Fraunhofer R&D Center Electromobility Bavaria

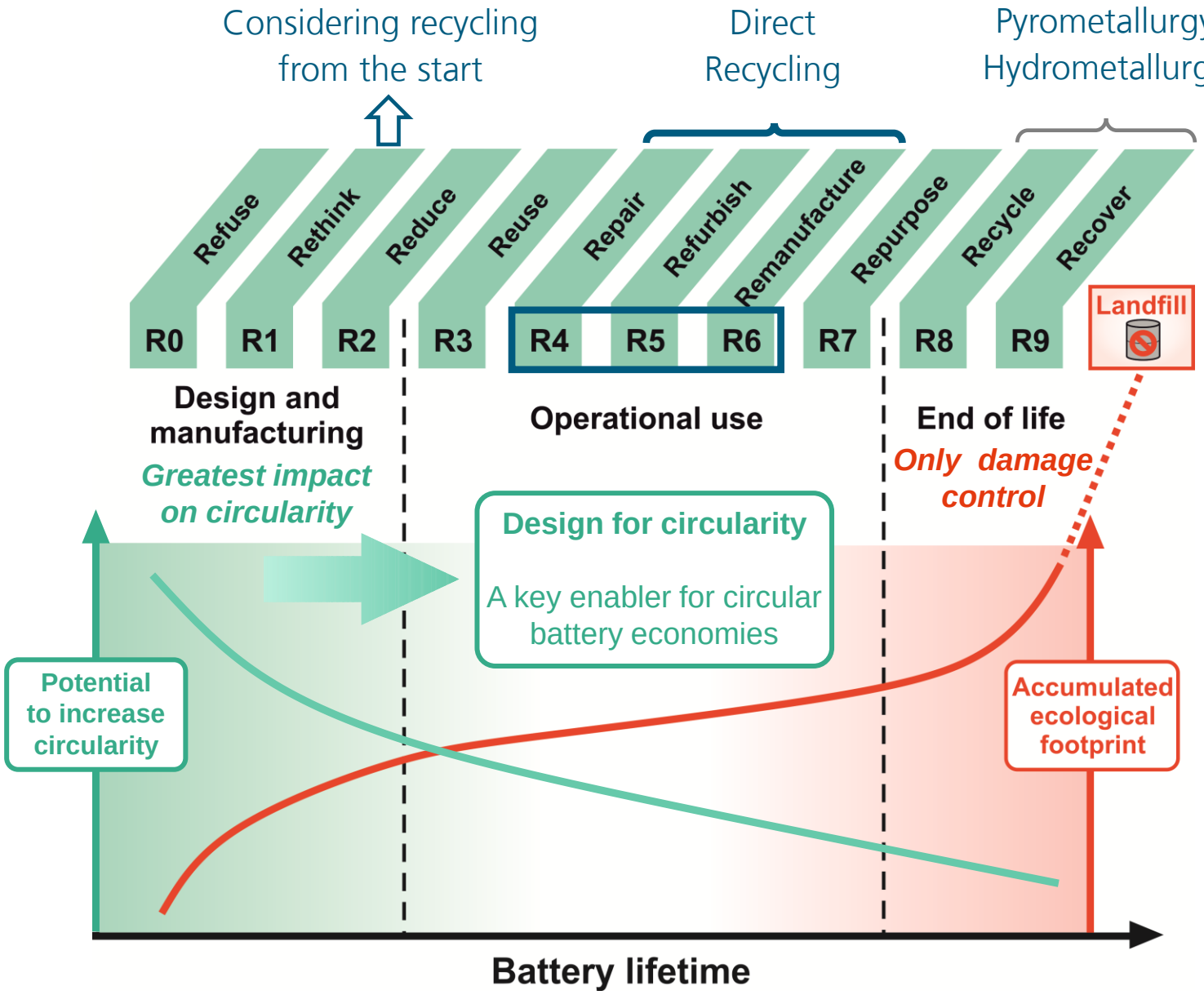
A circular perspective on battery recycling – The role of low-cost chemistries

Andreas Wolf

13.11.2025, A3PS, Vienna

Circular economy

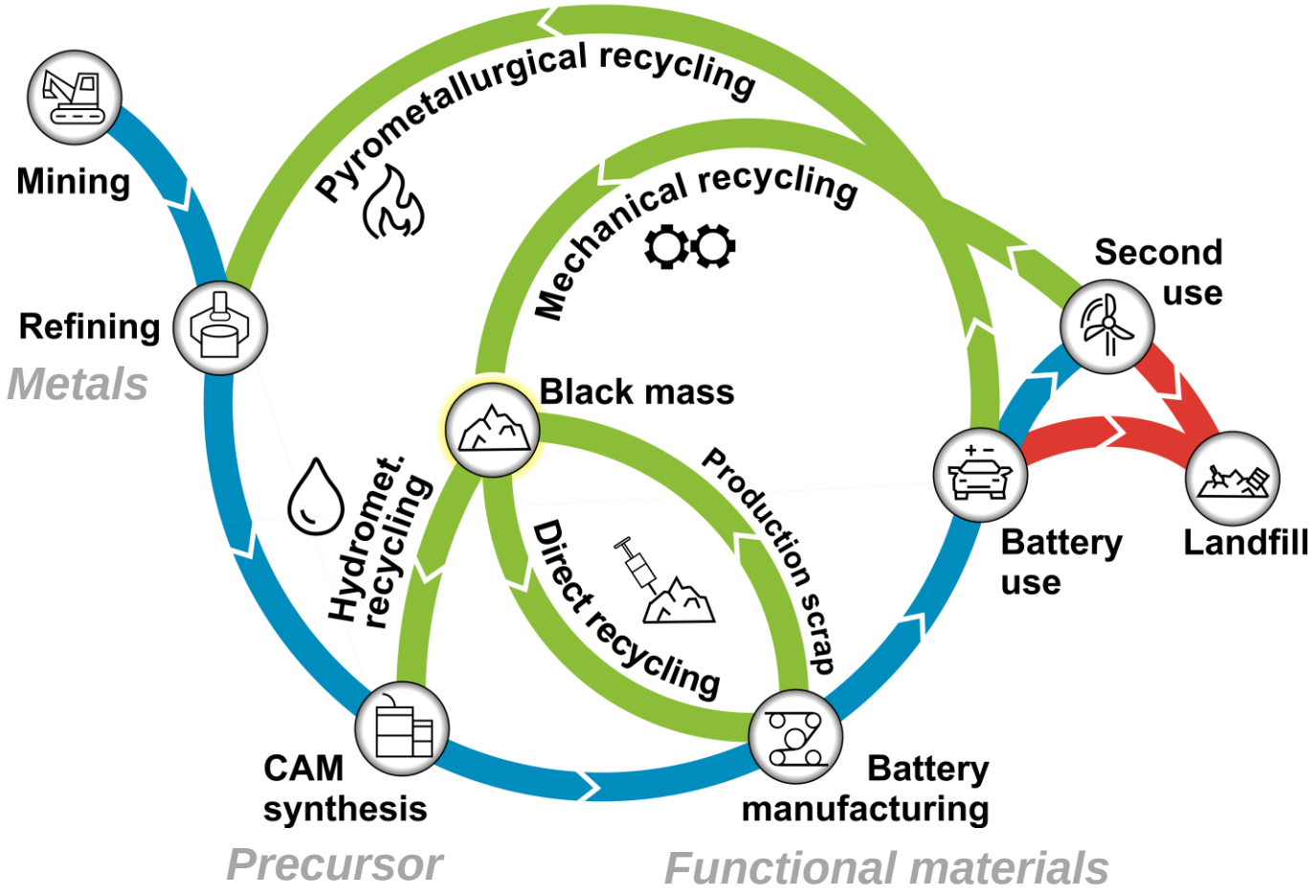
The R9 framework



Andreas Wolf *et al., Circular battery design: investing in sustainability and profitability,* ***Energy Environ. Sci.***, 2024, Advance Article (DOI:10.1039/D4EE03418J)

Battery recycling

Different recycling methods



Benefits of different recycling methods

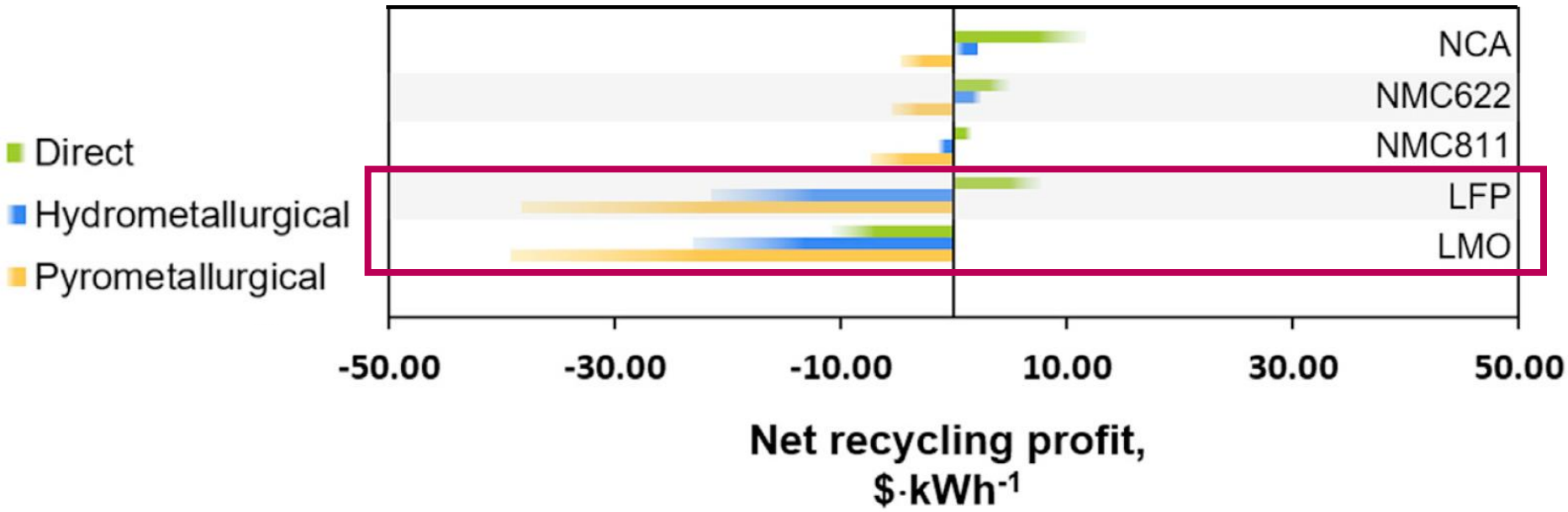
- **Pyrometallurgy**: Established processes, high recovery rates for standard metals, small demand for pretreatment
- **Hydrometallurgy**: Established processes, relatively high total recovery rates, reduced energy demand
- **Direct recycling**: Highest recovery rates possible, reduced carbon emissions, closed loop recycling

Adapted from Gaines, L.; Dai, Q.; Vaughey, J.T.; Gillard, S. Direct Recycling R&D at the ReCell Center. Recycling 2021, 6, 31. https://doi.org/10.3390/recycling6020031

Techno-economic perspective on battery recycling

Recycling of a Tesla Model S battery-pack in the United Kingdom,

assuming different cathode chemistries and medium scale developed direct recycling



No cobalt
No nickel

Same trend expected for SIBs

*numbers result from a specific parameter set of transportation cost, energy cost, labor cost, raw material prices, safety standards, location of collection and location of recycling facility, import and export tariffs,

Lander, L. *et al.* Financial viability of electric vehicle lithium-ion battery recycling. *iScience* **24,** 102787; 10.1016/j.isci.2021.102787 (2021).

Key of direct battery recycling

Regeneration & Upcycling of spent active materials

[2]

after

Upcycling

[1]

before

Restoration

[1]

after

upcycled active material
(active material with properties of new material generation)

Output: e.g., **NMC811**

Upcycling

degraded active material

Input: e.g., degraded **LFP**
Input: e.g., degraded **NMC532**

Regeneration / restoration

regenerated / restored active material
(with similar properties as fresh active material)

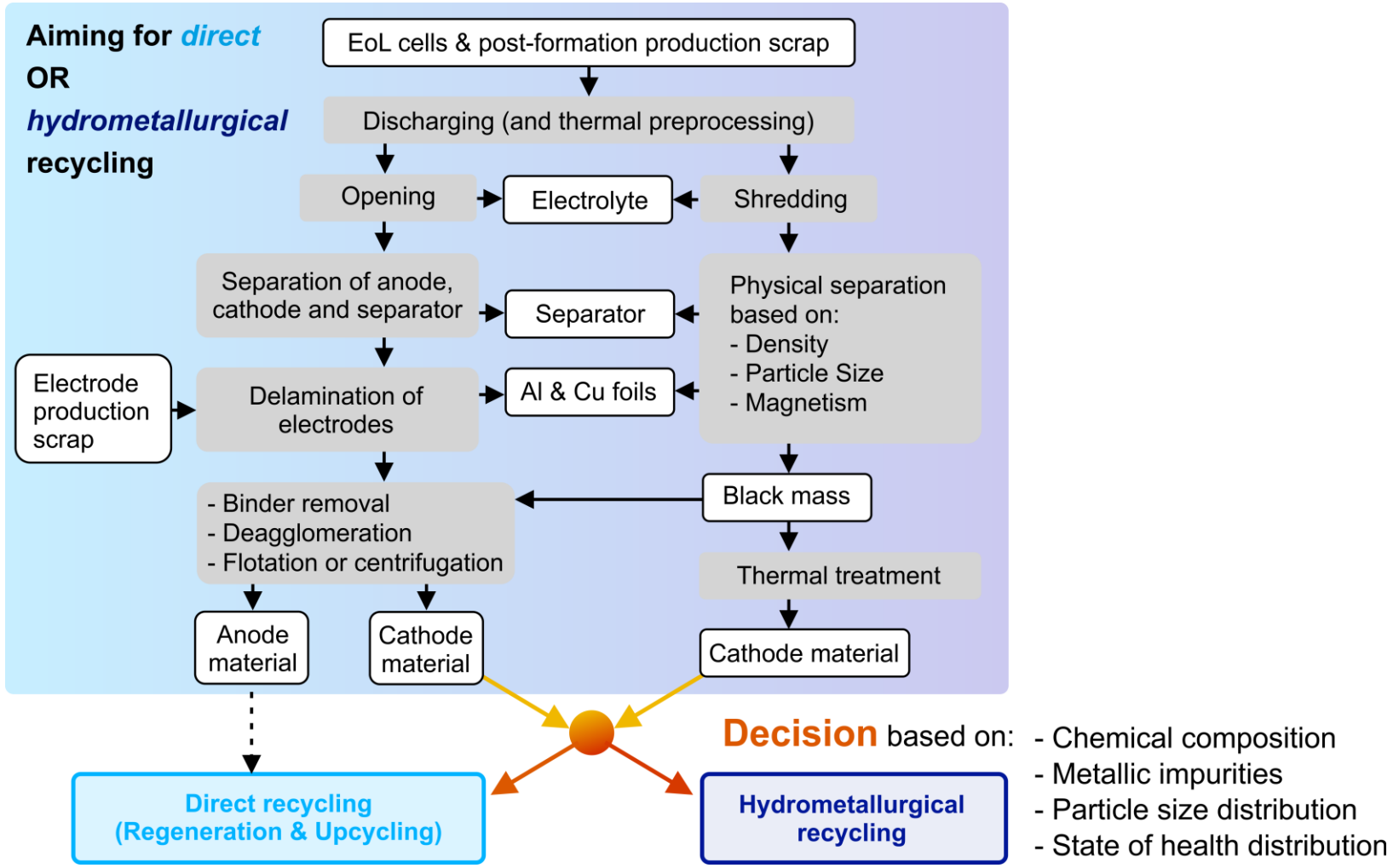
Output: e.g., **LFP**, **NMC532**

[1] https://www.myheimat.de/hannover-gross-buchholz/c-freizeit/vorher-nachher-was-auto-schrauber-wirklichkeit-werden-lassen_a2689412#gallery=default&pid=3168939, accessed in May 2025

[2] https://www.golem.de/news/konzeptstudio-toyota-zeigt-futuristisches-elektroauto-von-lexus-1910-144595.html, accessed in May 2025

REUSE Rewind Fraunhofer ISC

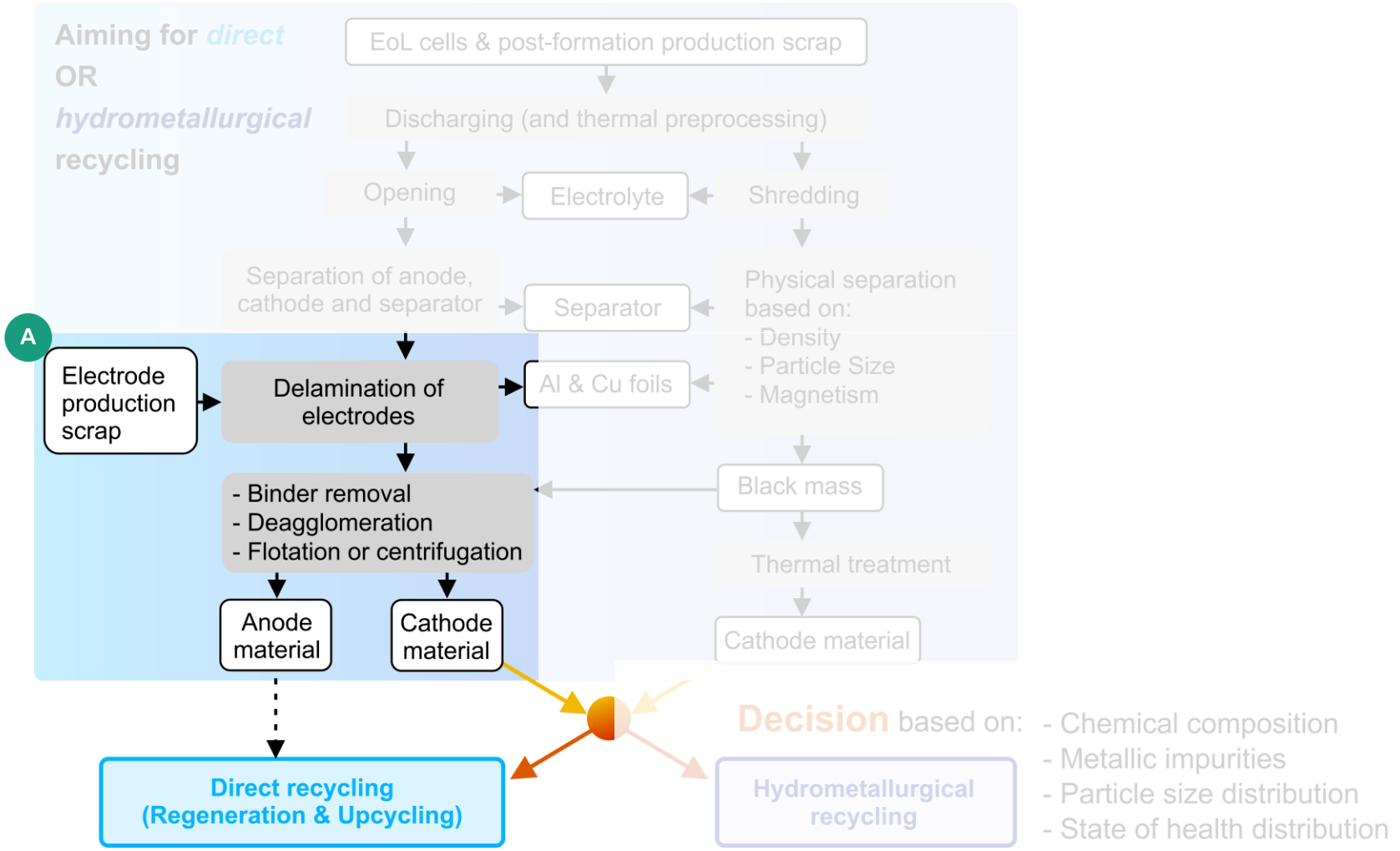
Battery recycling – Aiming for direct or hydrometallurgical recycling



Battery recycling – Direct recycling of production scrap

A

- High industrial relevance
- Relevant for all cell chemistries (NMC, LFP, graphite, etc.)
- No aged active materials
- Economy and sustainability come together



Battery recycling – Direct recycling of production scrap

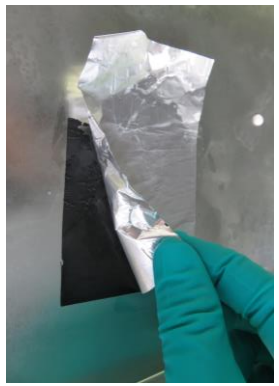
Example: Coating detachment for LFP electrodes

Aqueous Delamination

Steam Delamination

Ultrasonic-assisted Delamination

Ice-Stripping



Adapted from Adv. Energy Mater. 2025, 2405924

Induction Heating

Wide range of water-based processes partly combined with mechanical processes

Dry method without aluminum impurities

Scalability

Induction Heating

Ultrasonic-assisted Delamination

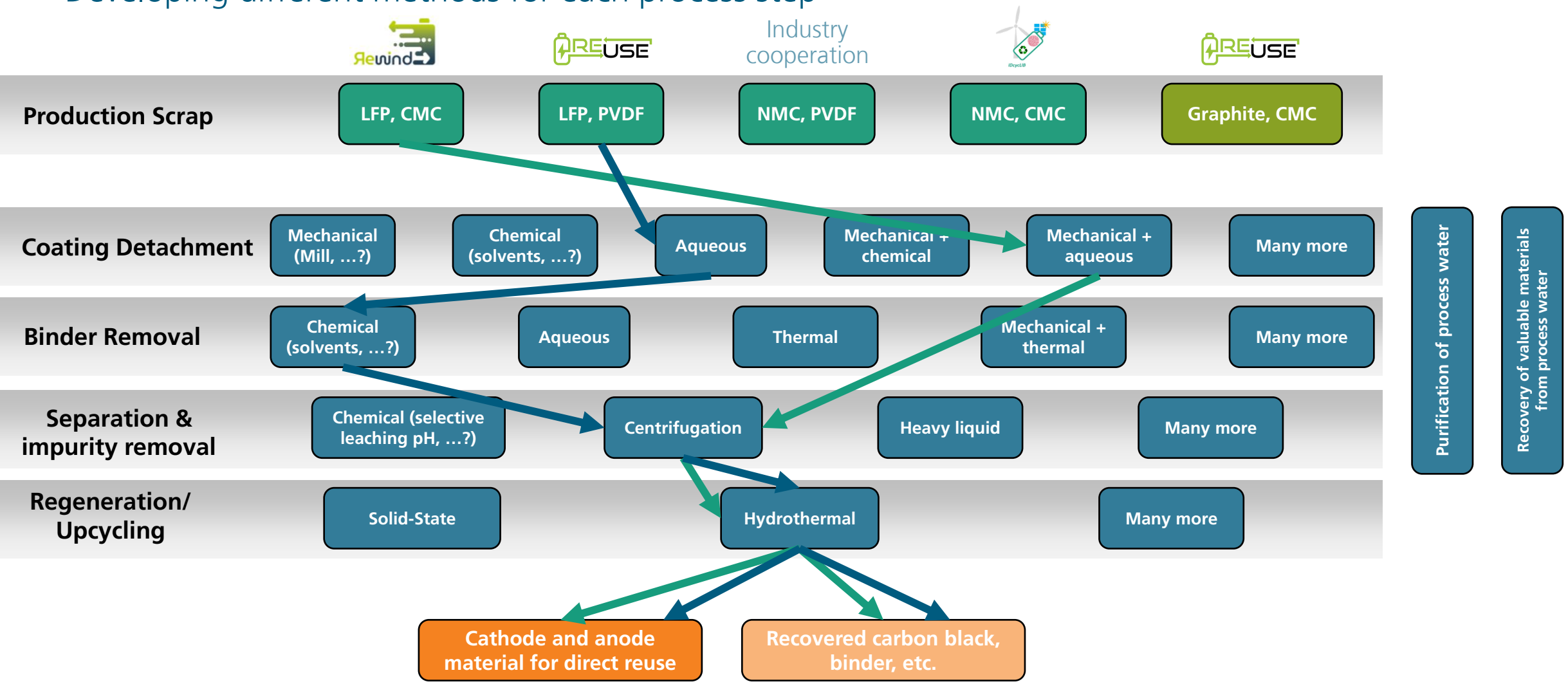
Steam Delamination

Aqueous Delamination

Publications in preparation

Battery recycling – Direct recycling of production scrap

Developing different methods for each process step



Battery recycling – Direct recycling of production scrap

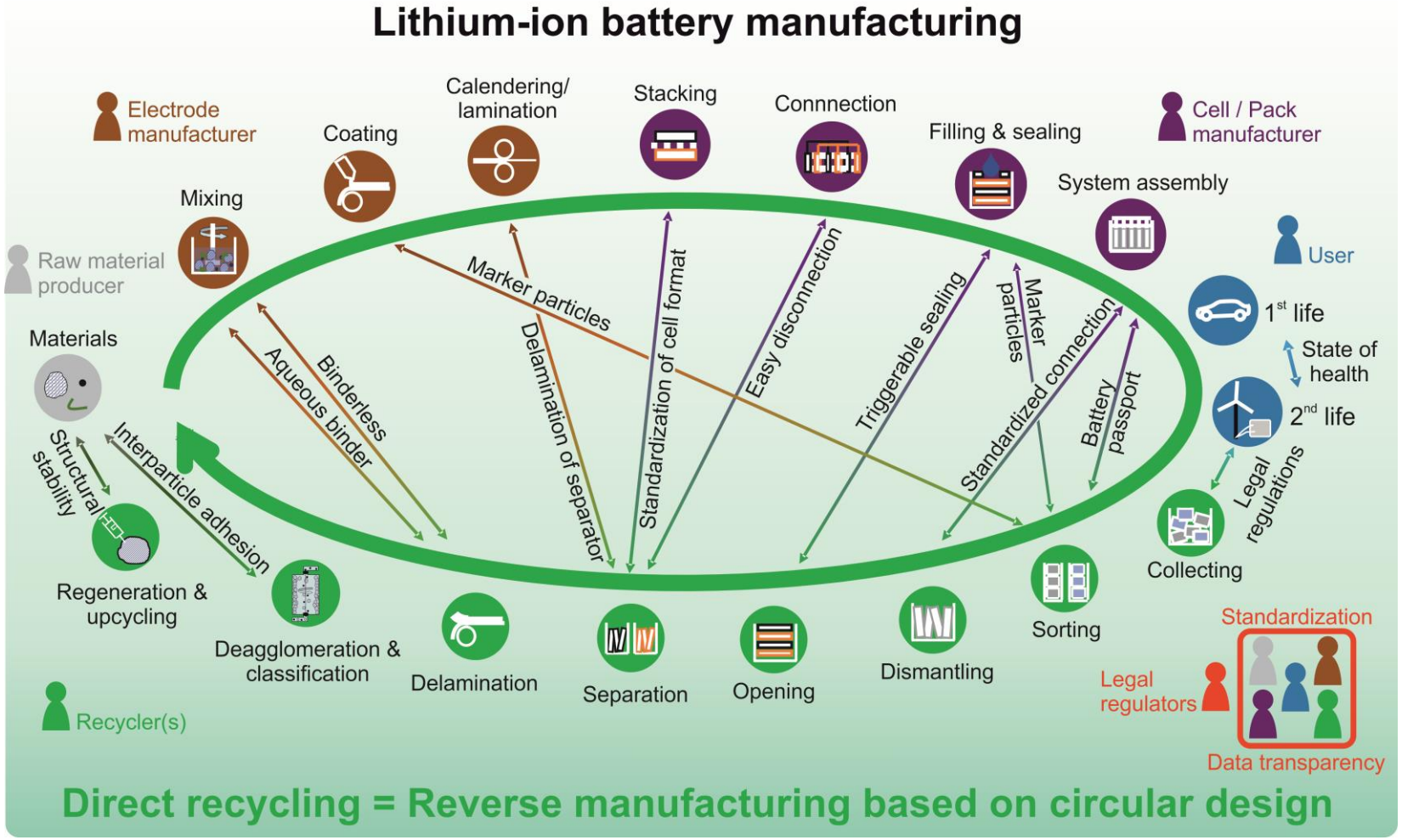
Find the best way!

Key findings

- Removal of the binder is crucial for recycling success, especially with PVDF & PTFE
- There is not *the one direct recycling process*, strong dependence on additives and active material (chemistry, surface modification, particle size and shape) in addition to binder
- Deep understanding of the interaction of different recycling process steps and active material necessary

Future Batteries

The steps towards circular-designed batteries



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Conference on BATTERY DIRECT RECYCLING

3.–5. Februar 2026 / Wuerzburg

www.direct-recycling-conference.de

Call for abstracts until 31st August 2025

SESSIONS

1 Policy and Market
2 Direct Recycling Methods and Processes
3 Sustainability and Digitalization
4 Design for Circularity

Thank you for your attention

Contact

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