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

Battery Digital Twin with Physics, Data and AI

ESIA, Strasbourg, France

4/14/2025
Prof. 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

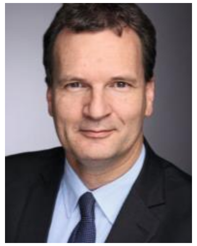
RWTH AACHEN UNIVERSITY

Center for Ageing, Reliability and Lifetime Prediction for Electrochemical and Power Electronic Systems – Supporting battery applications, production and material design

- State government and Federal government invest about 110 Million Euros for building this center in Aachen
- 5000 m^2 of net area for laboratories and offices
- 5000 battery testing channels and environmental stress lab
- Chemical labs for post-mortem analysis and material analysis
- Clean room & Dry room, CT & Microscopy
- Largest university research group in Europe for battery system technologies
  - More than 30 years of experience in battery system technologies
  - More than 80 researchers
  - More than 10 million € total budget per year

Prof. Martin Winter

Prof. Egbert Figgemeier



Prof. Dirk Uwe Sauer

Prof. Weihan Li

Prof. Joachim Mayer

Prof. Christoph Broeckmann

PD Dr. Gunther Brunklaus

Prof. Rik W. De Doncker

Prof. Maria Kateri

Prof. Hans-Georg Steinrück

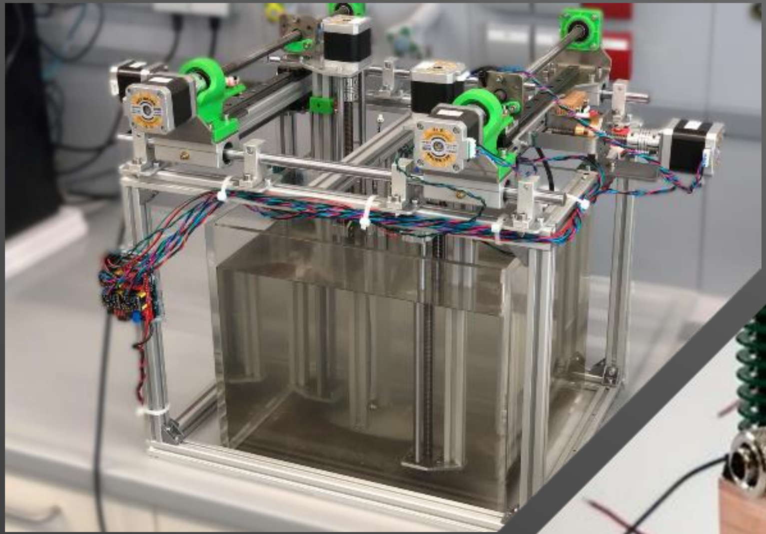
- Interdisciplinary team from chemistry, physics, mathematics, material science, electrical and mechanical engineering

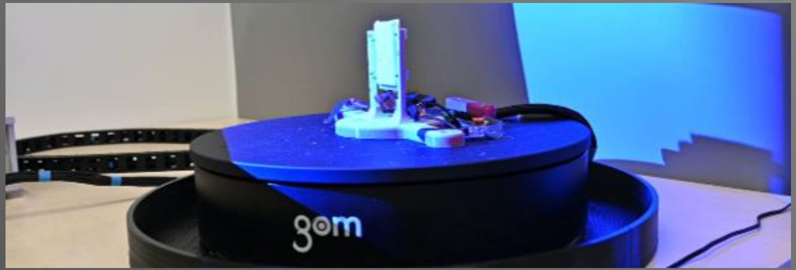
Center for Ageing, Reliability and Lifetime Prediction for Electrochemical and Power Electronic Systems – Supporting battery applications, production and material design

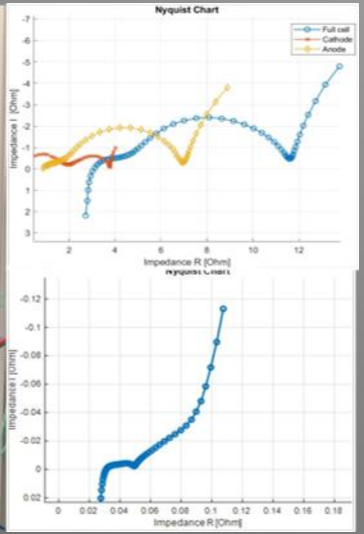
Post Mortem Laboratory

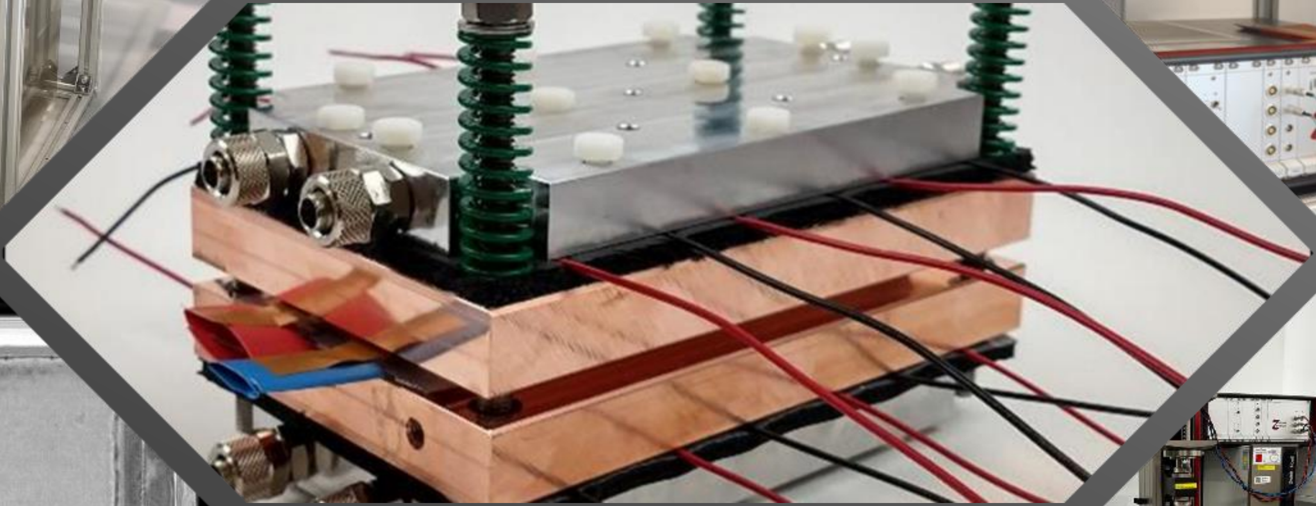
Battery Testing

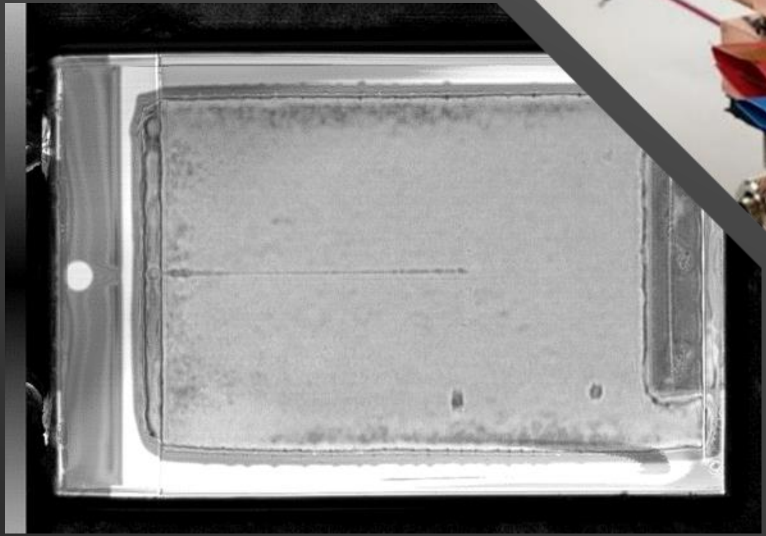
Battery Sensors

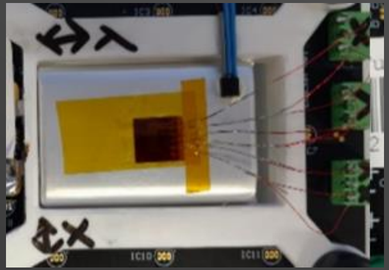


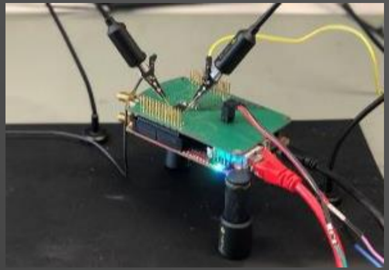


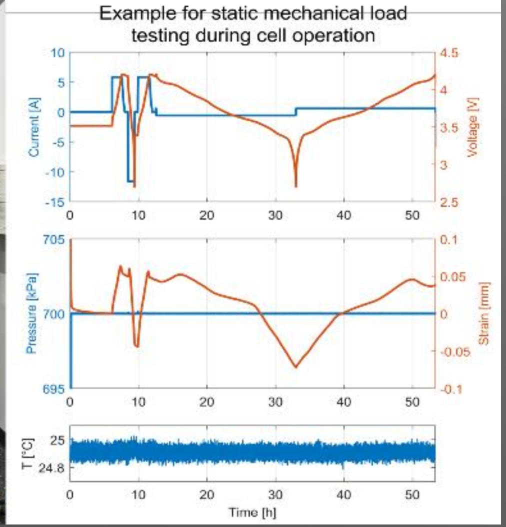






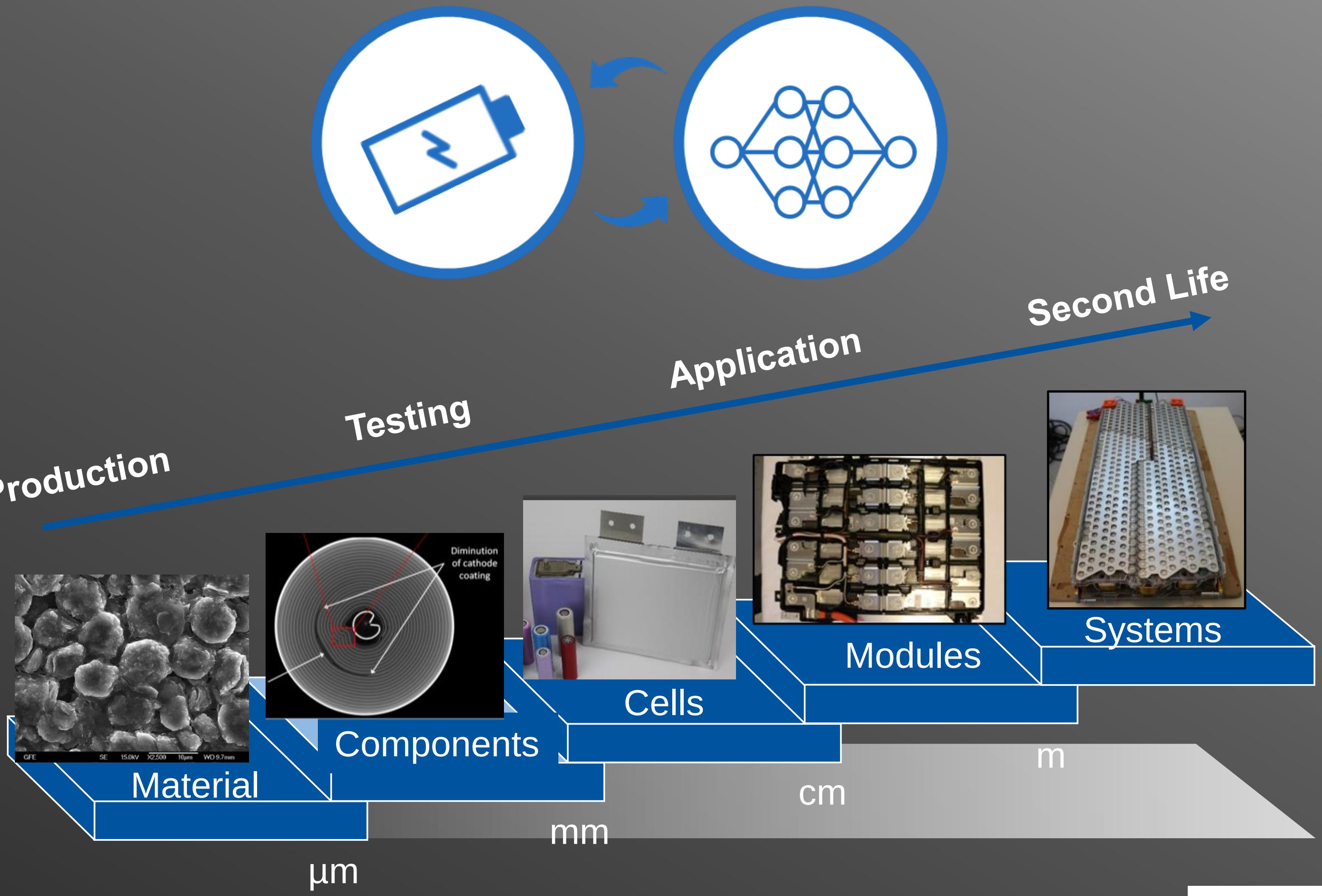






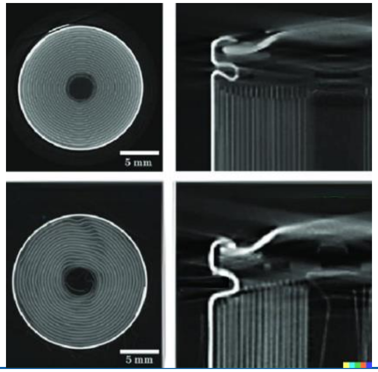
Environmental Loads

Research Group Artificial Intelligence and Digitalization for Batteries

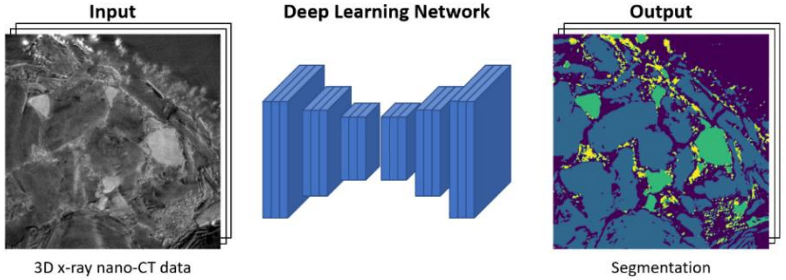


Research at Battery Material & Component Level

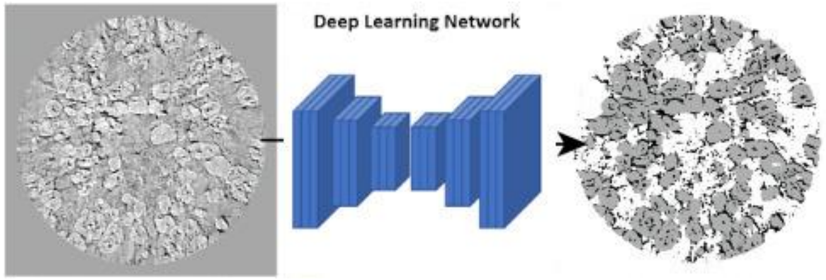
- Anomaly Detection in Battery Production



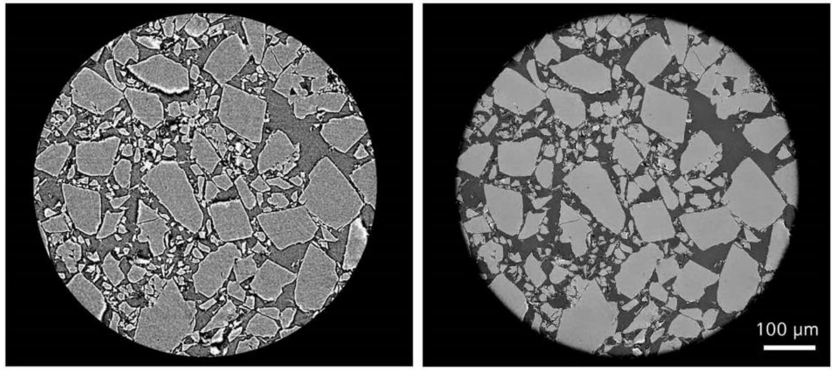
- Supervised Segmentation for Battery Analysis



- Denoising CT images with deep learning



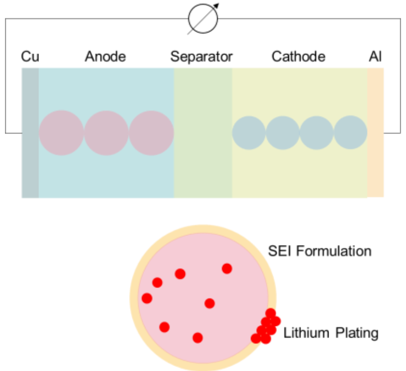
- Enhancing CT images with deep learning



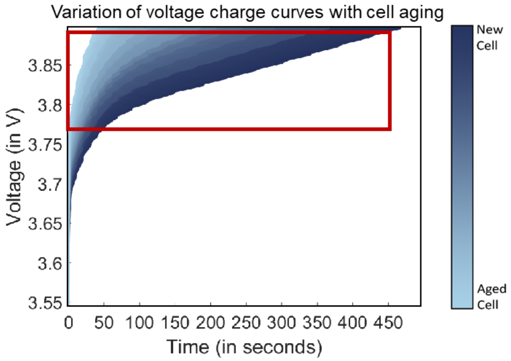
Research at Battery Cell Level

- Digital twin

- Parameter identification



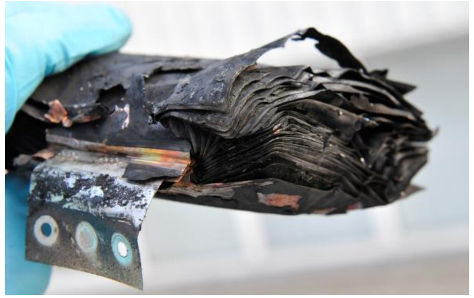
- Aging diagnosis



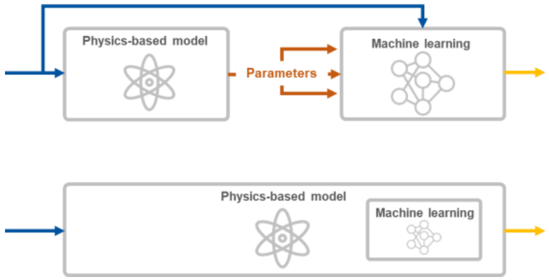
- Fast characterization for production line

- Battery state estimation

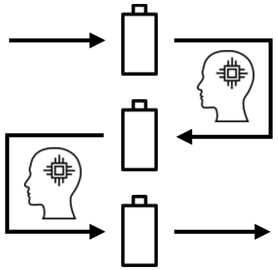
- Battery fault detection



- Ageing prognosis

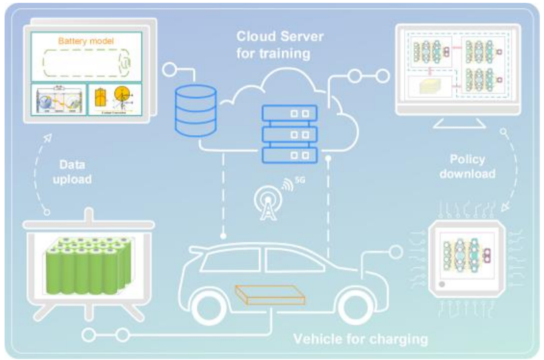


- Feedback-based testing

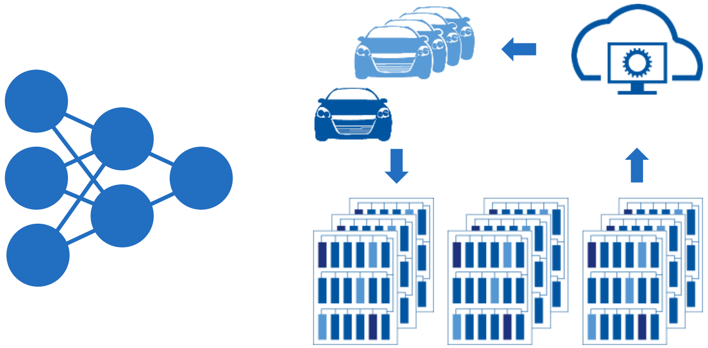


Research at Battery System Level

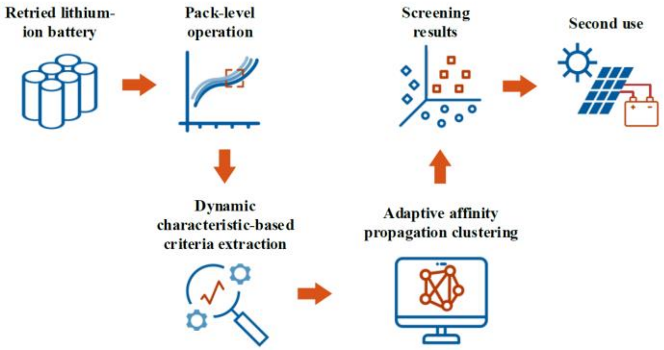
- Fast charging



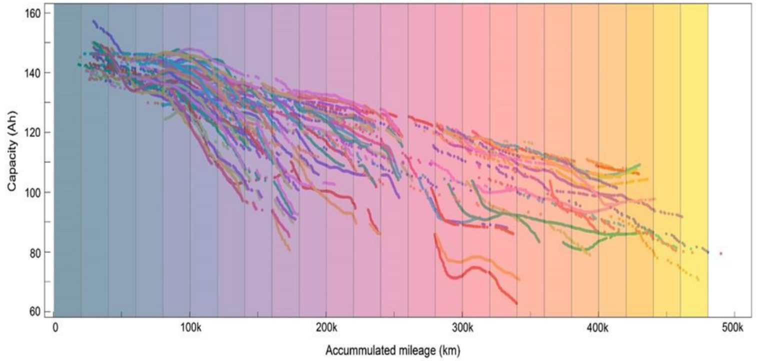
- Operation strategy



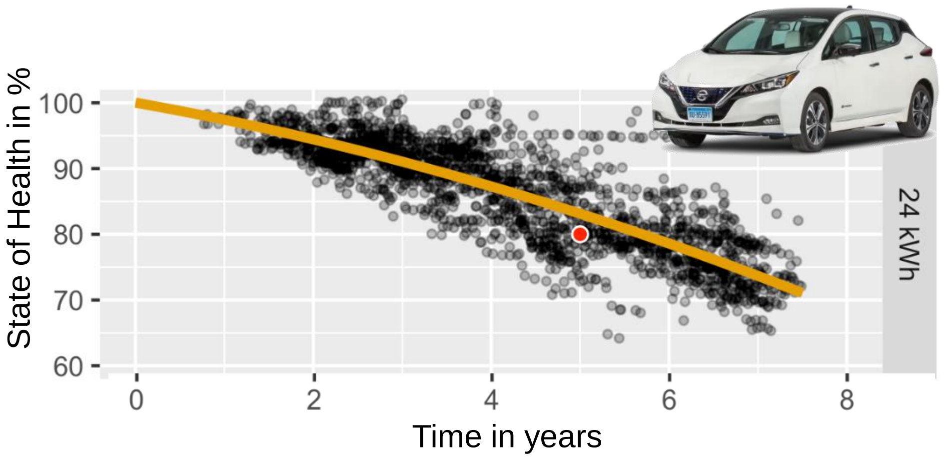
- Fast screening for Second Use



- Field data analysis

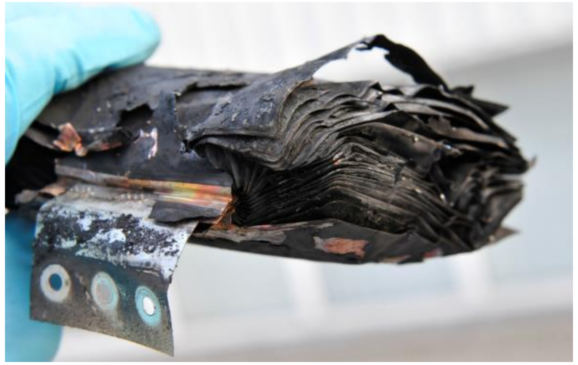


Batteries age differently over their lifetime



Source: https://flipthefleet.org

Battery cell after Thermal Runaway



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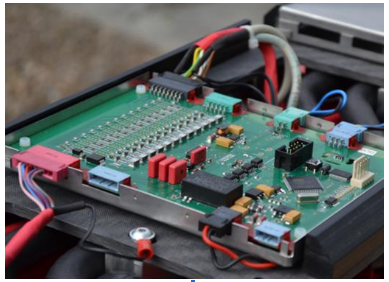
More efficient and reliable battery use possible?

Battery management system (BMS)

Low computation power

BMS



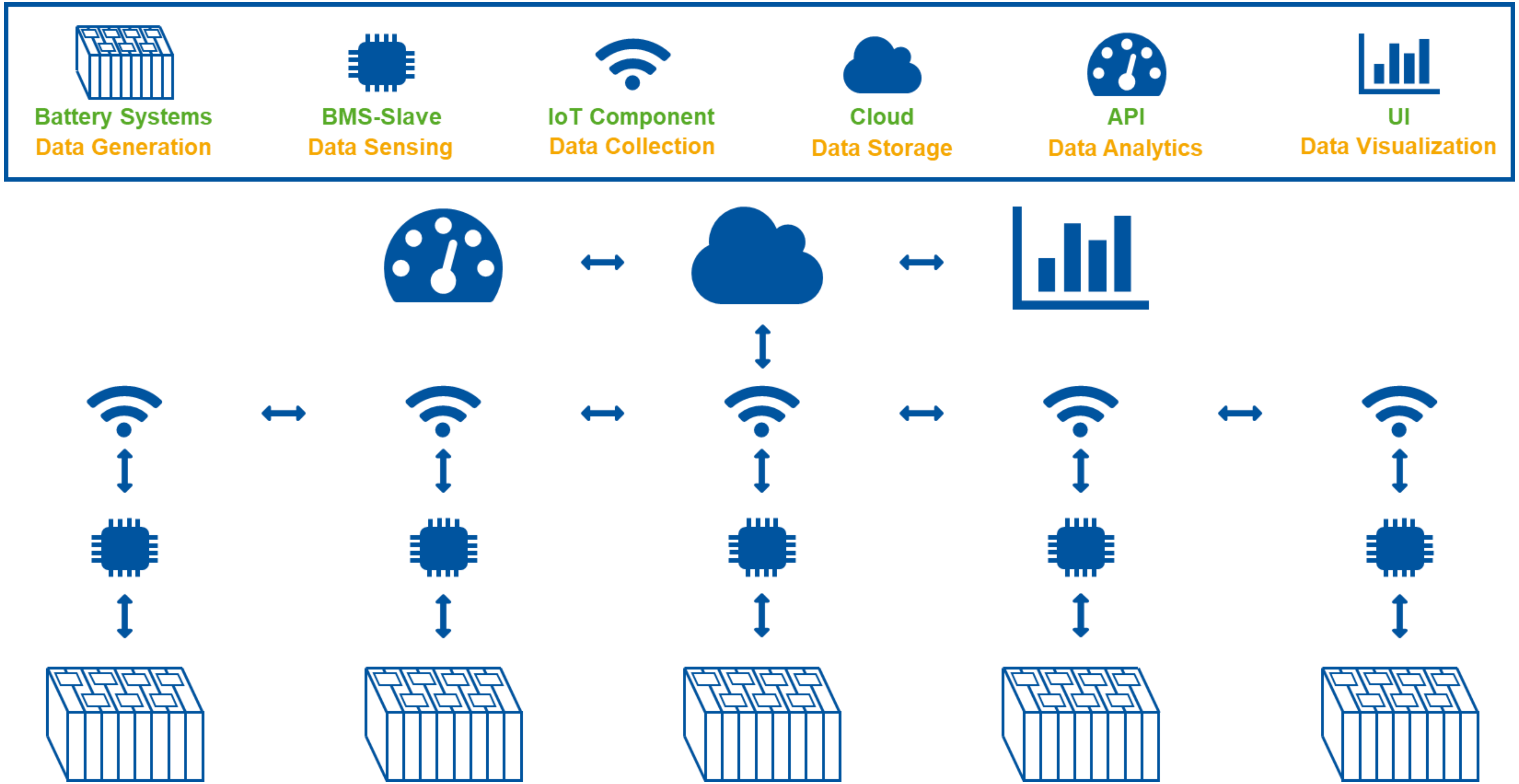
Low data storage capability

Measurement & preprocessing
- Voltage
- Current
- Temperature

Safety enhancement
- Cell balancing
- Charging control
- …

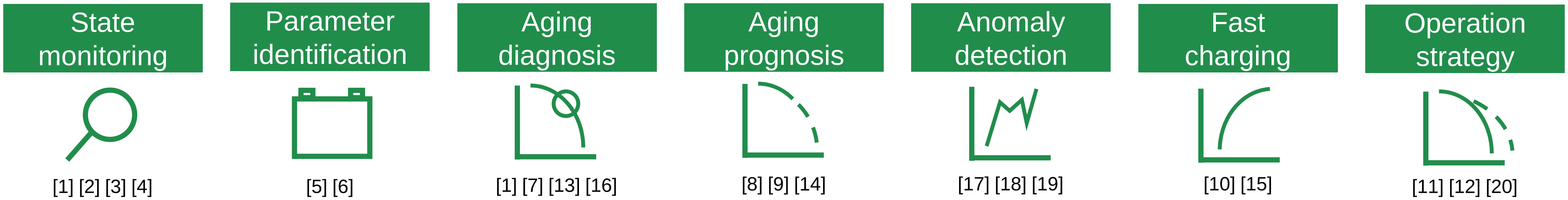
Diagnostics & monitoring
- State of Charge
- State of Health
- …

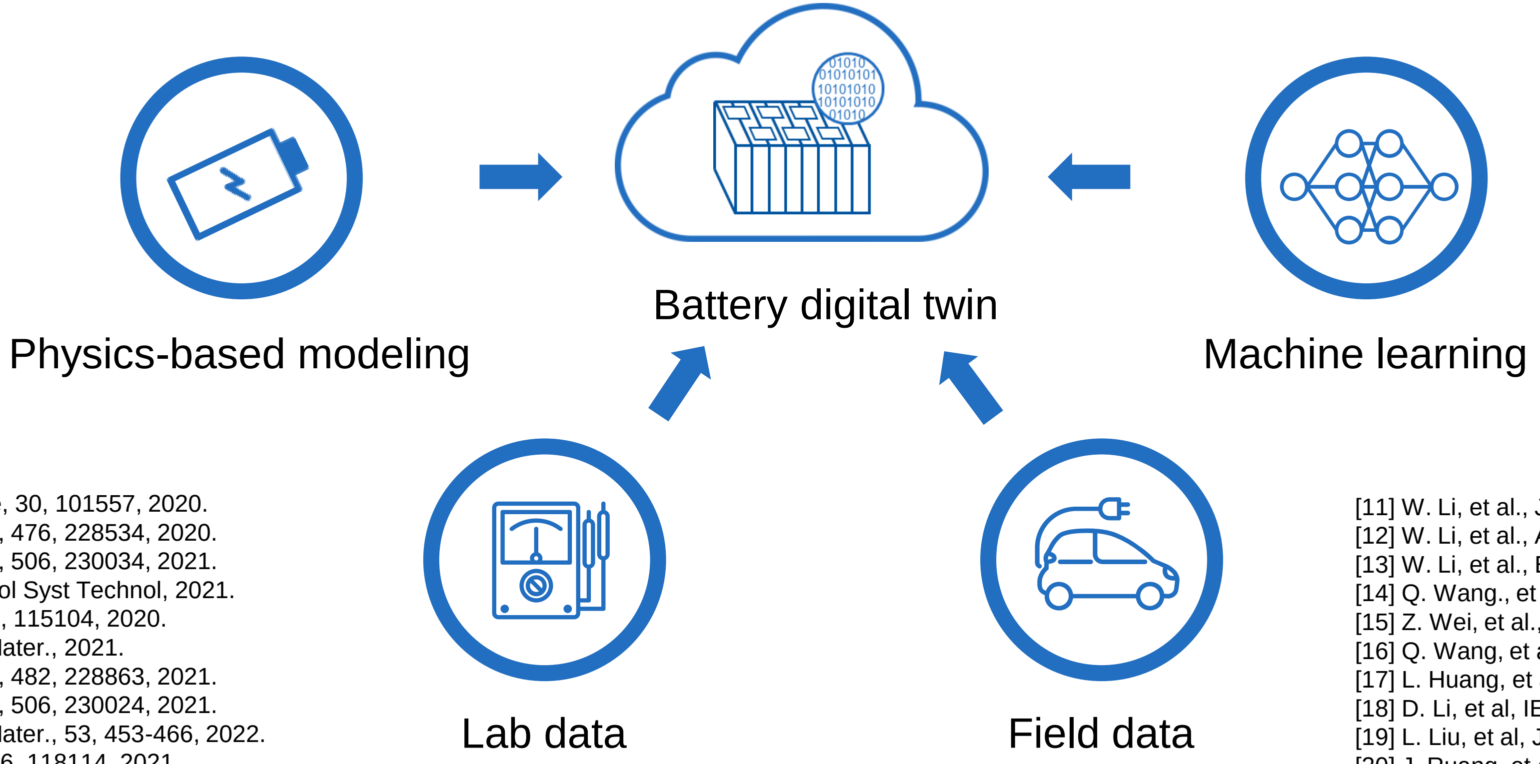
Cloud battery management system



W. Li, et al. J. Energy Storage, 30, 101557, 2020.

Battery digital twin: the fusion of physics, data and machine learning

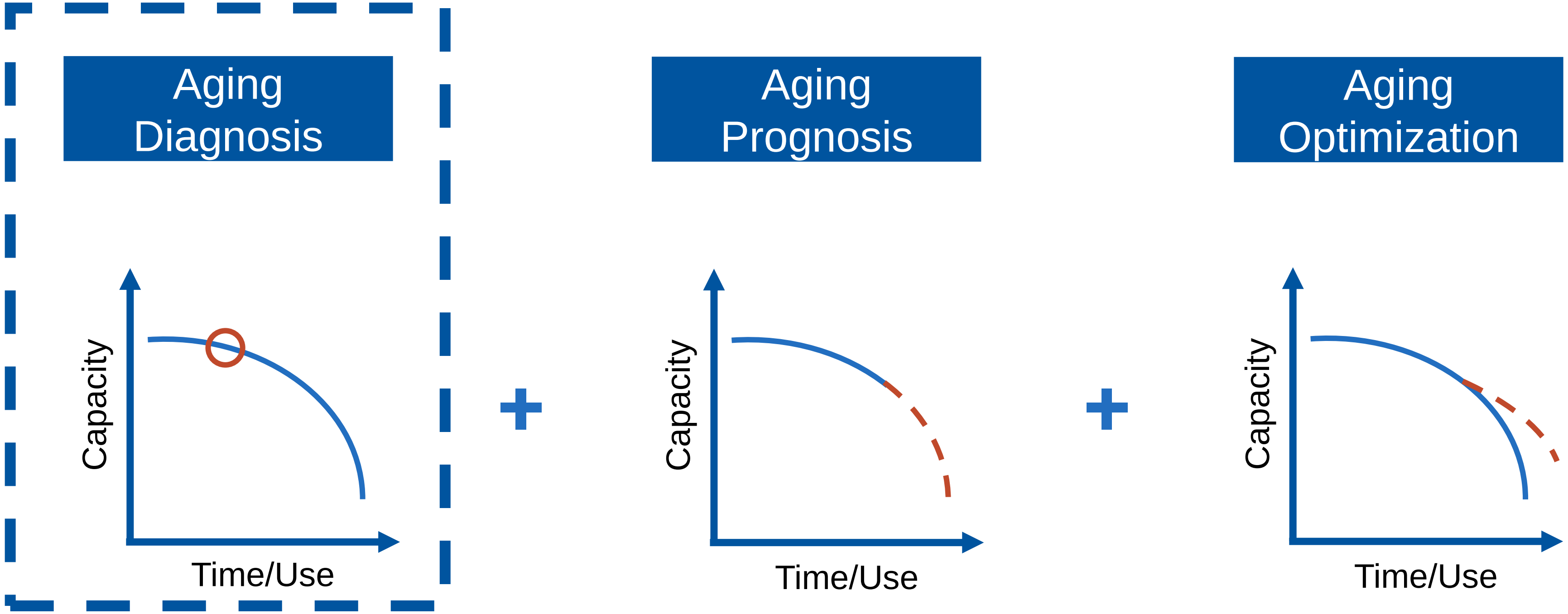




[1] W. Li, et al., J. Energy Storage, 30, 101557, 2020.
[2] W. Li, et al., J. Power Sources, 476, 228534, 2020.
[3] W. Li, et al., J. Power Sources, 506, 230034, 2021.
[4] W. Li, et al., IEEE Trans Control Syst Technol, 2021.
[5] W. Li, et al., Appl. Energy, 269, 115104, 2020.
[6] W. Li, et al., Energy Storage Mater., 2021.
[7] W. Li, et al., J. Power Sources, 482, 228863, 2021.
[8] W. Li, et al., J. Power Sources, 506, 230024, 2021.
[9] W. Li, et al., Energy Storage Mater., 53, 453-466, 2022.
[10] W. Li, et al., Appl. Energy, 306, 118114, 2021.

[11] W. Li, et al., J. Energy Storage, 36, 102355, 2021.
[12] W. Li, et al., Appl. Energy, 293, 116977, 2021.
[13] W. Li, et al., Energy Storage Mater., 53, 391-403, 2022.
[14] Q. Wang., et al., Cell Reports Physical Science, 4(12), 2023.
[15] Z. Wei, et al., Energy Storage Mater., 56, 62-75, 2023.
[16] Q. Wang, et al., Appl. Energy, 350, 121747, 2023.
[17] L. Huang, et al., Int. J. Energy Res., 2021.
[18] D. Li, et al, IEEE Trans. Power Electron., 2022.
[19] L. Liu, et al, J. of Energy Chemistry, 61, 269 – 280, 2021.
[20] J. Ruang, et al, IEEE Trans. Veh. Technol., 2023

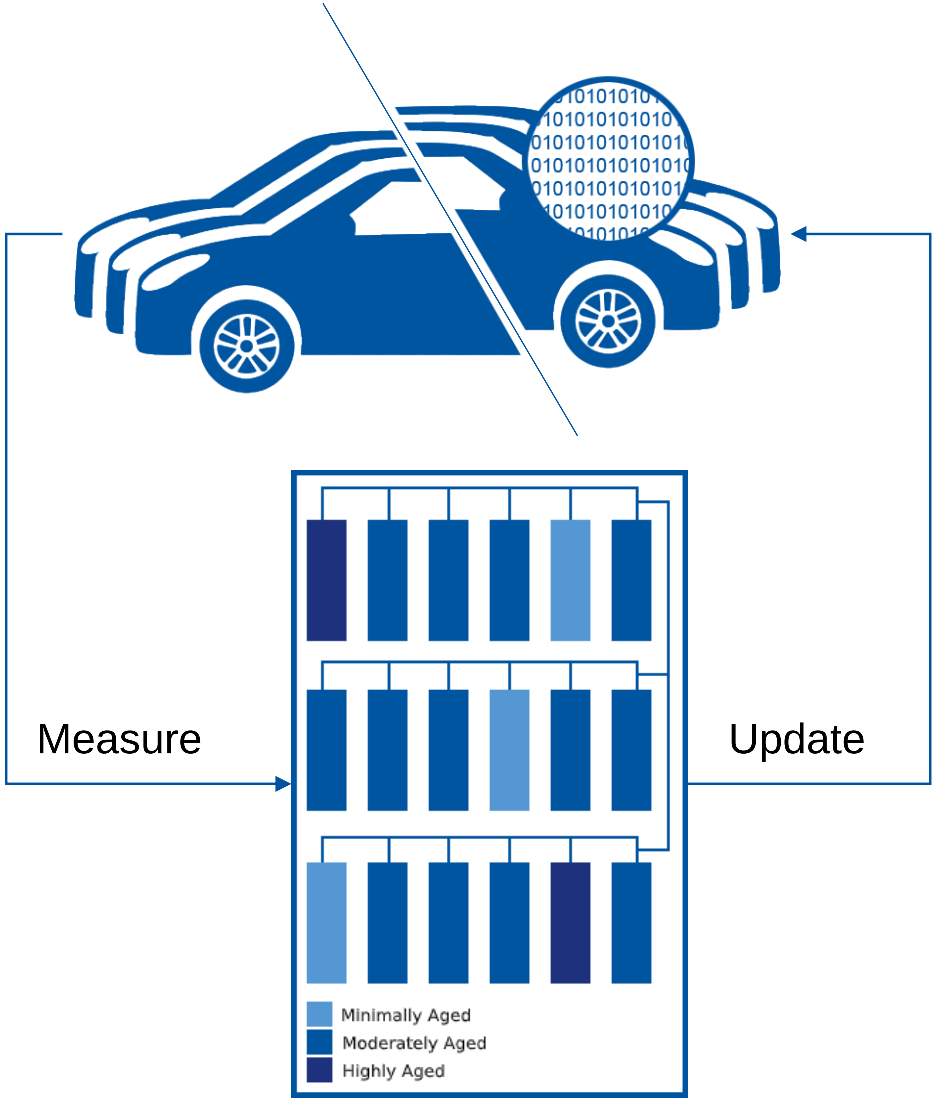
Agenda



Aging Diagnosis
Capacity
Time/Use
+
Aging Prognosis
Capacity
Time/Use
+
Aging Optimization
Capacity
Time/Use

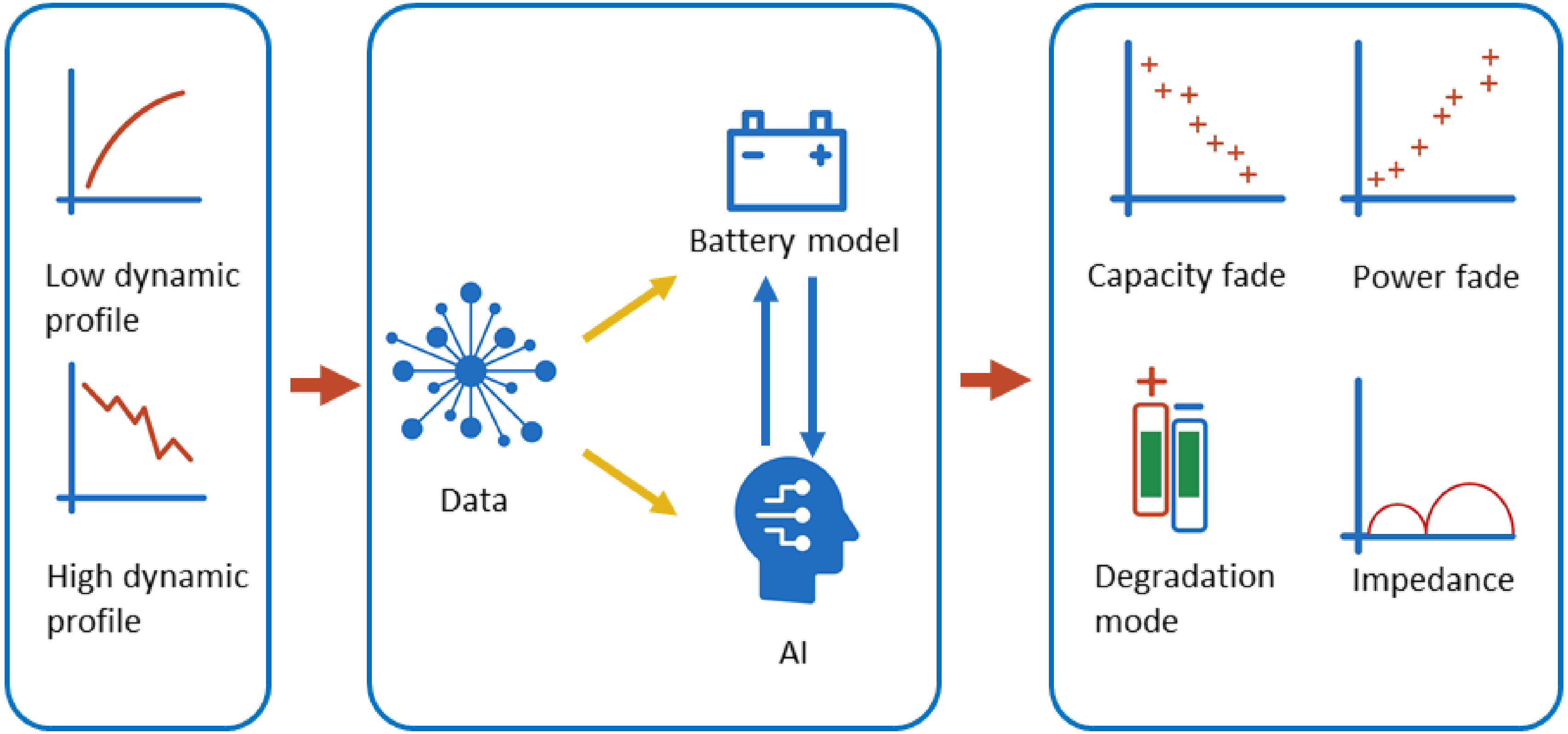
Aging diagnosis – Online parameter identification

- Seamlessly monitoring of the battery cells
  - Battery internal states
    - State of charge
    - Internal physical states
  - Battery parameters
    - SOH-C
    - SOH-R
    - **Impedance?**
    - **Degradation mode?**



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.

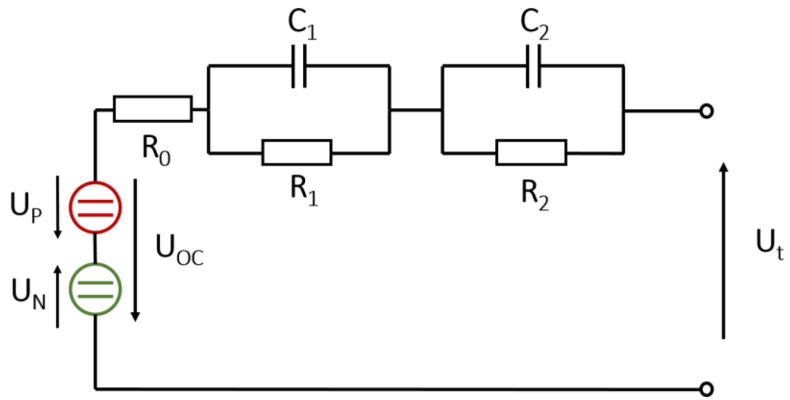
Combining the impedance-based model and OCV reconstruction model

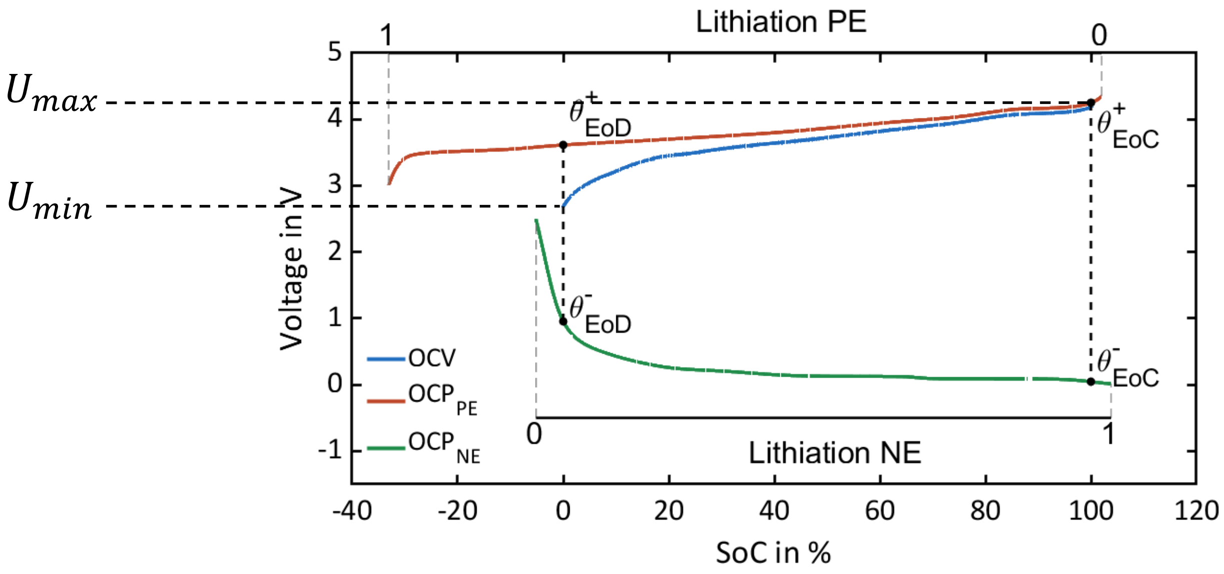
- Equivalent-circuit model
  - Ohmic resistance
  - Charge transfer
  - Diffusion
- OCV reconstruction model
  - Electrode OCP
  - OCV balancing parameters
  - Cut-off voltages: U_{max}, U_{min}

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

↓ U_{max}, U_{min}

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

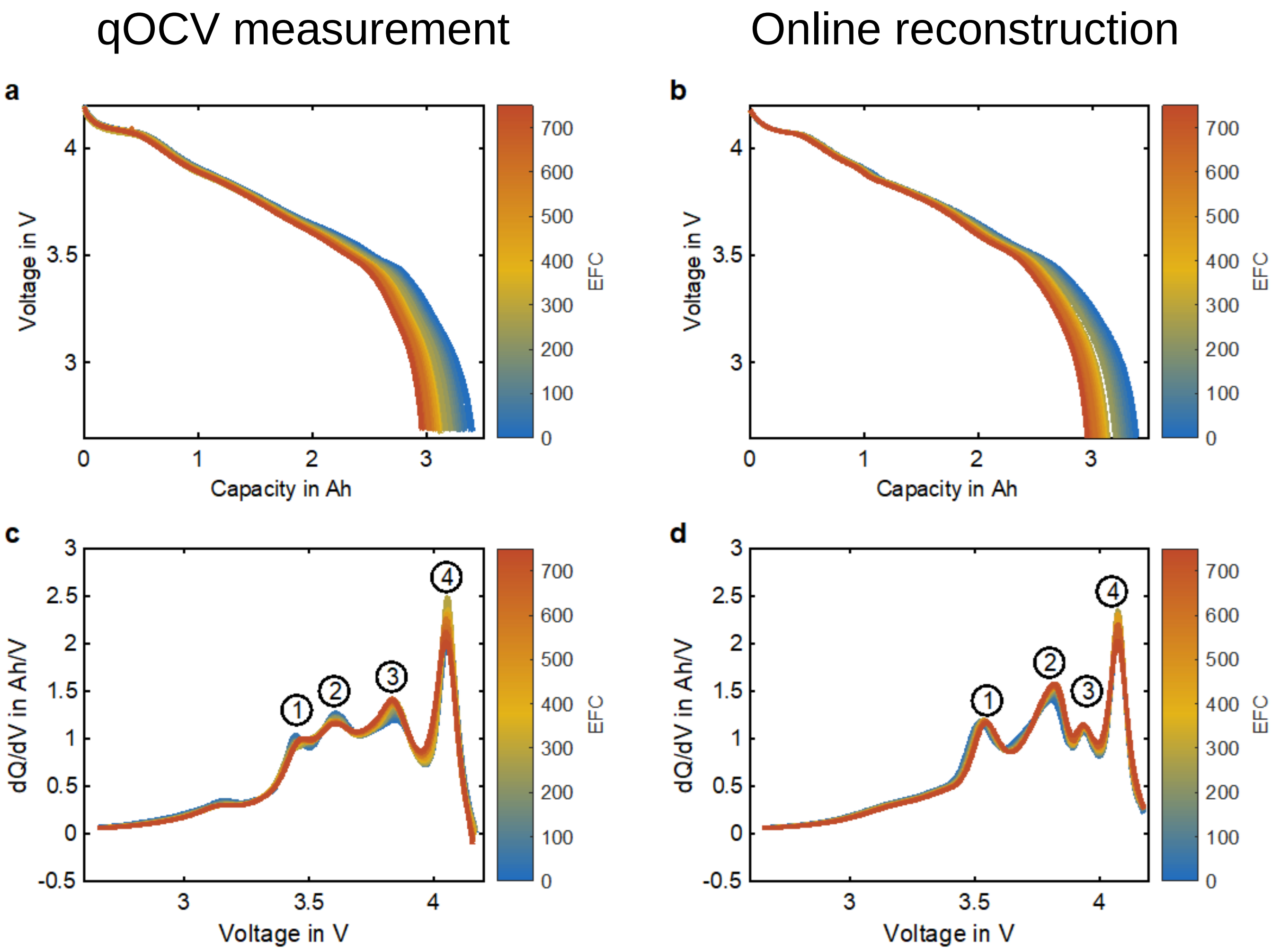




Li W, et al. **2022,** Energy Storage Materials, 53, 391-403.

Online OCV reconstruction

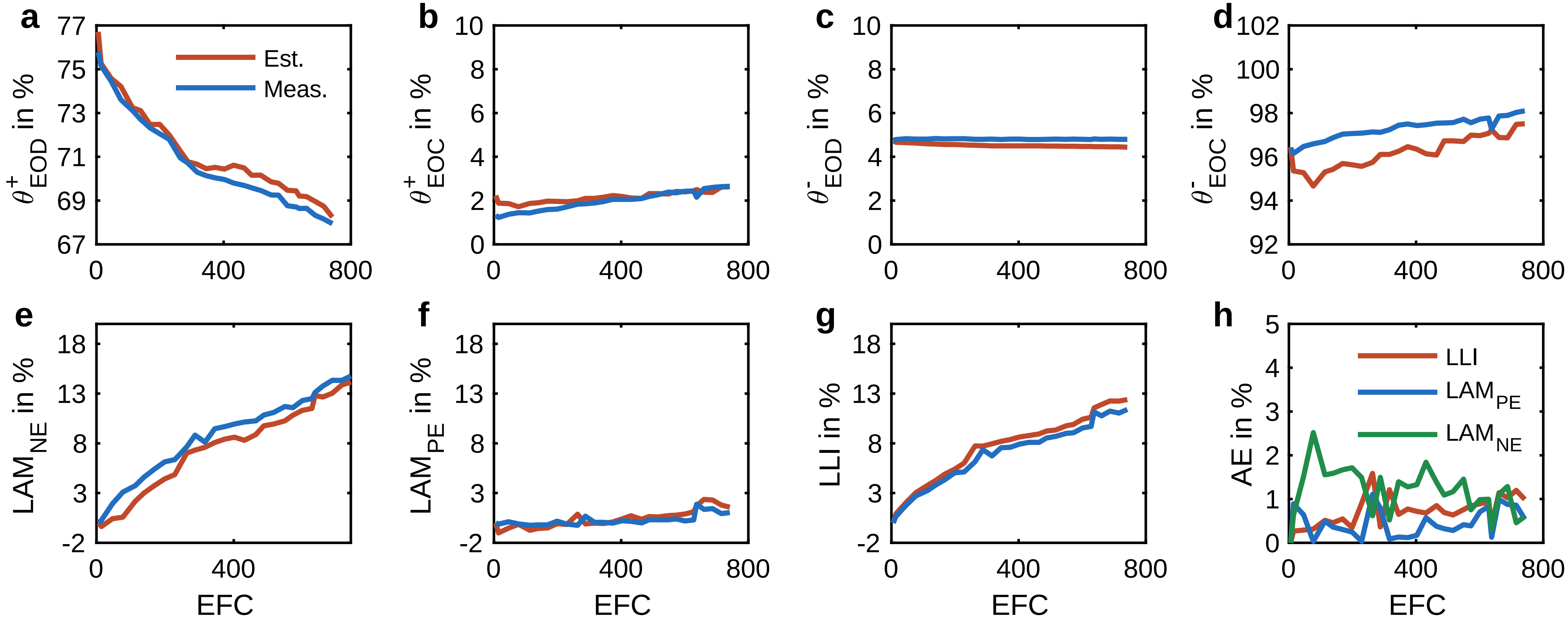
- OCV reconstruction
  - Benchmark: qOCV test
- Incremental capacity analysis
  - Qualitative evaluation of the degradation modes



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

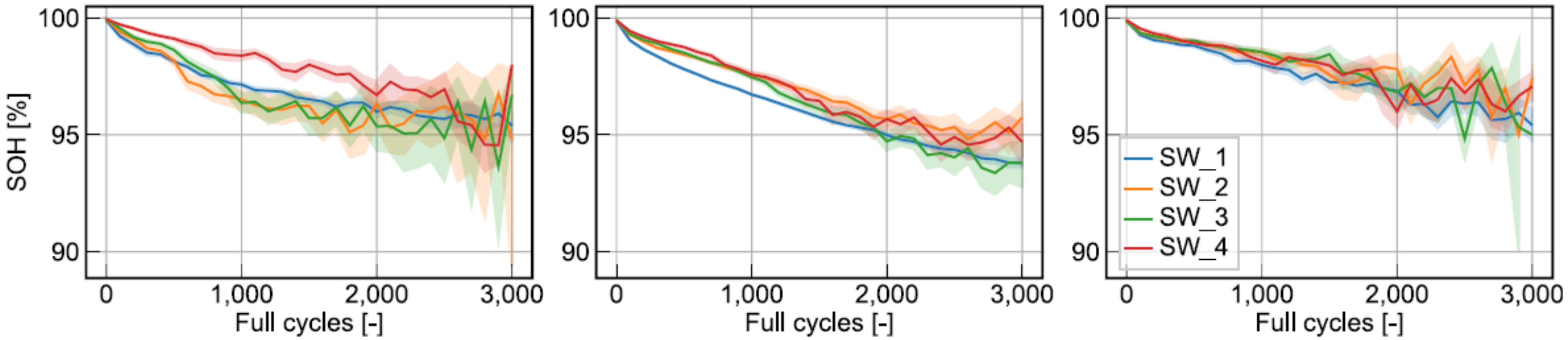
Online aging mode identification

- Identification results of stoichiometric parameters and degradation modes



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

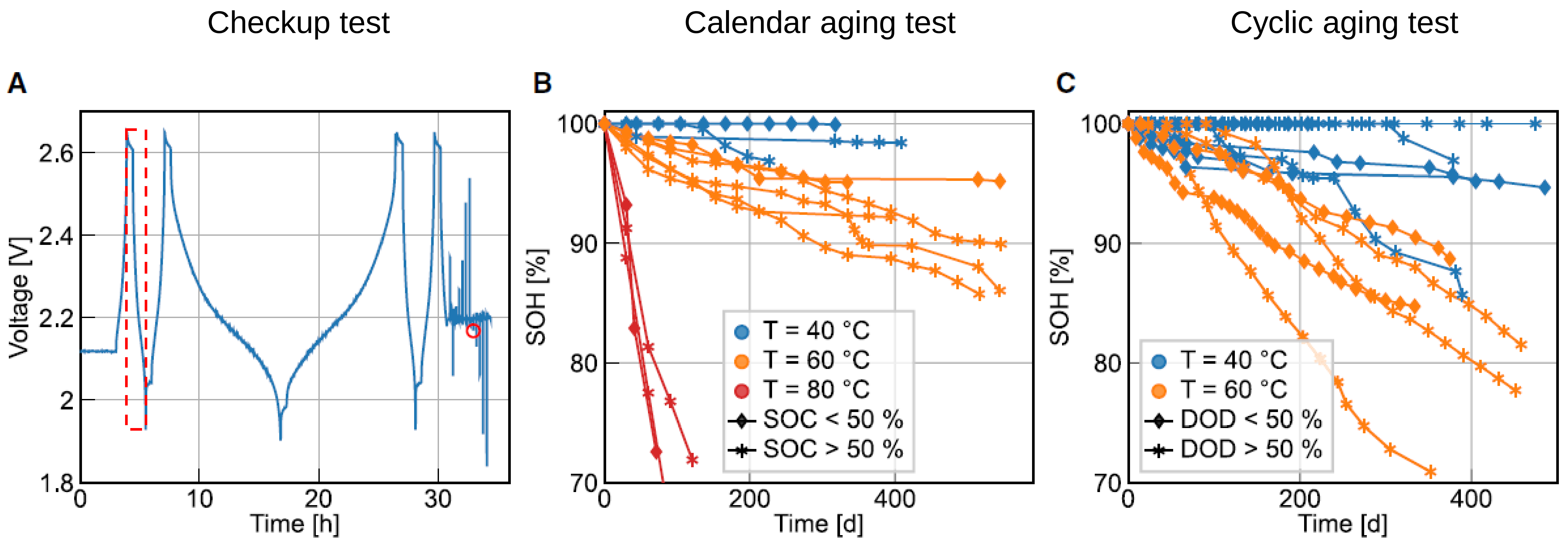
Overview of the variables in field data



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.

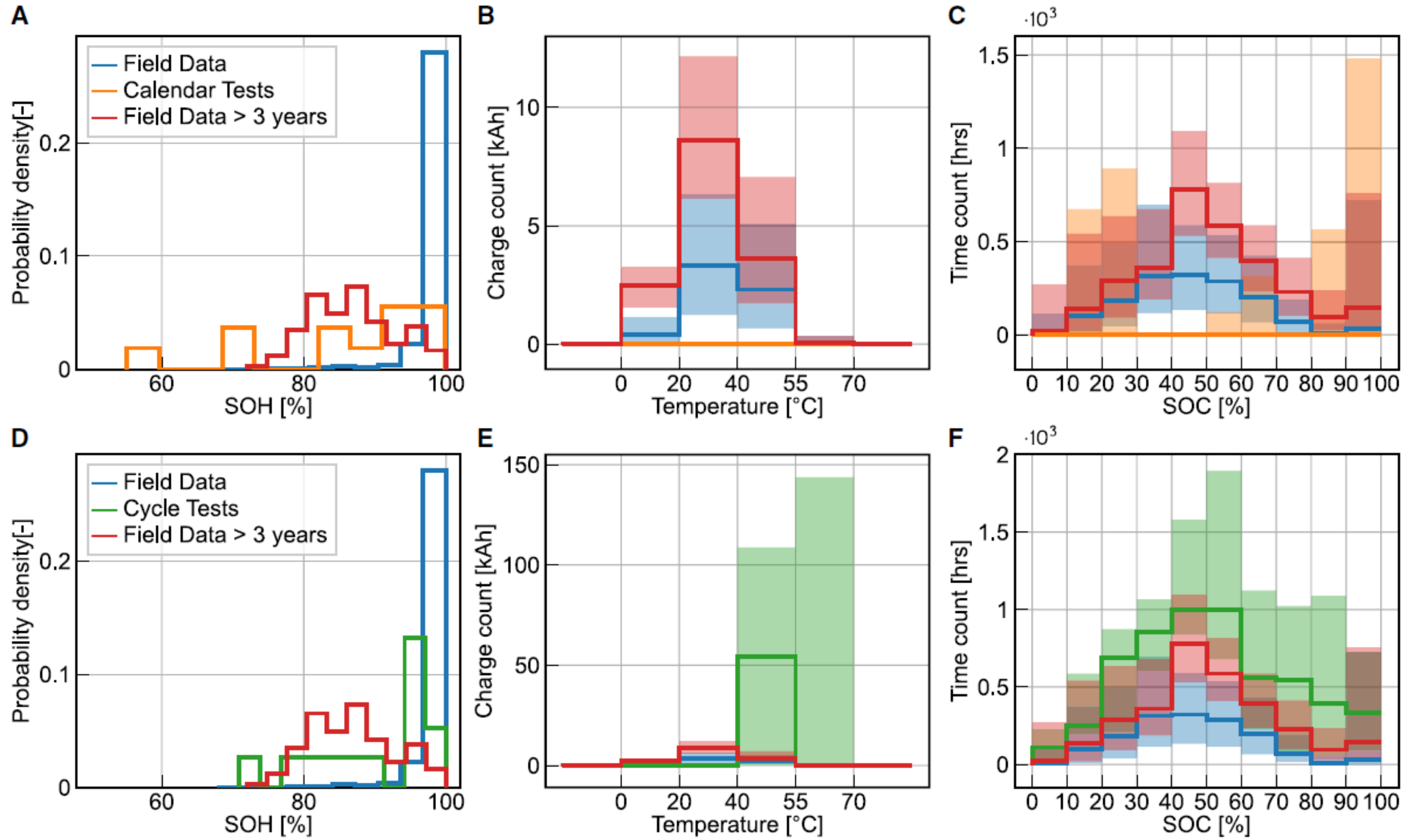
Laboratory data for both calendar and cyclic aging



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

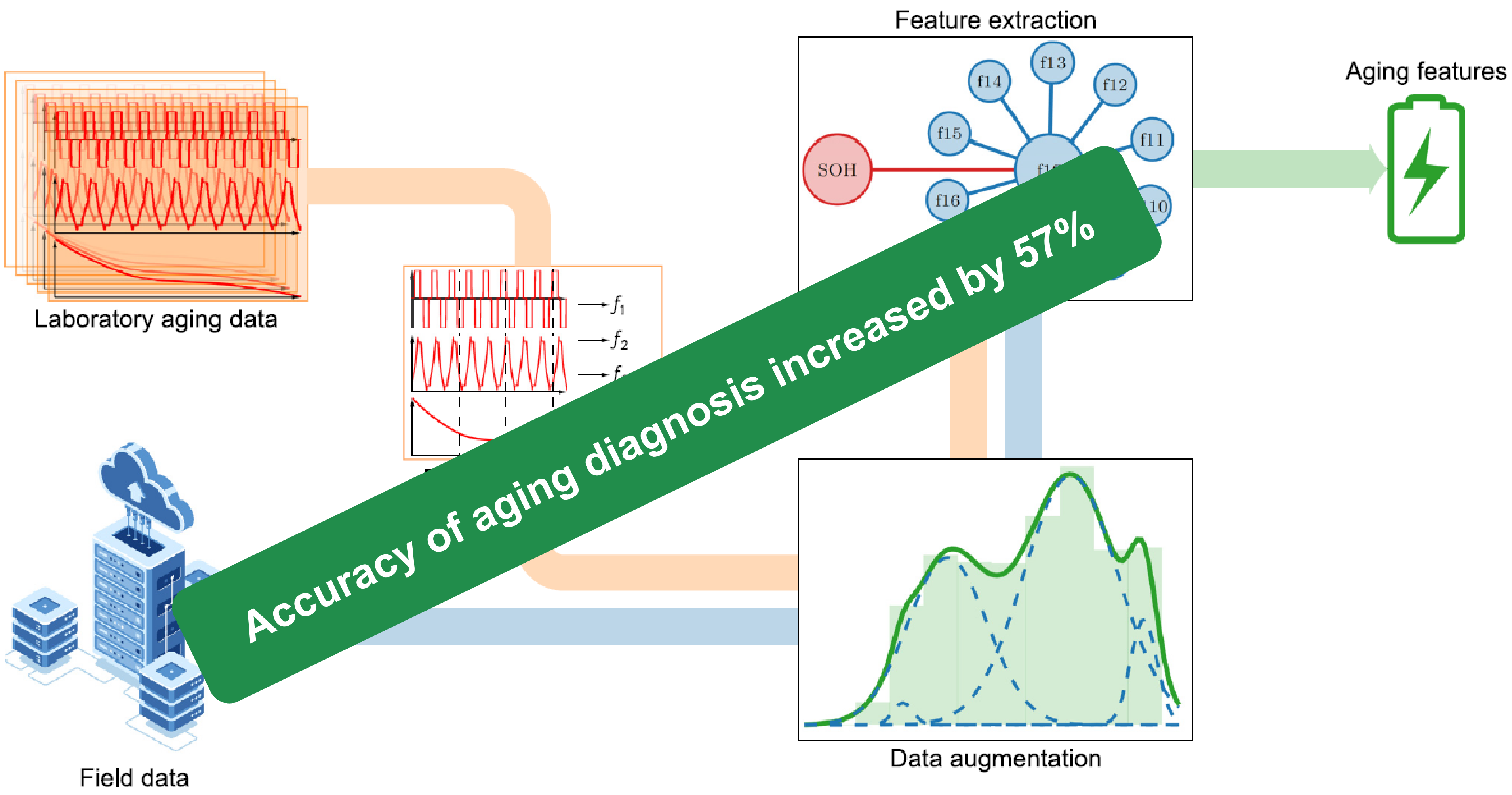
Field data vs. laboratory data for aging diagnosis

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



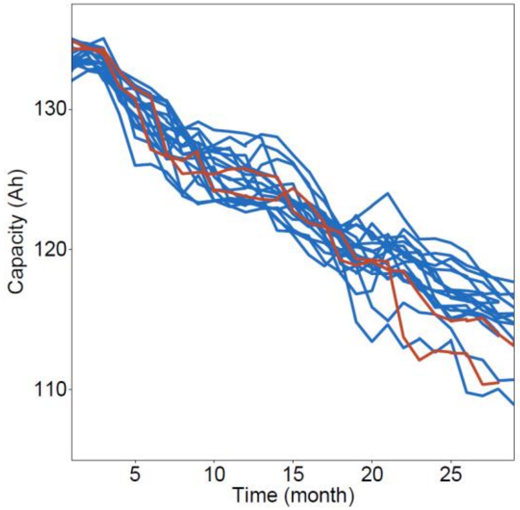
V. Steininger, et al., Cell Reports Physical Science 4, 101596, 2023.

Feature extraction framework to integrate laboratory and field data

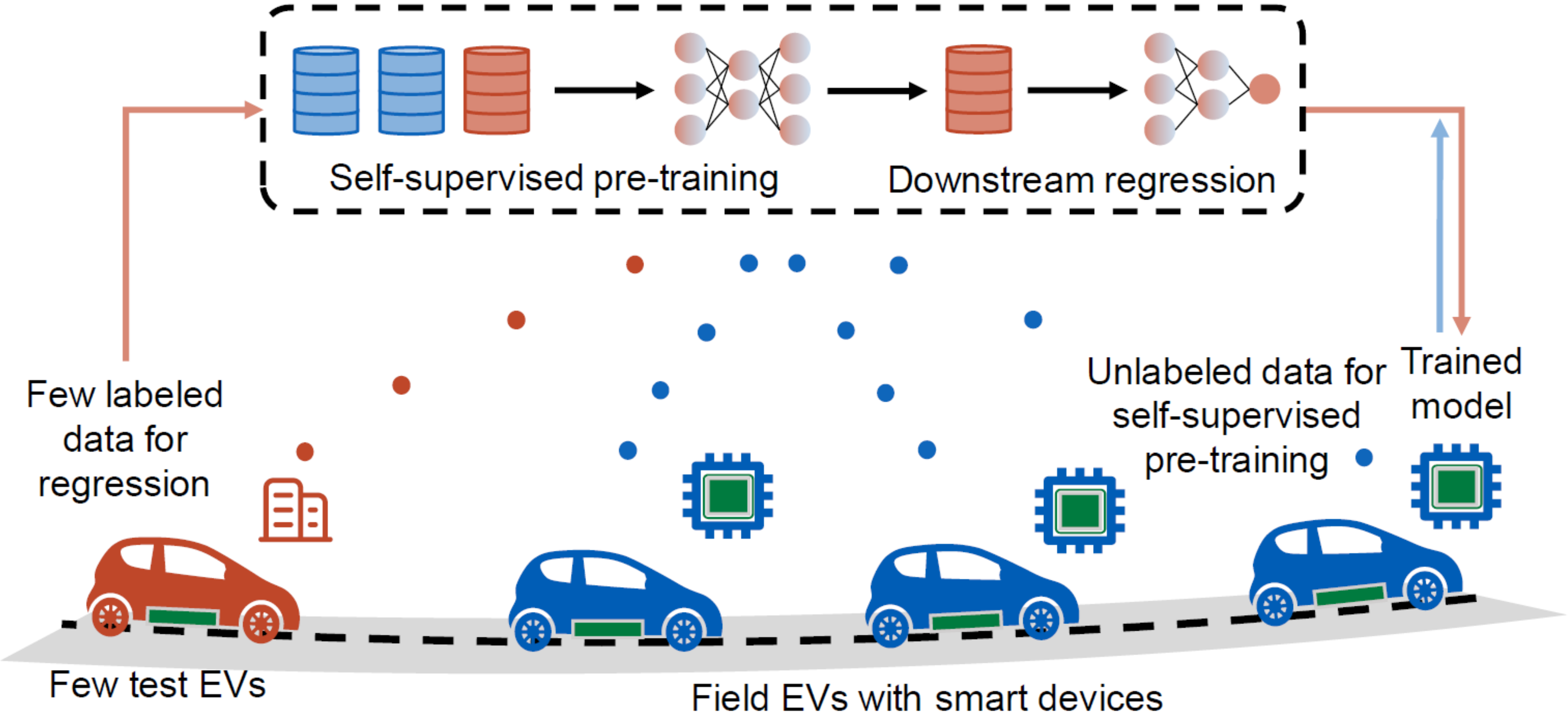


V. Steininger, et al., Cell Reports Physical Science 4, 101596, 2023.

Self-supervised learning for large scale unlabeled field data (20 vehicles)



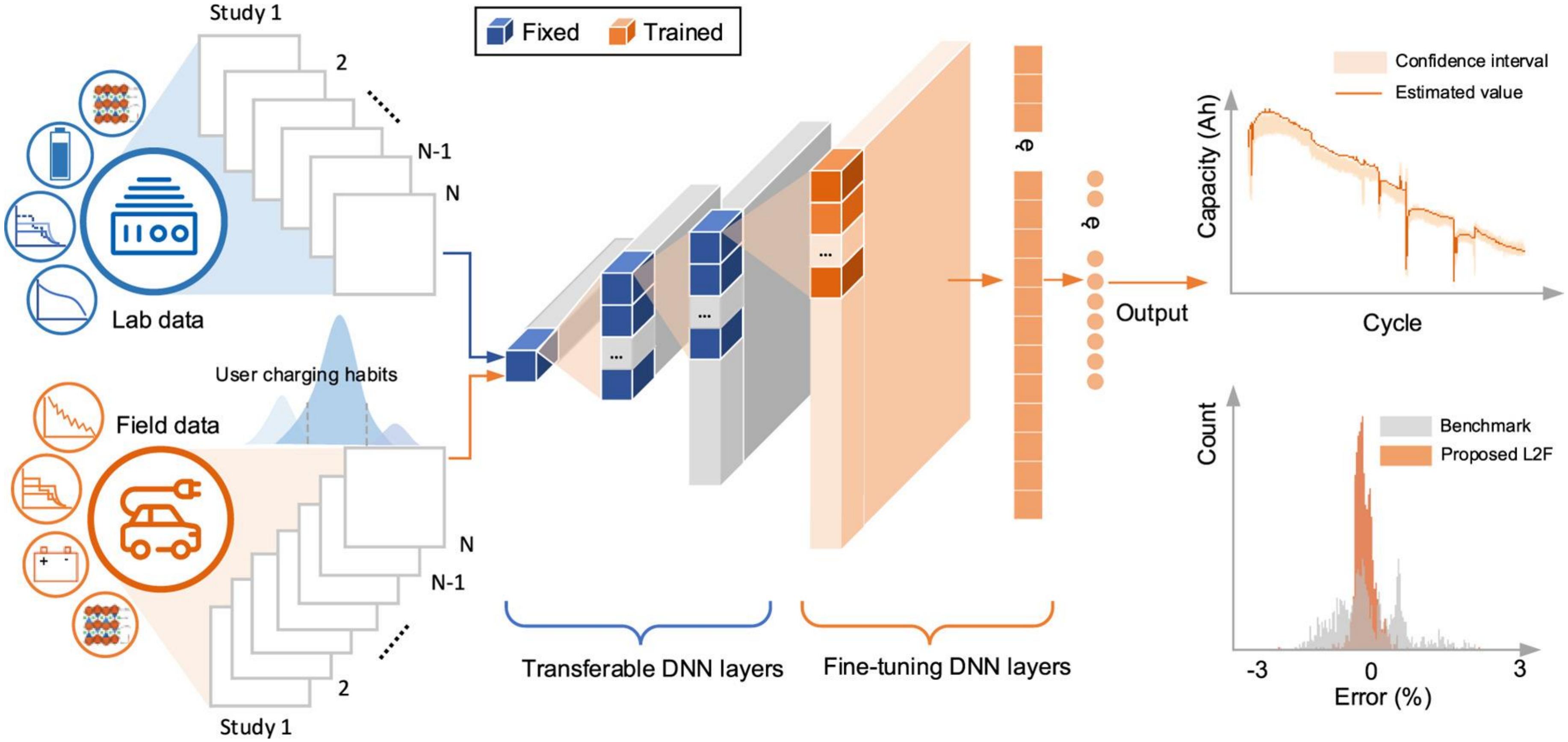
Open source



Q. Wang, et al., Journal of Energy Chemistry,2024, 99, 681 – 691.

Transfer learning between different battery cells

- Transfer learning for capacity estimation from laboratory to field application
- Successful transfer between two batteries with the same chemistry but different formats and capacity



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

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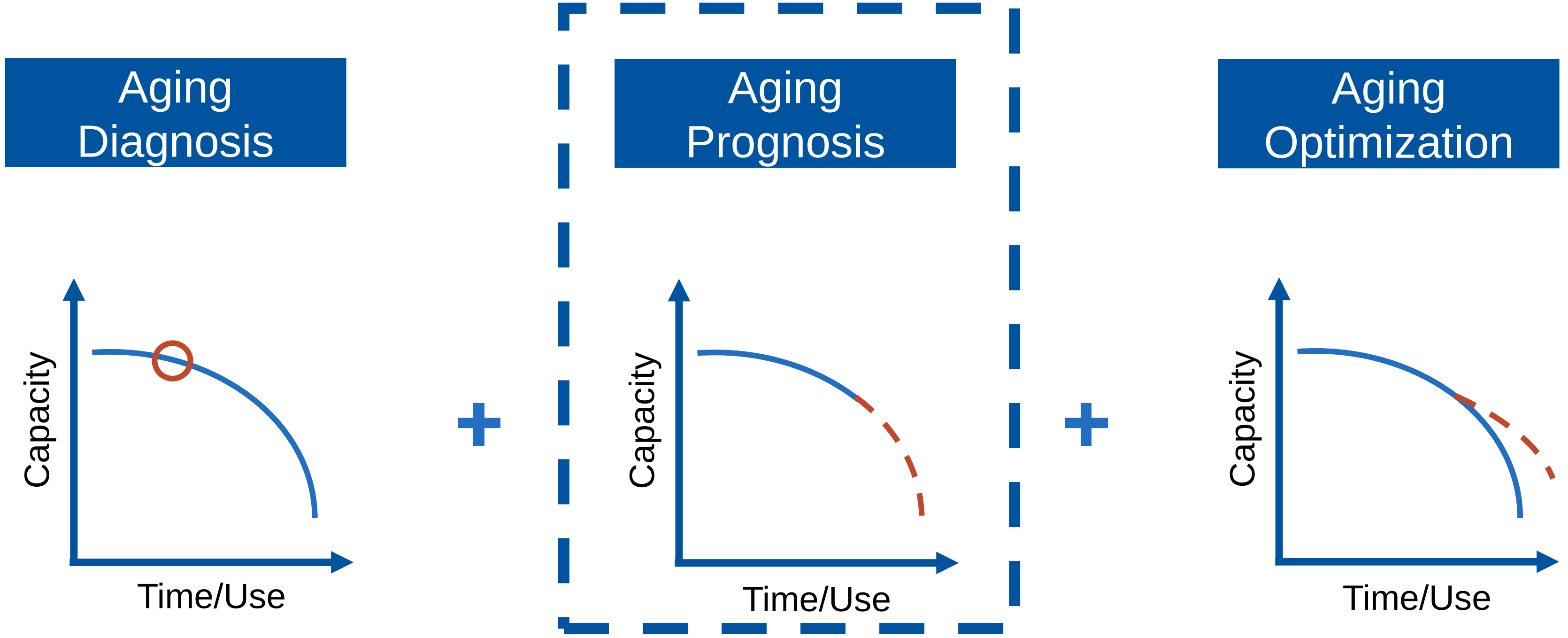
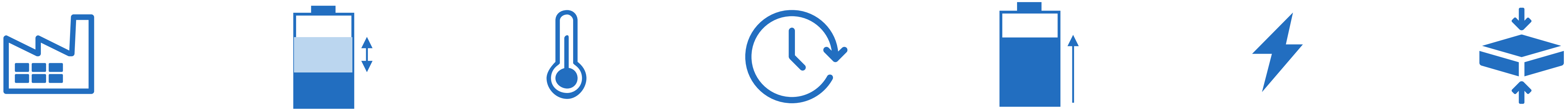
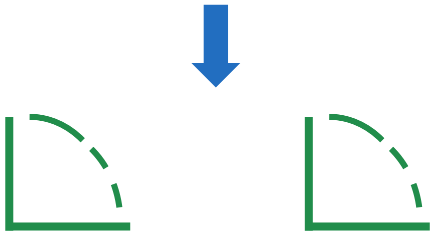

Aging Diagnosis
Aging Prognosis
Aging Optimization
Capacity
Time/Use
Capacity
Time/Use
Capacity
Time/Use

Challenges in battery aging prediction



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



Capacity fade | Power fade

First life

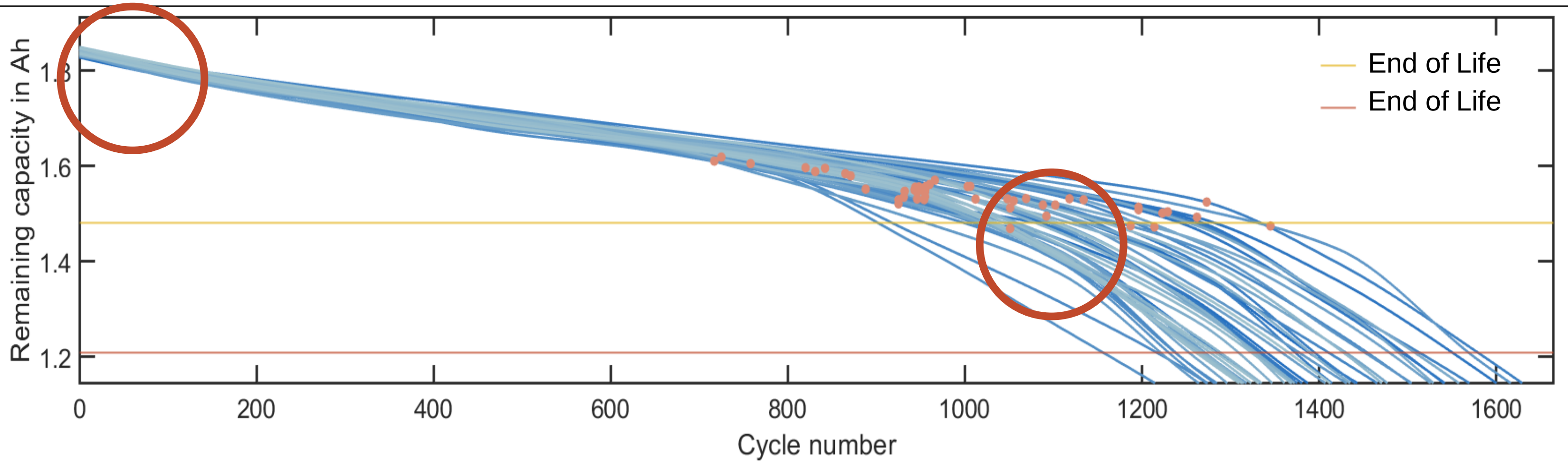
https://www.zdnet.com/article/electric-vehicles-are-the-future/

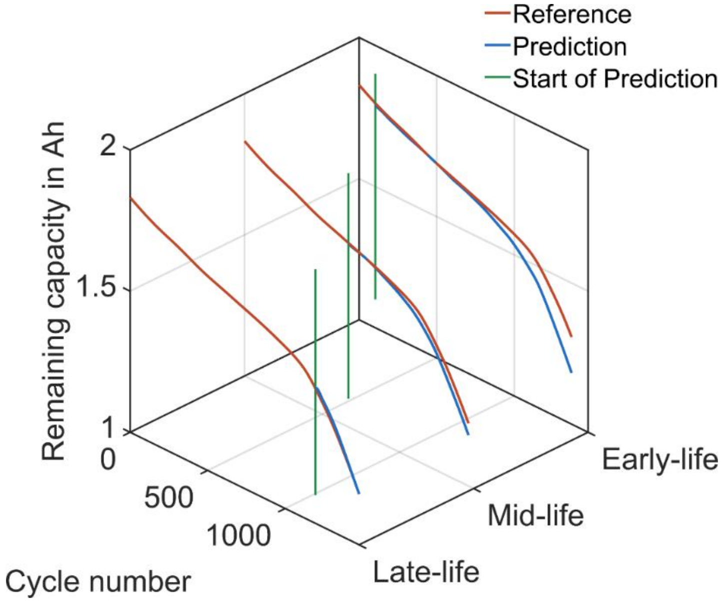
- How long is the 1st life?
- What is the residue value after 1st life?
- How long is the 2nd life?
- How reliable is the battery in 2nd life?
- Which 2nd life use case is more suitable?

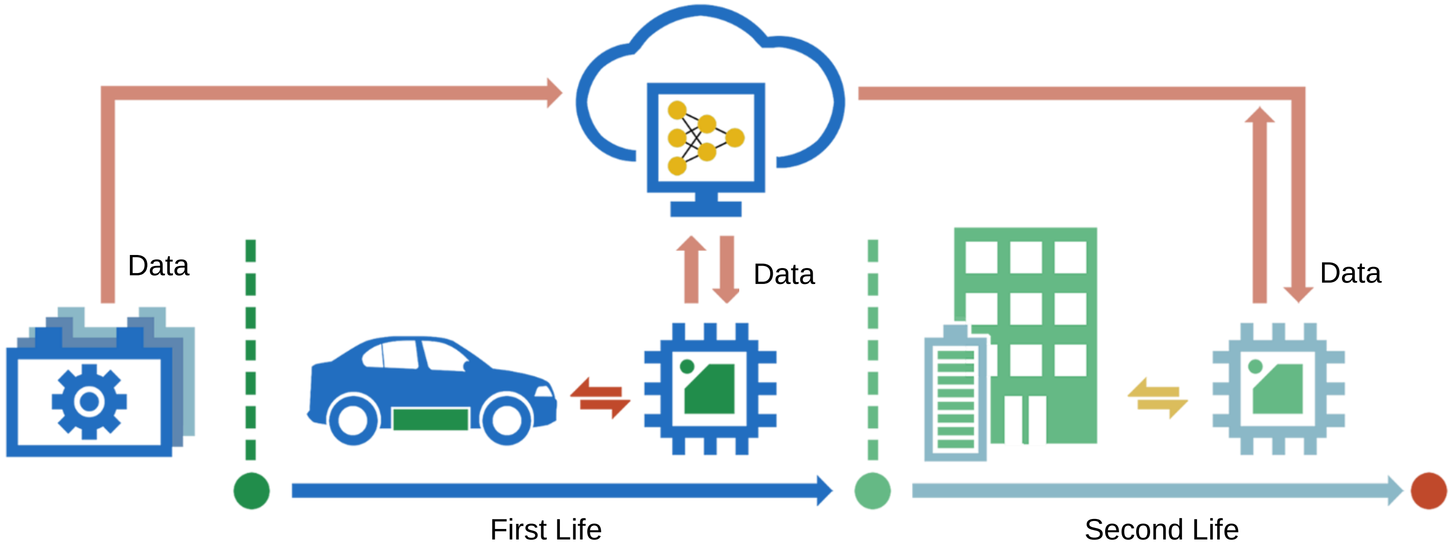
Second life

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

One-shot prediction of service life with sequence-to-sequence learning

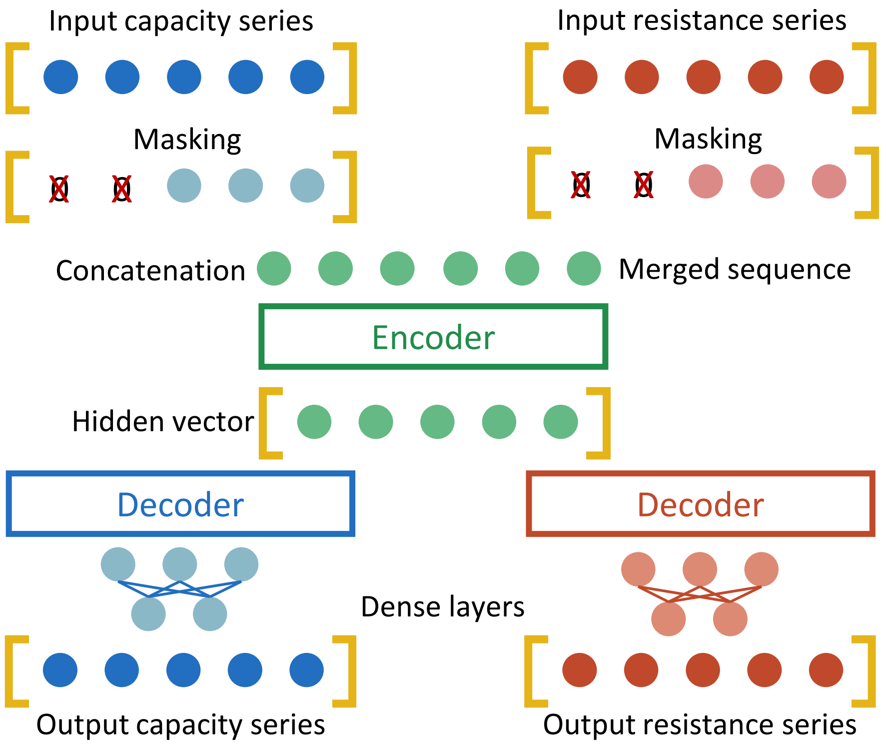


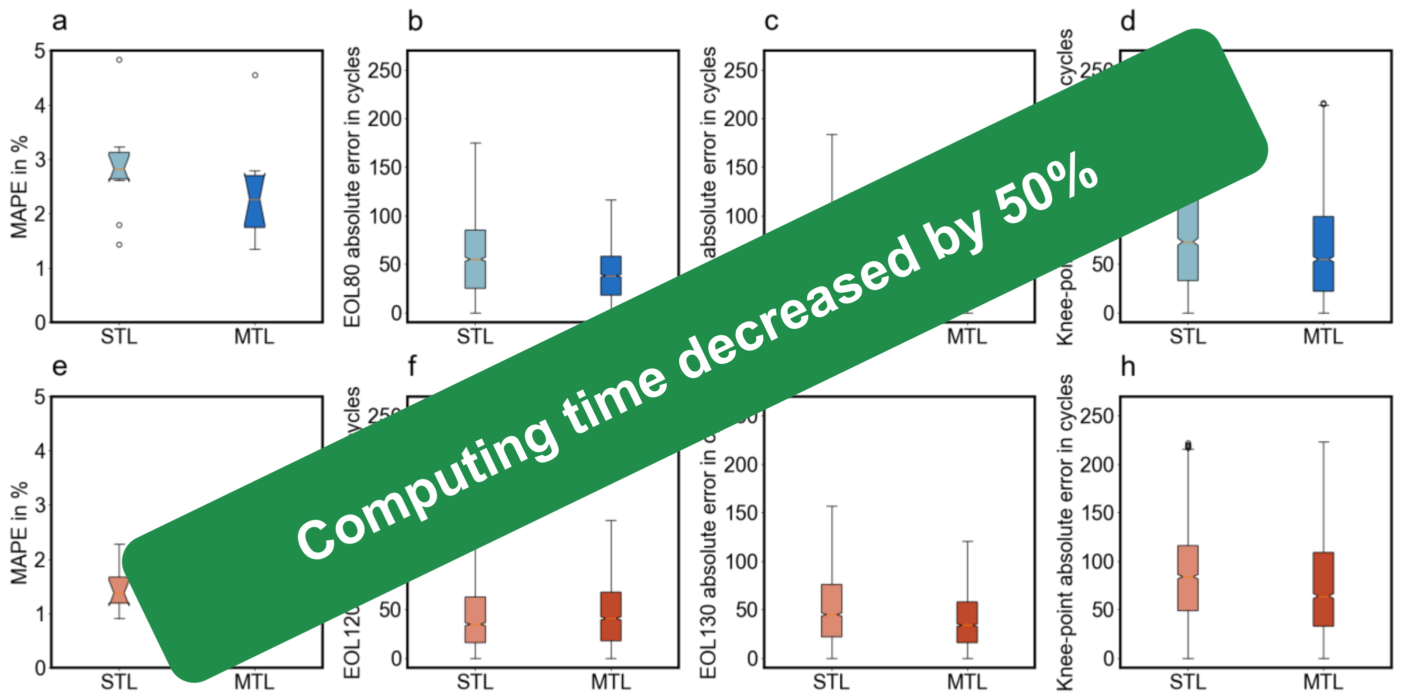




W. Li, et al., J. Power Sources, 506, 230024, 2021.

Capacity fade and power fade co-prediction with multi-task learning

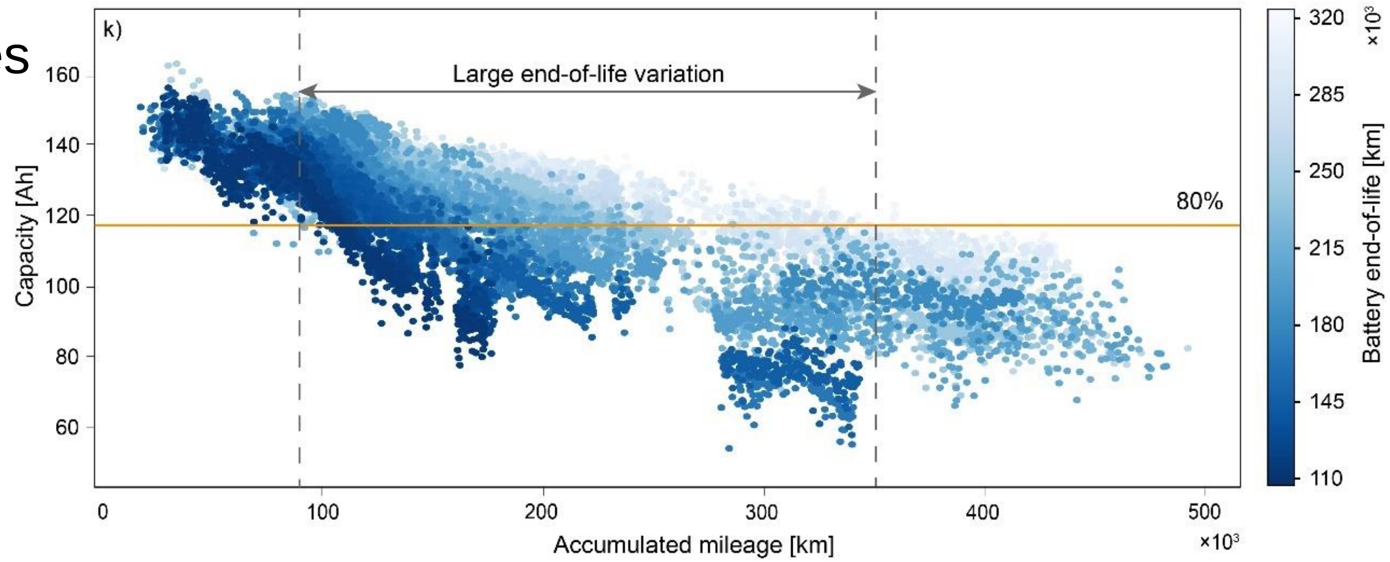


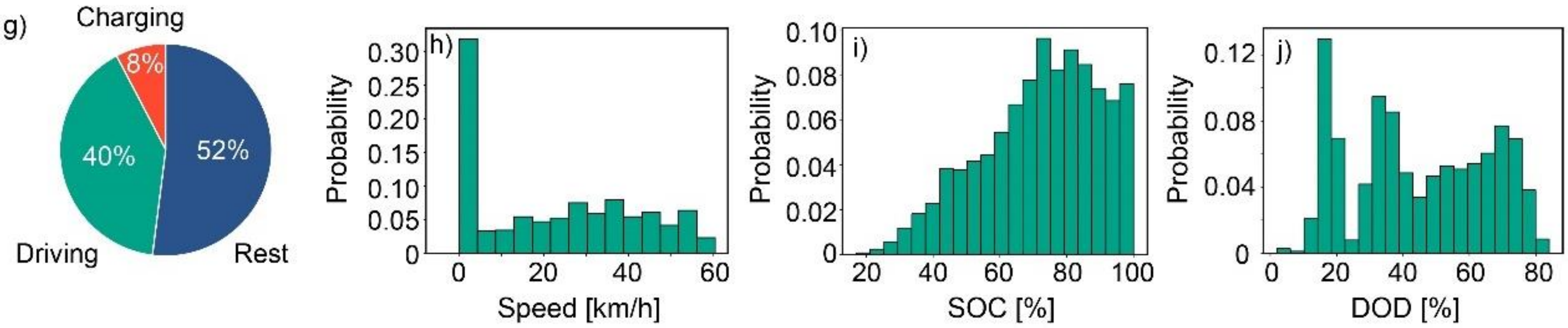


W. Li, et al., Energy Storage Materials, 53, 453-466, 2022.

Lifetime prediction from large-scale field data

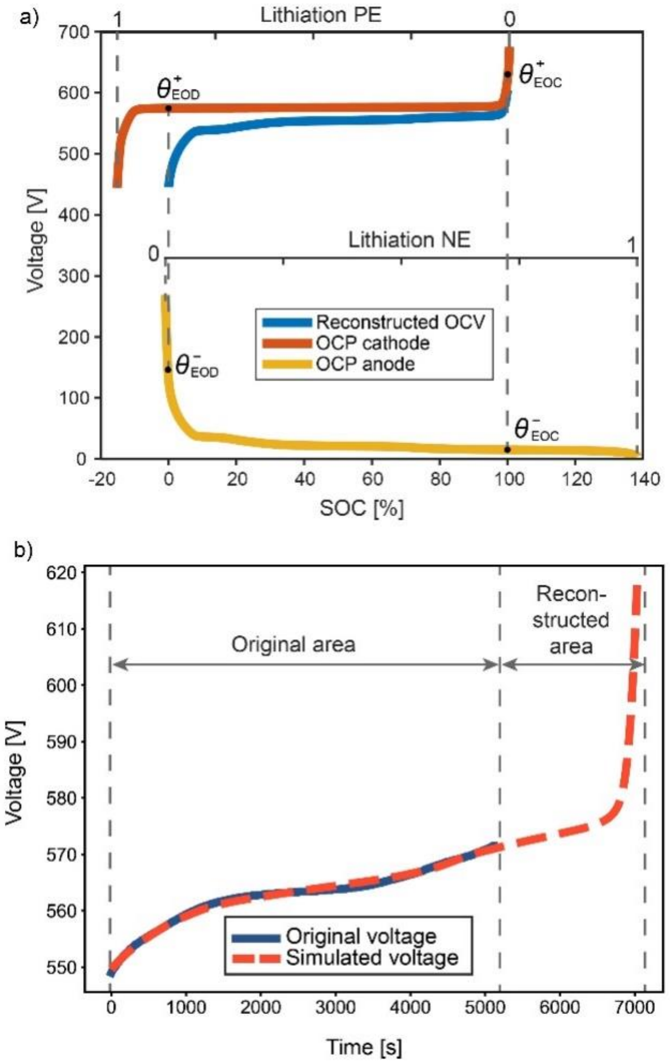
- Real-world operating data of electric buses
  - 60 EVs
  - Over 3 years of time, 400k km of mileage
  - 48 GB data, 240 million rows
  - Over 100 raw features





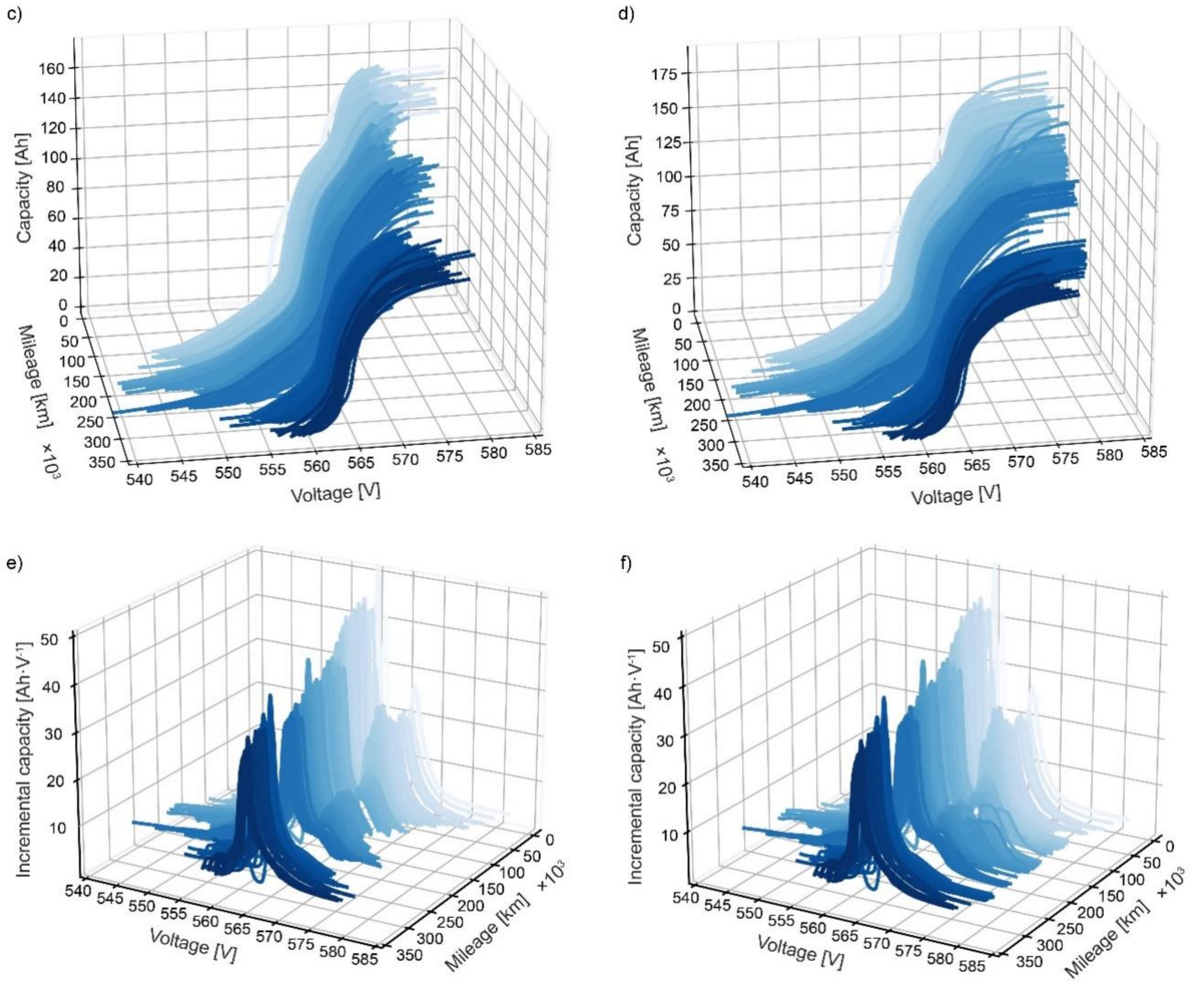
Q. Wang, et al., Cell Reports Physical Science, 4(12), 2023.

Data preprocessing and charging curve reconstruction



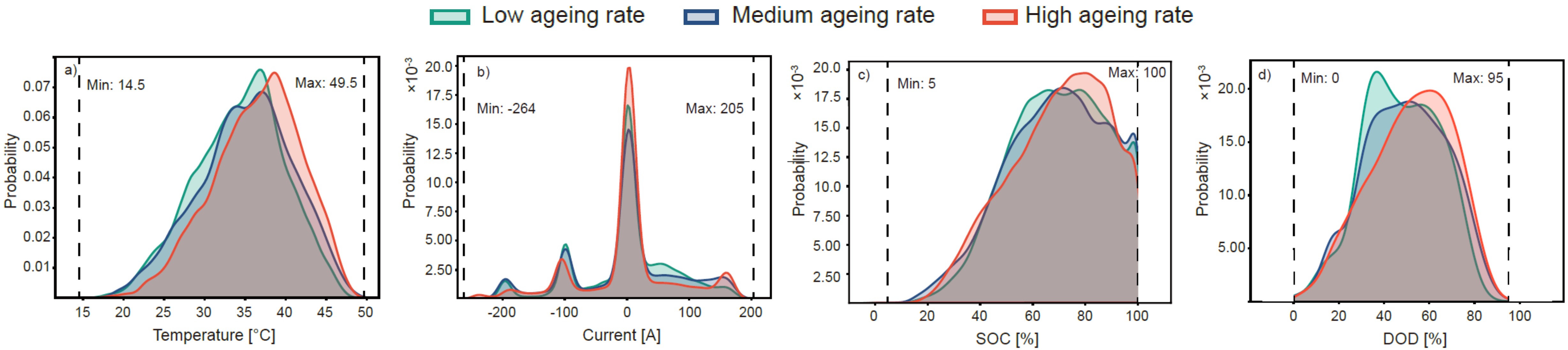
Raw data

Reconstructed data



Q. Wang, et al., Cell Reports Physical Science, 4(12), 2023.

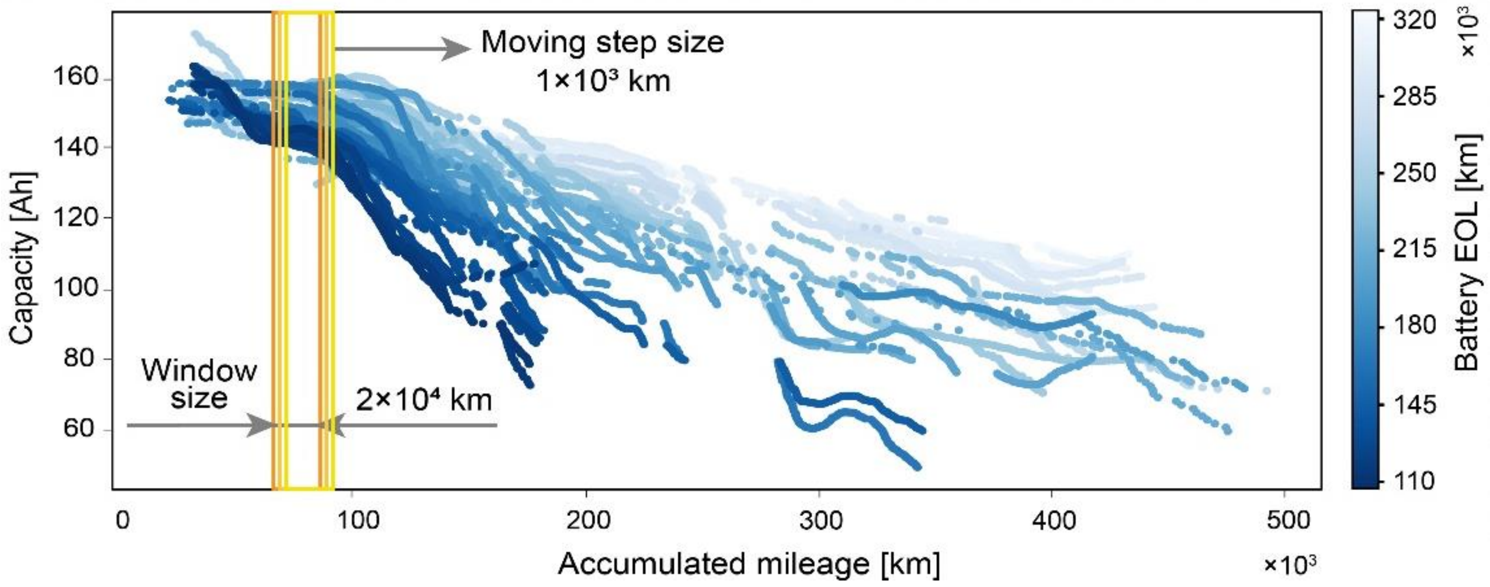
Statistical distributions of stress factors of vehicles with different ageing rates



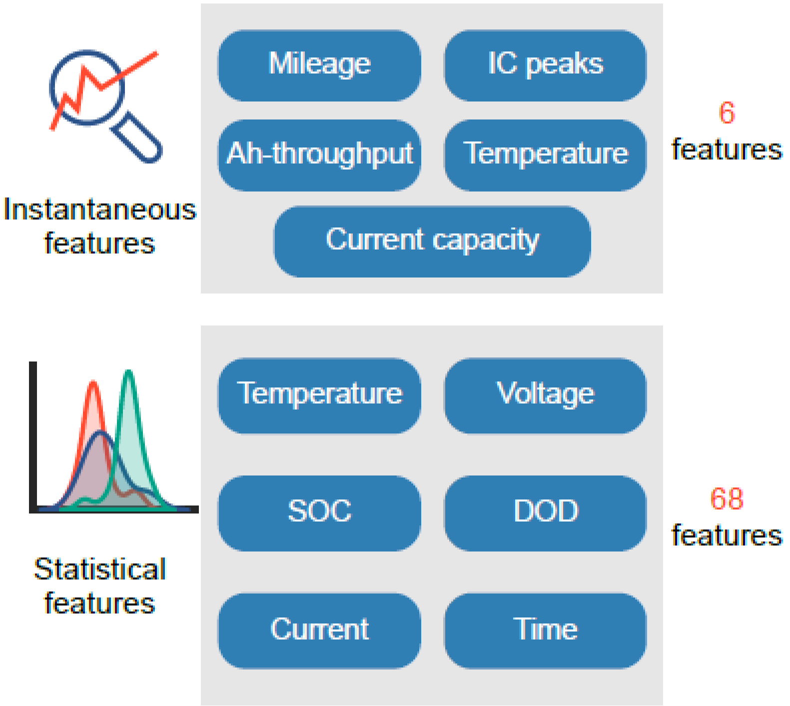
Q. Wang, et al., Cell Reports Physical Science, 4(12), 2023.

Statistical feature engineering with multi-level strategy

Data interval division

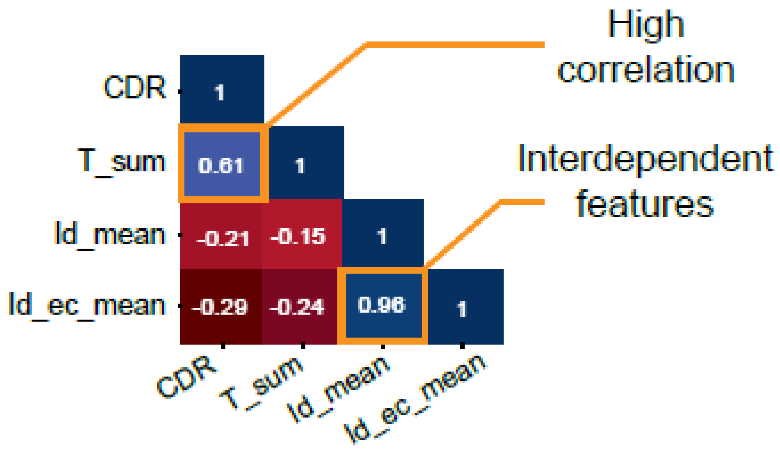


Feature pool construction

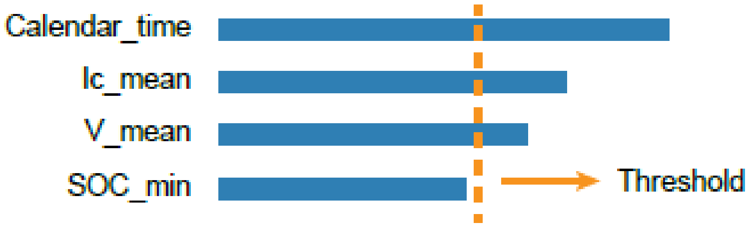


Q. Wang, et al., Cell Reports Physical Science, 4(12), 2023.

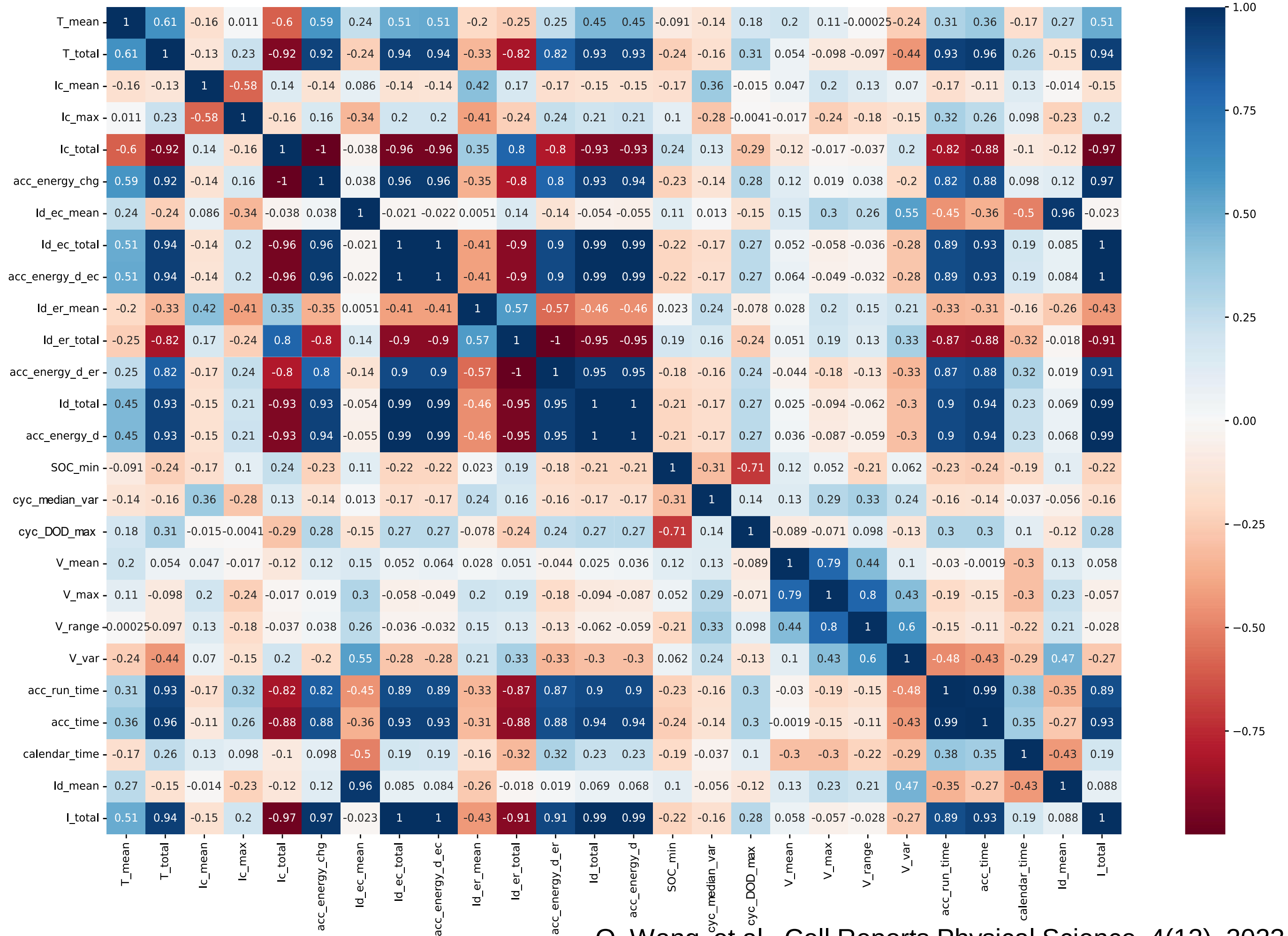
Feature selection with correlation analysis



Correlation analysis

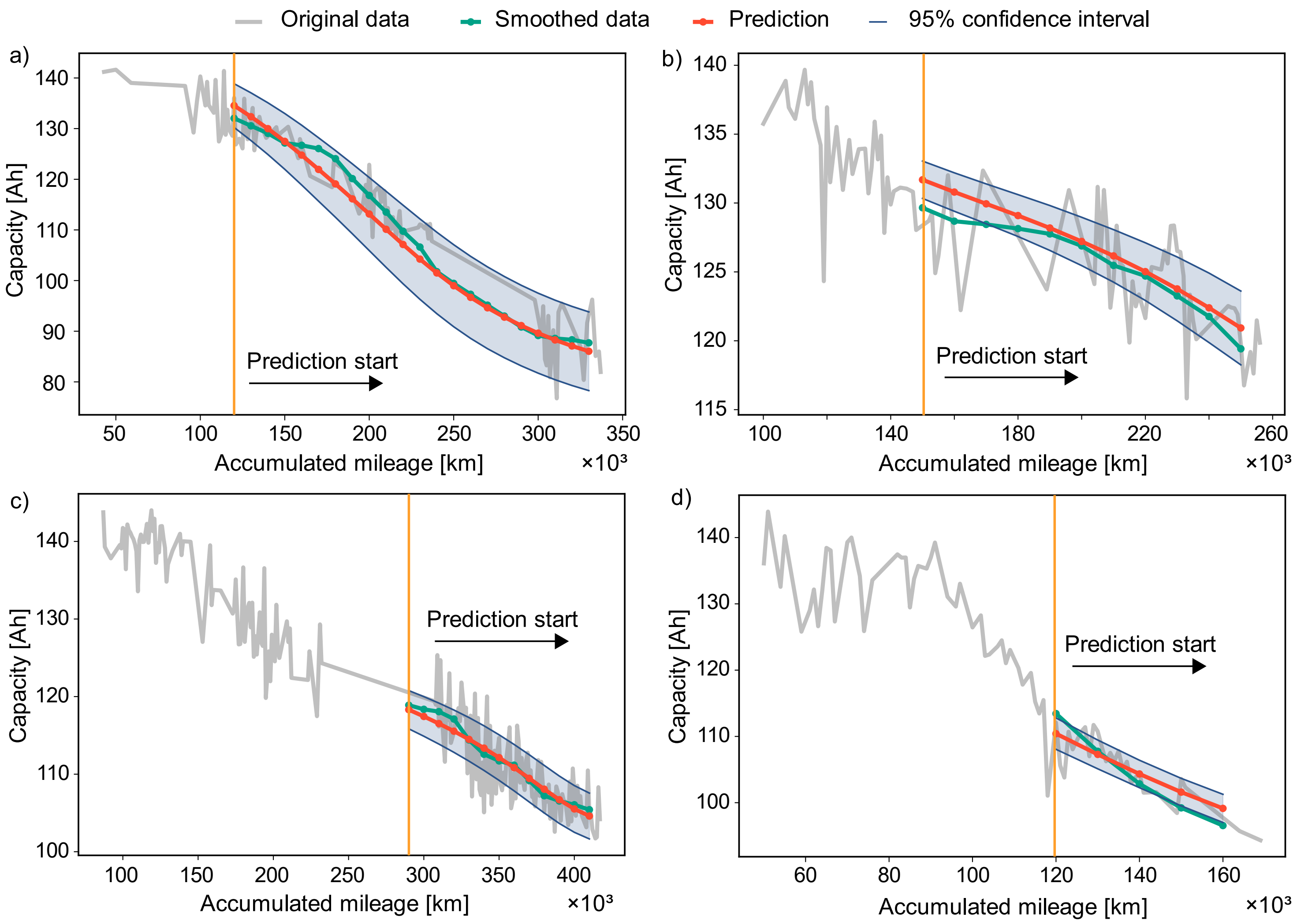


LightGBM feature importance



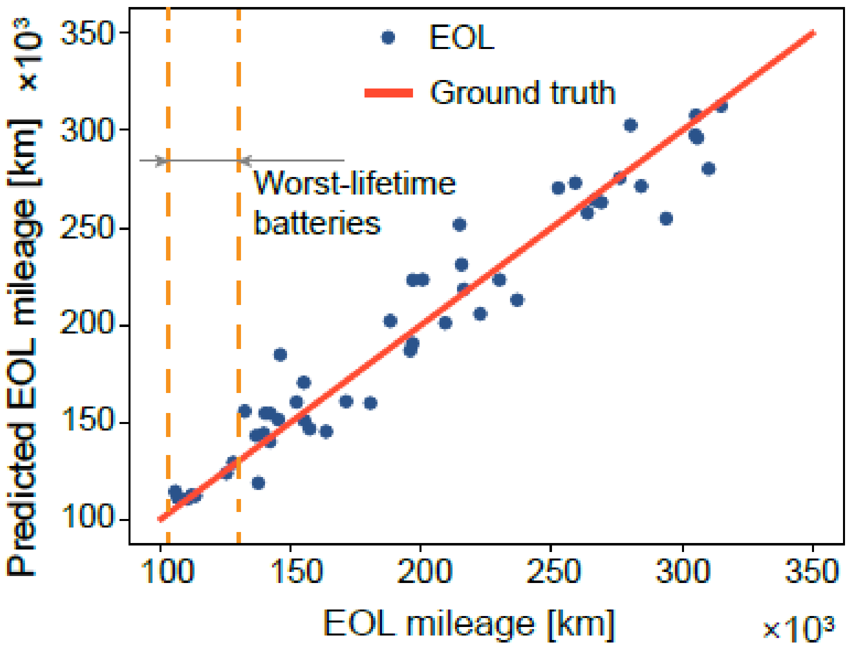
Q. Wang, et al., Cell Reports Physical Science, 4(12), 2023.

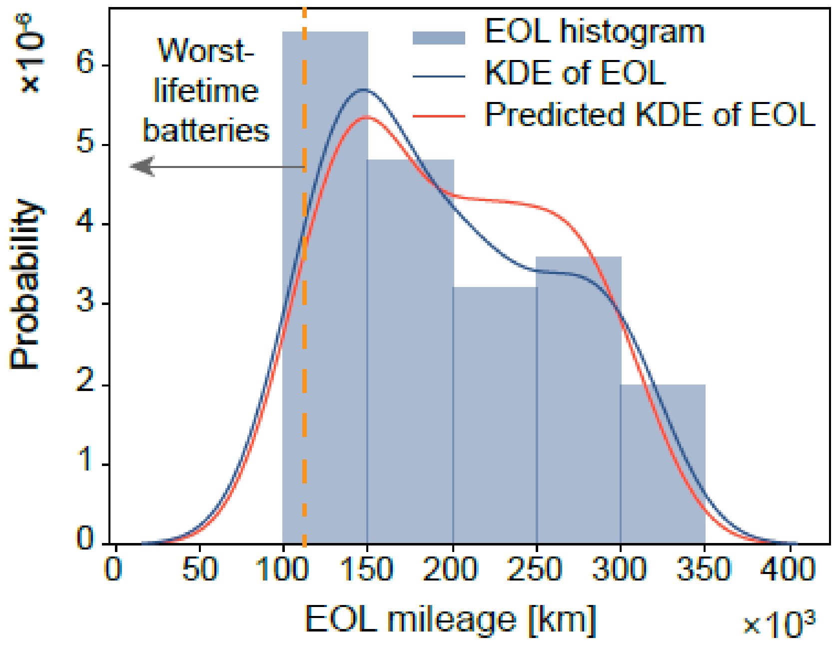
Uncertainty-aware degradation prediction



Q. Wang, et al., Cell Reports Physical Science, 4(12), 2023.

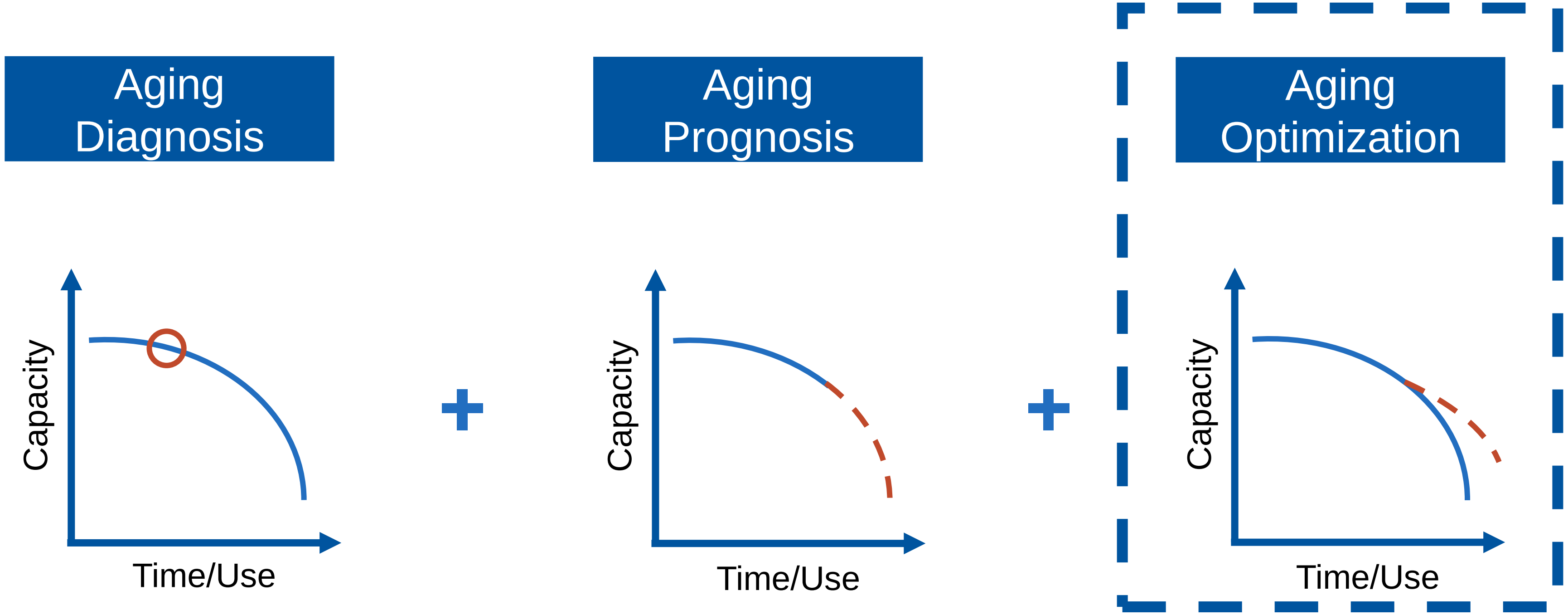
Failure distribution is as important as lifetime prediction for warranty



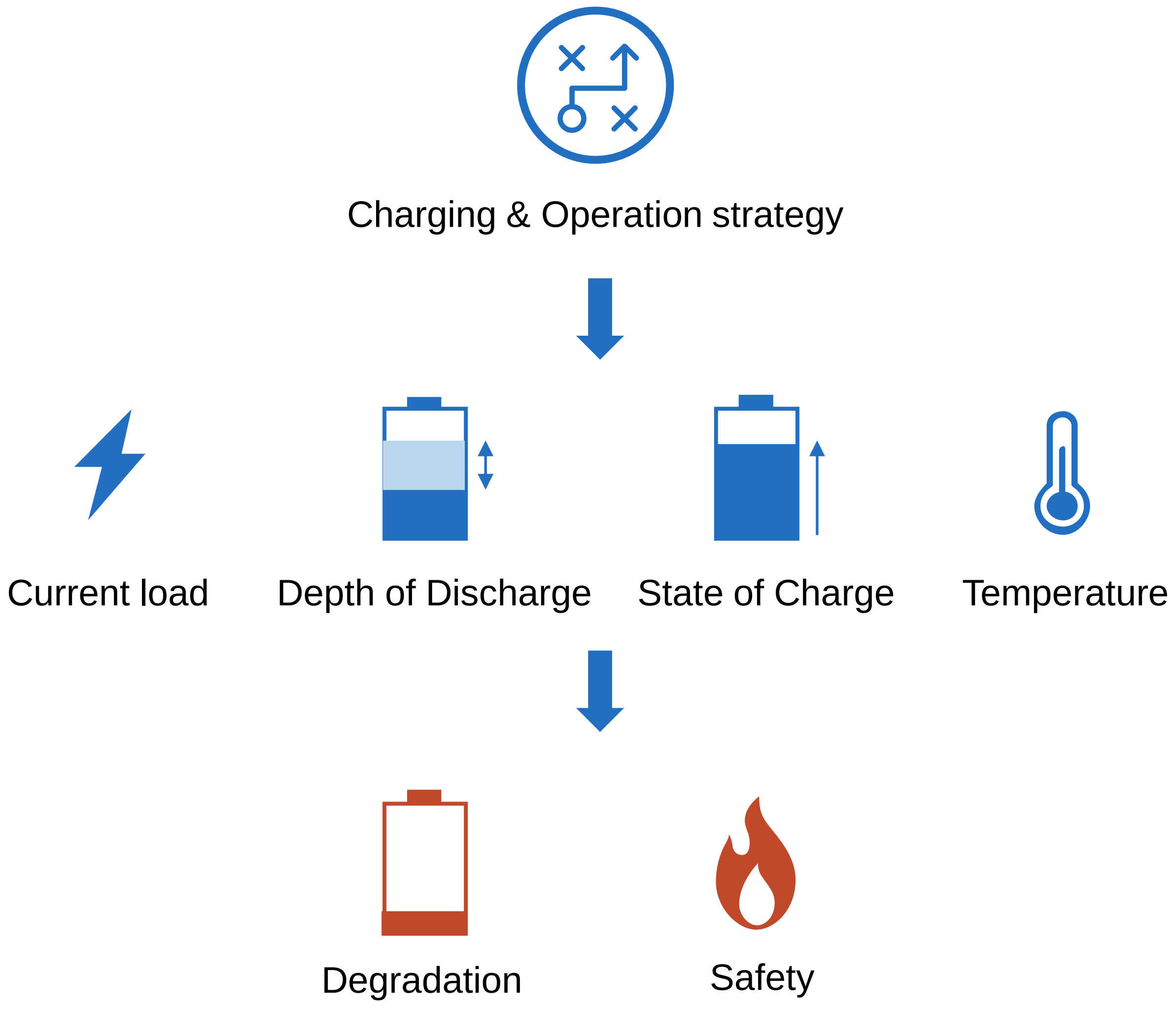


Q. Wang, et al., Cell Reports Physical Science, 4(12), 2023.

Agenda


Aging Diagnosis
Capacity
Time/Use
+
Aging Prognosis
Capacity
Time/Use
+
Aging Optimization
Capacity
Time/Use

Challenges in aging optimization



Fleet management

https://driivz.com/solutions/ev-fleets/

Energy management

https://www.aroundhome.de/magazin/energie/smart-grid-intelligente-stromnetze-fuer-die-erhoffte-energiewende/

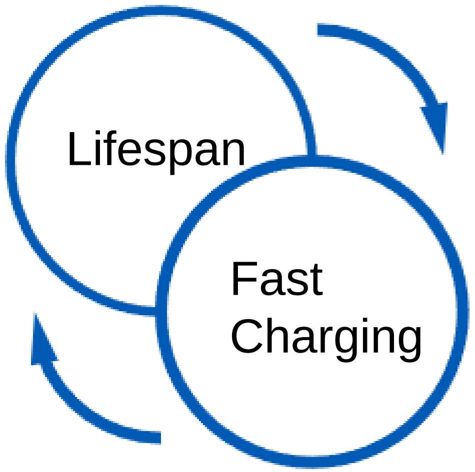
- How to develop safety- and aging-conscious operation strategies?
- How to develop updatable operation strategies?
- How to consider a large dimension of states?

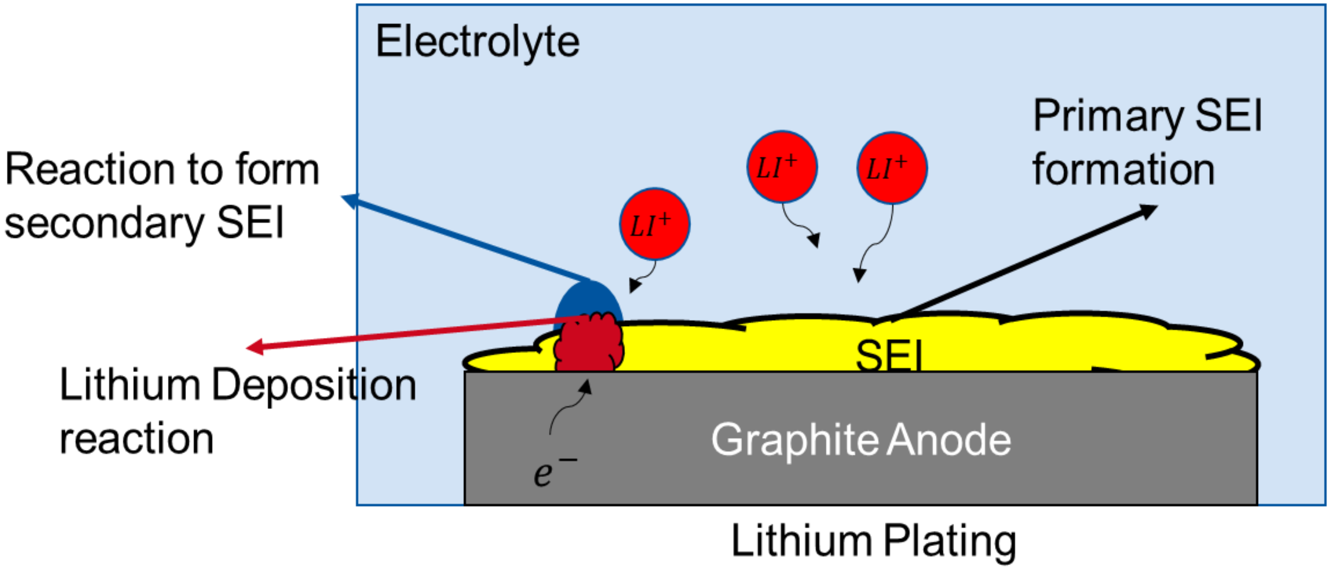
CARL Center for Ageing, Reliability and Lifetime Prediction of Electrochemical and Power Electronic Systems
RWTH AACHEN UNIVERSITY

Fast Charging Trade-off

- Trade-off between fast charging and ageing

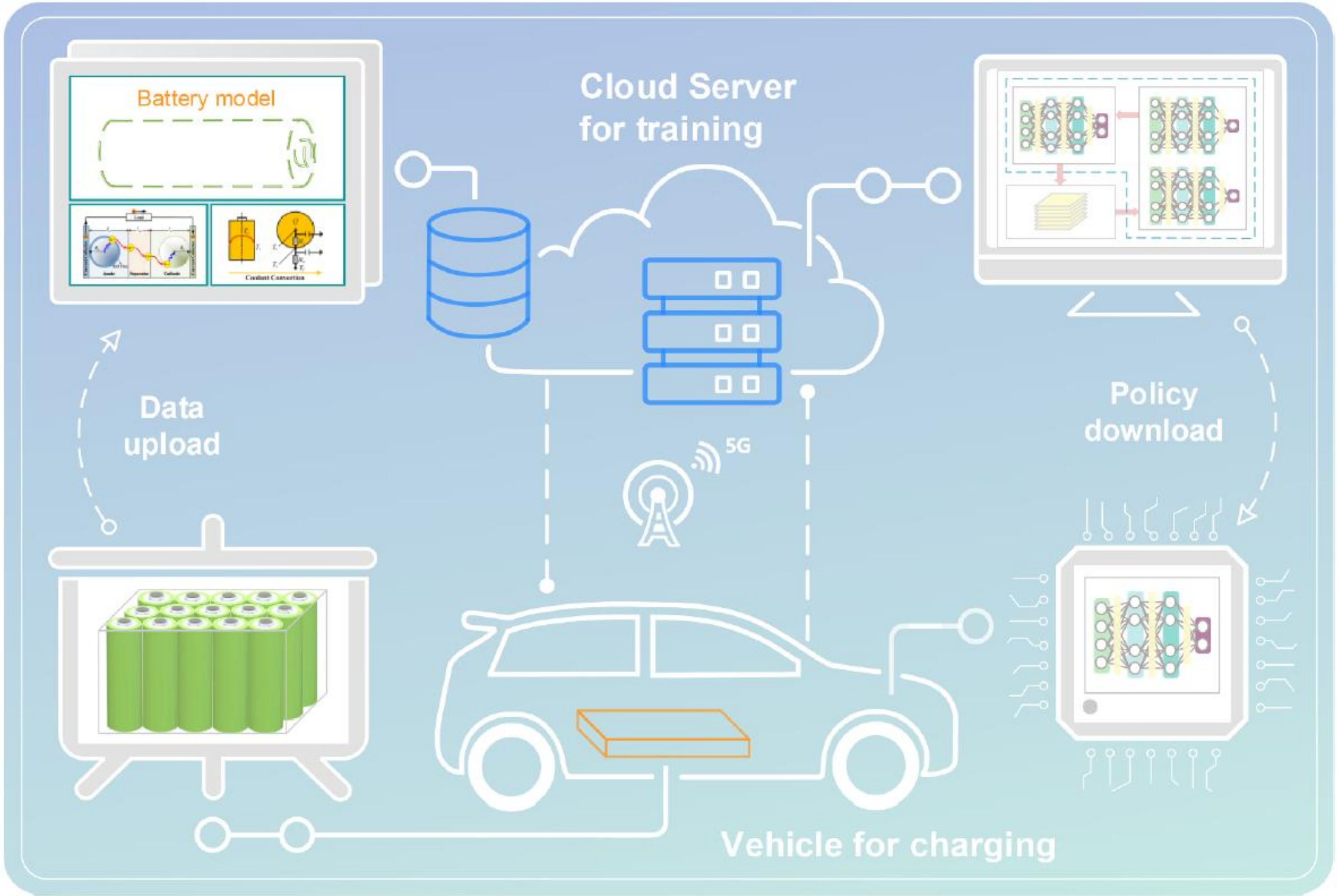
- Lithium plating





M. Sanne, et al., 2024, in preparation

Aging-aware fast charging with reinforcement learning

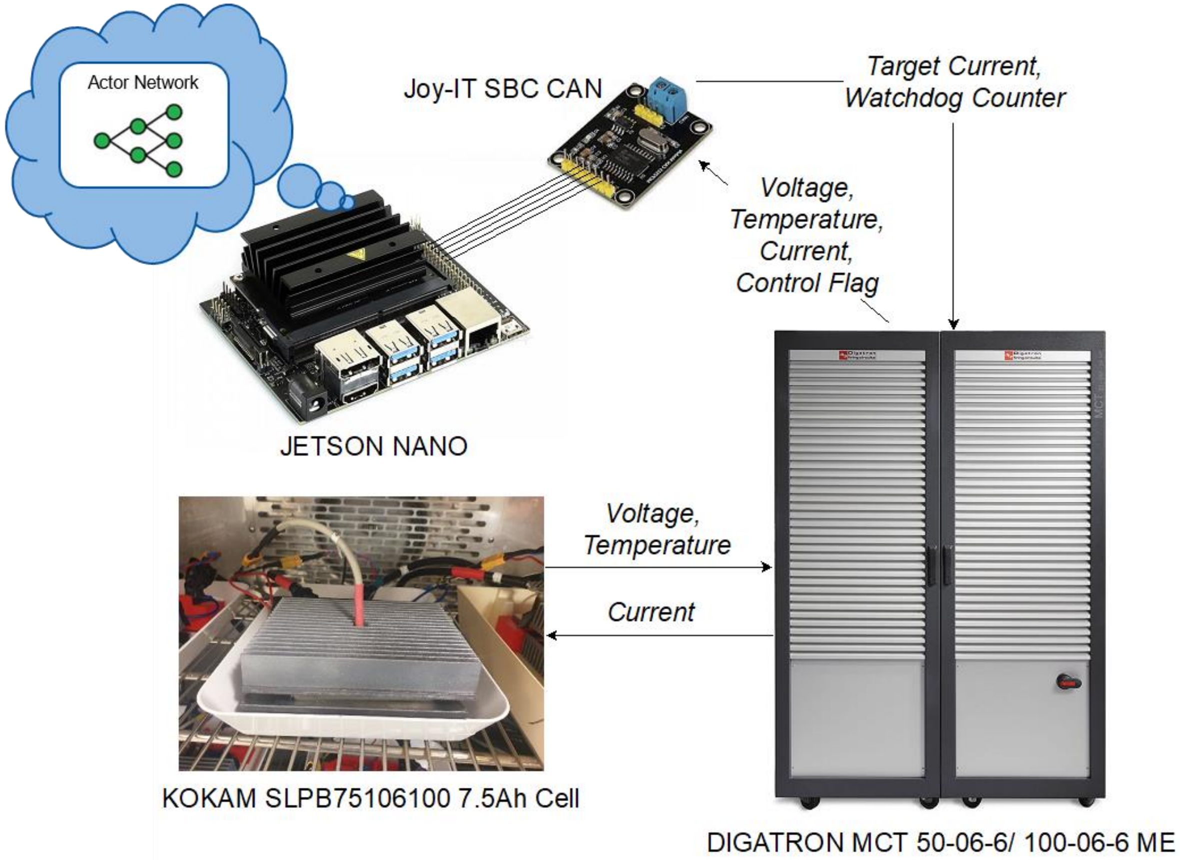


Z. Wei, et al., Energy Storage Materials, 56, 62-75, 2023

Testing Procedure - Experimental Setup

- Scenario
  - Charge from 10% SOC to 80% SOC
  - Temperature 0 °C
  - Active Cooling with Aluminium Cooling Plates
  - Charging Time ~ 54 minutes

- Benchmarks
  - Constant Current Constant Voltage (CCCV)
  - Multistage Constant Current (MCC)

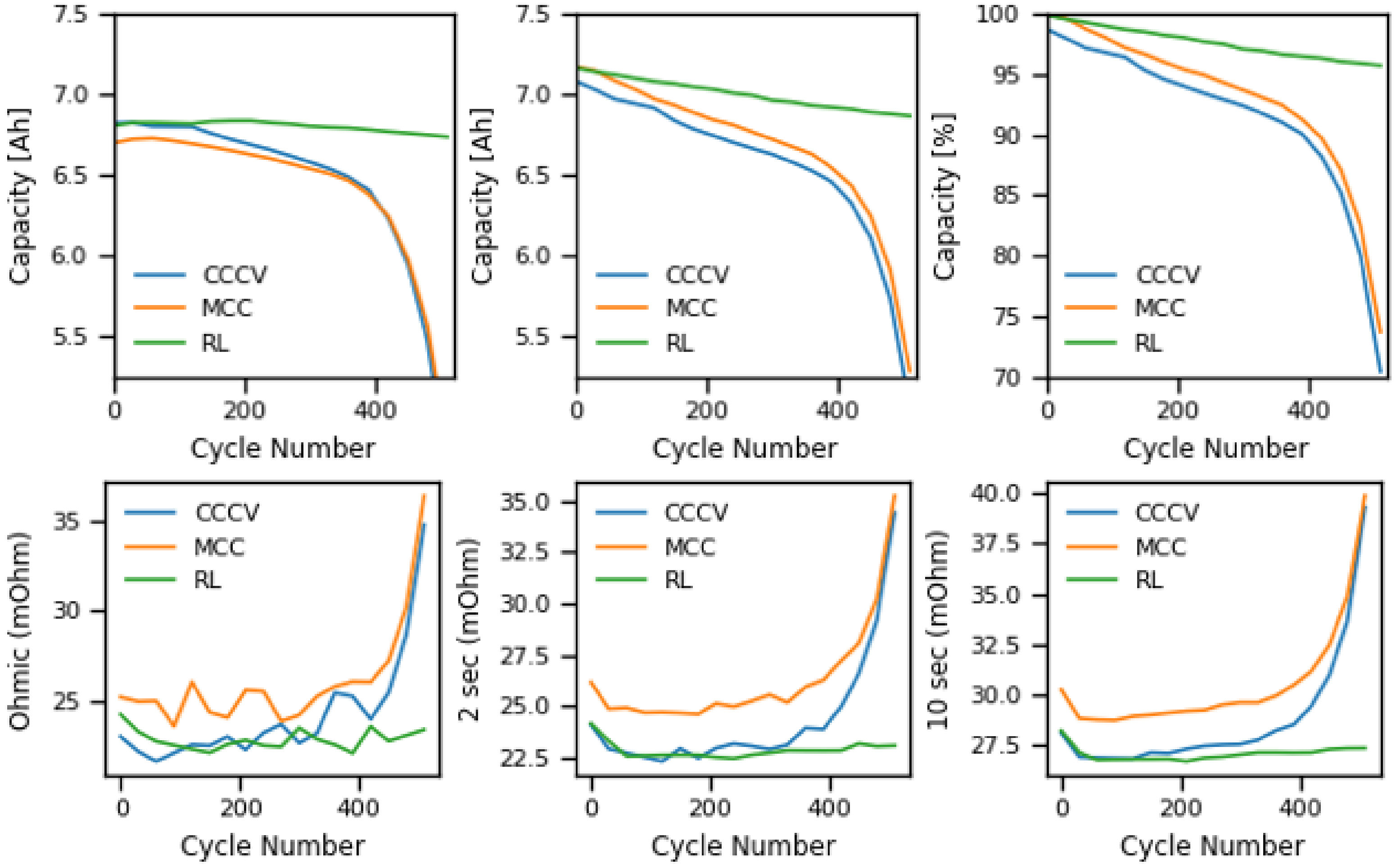


M. Sanne, et al., 2025, in preparation

Battery lifetime extension with intelligent fast charging

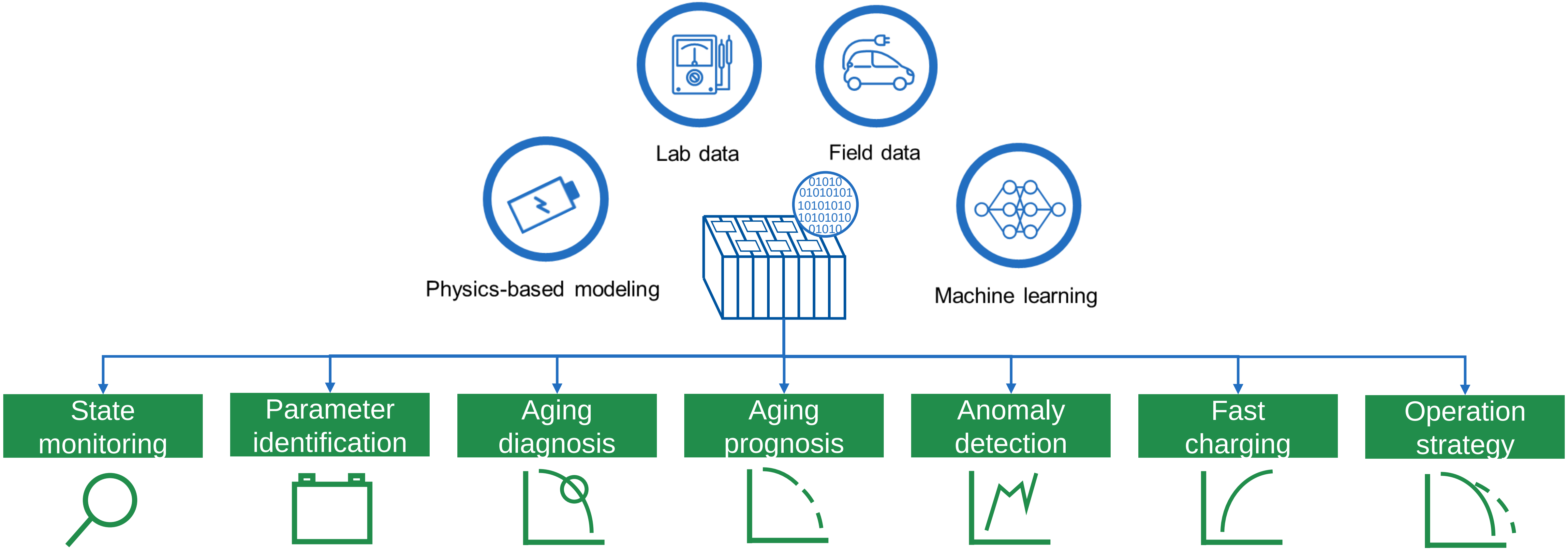
- Benchmarks
  - CCCV @ 0.787 C
  - MCC @ 1.25, 1.05, 0.85, 0.5 C

- Improved model performance



M. Sanne, et al., 2025, in preparation

Summary



- Battery digital twin with revolutionary battery management functionalities
- Fusion of physics-based and machine learning models
- Full life cycle monitoring, prediction and control of battery dynamics

Artificial Intelligence and Digitalization for Batteries @ RWTH Aachen University

Part of the group, March 2025

Gefördert durch:
Bundesministerium für Bildung und Forschung

Gefördert durch:
Bundesministerium für Wirtschaft und Klimaschutz

Gefördert durch:
Bundesministerium für Digitales und Verkehr

MARIE CURIE ACTIONS

Alexander von HUMBOLDT STIFTUNG

Ministerium für Kultur und Wissenschaft des Landes Nordrhein-Westfalen