Aluminium Ion Batteries at Fraunhofer IISB: Progress and Challenges towards Application

Fraunhofer IISB

Fraunhofer-Institut für Integrierte Systeme und Bauelemente-technologie IISB

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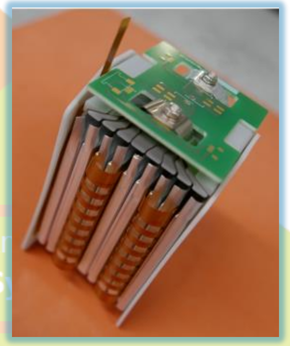
22.05.2025

Fraunhofer IISB know-how center: Battery Systems4Future



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Materials

Devices

Packaging

Power Conversion Systems

Energy Storage Systems

Unique research environment for (high power) storage technology development

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Aluminium/Graphite dual-ion batteries (AIB / AGDIB)

Motivation

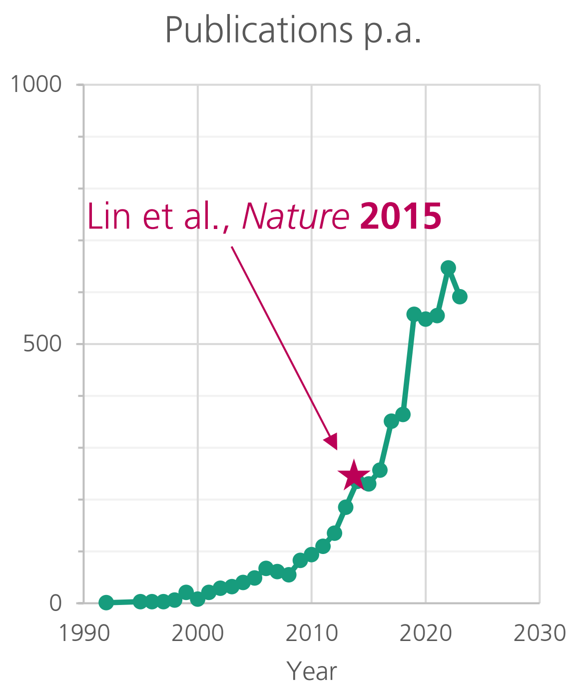
Advantages

- Low-cost & abundant electrode materials
- No critical raw materials (Li, Co, Ni)
- No flammable electrolyte

- Medium energy density (comparable to Pb-acid)
- High-rate capability (up to 20 A/$g_{Graphite}$)
- High power density (9 kW/$kg_{Graphite}$)
- Long cycle life (> 20.000)
- High Coulomb efficiency (>95%)

High power battery meeting dynamical requirements

- Dynamical grid stabilization
- Hybrid mobile applications, power peak booster



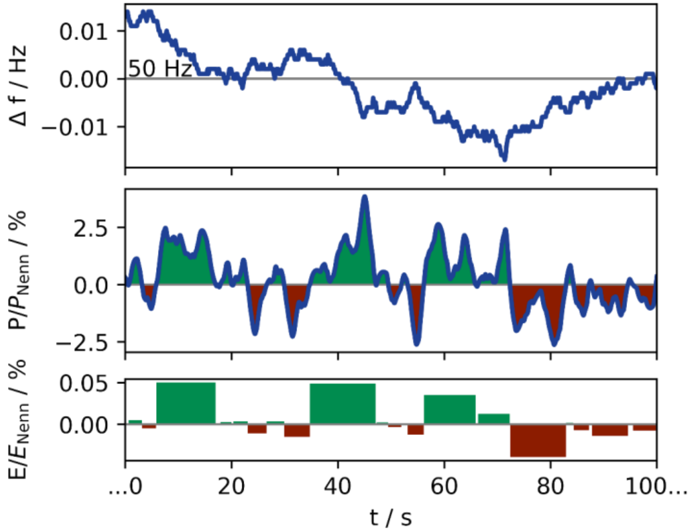
Scopus search „Al ion battery“

Wunderwald et al., *Nachr.Chem.* **2023**

Propects

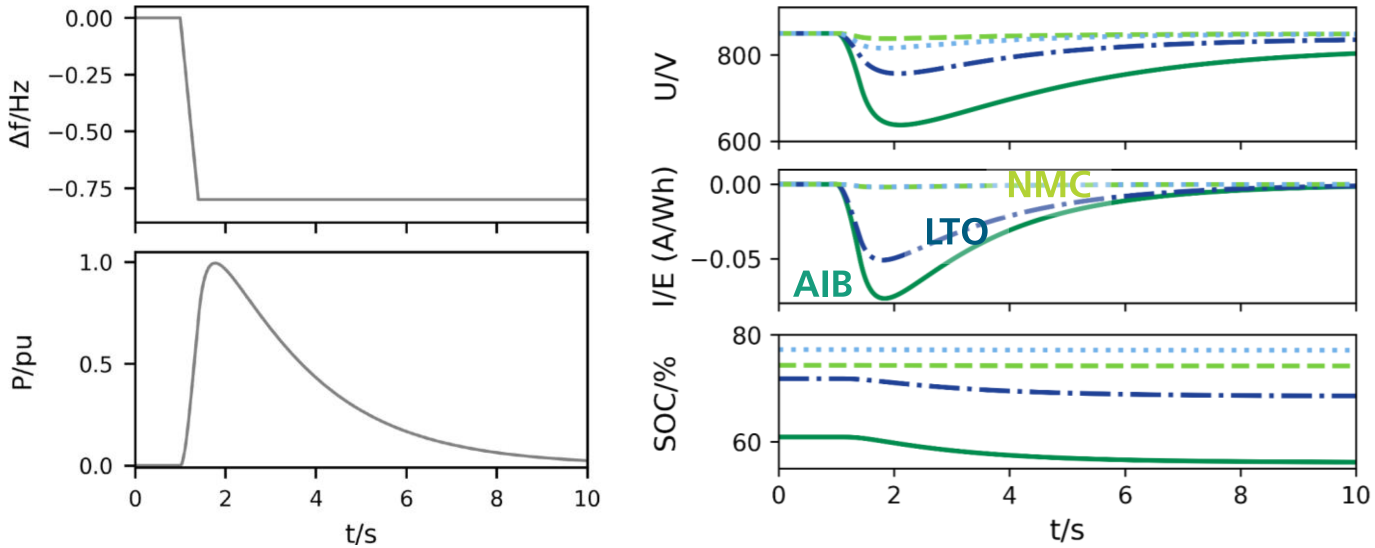
Case study: dynamical grid stabilization by battery energy storage systems (BESS)

Requirements for instantaneous reserve



- Analysis of grid microcycles
- High cycle stability
- high symmetrical power, medium energy required

Simulated frequency drop for different battery technologies



- NMC's disadvantage: limited charge rate
- AIB's high rate capability enables storage system with high P/E ratio

J. Klink et al., *Energy Reports* **2025**
J. Klink et al., *Advanced Battery Power* **2024**
Benger et al., *Advanced Battery Power* **2022**

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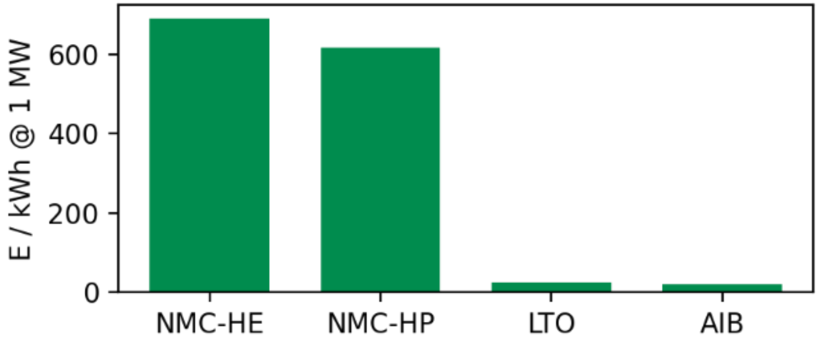
Prospects

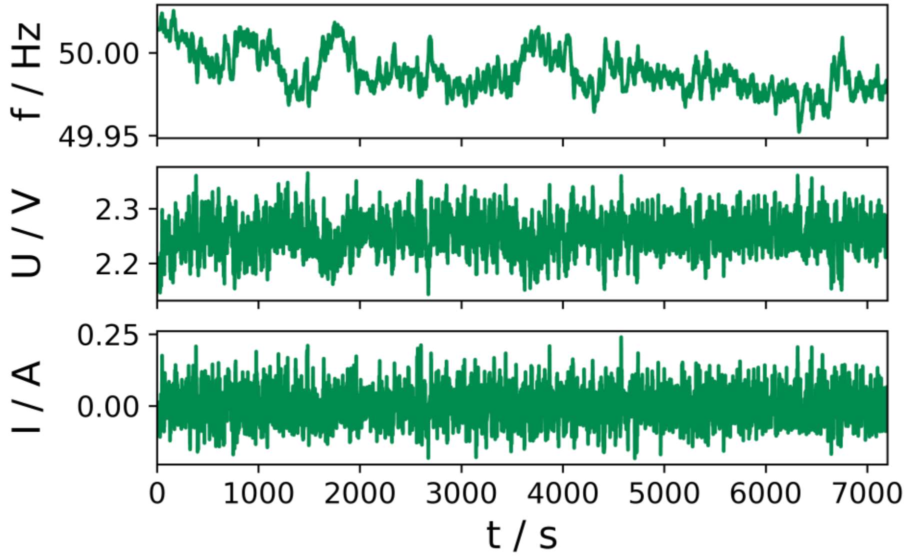
Case study: dynamical grid stabilization by battery energy storage systems (BESS)

BESS system configuration



- NMC: not suitable for instantaneous reserve only
- AIB: symmetrical performance enables power-focused design

Experimental emulation of instantaneous reserve with AIB



- Provision of instantaneous reserve based on real frequency data with AIB pouch cell

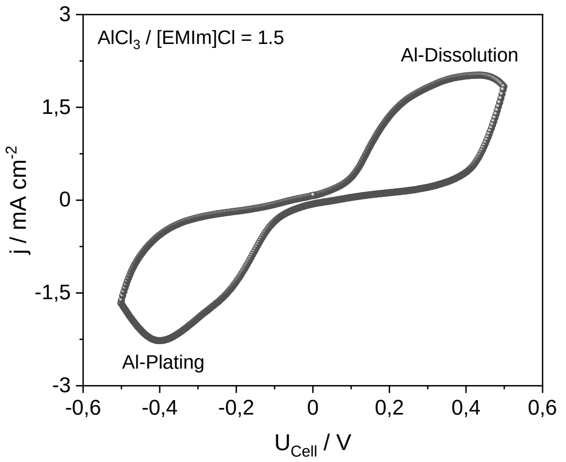
Outcomes

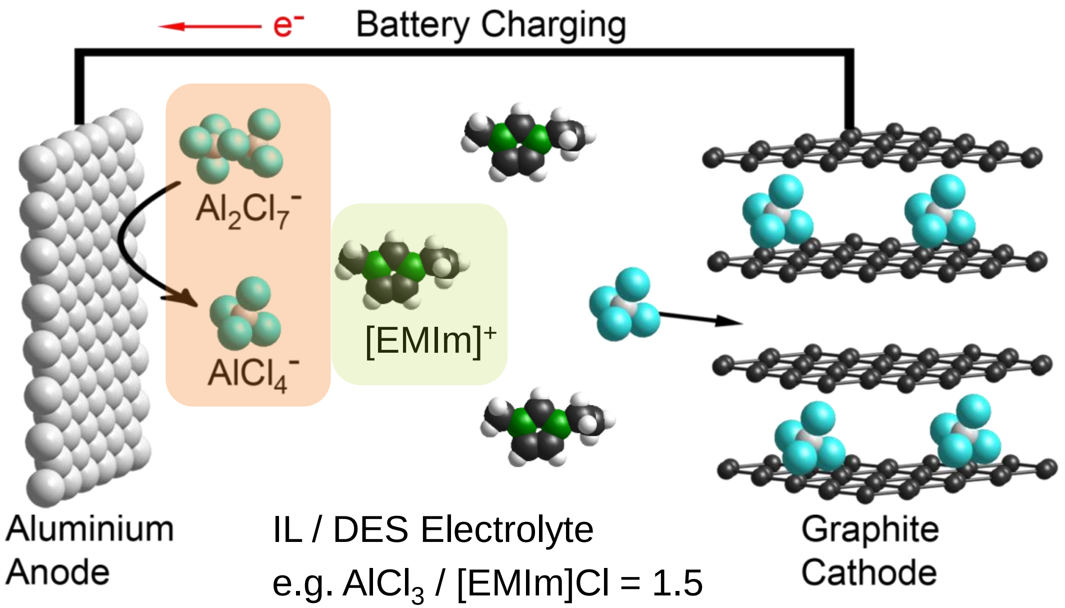
- Long term stable AIB pouchcells exhibiting high P/E ratio
- AIB meets the requirements
  a) instantaneous reserve
  b) dynamical load balancing
- Bridges the gap between supercaps & LTO

J. Klink et al., *Advanced Battery Power* **2024**
Benger et al., *Advanced Battery Power* **2022**

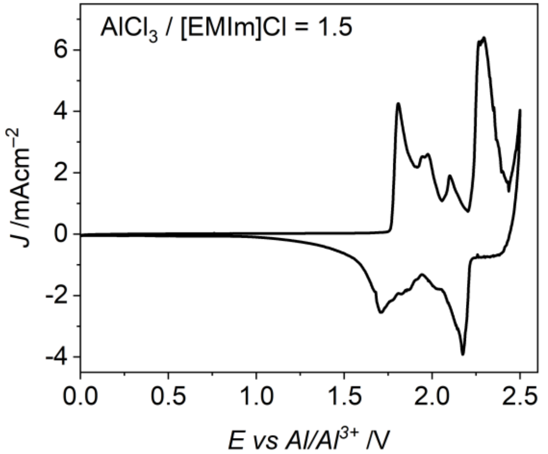
Cell Chemistry

Al dissolution & plating





Intercalation into graphite



$$4\,Al_2Cl_7^- + 3\,e^- \rightleftharpoons Al + 7\,AlCl_4^-$$

Chloroaluminates

- Electroactive species
- Ratio depends on $AlCl_3$ content
- Concentration affects battery performance

Cations & neutral species

- Indirect influence
- Affect species equilibria

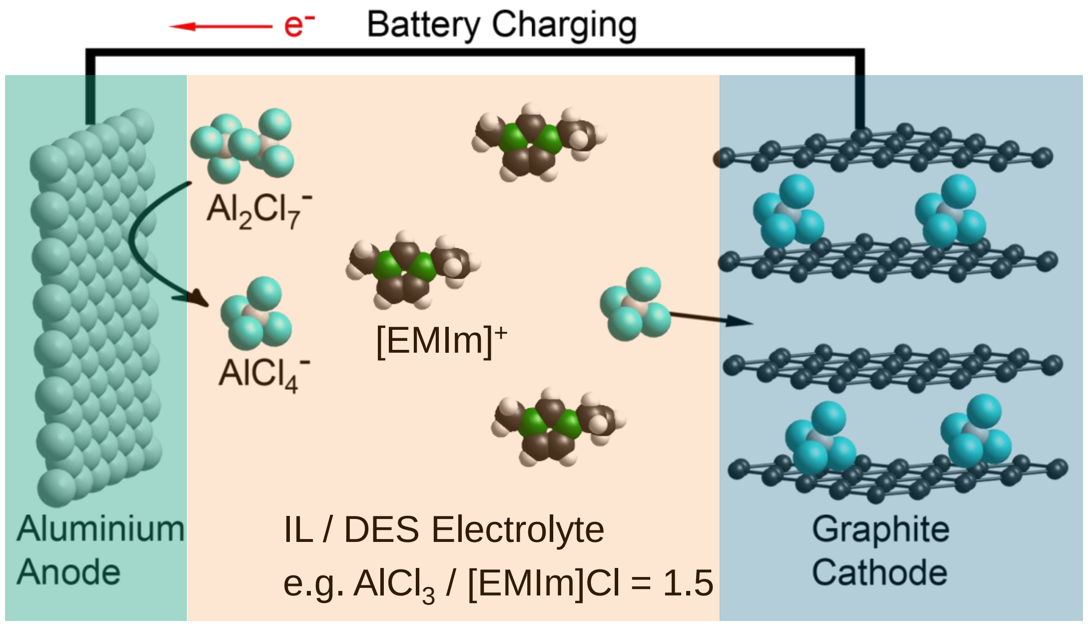
$$3\,C_n + 3\,AlCl_4^- \rightleftharpoons 3\,C_n[AlCl_4] + 3\,e^-$$

Advantages & Challenges

Anode

✓Cheap alloy materials

× Dendrite growth



Cathode

✓Cheap natural graphite

✓Water-based slurry

× Suitable current collector: Mo

Electrolyte

✓IL or cheap DES (e.g. urea based)

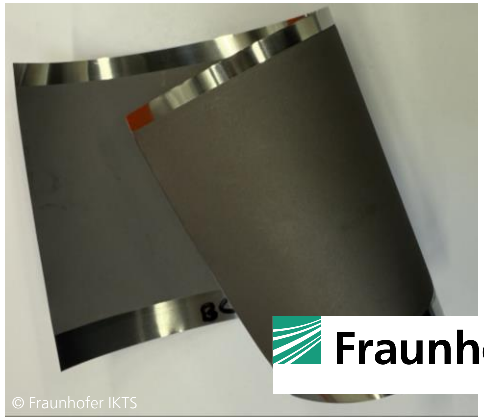
× Highly corrosive – stable materials required

× Charge carrier storage – large amount required

Research topics
Upscaling

Cathode manufacturing

- Passive materials:
  binders, current collector
- Manufacturing parameters:
  coating & calendaring



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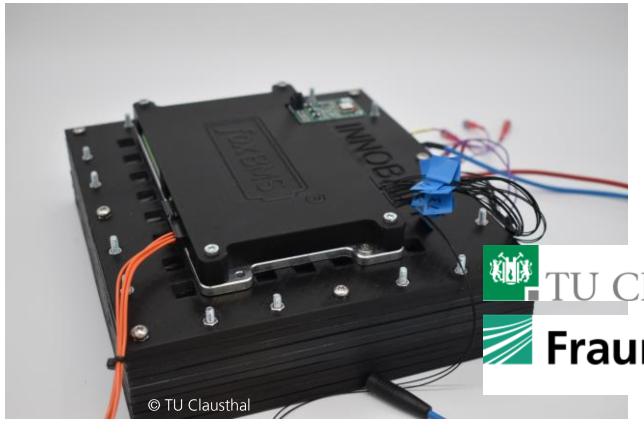
Pouch cell design

- Casing materials
- Manufacturing process

System demonstrators

- Module construction
- BMS & sensor integration



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Evaluate new cell chemistries close to application environments

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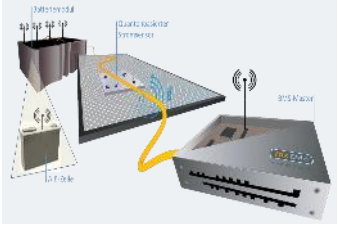
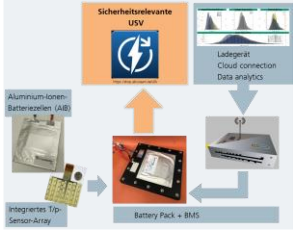
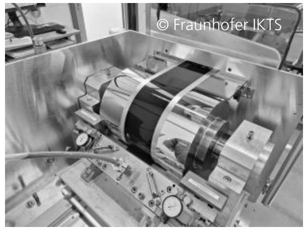
AIB projects at IISB

TRL2	TRL3	TRL4	TRL5	TRL6	TRL7

Cell chemistry investigations → Pouch cell demonstrators → **System demonstrators** → Pilot manufacturing







ALIBATT

ALBATROS+

BattNutzung GridBatt

INNOBATT
Eine Batterie neu denken.

IISB: FUNKTIONAL

BALU

BMWE: SALSA

Advanced characterization

SMWK: SaxBattEmpower

THM-Sonderfinanzierung

BMBF: InfraDatRec

IISB: OptoBatt

STAATSMINISTERIUM FÜR WISSENSCHAFT KULTUR UND TOURISMUS
Freistaat SACHSEN
With funding from the: Federal Ministry of Research, Technology and Space

Advanced characterization

Materials: structure & morphology

Unravelling structure-property relations

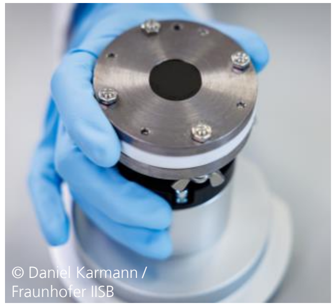
- Pristine materials
- Electrochemical properties
- Operando examinations
- Post-mortem analyses

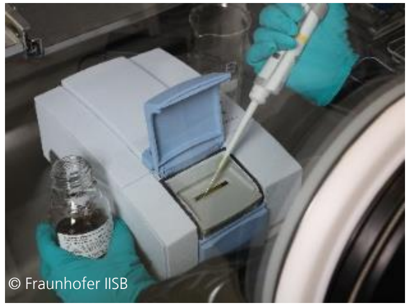
Operando methods

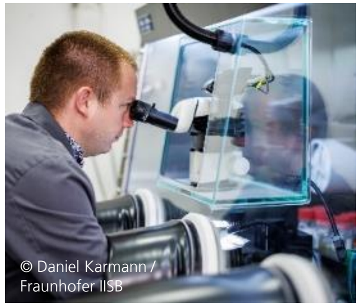
- X-ray diffraction
- Raman spectroscopy
- Light microscopy
- Adapt operando cells

Ex-situ material analyses

- inert conditions often possible
- IR spectroscopy
- SEM/EDX
- Light microscopy
- Water content (Karl-Fischer coulometry)
- Particle size (laser diffraction)
- BET surface (N_2 adsorption)







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Advanced characterization

Electrochemical methods

Material properties

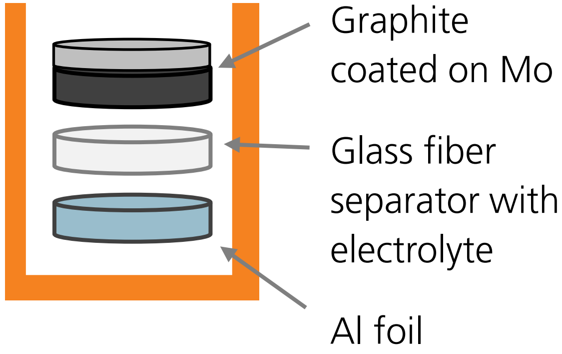
- Ionic conductivity of electrolytes
- Electrochemical surface analysis

Half / full cell evaluation

- Test cells dependent on material & topics
- Temperature-dependent measurements
- Inert conditions

Pouch cell prototyping

- Analyse new materials in application relevant scaling
- Adapt materials & manufacturing to cell chemistry



  Public

Electrolyte
Deep eutectic solvents

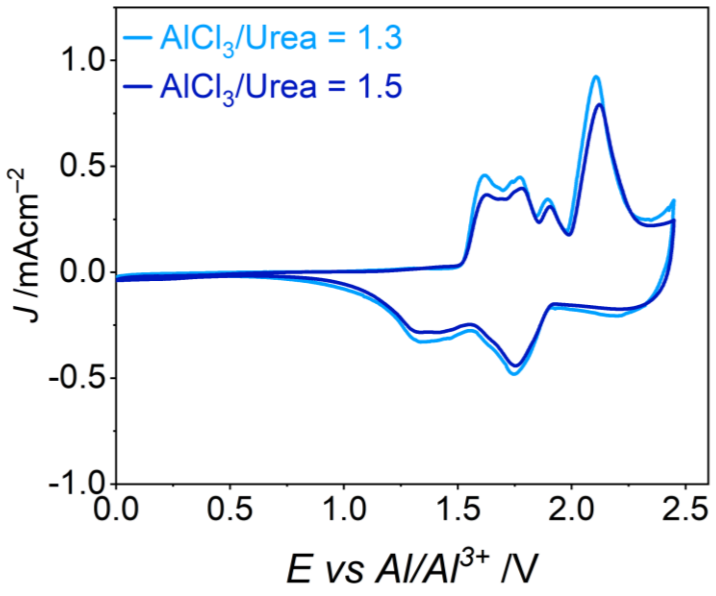
Urea based electrolytes

- ✓ Extremely cheap electrolyte:
  $AlCl_3$/urea 19000 €/t
  $AlCl_3$/[EMIm]Cl 65000 €/t
- ✓ Similar intercalation mechanism
- ✓ Similar capacities
- ✓ Less corrosive than ILs
- ✓ First tests using technical urea

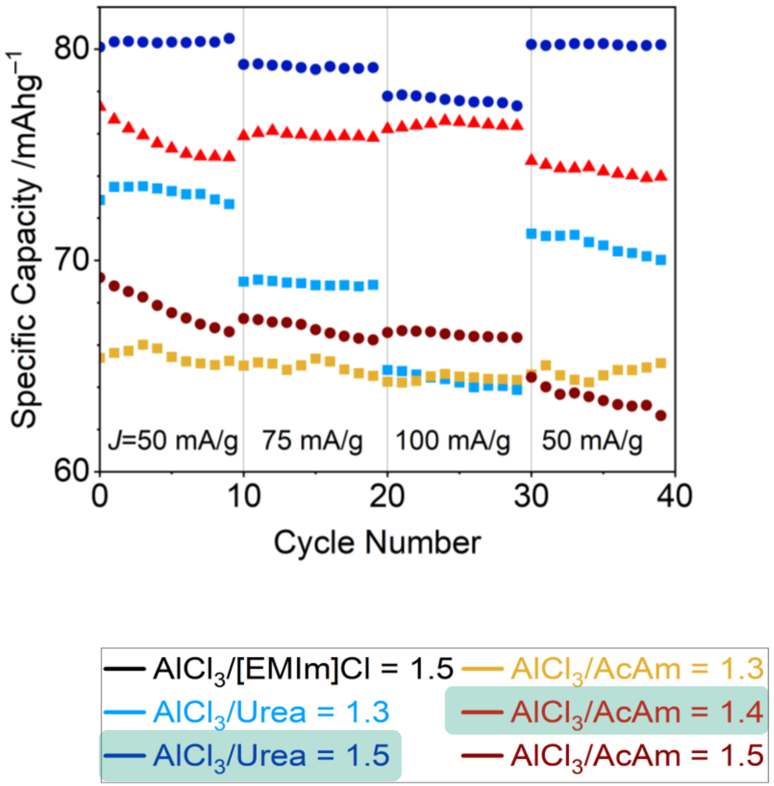
➢ Performance depends on Al speciation

➢ Lower ionic conductivity than ILs

Cyclovoltammetry



Charge / discharge cycling



Electrolyte

Deep eutectic solvents

Species equilibria

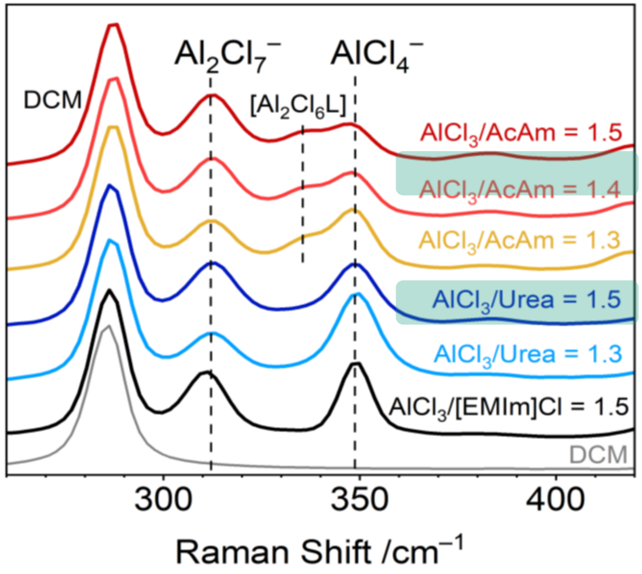
<u>For $AlCl_3$ / Amide L = 1</u>

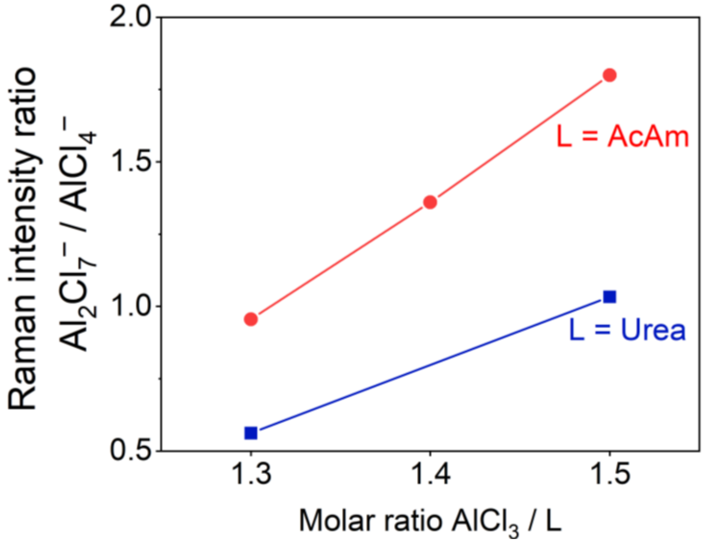
$$2\ AlCl_3 + 2\ L \rightarrow AlCl_4^- + [AlCl_2L_2]^+ \rightleftharpoons 2\ [AlCl_3L]$$

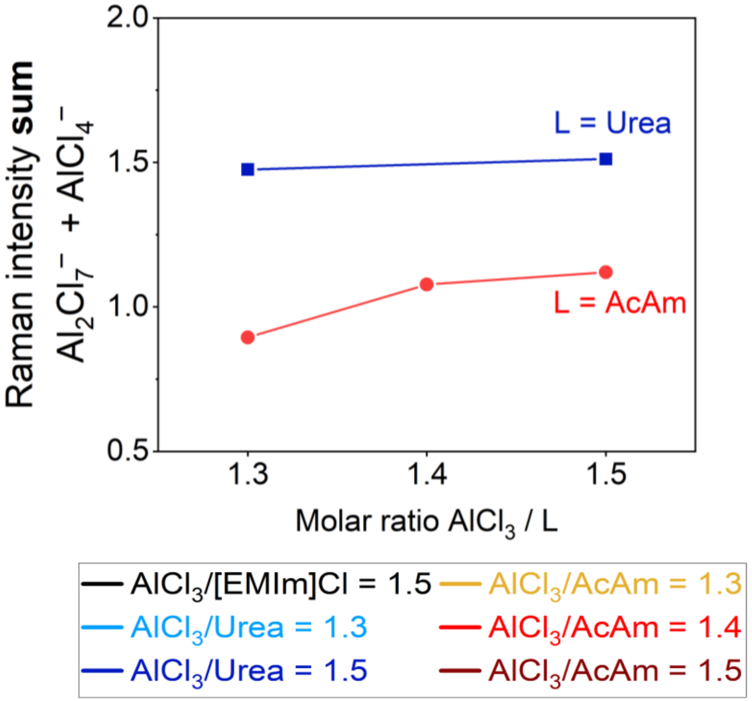
<u>Additional $AlCl_3$</u>

$$AlCl_4^- + [AlCl_2L_2]^+ + AlCl_3 \rightarrow Al_2Cl_7^- + [AlCl_2L_2]^+ \rightleftharpoons [AlCl_3L] + [Al_2Cl_6L]$$

$AlCl_4^-$ / $Al_2Cl_7^-$ concentration



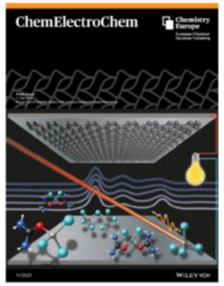




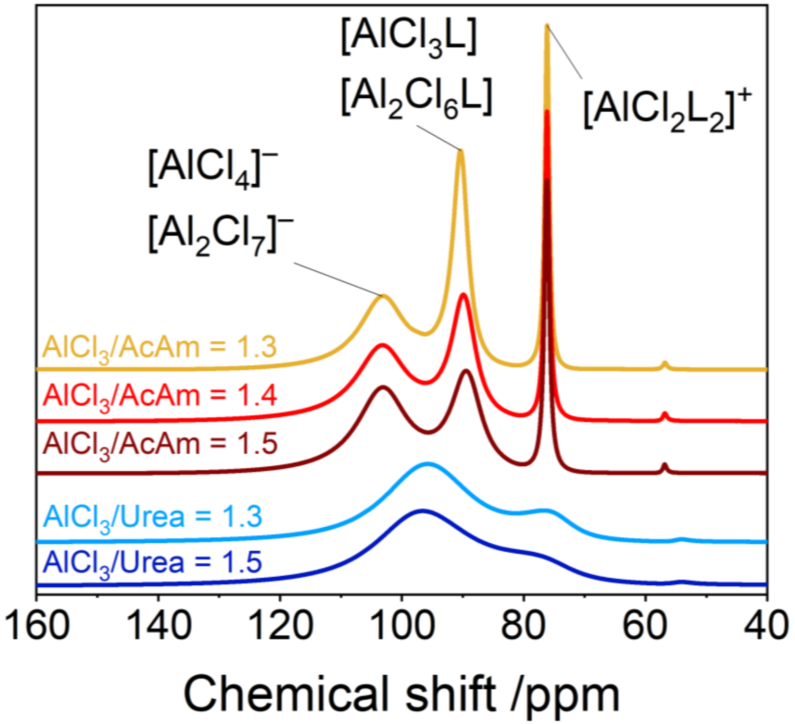
Electrolyte

Deep eutectic solvents

F. Jach et al., *ChemElectroChem* **2021**



^{27}Al NMR spectra



Relevant electrolyte properties

$AlCl_3$ / AcAm

- Higher anion concentration for higher $AlCl_3$ content

$AlCl_3$ / Urea

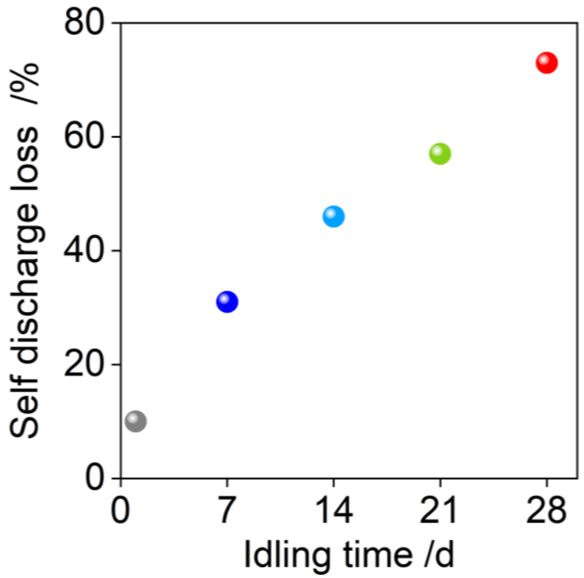
- High anion concentration
- High exchange rates of neutral & anionic species

➢ **Anion ratio**
➢ **Overall anion concentration**

Tuning of Al species to improve performance

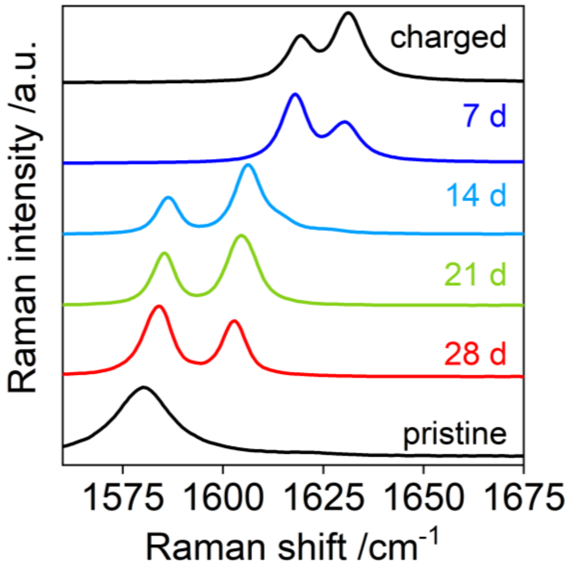
Failure mechanisms
Self-discharge

Self-discharge capacity loss



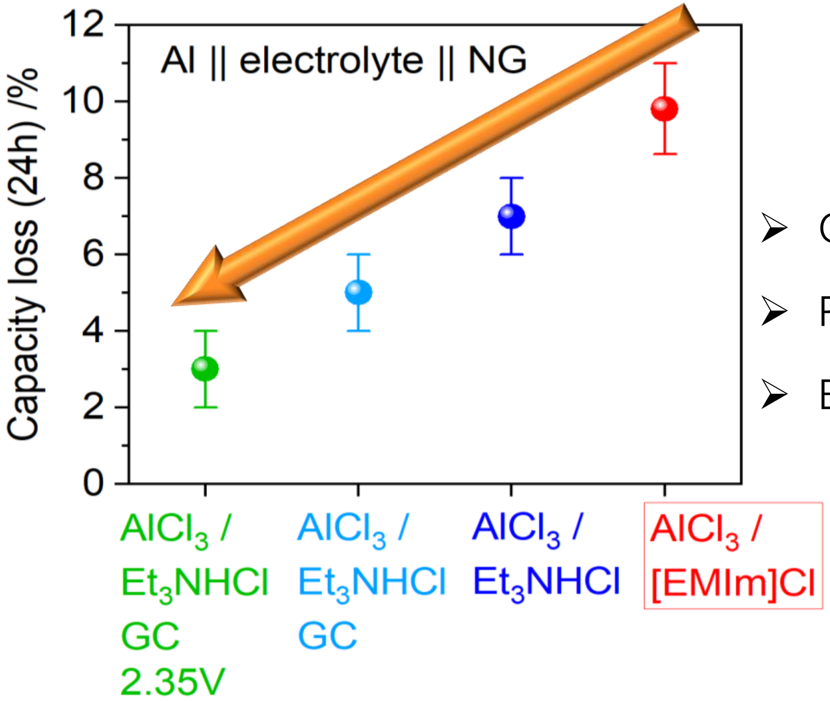
➢ No irreversible capacity loss

Raman spectroscopy



➢ Deintercalation mechanism confirmed

Reducing self-discharge



- ➢ Current collector
- ➢ Potential limit
- ➢ Electrolyte cations

➢ Reducing self-discharge capacity loss from 10% to 3%

  Public M. Bamberg et al., *Electrochim. Acta* **2024**

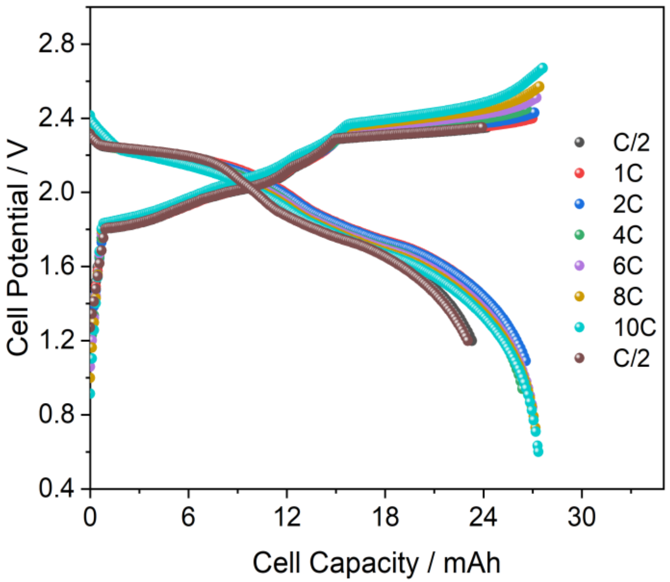
Pouch cell developement

Single-layered cells

Single-layerd cells

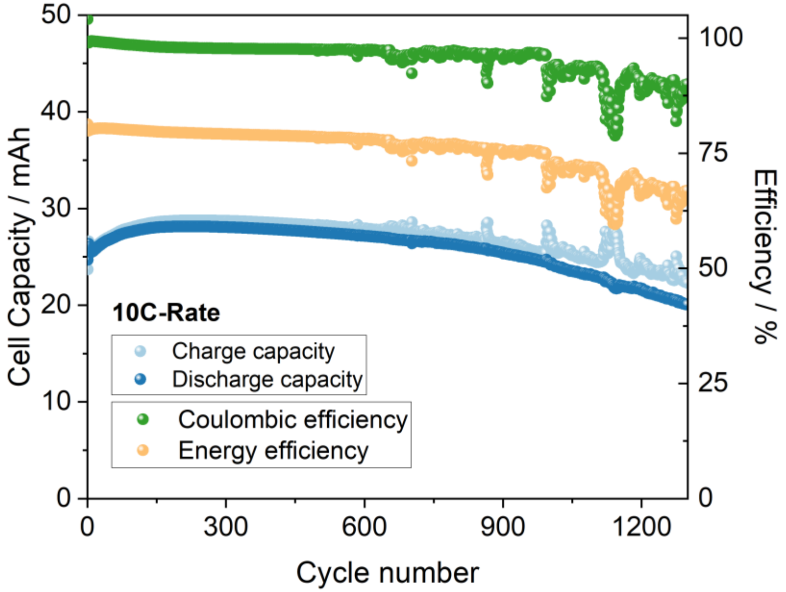
Rate capability

- High rate capabality with stable capacitites up to 10 C



Cycle life

- Cycle stability >1200 cycles



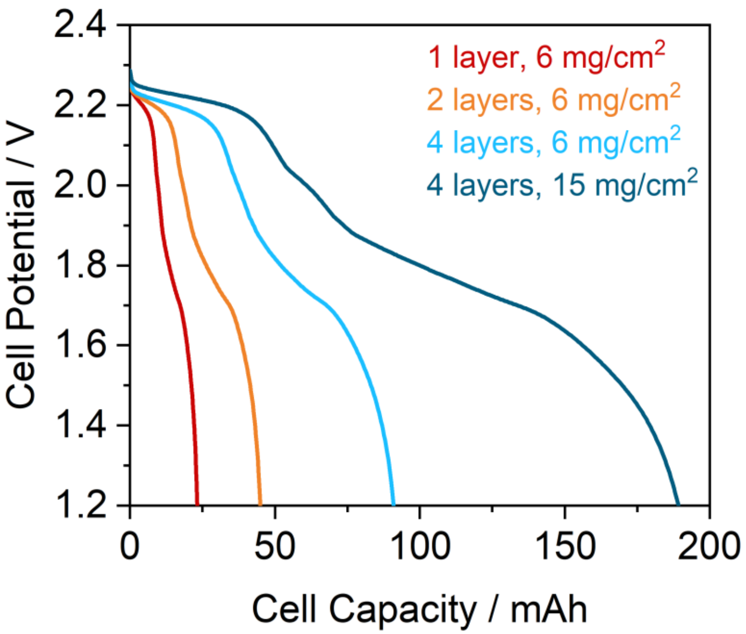
Pouch cell developement

Multi-layered cells

4-layered cells

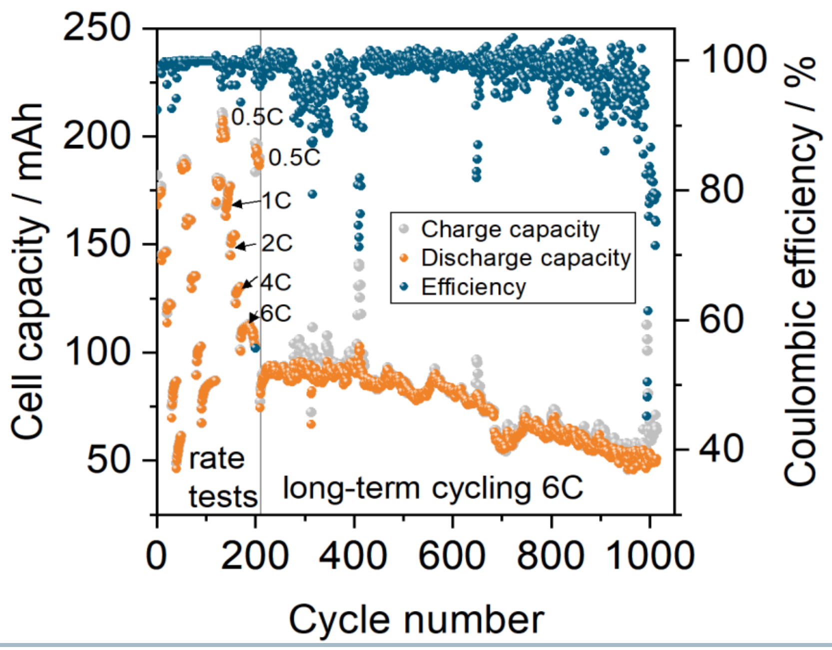
Cell capacities

- Raising cell capacities within to 200 mAh



Cycle life

- Similar cycling stabilities
- Optimizing high rate capability ongoing

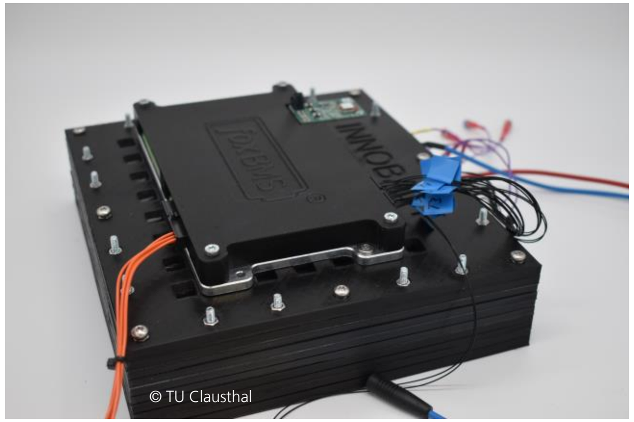


Aluminium/Graphite dual-ion batteries

Progress & Challenges

Progress

- Low cost materials ✓
  - Al alloys
  - Natural graphite
  - Bio-based binders
  - Urea electrolytes
- Improved shelf life ✓
- High rate capability up to 10C ✓
- Pouch cells: >1200 cycles, 200 mAh ✓
- BMS integration ✓



Challenges

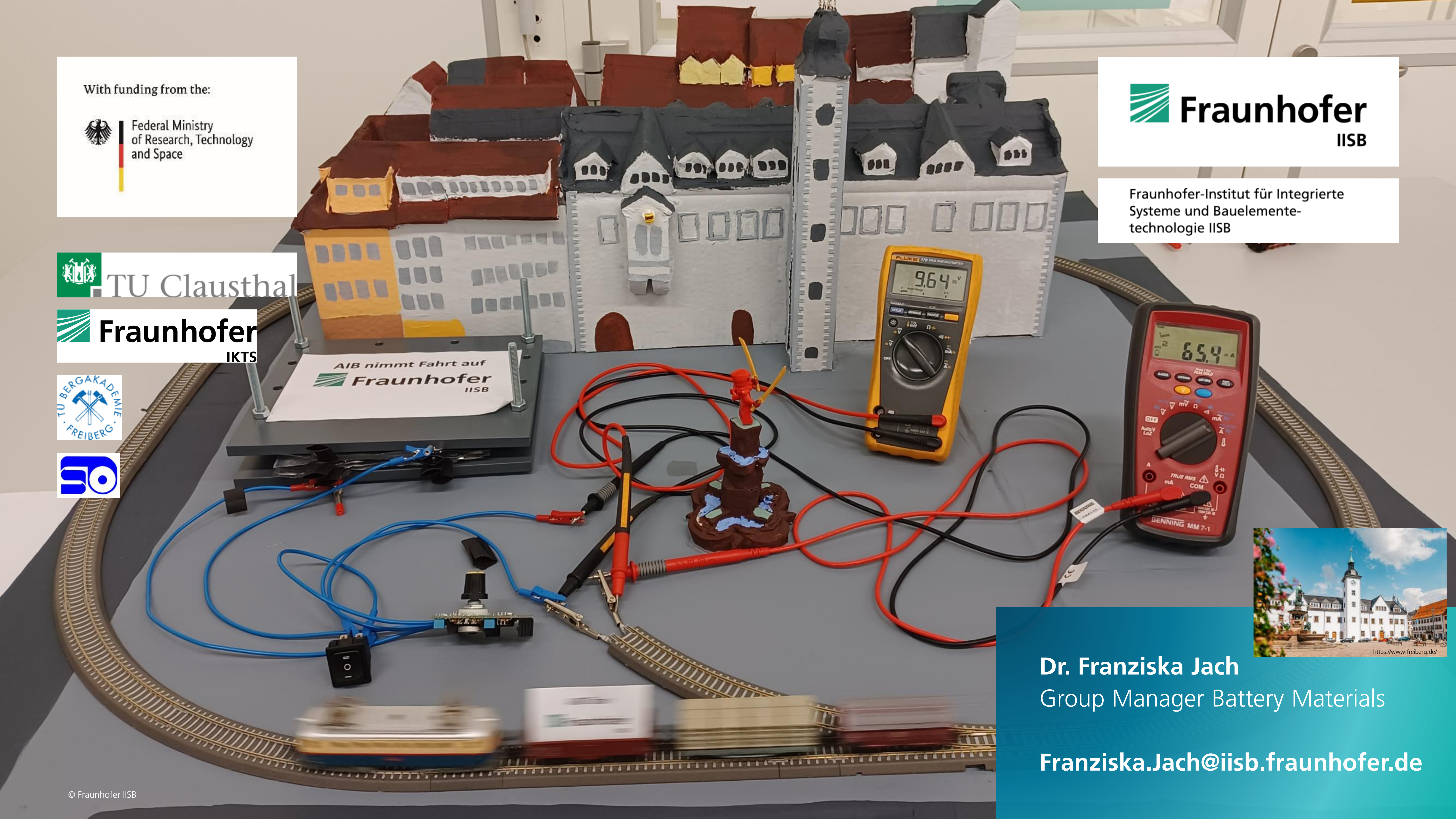
- Low cost & corrosion resistant current collector
- avoiding dendrite formation

Upscaling: next steps

➢ *R2R electrode manufacturing*

➢ *Pilot manufacturing*

➢ AGDIB technology as a feasible low cost alternative for high power storage



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