Source: Fraunhofer ISE/Dirk Mahler

Dry Electrode Processing for Sodium-Ion Batteries: Transition from PFAS-Based to PFAS-Free Binders

Oliver Fitz, Stefan Ingenhoven, Svenja Kalthoff, Felix Gottwald, Lea Eisele

Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

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IBPC Braunschweig 2025

Department Electrical Energy Storage

Center for Electrical Energy Storage

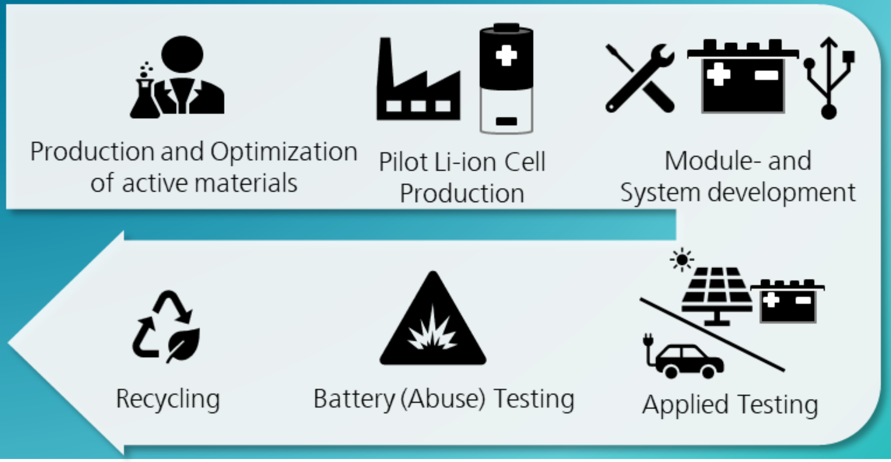
Funded by:

Baden-Württemberg
Ministerium für Wirtschaft, Arbeit und Tourismus

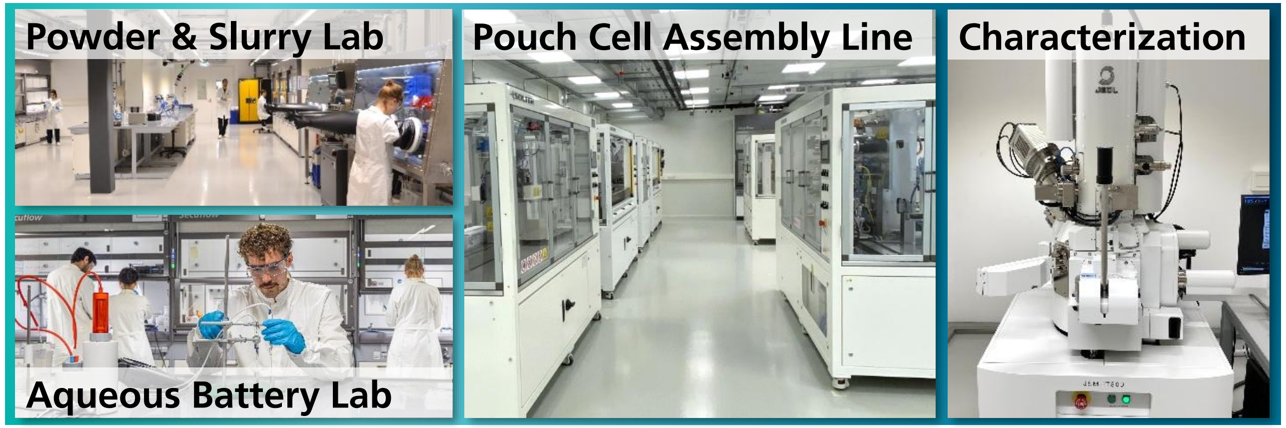
Bundesministerium für Bildung und Forschung

- Floor space: ~ 4,000 m², Lab space: ~1,140 m²
- R&D personnel: ~100+
- R&D battery technologies:
  Lithium-, Sodium-, Zinc-based Batteries
- Transfer of basic research to industrial level

Motivation: **R&D along the value chain**



Business Areas



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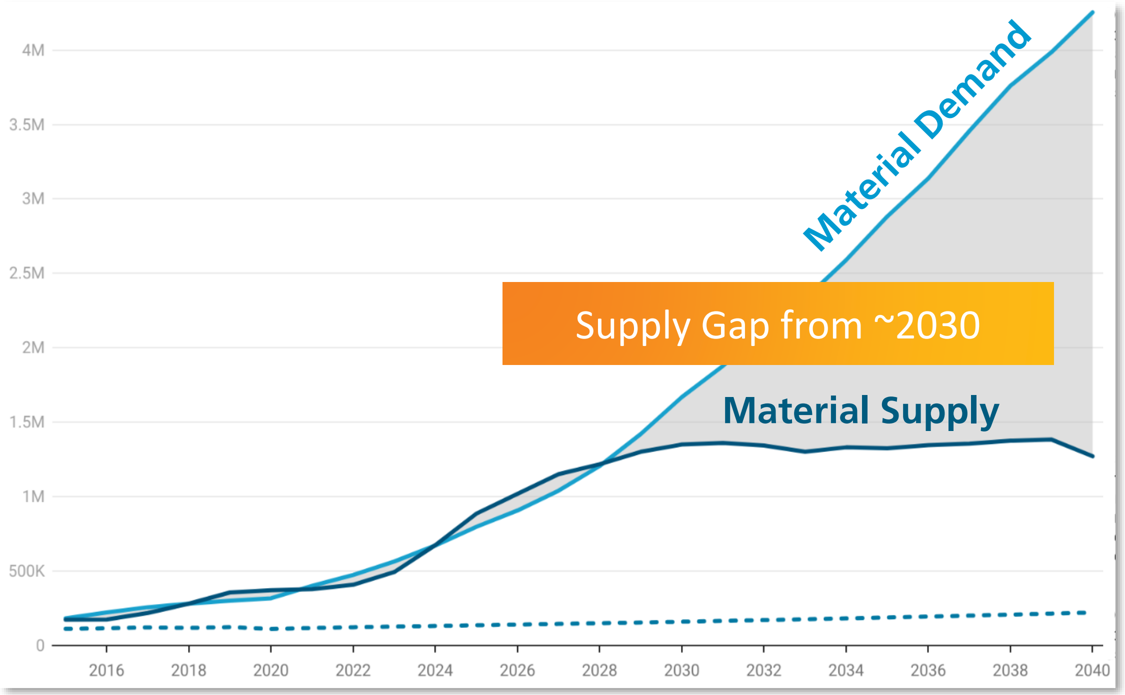
Introduction of Sodium-Ion Batteries & Dry Electrode Processing

Introduction of Sodium-Ion Batteries

Motivation

Supply vs. Demand of **Lithium** until **2040** in tons [1]

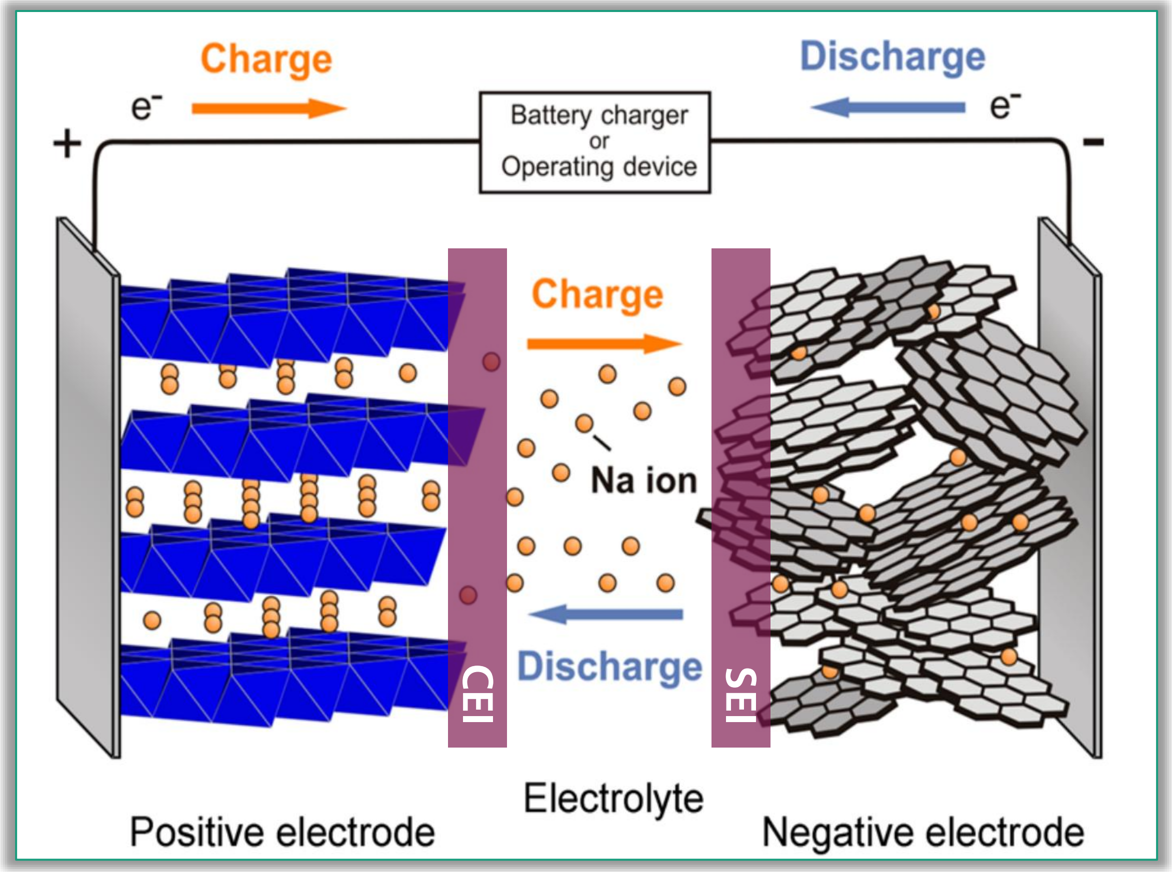


Advantages of Sodium-Based Batteries

- **Raw material availability**
- **Cost:** material & cell design level
- **Performance**: low-temperature operation potential
- **Transfer of functioning principles** and **production technology** from Lithium-Ion Battery (LIB) technology

[1] https://rmis.jrc.ec.europa.eu/analysis-of-supply-chain-challenges-49b749

Introduction of Sodium-Ion Batteries
Materials for Sodium-Ion-Batteries



„Rocking-Chair" Principle

Cathode

- **Prussian blue analoges** (e.g. $Na_2Mn[Fe(CN)_6]$)
- **Layered oxides** (e.g. $NaMO_2$ with M=Mn/Fe/Ni/Cu/Co …)
- Polyanionic compounds (e.g. $Na_3V_2(PO_4)_3$ – NASICON)

Anode

- **Hard Carbon** from biological or synthetic (waste) materials

Current Collector → **Aluminium** for both electrodes

Electrolyte

- established LIB electrolyte components (e.g. **$NaPF_6$ in EC:DMC**)
- high solubility of classical **SEI** species

Separators and **cell casing** → established LIB materials

Yabuuchi et al. (2014). *Chemical Reviews*, 114(23), 11636–11682. https://doi.org/10.1021/cr500192f

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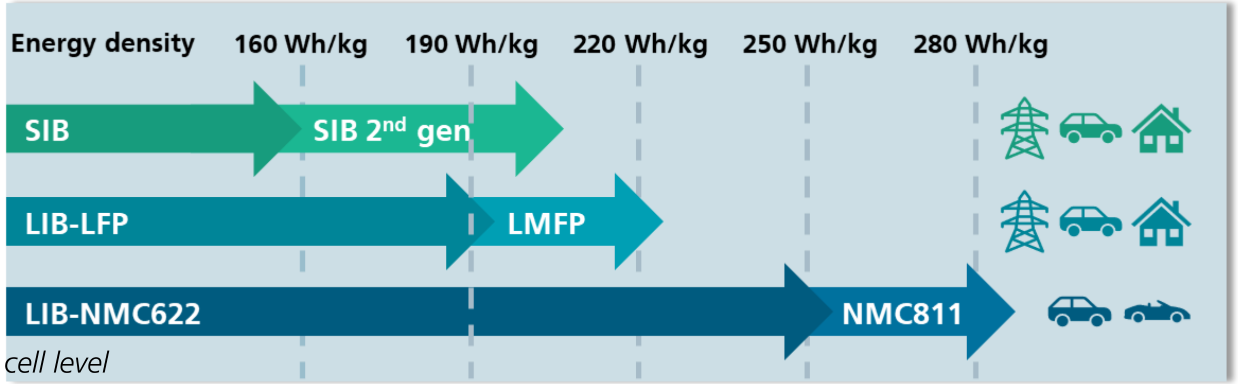
Introduction of Sodium-Ion Batteries

Challenges on the verge of market entry



[1] A. Yao et al., nature energy, 2025.
[2] A. Rudola et al., J. Mater. Chem. A, 2021.

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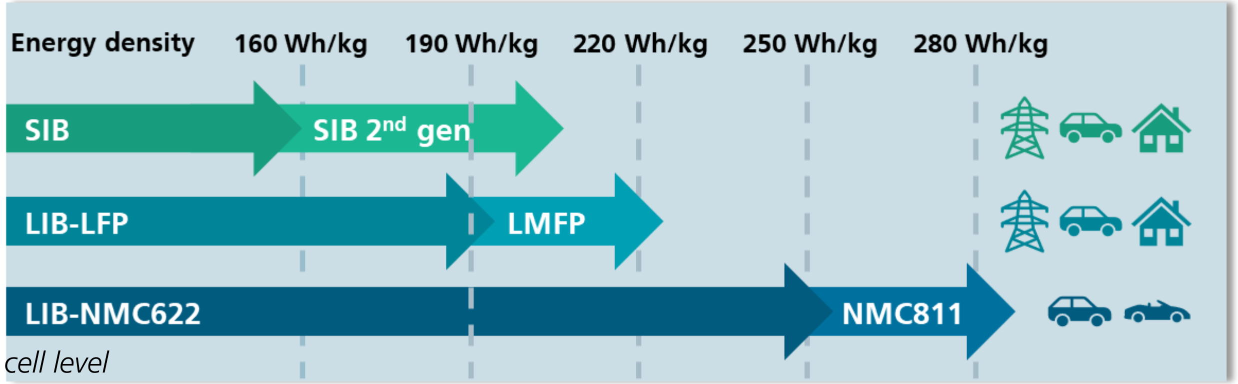
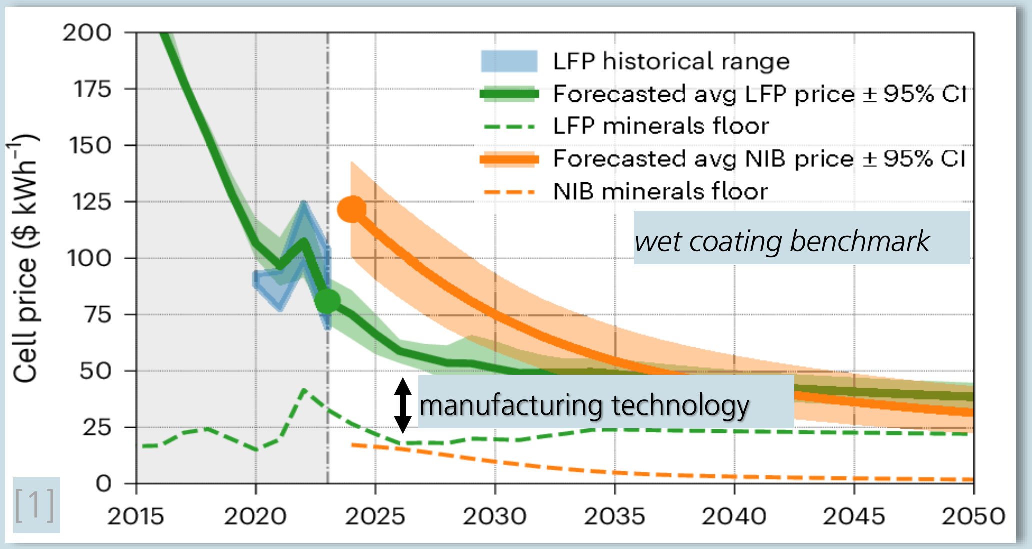
Introduction of Sodium-Ion Batteries

Challenges on the verge of market entry



Cost



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Introduction of Sodium-Ion Batteries

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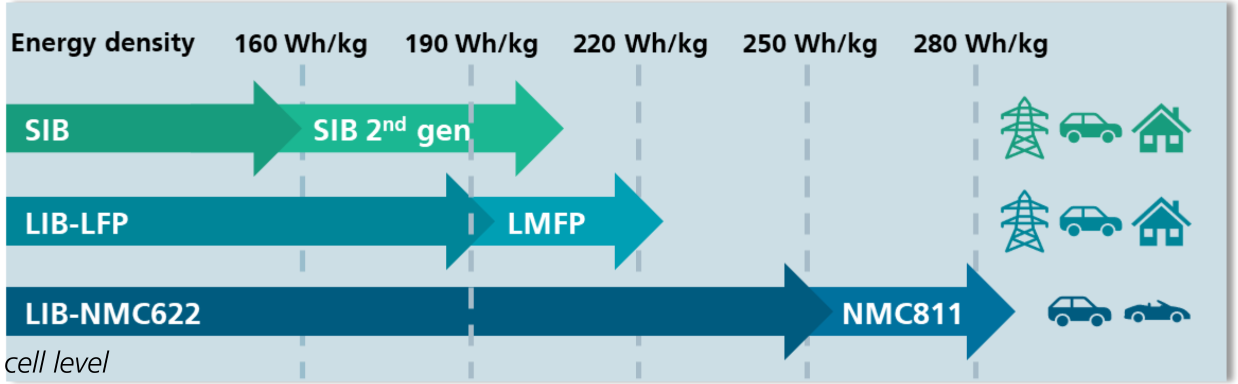

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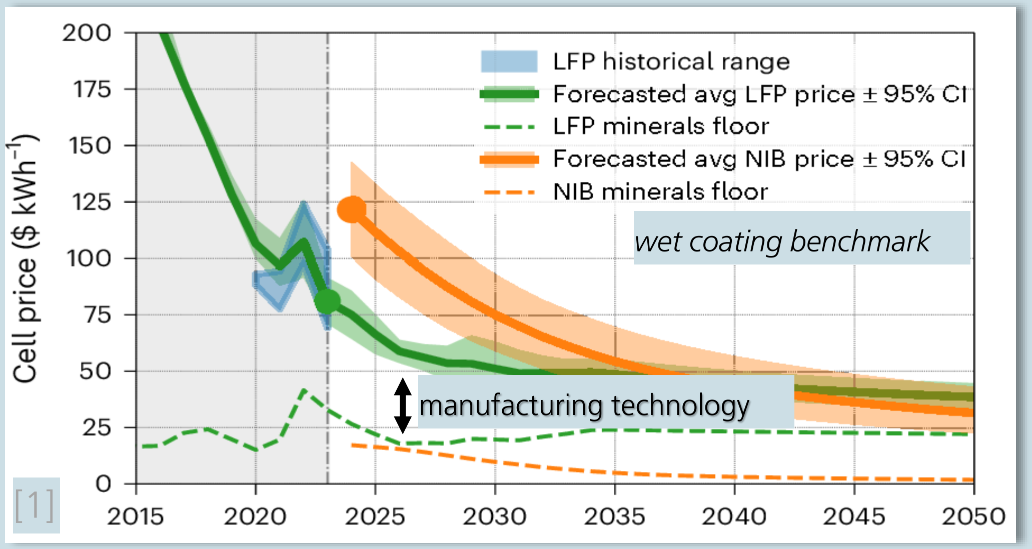

Cell chemistry depends on factors such as

- ✓ Costs
- ✓ Availability of resources
- ✓ Cycle life
- ✓ Energy density
- ✓ Power density
- ✓ Safety
- ✓ Cell design
- ✓ Intended application

↔ **Dry Electrode Processing**

[1] A. Yao et al., nature energy, 2025.
[2] A. Rudola et al., J. Mater. Chem. A, 2021.

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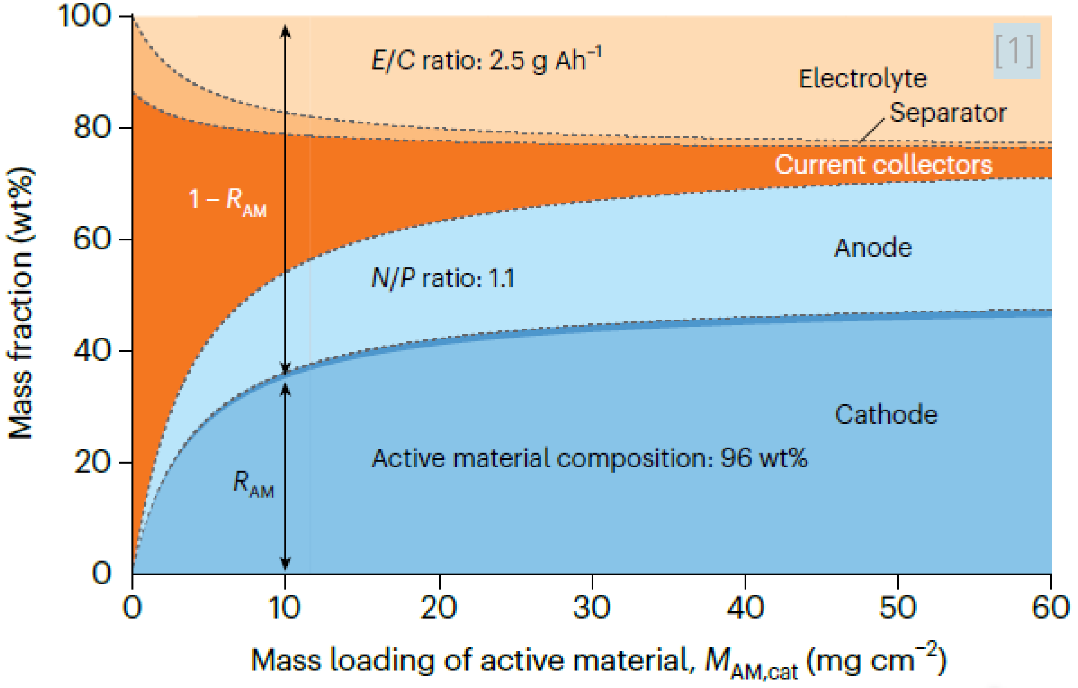
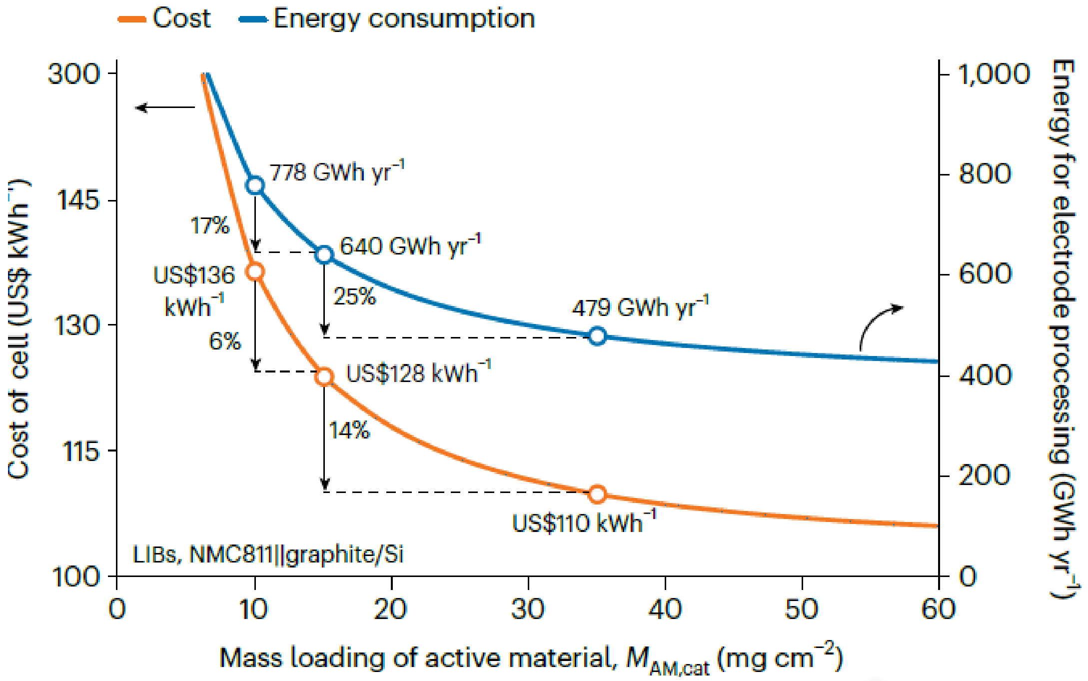
Dry Electrode Processing
High mass loading

Energy density



improved **active-to-passive-material ratio** → **Energy density**

Cost advantage



higher **AM*-share** → lower **costs**

[1] Kim et al., nature energy, 2025.

*** AM = active material**

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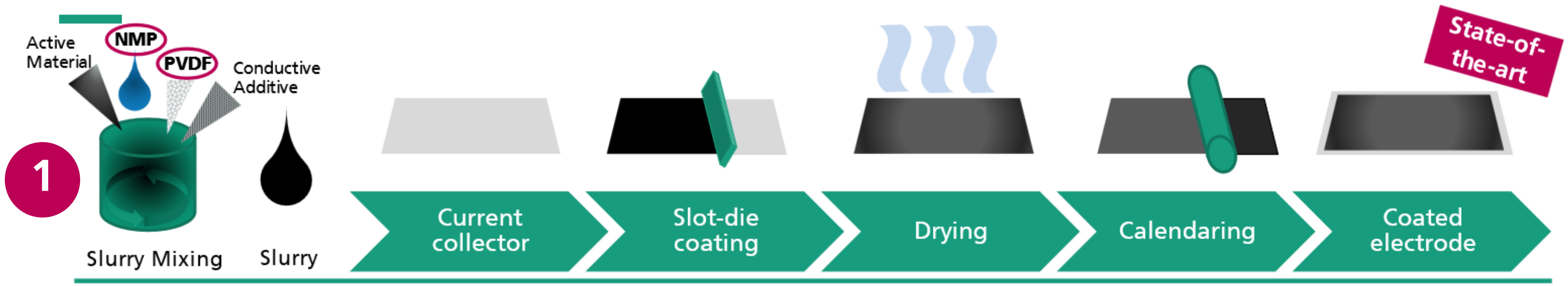
PFAS-free & High-Mass Loading Dry Electrode @ISE

PFAS-free & High-Mass Loading Dry Electrode

Process overview



PFAS-free & High-Mass Loading Dry Electrode

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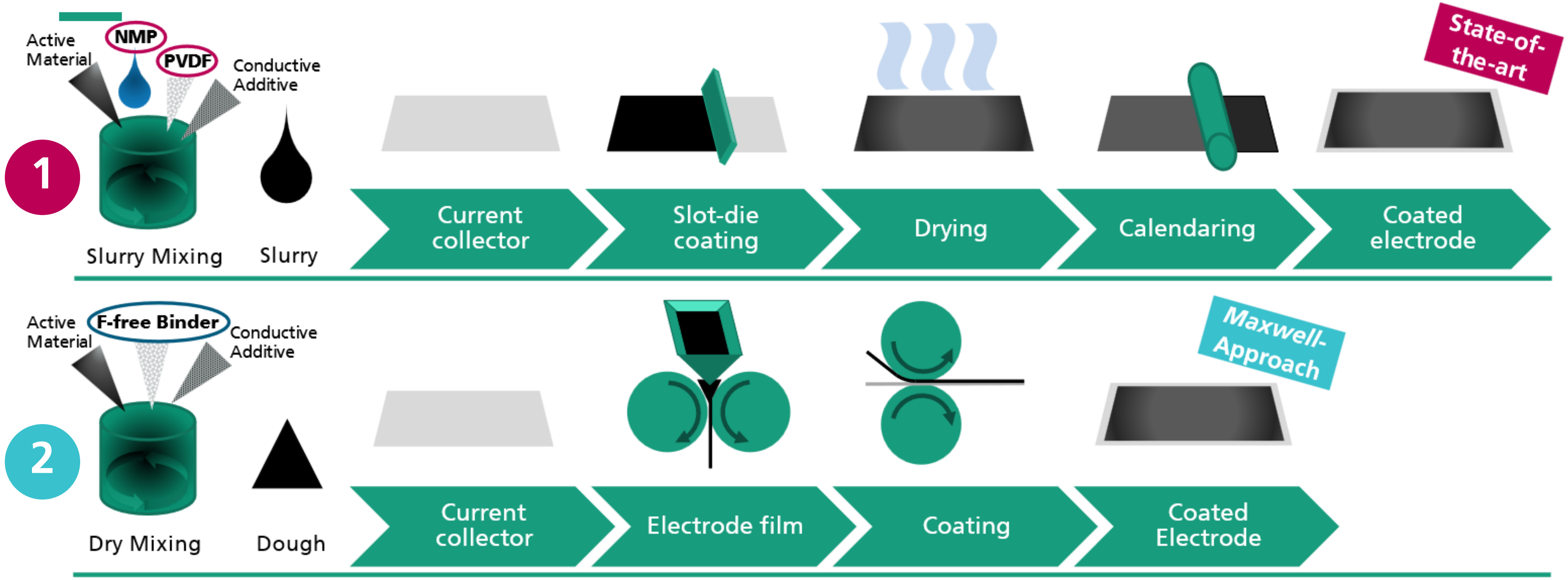

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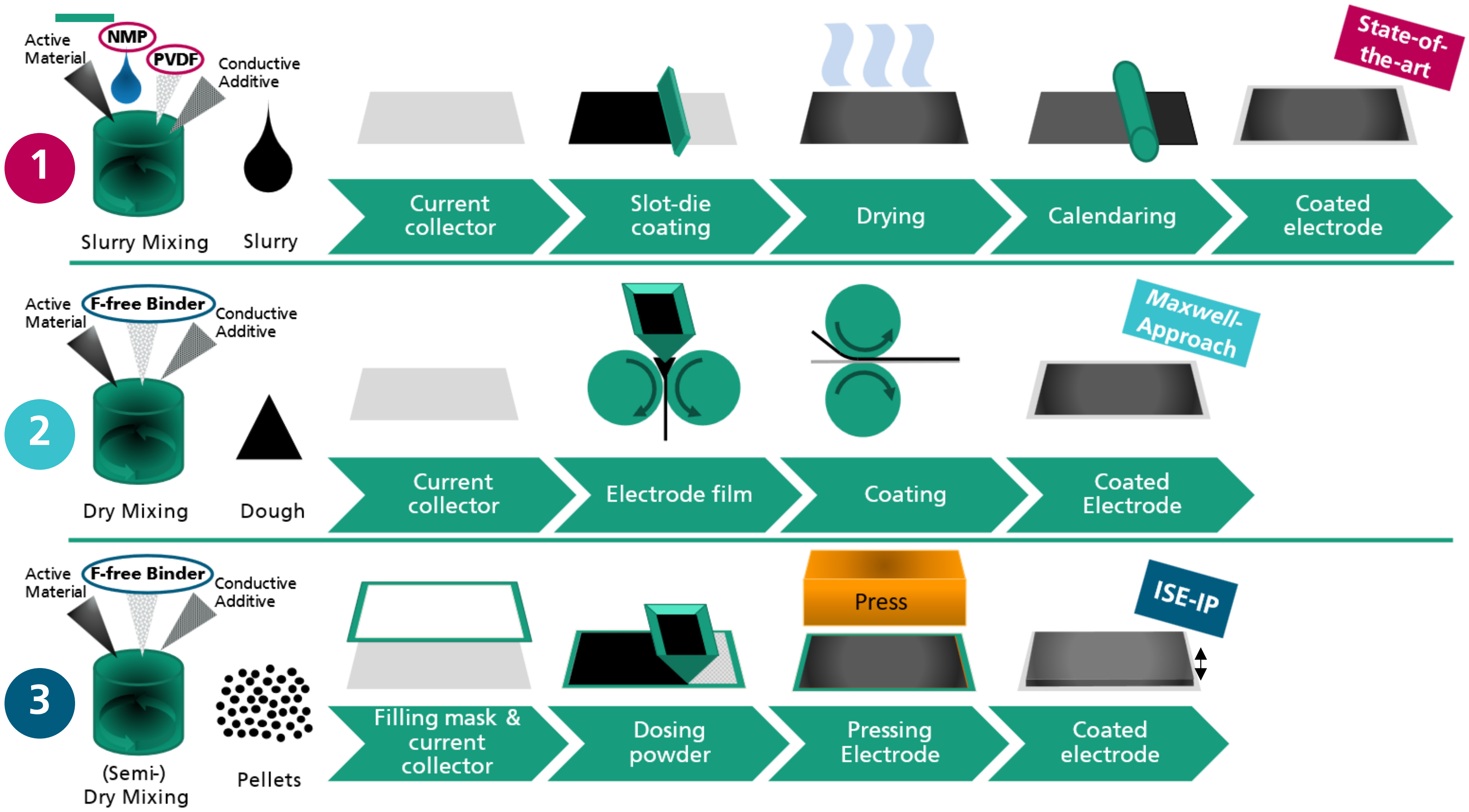

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PFAS-free & High-Mass Loading Dry Electrode

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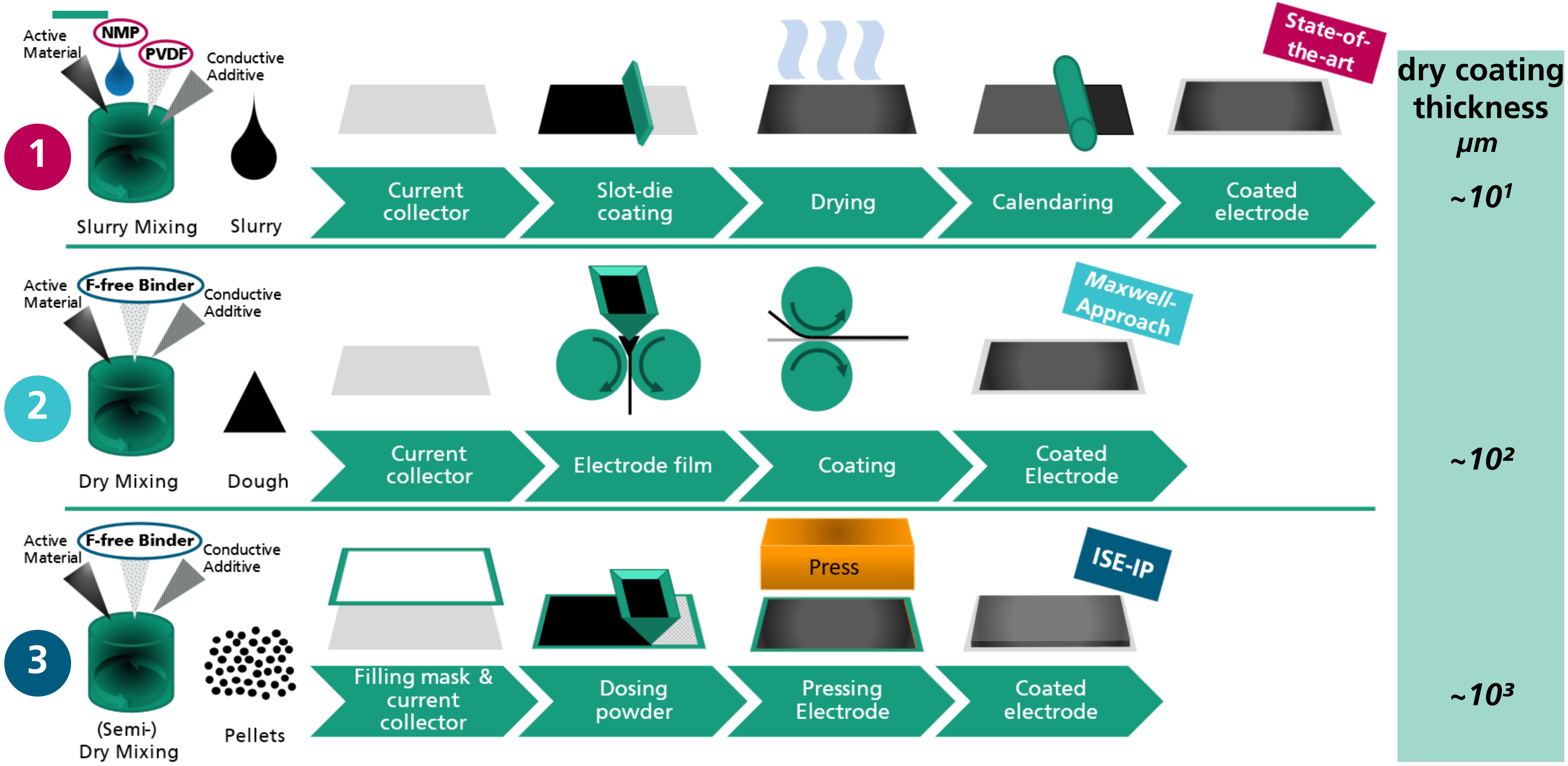

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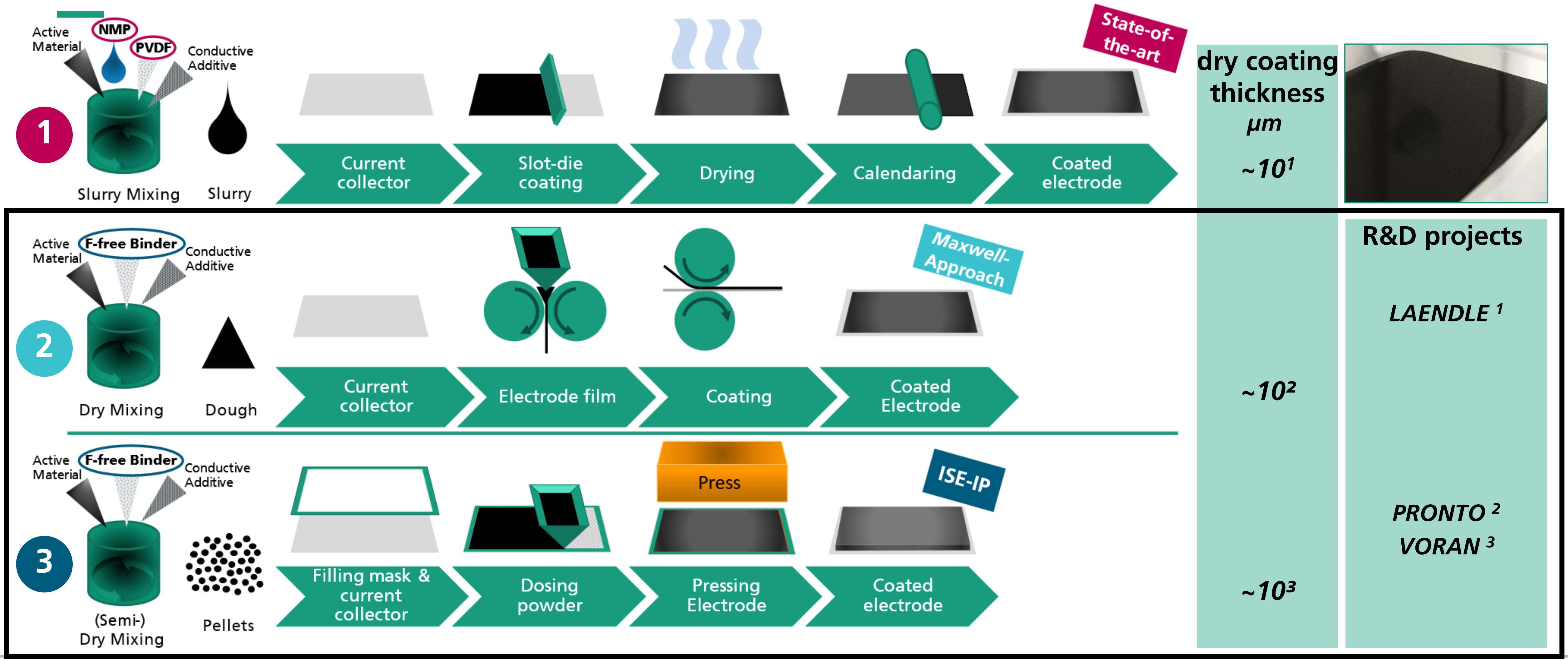


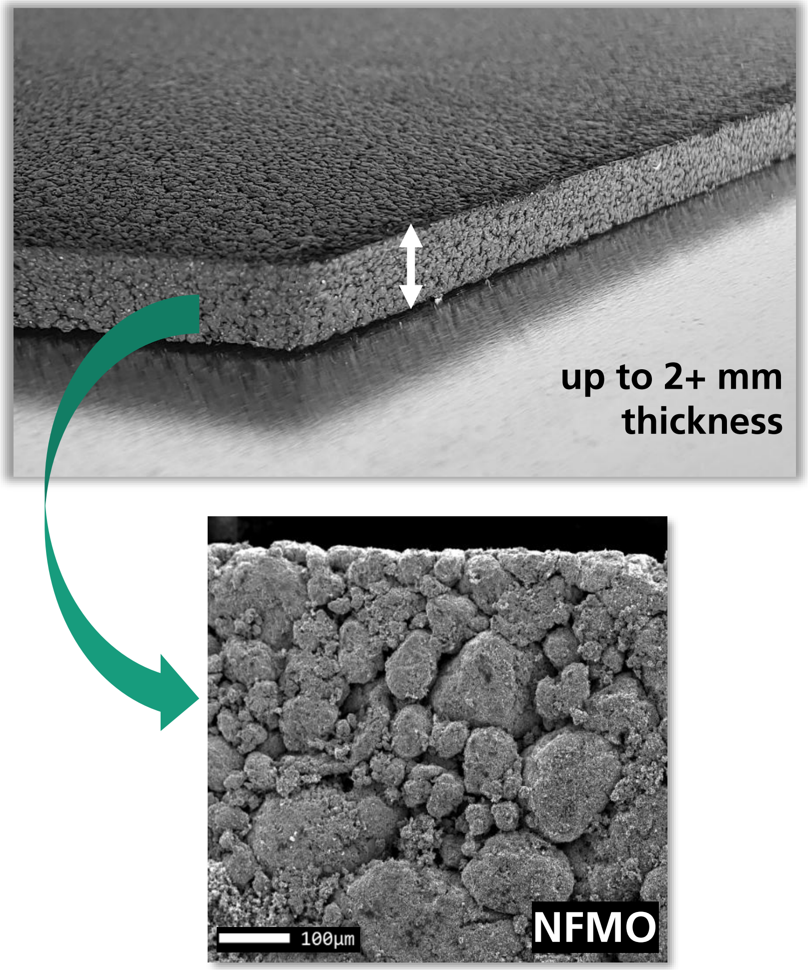
[1] https://www.ise.fraunhofer.de/en/research-projects/laendle.html
[2] https://www.ise.fraunhofer.de/en/research-projects/pronto.html
[3] https://www.ise.fraunhofer.de/en/research-projects/voran.html

PFAS-free & High-Mass Loading Dry Electrode

Electrode fabrication

3 ISE-IP

- ✓ Tunable **morphology & porosity** (30…80 %)
  - ➢ Tunable **ion transport**
- ✓ Tunable **thickness** 400…2000+ µm
- ✓ **PFAS-free** binders - not limited to PVDF/PTFE



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hechinger advanced clean production acp Universität Stuttgart KIT HIU Electrochemical Energy Storage Fraunhofer ISE

PFAS-free & High-Mass Loading Dry Electrode

Electrochemical data

3 ISE-IP

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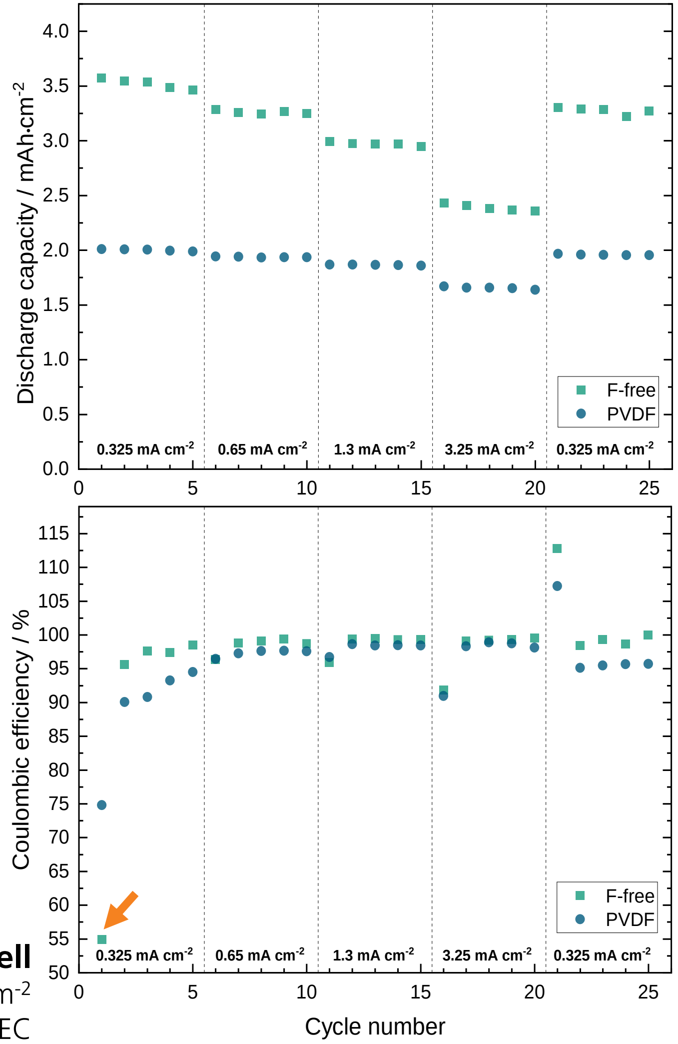
- ⌛ low **initial coulombic efficiency** (iCE) → further development
  - → **electrode-electrolyte interface**



NFMO-HC full cell
2.0-4.0V / 65 mg_{NFMO} cm^{-2}
1M $NaPF_6$ in EC:DMC + 2% FEC

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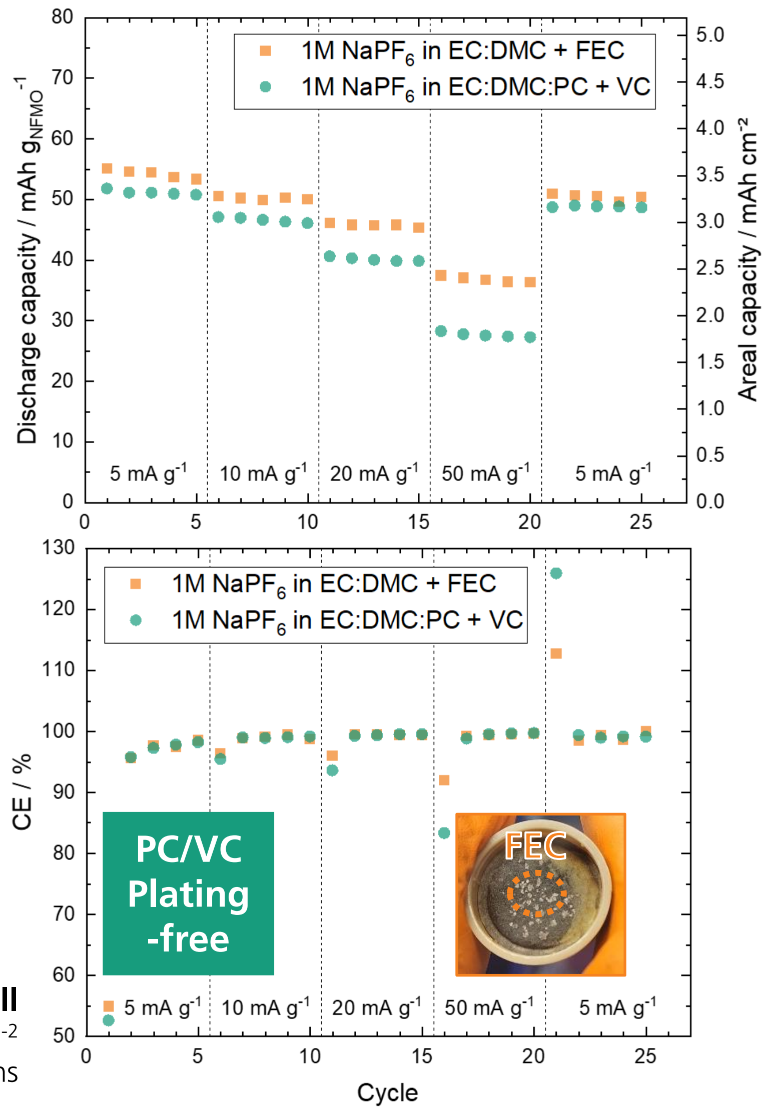
- ⌛ Sodium **plating** → electrolyte additives



NFMO-HC full cell
2.0-4.0V / 65 mg_{NFMO} cm^{-2}
1M $NaPF_6$ in EC:DMC + modifications

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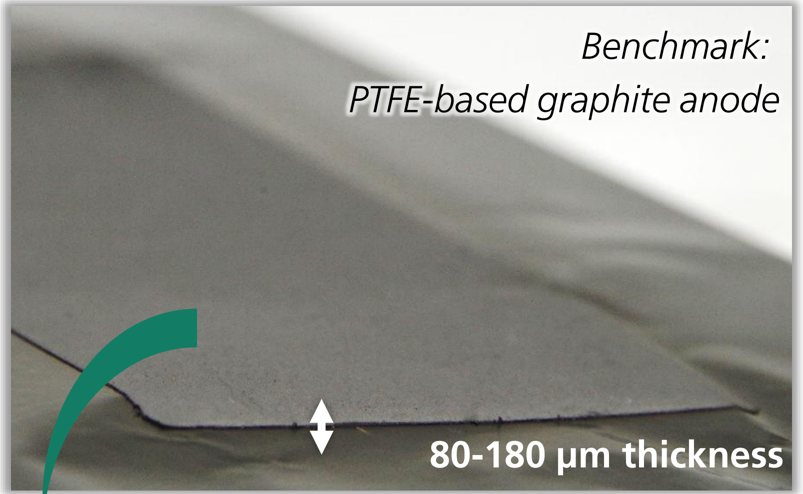
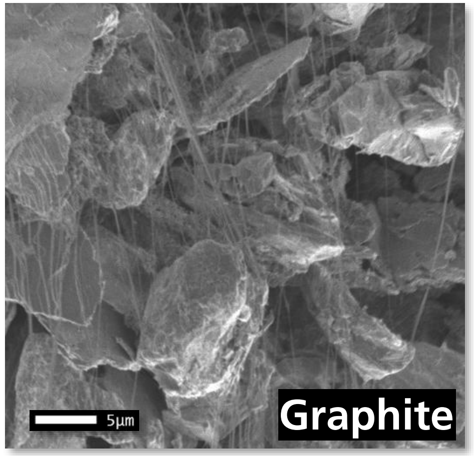
PFAS-free & High-Mass Loading Dry Electrode

Electrode fabrication

2 Maxwell-Approach

- ✓ Tunable **thickness** 80…180 µm
- ⌛ **areal capacities** → ongoing research
- ⌛ **initial coulombic efficiency (iCE)** → ongoing research





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IKA Fraunhofer ISE

PFAS-free & High-Mass Loading Dry Electrode

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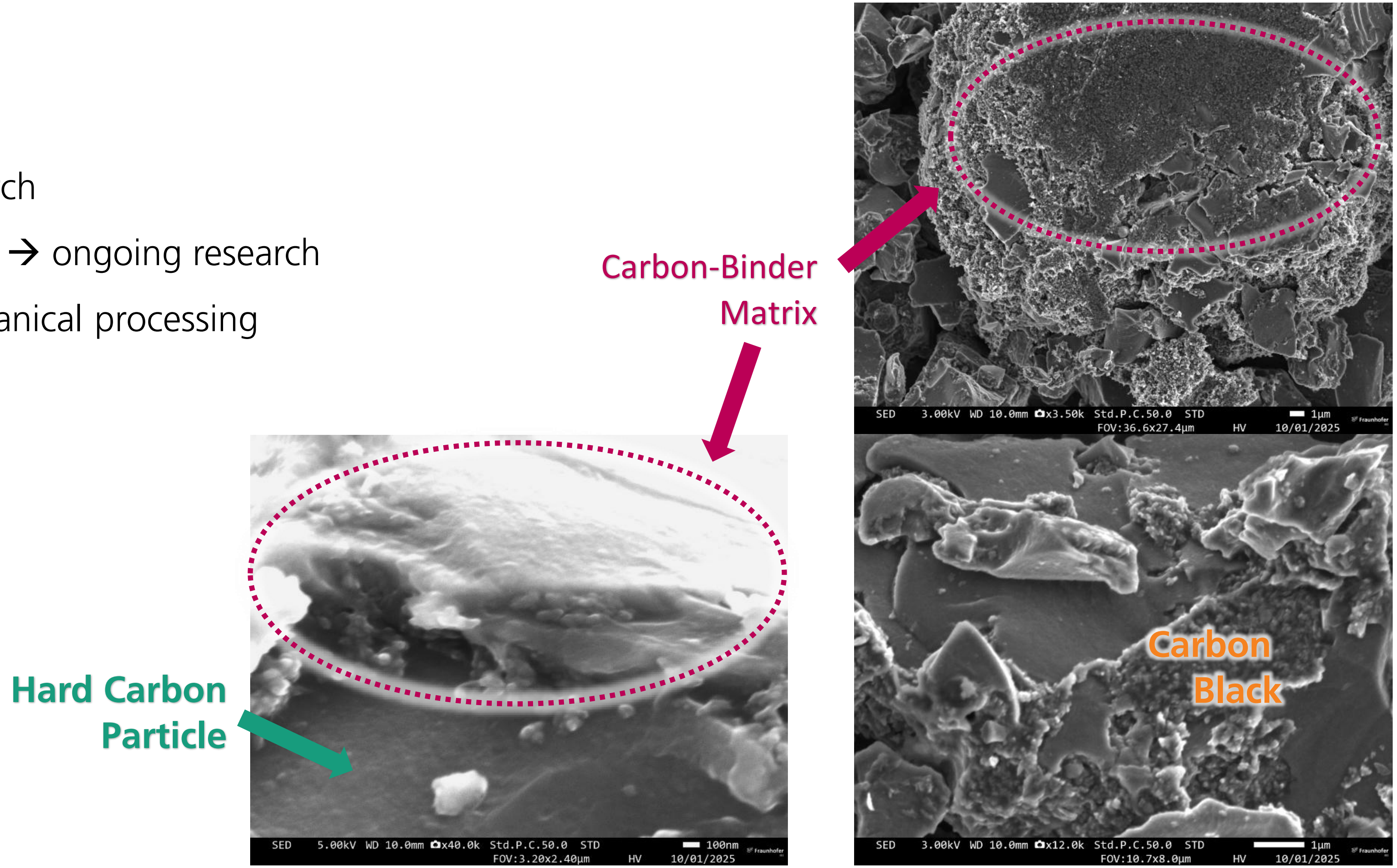
- ⌛ **PFAS-free** binders → thermomechanical processing
  → preliminary results



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Overview, Summary & Outlook

Overview

Road to Dry-Coated, High-Mass Loading, PFAS-Free Battery Electrodes

1 State-of-the-art

– Mass loading: limitations in thickness
– Energy density: limits in active-to-passive-material ratio & porosity
– Cost: well-established process, but high CAPEX/OPEX
– Binder: limitations for PFAS-free binders for cathode
+ Continous: scalable, reproducible
+ Fast: high throughput

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2 Maxwell-Approach

? Mass loading: higher than **1**, lower than **3**
– Energy density: limits in active-to-passive-material ratio & porosity
+ Cost: less energy & footprint demands
? Binder: PFAS-free binders to be examined
+ Continous: scalable, reproducible
+ Fast: transfer of well-established fabrication platforms

3 ISE-IP

+ Mass loading: increased flexibility in material composition & thickness
+ Energy density: improved active-to-passive material ratio
+ Cost: low energy & footprint demand → low CAPEX/OPEX
+ Binder: PFAS-free validated
? Batch: reproducibility on industrial scale to be examined
? Fast: throughput to be examined

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Summary & Outlook

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Structure-property relationship of dry-processed battery electrodes

3 ISE-IP

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- + …ontin… …le
- + … …ed fabr…

3 ISE-IP

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Structure-property relationship of dry-processed battery electrodes

Ideal fabrication process depends on intended battery application

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Thank You!

Dr. Oliver Fitz
Group Manager Battery Cell Technology
Department Electrical Energy Storage

+49 761 4588 2393
oliver.fitz@ise.fraunhofer.de

Fraunhofer für Solare Energiesysteme
Heidenhofstraße 2
79110 Freiburg
www.ise.fraunhofer.de

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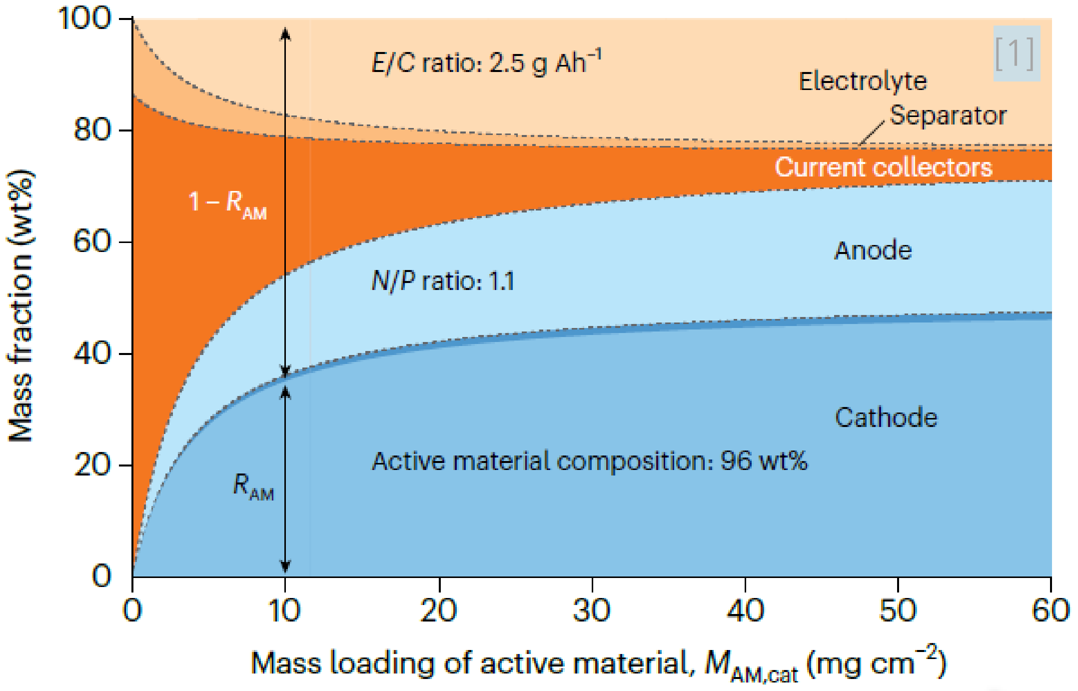
Dry Electrode Processing

High mass loading

Energy density



improved **active-to-passive-material ratio** → **Energy density**

Cost advantage

Cost reduction potential of

- 16-22% in direct labor[1]
- 14-19% in equipment cost[1]
- 13-17% plant area[1]

compared to **wet processing** for LIBs

Benefits of **dry processed electrodes**

- Avoidance of NMP evaporation and recuperation
- Reduced binder contents & improved distribution
- Reduced footprint of production plant

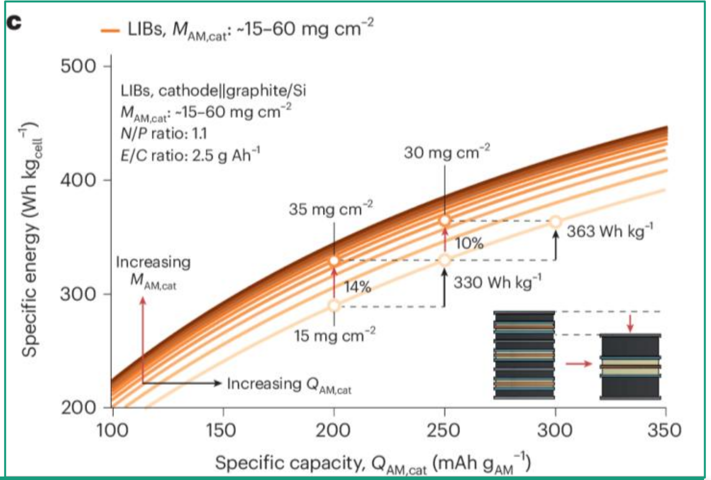
[1] Kim et al., nature energy, 2025.

*** AM = active material**

[1]Ludwig et al., Scientific Reports, 2016.

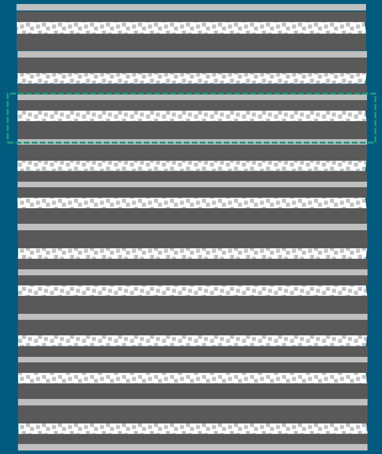
Dry Electrode Processing

Influence on cell design



Conventional cells *

1880µm



10 mAh cm_{cell}^{-2}

10 layers à 1 mAh $cm_{electrode}^{-2}$

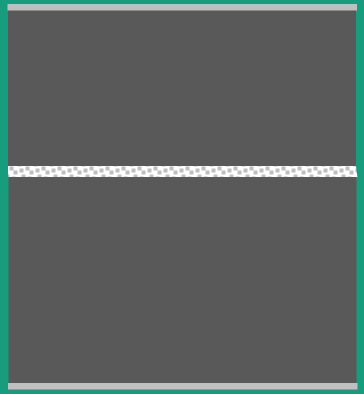
10 separators à 12µm

10 cathode coatings à **60** µm

10 anode coatings à **80** µm

10 current collectors 15 µm

Current at 1C
= 1 mA cm-2



1630µm

*High mass loading cells

10 mAh cm_{cell}^{-2}

1 layers à 10 mAh $cm_{electrode}^{-2}$

Current at 1C
= 10 mA cm-2

1 separator à 12µm

1 cathode coatings à **985** µm

1 anode coatings à **625** µm

1 current collectors 15 µm

[1] Kim et al., nature energy, 2025.

*extrapolated from: Laufen et al., Cell Press, 2024.

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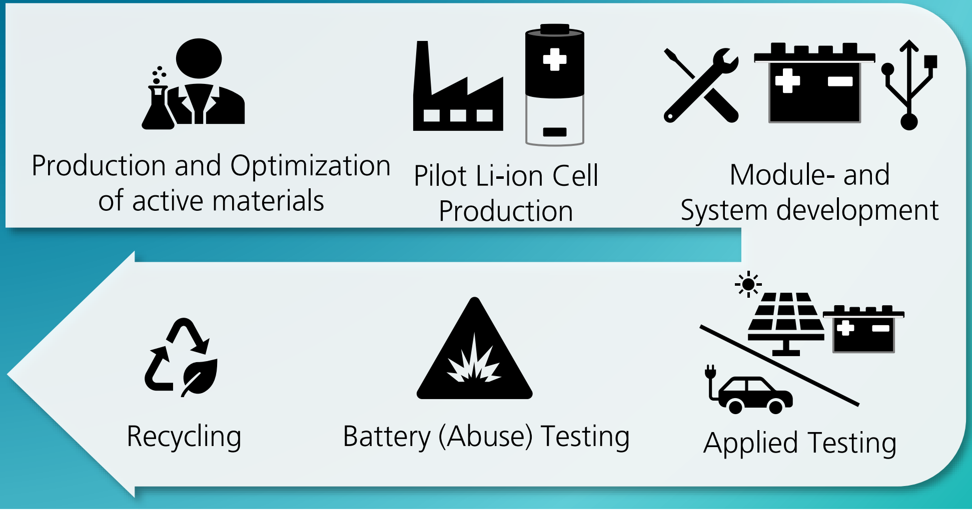
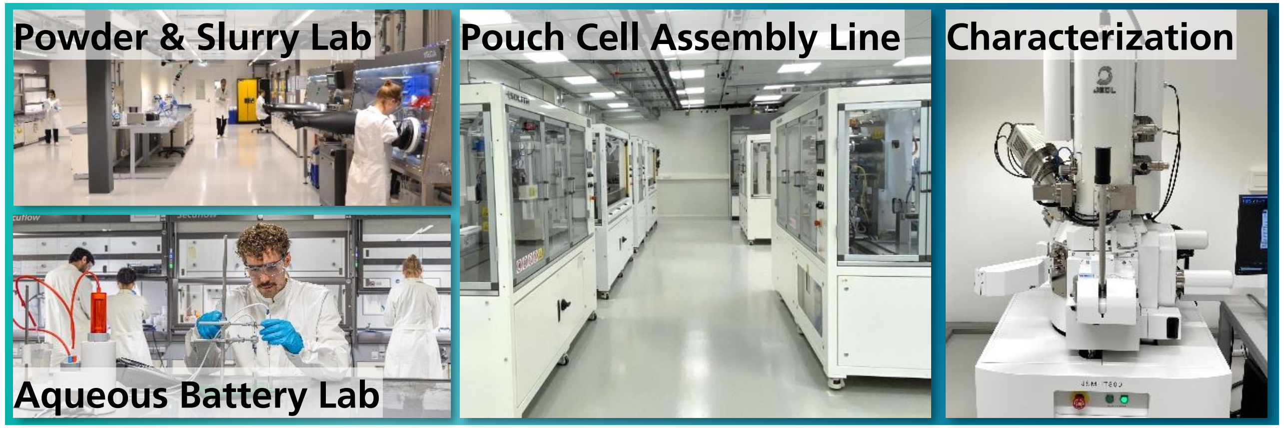
- Transfer of basic research to industrial level

Motivation: **One-Stop-Shop**



Business Areas



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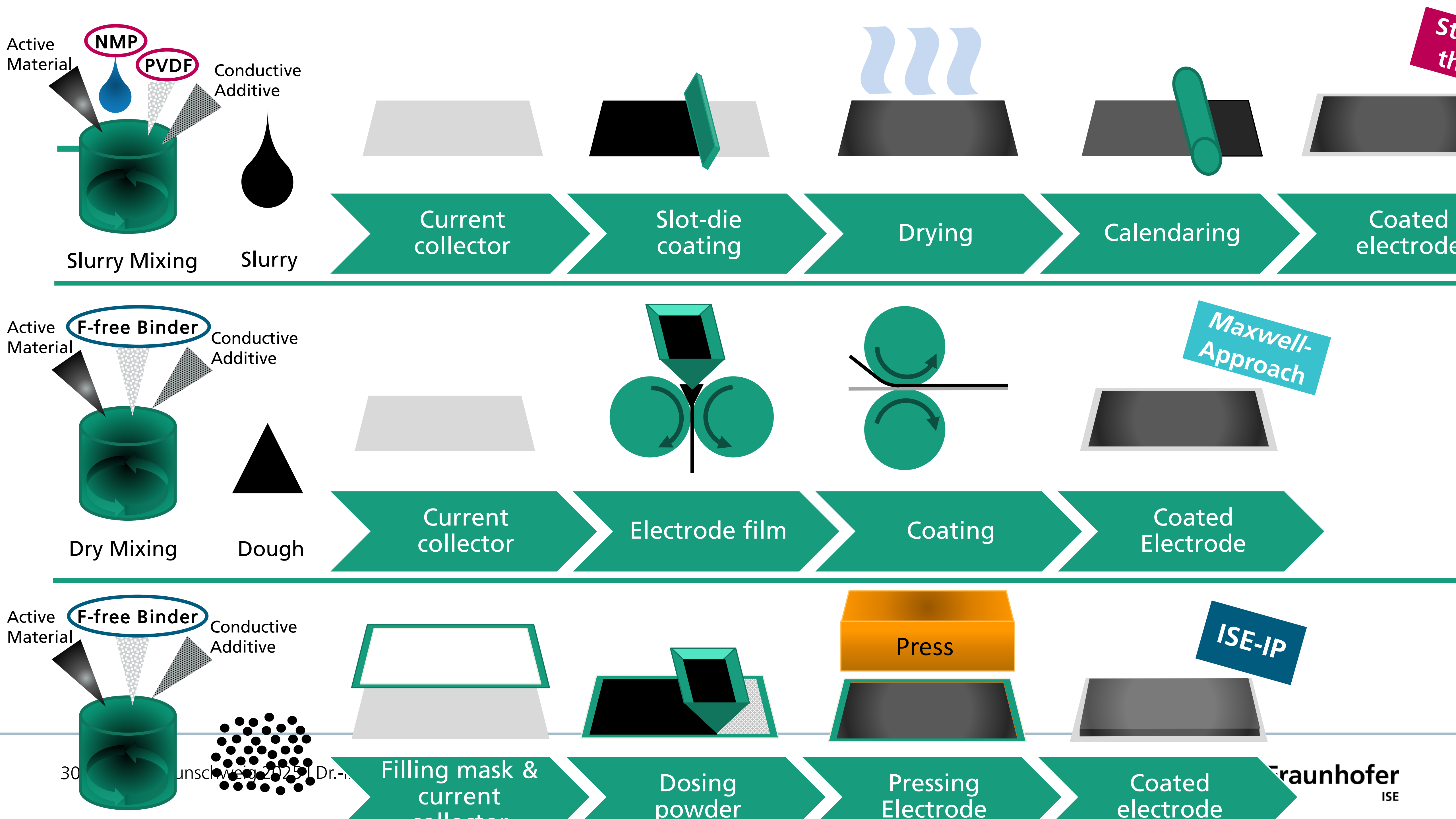
Active Material
NMP
PVDF
Conductive Additive
Slurry Mixing
Slurry
Current collector
Slot-die coating
Drying
Calendaring
Coated electrode
Active Material
F-free Binder
Conductive Additive
Dry Mixing
Dough
Current collector
Electrode film
Coating
Coated Electrode
Maxwell-Approach
Active Material
F-free Binder
Conductive Additive
Press
ISE-IP
Filling mask & current
Dosing powder
Pressing Electrode
Coated electrode

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3 ISE-IP

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