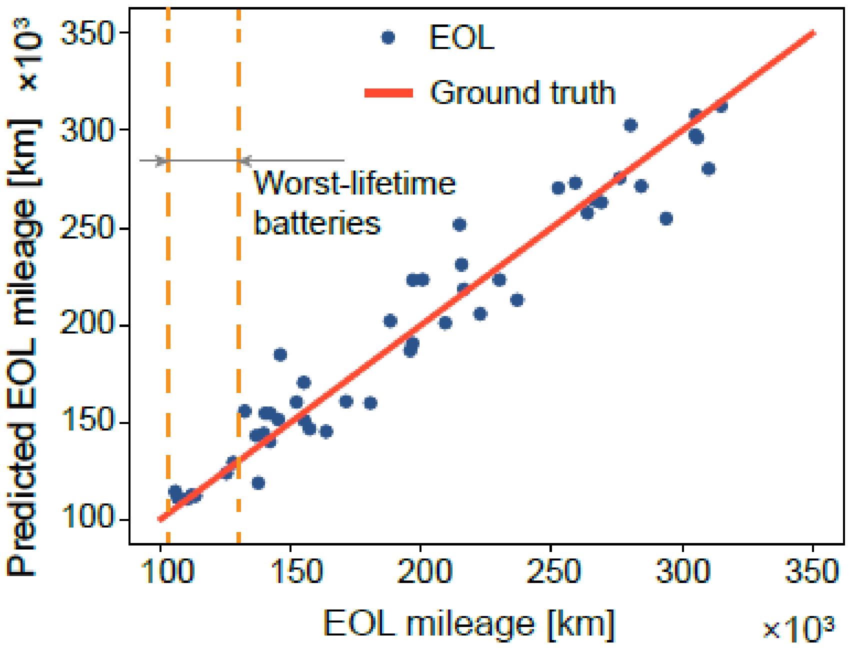
Q. Wang, et al., Cell Reports Physical Science, 2023.

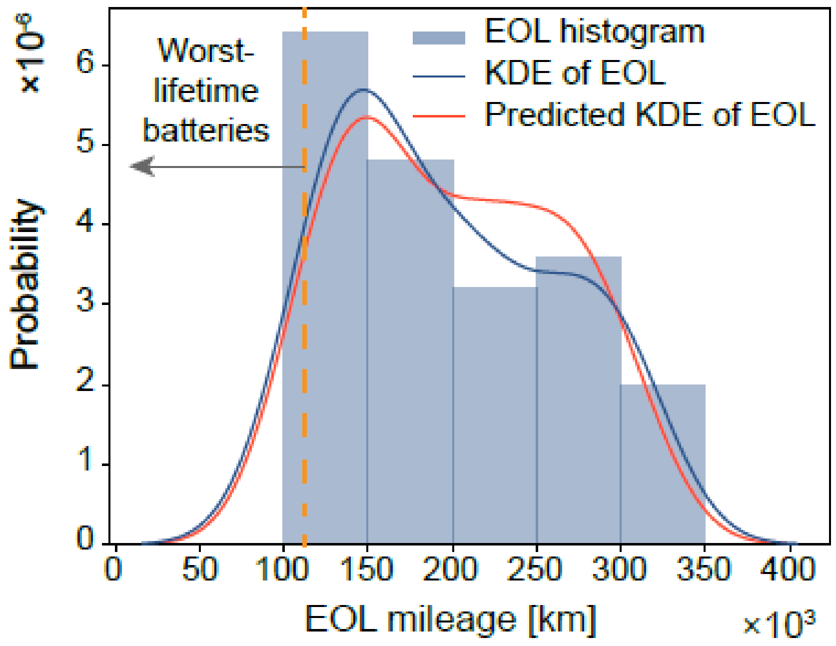
Uncertainty-aware degradation prediction



Q. Wang, et al., Cell Reports Physical Science, 2023.

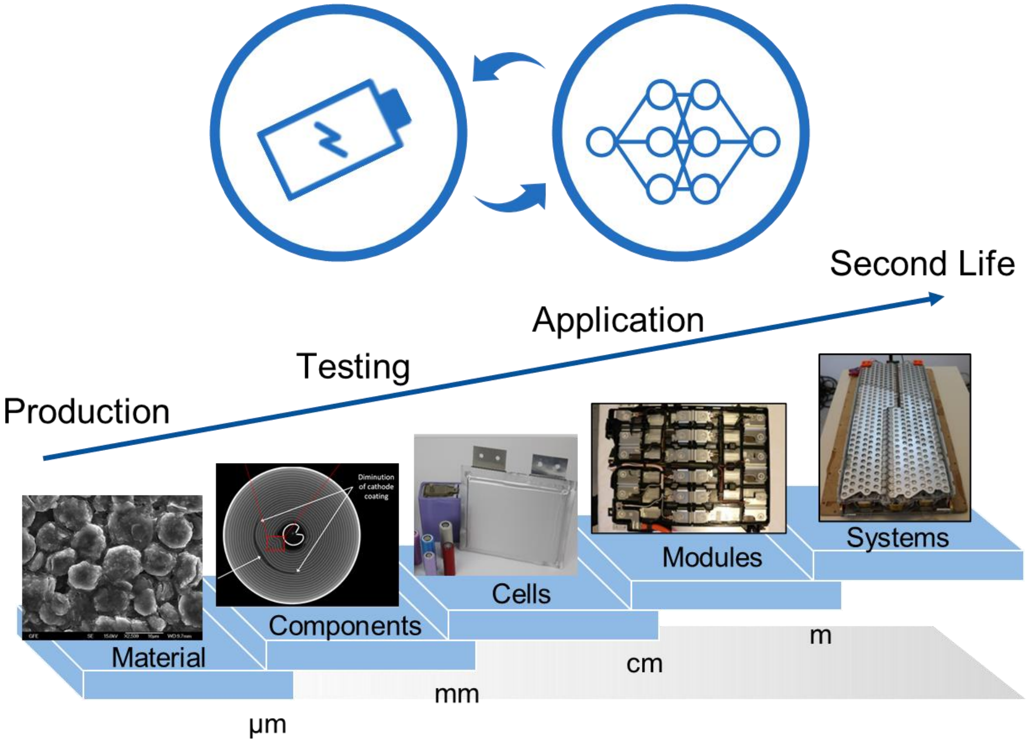
Failure distribution is as important as lifetime prediction for warranty





Q. Wang, et al., Cell Reports Physical Science, 2023.

Artificial Intelligence for Batteries @ RWTH Aachen University



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Kompetenzcluster Batterienutzungskonzepte

MARIE CURIE ACTIONS

Ministerium für Kultur und Wissenschaft des Landes Nordrhein-Westfalen


Hanna Hoch


Daniel Bergmann


Paul Busch


Justin Herdegen


Thorsten Tegetmeyer-Kleine


Runyang Lian


Thomas Ngo


Daniel Luder


Jue Chen


Satish Rapol