Technische Universität Braunschweig

BLB BATTERY LABFACTORY BRAUNSCHWEIG

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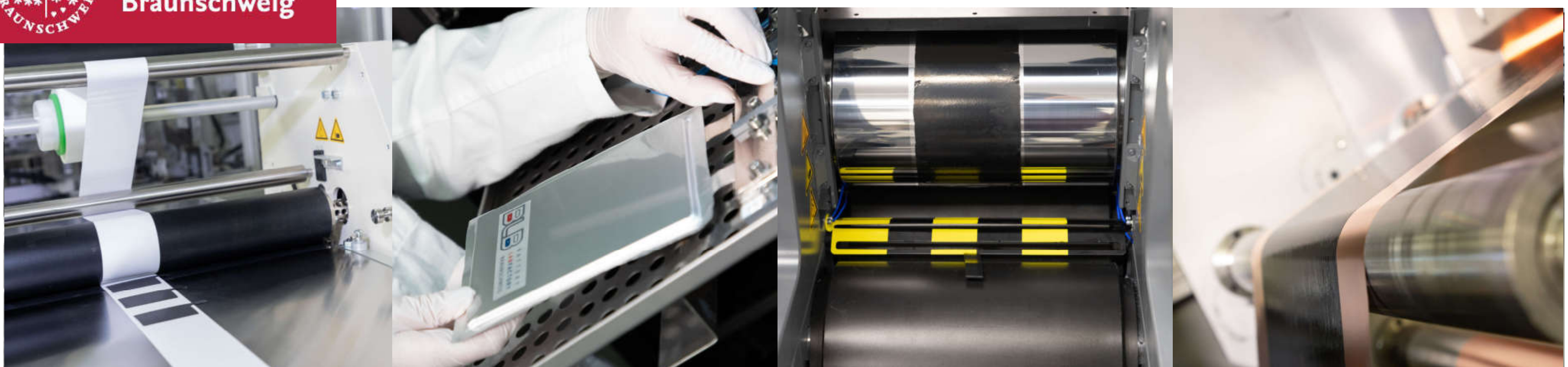


Nachhaltige Produktion heutiger und zukünftiger Batteriegenerationen mit zirkulärer Wertschöpfung von Produktionsabfall und EoL-Batterien

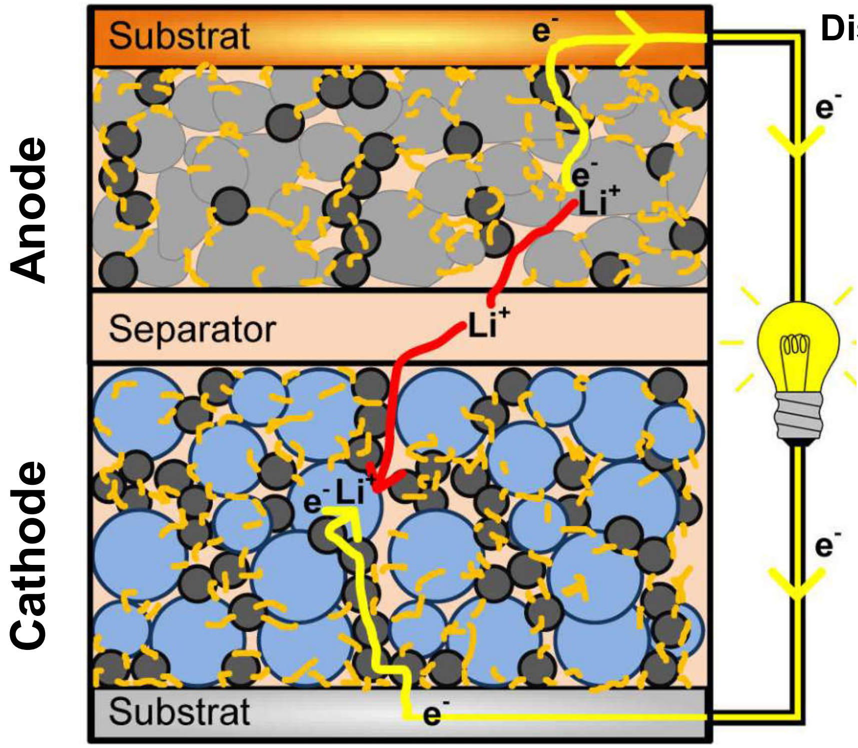
Prof. Dr.-Ing Arno Kwade, Institut für Partikeltechnik & Battery LabFactory Braunschweig

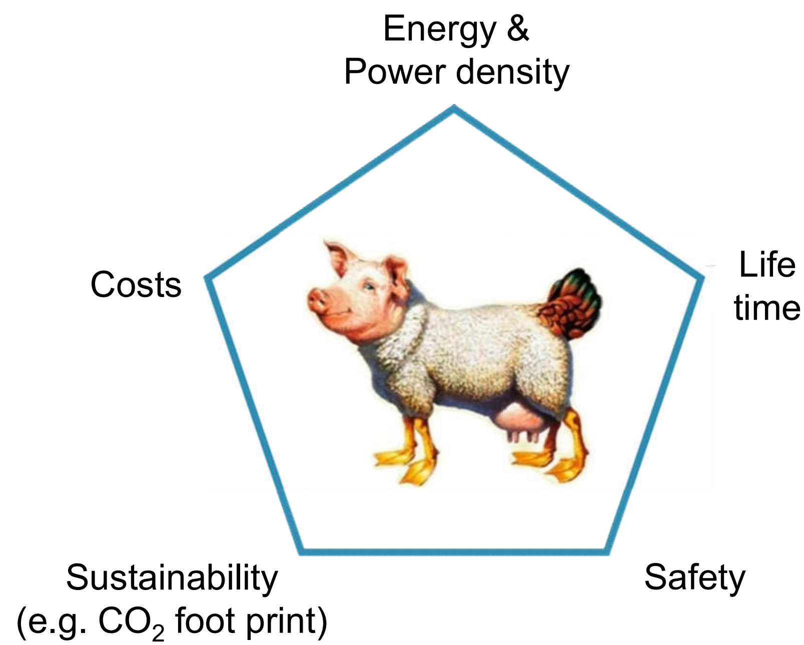
Content

Content

1. Motivation for Sustainable and Circular Battery Production
2. Ways to reduce CO_2-Impact in Production
3. Closed-loop Circulation of Production Scrap & EoL Batteries
4. Perspective Circular Production of Solid State Batteries
5. Conclusion and Outlook

Components and function of Lithium-ion battery





A. Kwade et.al. (2018) Nature Energy 3 (4), pp. 290-300

Next Lithium-Ion Battery Generations – My Opinion

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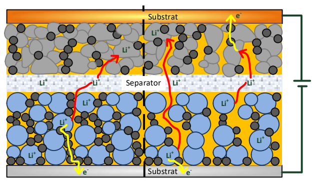
Lithium-Ion



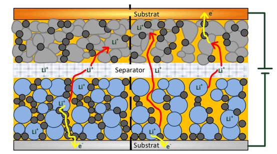
NCM622/NCM811/
NCA vs. Graphite

Material,
Electrode and
cell design
improvement

Maximizing cell performance

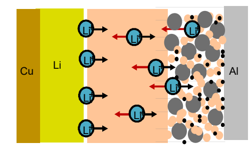
Minimizing cost/ ecological impact

Lithium-Ion



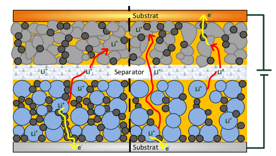
NCM9.5.5 vs Si/C

Solid State



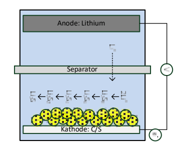
NCM9.5.5 vs. Li

Lithium-Ion or Na-Ion



NCM307/LFP/LMO vs Graphit

LiS



S-C vs. Li

- Diversification of cell technologies, sizes and designs
- Different generations of high performance batteries will coexist
- Lower cost battery cells with better ecological footprint but lower performance will also be developed

Doose, S. et al. *Metals* 2021, 11, 291. https://doi.org/10.3390/met11020291

For EVs the environmental impacts shift to the production

Importance to avoid problem shifting

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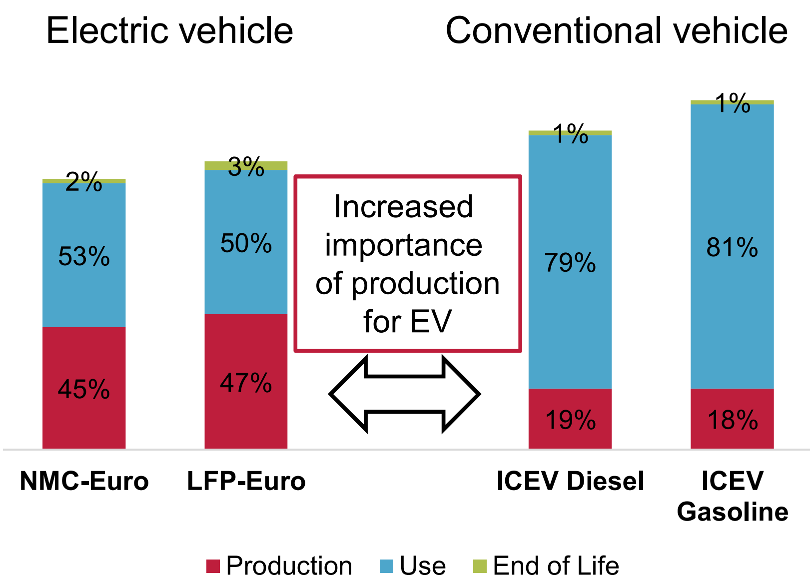
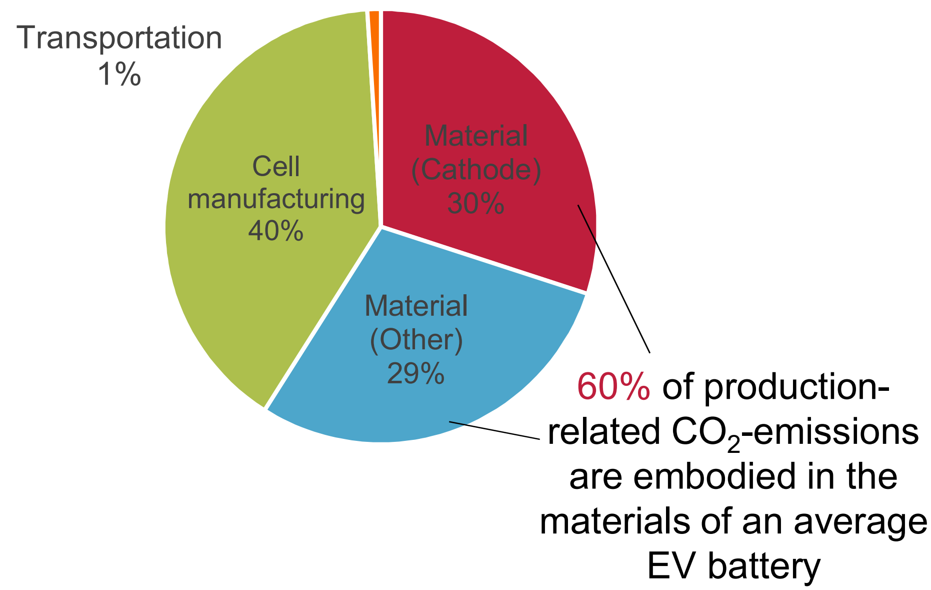
GWP (kg CO_2) per km driven (normalized)

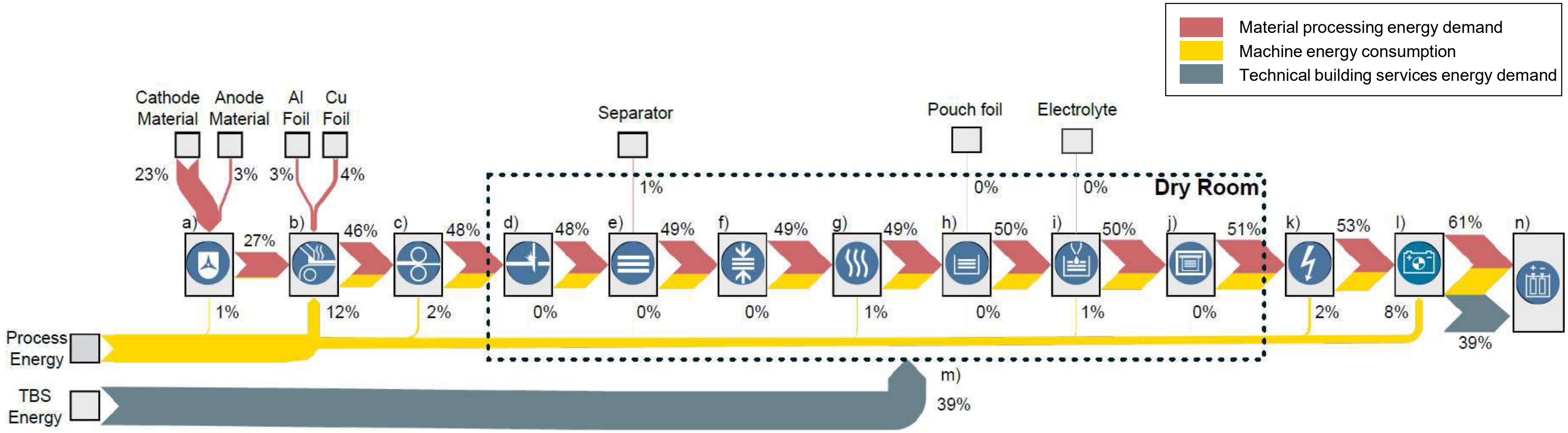


Cradle-to-gate CO_2 emissions of NMC batteries



Data from Hawkins et al. (2013), Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles, *Journal of Industrial Ecology*, 17(1):53–64 and Ciez R E, Whitacre J F (2019) Examining different recycling processes for lithium-ion batteries. *Nature Sustainability*. 2(2):148–156.

Embodied Energy in the battery cell production



Benchbatt

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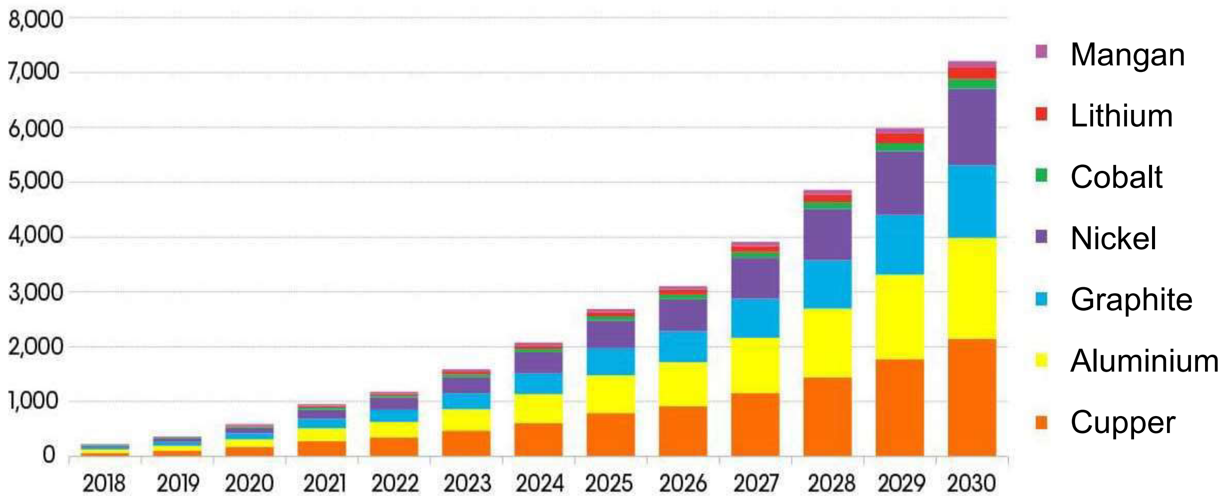
Thomitzek M, Cerdas F, Thiede S, Herrmann C (2019) Cradle-to-Gate Analysis of the Embodied Energy in Lithium Ion Batteries. *Procedia CIRP*. 80:304–309.

Demand on raw materials
for electric vehicles

Metric tons x 10^3



Source: Electric Vehicle Outlook 2018, Bloomberg New Energy Finance. Note: Copper includes copper current collectors and pack wiring. Aluminium includes aluminium current collectors, cell and pack materials and aluminium in cathode active materials.

- Sharp increase in material demand for cell production
- CO_2-impact of materials has to be minimized
- Social aspects of raw materials have to be taken into account

Content

Measures to reach a sustainable battery cell

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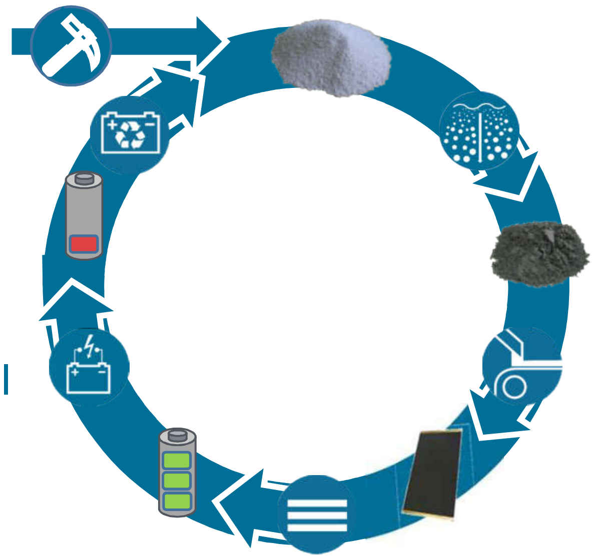
Sustainable, energy efficient raw material processing

Sustainable active and passive material synthesis

Energy efficient recycling processes

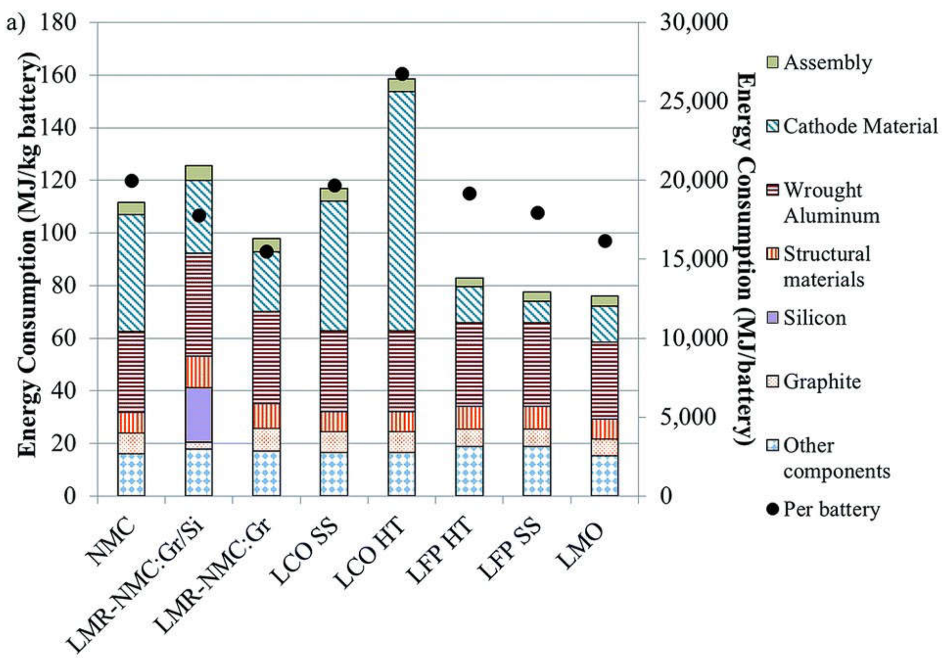


Closed material cycles

Energy efficient and robust electrode and cell production processes

Sustainable cell design

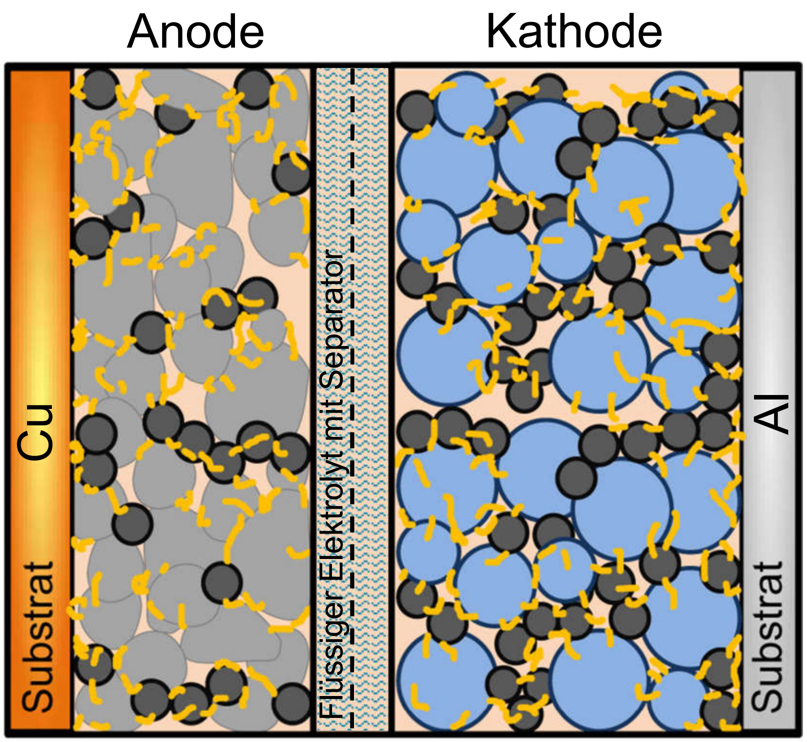
Potentials in active and passive material production



DOI: https://doi.org/10.1039/C4EE03029J

- Active / inactive material synthesis offers potential to reduce the CO_2 footprint
- Cathode material in particular shows high energy-saving potential
- Depending on the specific capacity of the active material, the energy consumption and CO_2-footprint per kg of battery can be improved
- Synthesis and processing to battery materials must be considered further (e.g. cathode active materials for , LFP aqueous processing – LFP, coated NMC)

Potentials of Sustainable Cell Design



- Water based binder, if possible based on biopolymers
- Cathode materials without or minimum amount of cobalt and nickel
- Thick electrodes to reduce relative content of Aluminium and Cupper
- Change of cell chemistry, e.g. towards Li-Sulfur or Sodium-Ion-Battery

Potentials of sustainable battery cell manufacturing

Process chain of lithium-ion battery cell manufacturing

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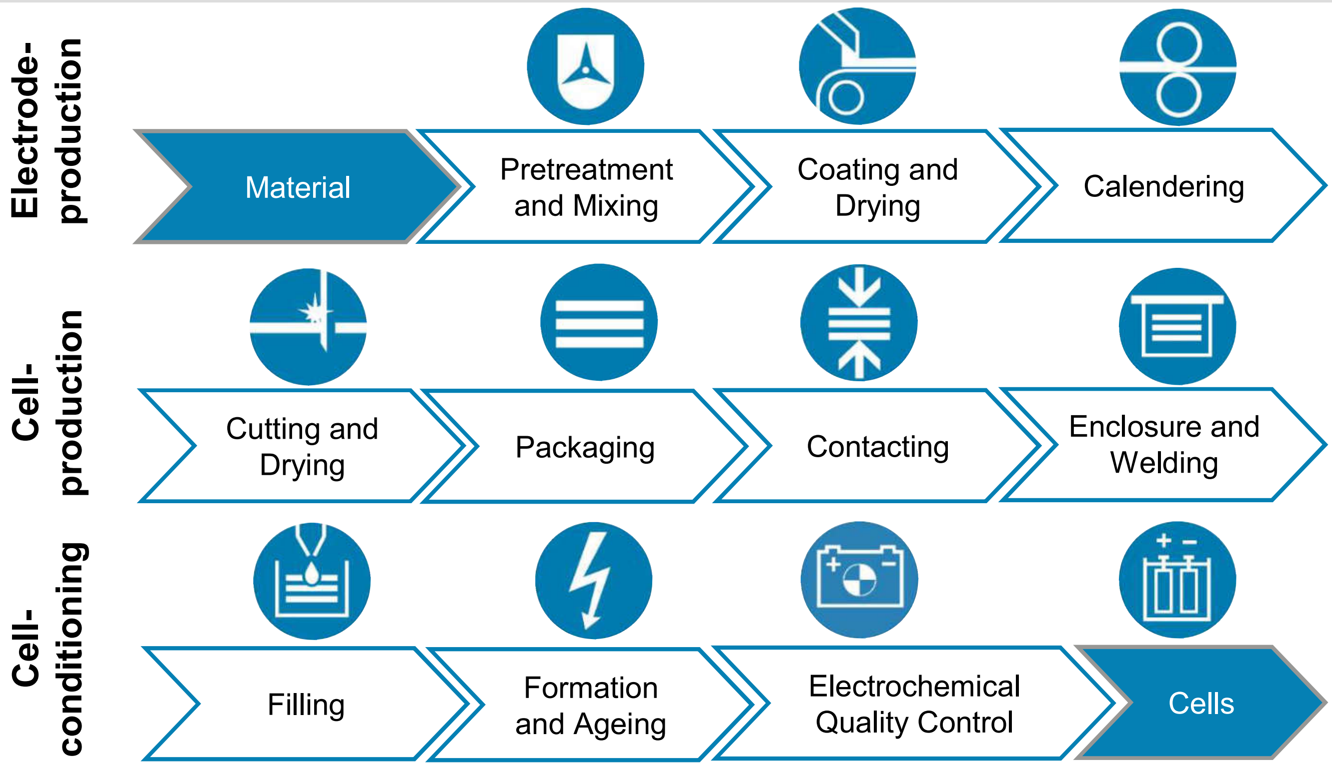

Kwade, A. and Haselrieder, W. et al.: *Current status and challenges for automotive battery production technologies.* Nature Energy, vol. 3, pages 290–300 (2018)

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Established electrode production

Different wet process routes

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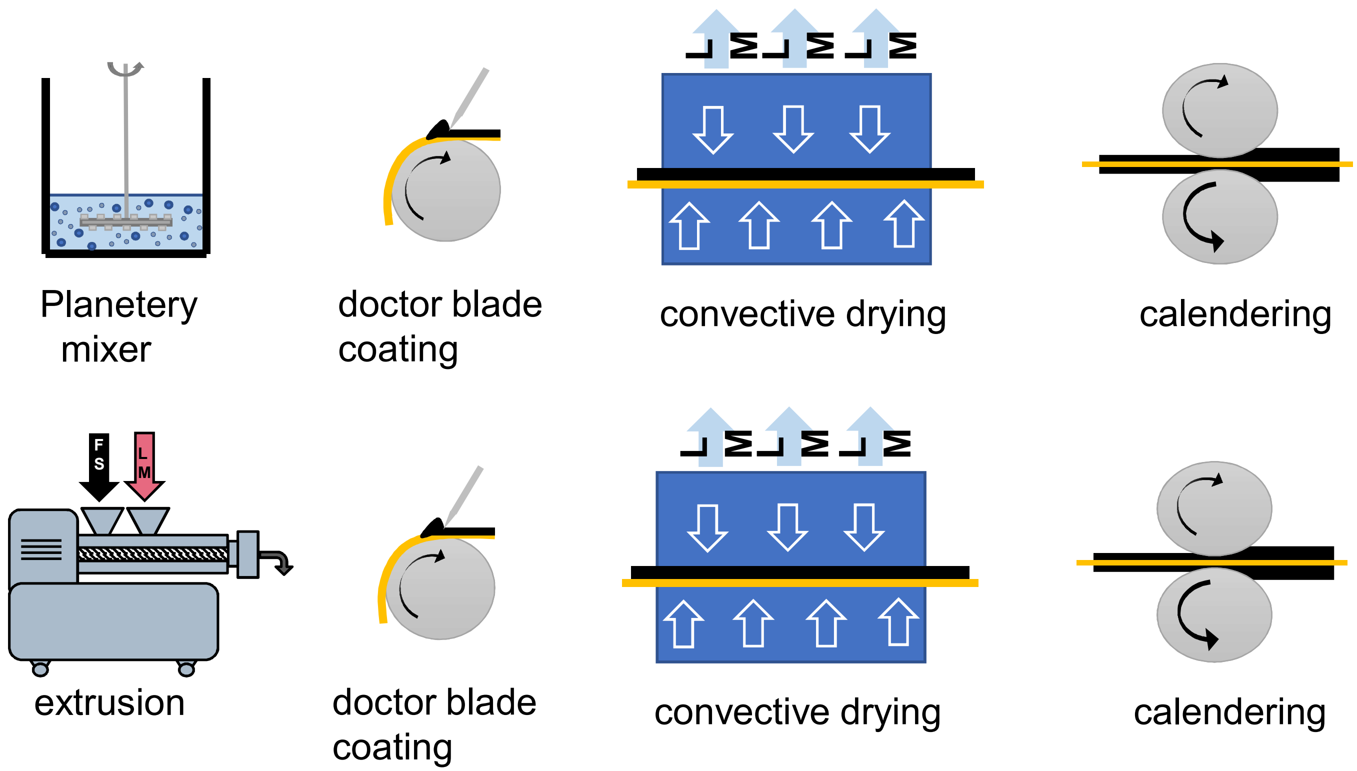
Batch processing of electrode paste

Continuous processing of electrode paste

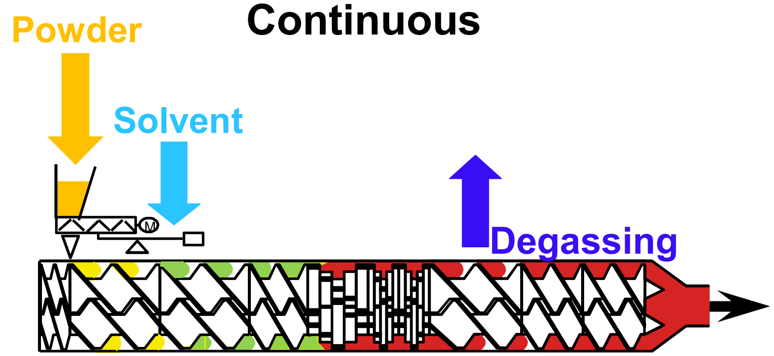


Sustainable electrode production
Continuous extrusion

Batch

vs.

Continuous



Processing time: > 2 h
Maximum solids content: 75 wt.-%

- Quality fluctuations
- Multiple machine units for quasi-continuous needed
- High maintenance

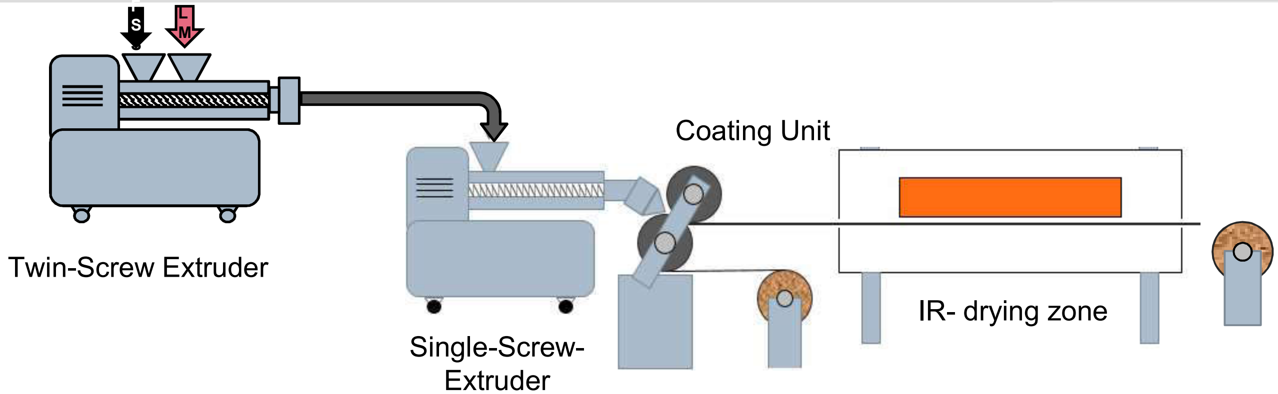
Residence time: < 10 min
Maximum solids content: 90 wt.-% [1]

- Energy efficient due to short resicence time
- Less investment costs
- Continuous dispersing and coating
- Higher solids contents possible
- Water based processes are more feasible

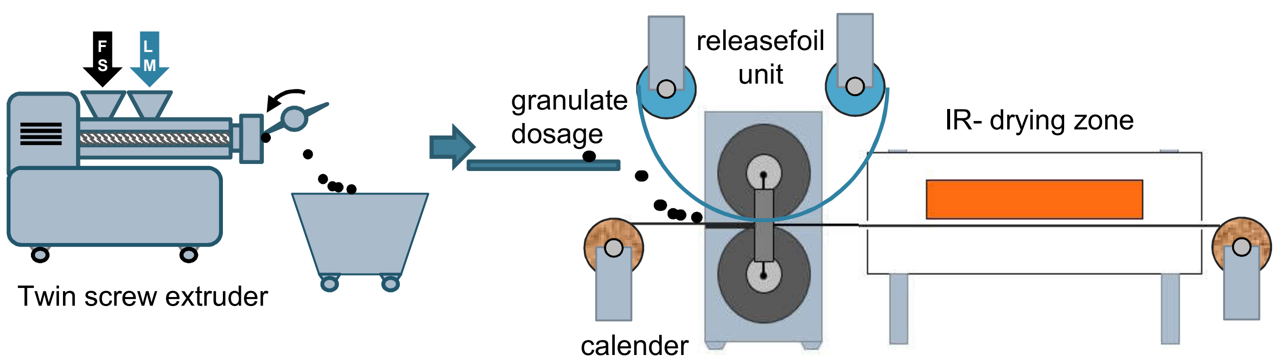
[1] Fig. according to Coperion GmbH

Sustainable electrode production
Direct tape extrusion and granule based coating

Direct tape extrusion (high viscous pastes)



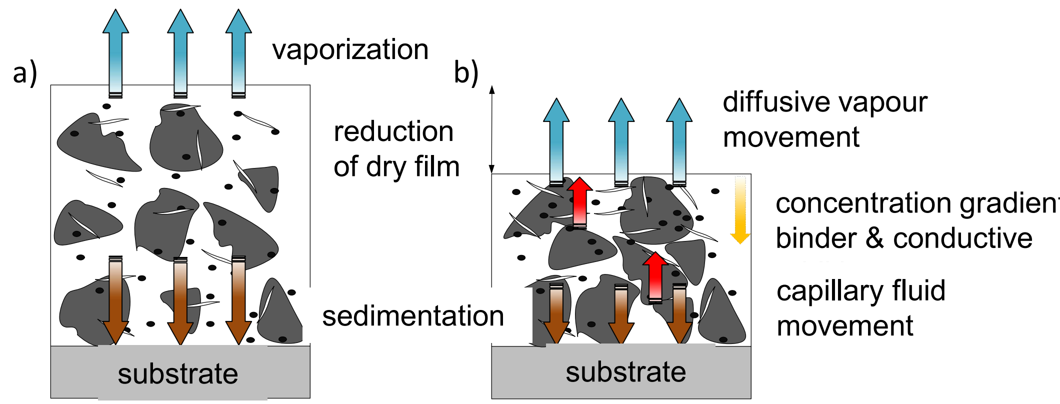
Wet granules based coating methode

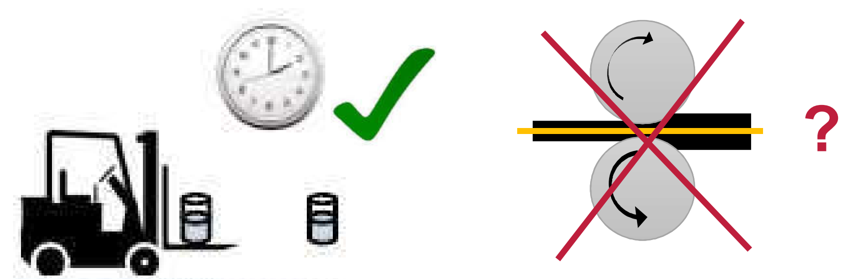


High viscous manufacturing of elektrodes

Potentials and novelty

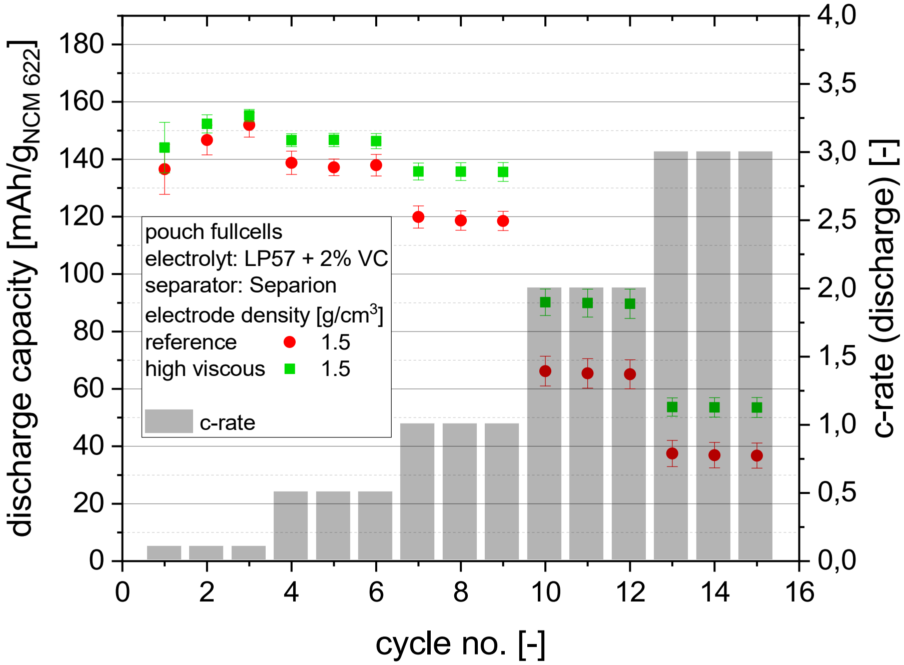
- Less investment and drying costs
- Less energy requirement and better GWP
- Time and location decoupling of dispersion and coating possible
- Increased initial electrode density
- No migration of binder and conductivity additives





Process based on wet granules

First test cell results



Standard process route:

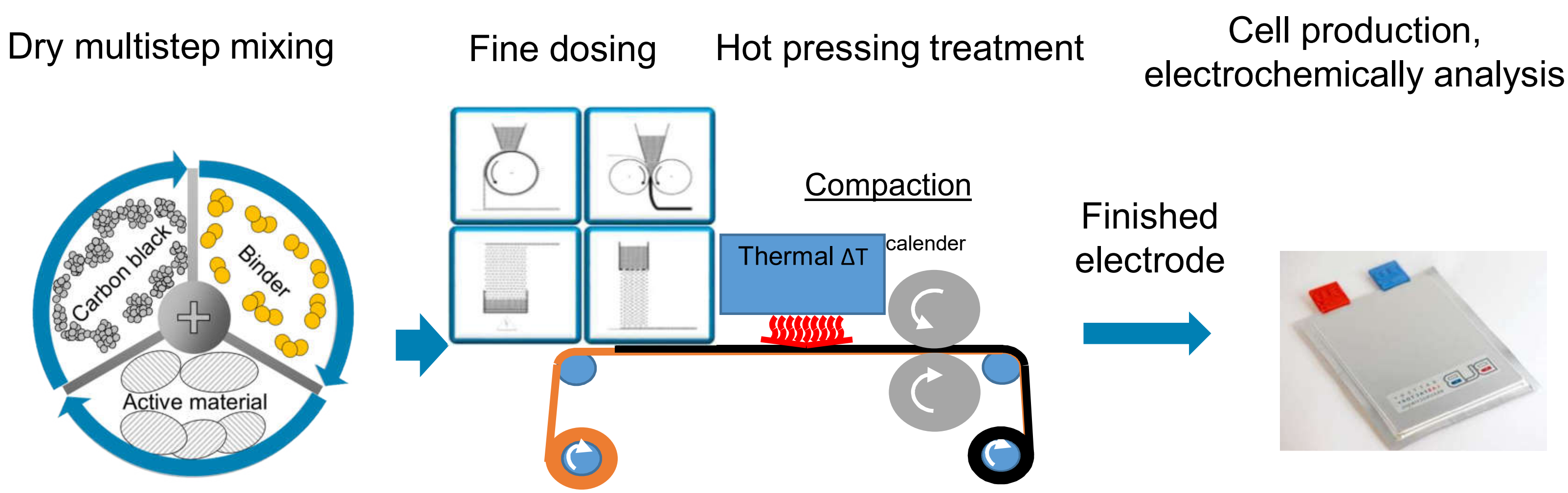
- Pore systems are formed by the evaporation of the solvent
- Assumption: Inhomogeneous compression of pore channels due to calendering

→ The diffusive resistance in certain areas of the electrode is increased

Granule based process route:

- More homogenous pore and material structure
- Higher initial capacity of high viscous processed electrode

Sustainable electrode production
Solvent-free dry coating as an alternative



- Reducing required heating energy up to 90 %
- Saving space due to shorter thermal sections, pointless waste gas treatment
- Reducing dwell time due to faster thermal process

Potentials of sustainable battery cell manufacturing

Process chain of lithium-ion battery cell manufacturing

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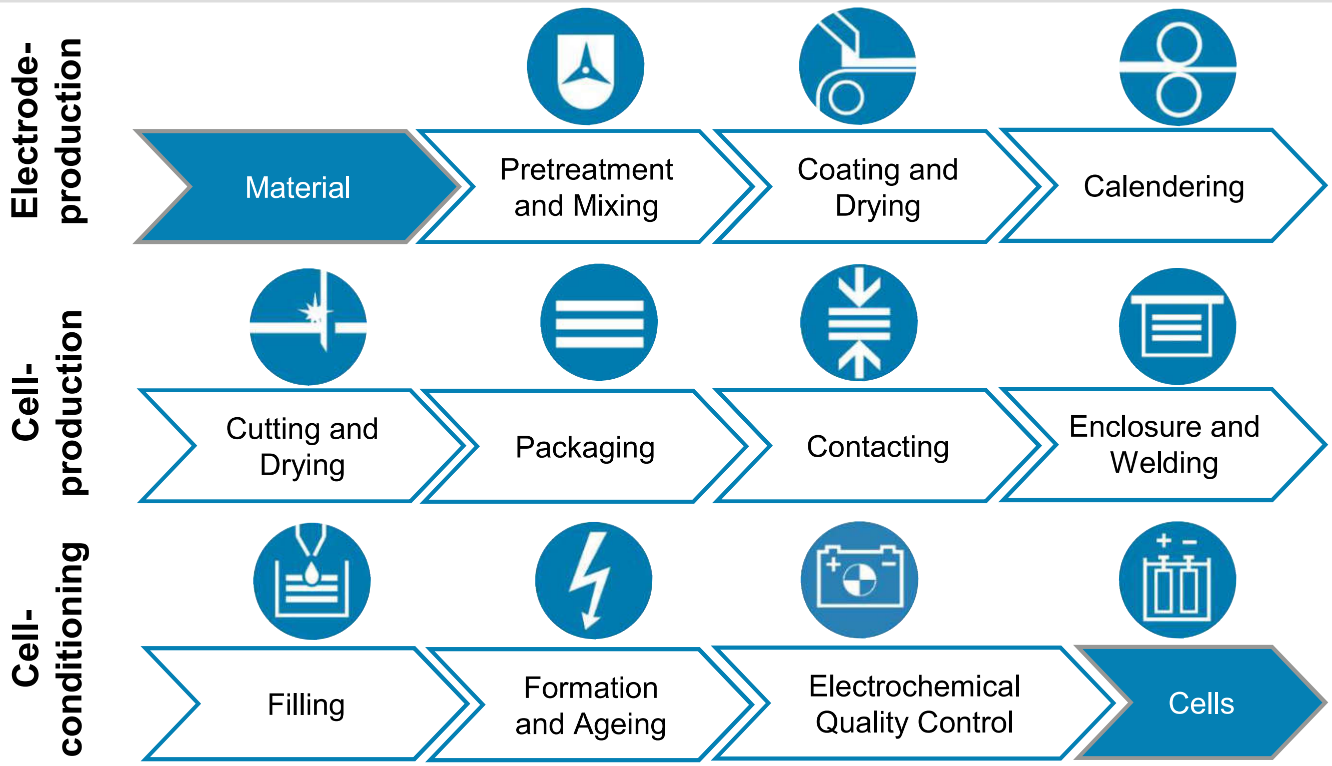

Kwade, A. and Haselrieder, W. et al.: *Current status and challenges for automotive battery production technologies.* Nature Energy, vol. 3, pages 290–300 (2018)

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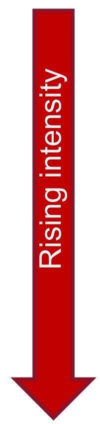
Investigation of different post-drying intensities

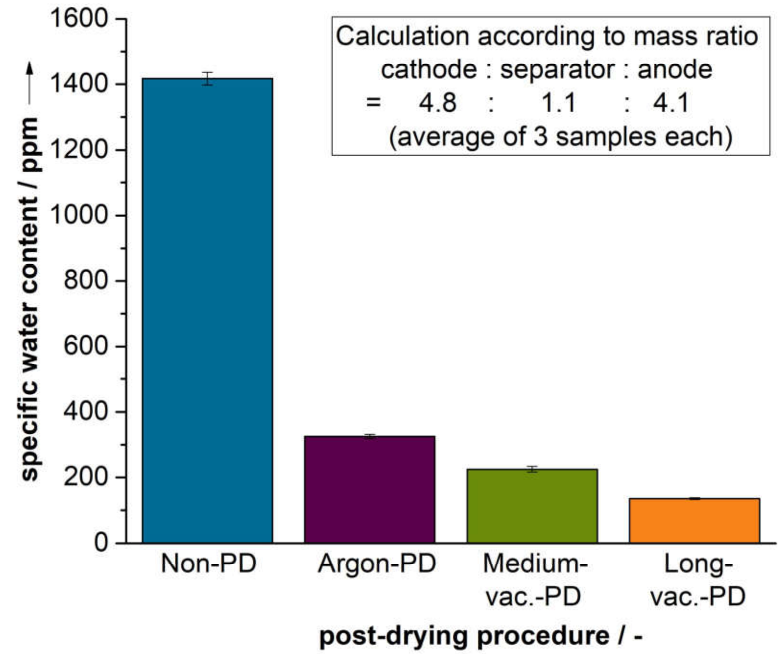
Comparison of remaining water content in total cells

Post-drying (PD) methods:

- Argon-PD:
  3x vacuum + 3x Argon purging in lock of glovebox (15min)
- Medium-vac.-PD:
  120°C / 18 h in vacuum, followed by manual purging (3 argon/vac. cycles)
- Long-vac.-PD :
  120°C / 96 h in vacuum, followed by manual purging (3 argon/vac. cycles)



→ Argon-PD already considerably reduces the remaining water content of total cells



[1]

[1] F. Huttner, W. Haselrieder, A. Kwade, The Influence of Different Post-Drying Procedures on Remaining Water Content and Physical and Electrochemical Properties of Lithium-Ion Batteries. *Energy Technology* **(2019)**. doi/10.1002/ente.201900245.

Investigation of different post-drying intensities for LIBs

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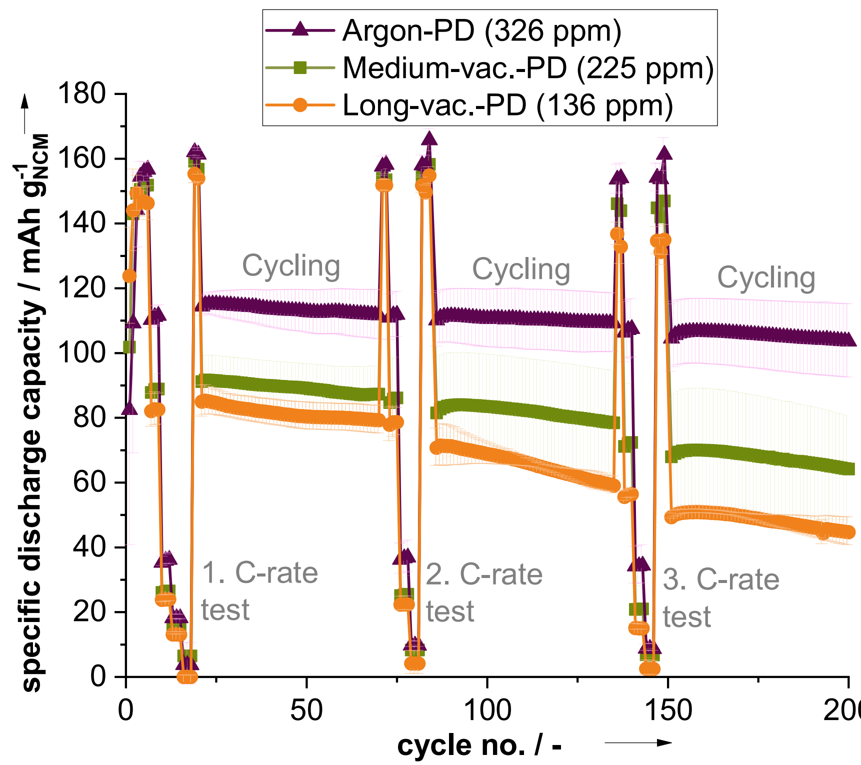
- Mild Argon-PD shows best cell performance despite highest moisture
- Cell performance not only dependent on residual moisture, but also significantly on post-drying intensity

→ Post-drying parameters must be chosen gentle enough to maintain sensitive binder network of electrodes

- Argon-PD: 3x vacuum / Argon purging (15min)
- Medium-vac.-PD: electr.: 120°C / 18 h in vac., sep.: 60°C / 4 h
- Long-vac.-PD : electr.: 120°C / 96 h in vac., sep.: 60°C / 4 h



[1]

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Sustainable cell production and conditioning

Material and energy flows in cell manufacturing

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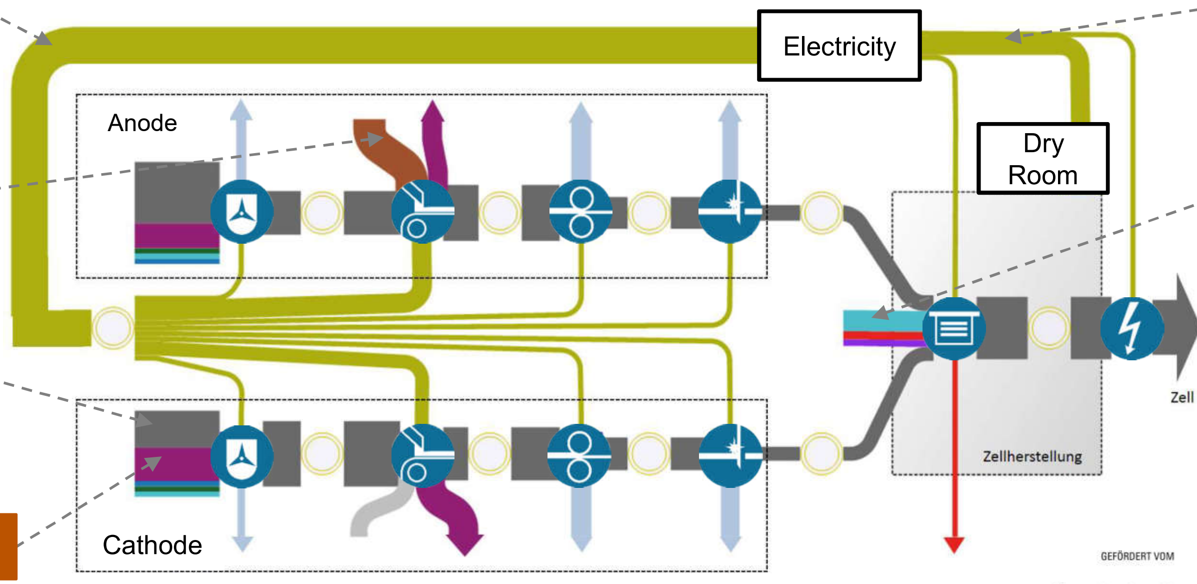
~ 45% to 60%

Cu – current collector

NMC

NMP (Solvent)



~ 35% to 55%

Electrolyte

Benchbatt

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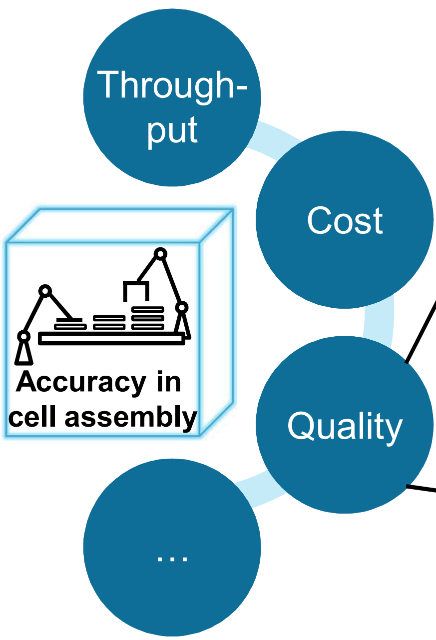
Mini-Environments instead of large dry rooms

Thomitzek M, Cerdas F, Thiede S, Herrmann C (2019) Cradle-to-Gate Analysis of the Embodied Energy in Lithium Ion Batteries. *Procedia CIRP*. 80:304–309.

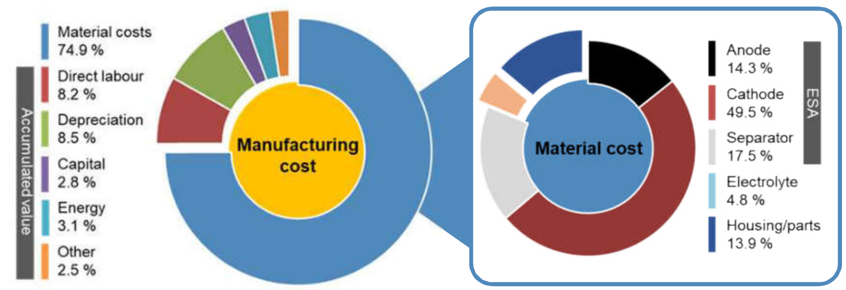
Sustainable cell production

Impact of accuracy in cell assembly



Cost aspects

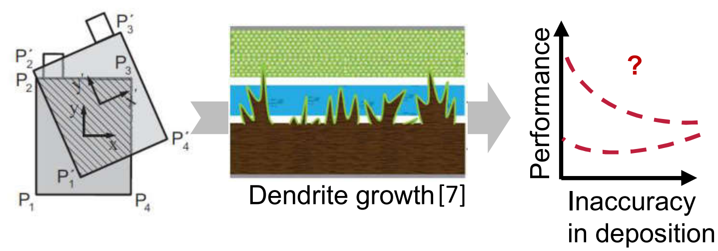
- Saving expensive raw material
- More expensive equipment



Cost allocation in lithium-ion battery production [6]

Performance aspects

- Inhomogeneous current density distribution
- Unwanted and dangerous side reactions
- Thermal runaway

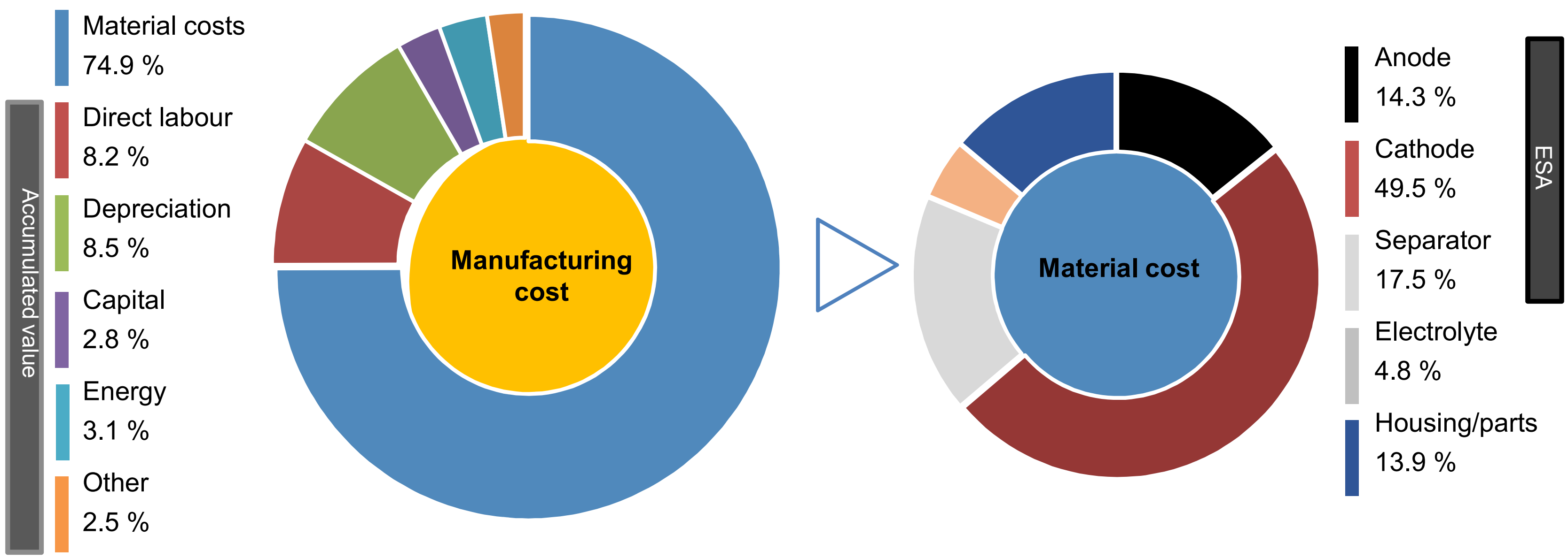


Influence of incorrect electrode deposition

Content

Cost breakdown production and material costs

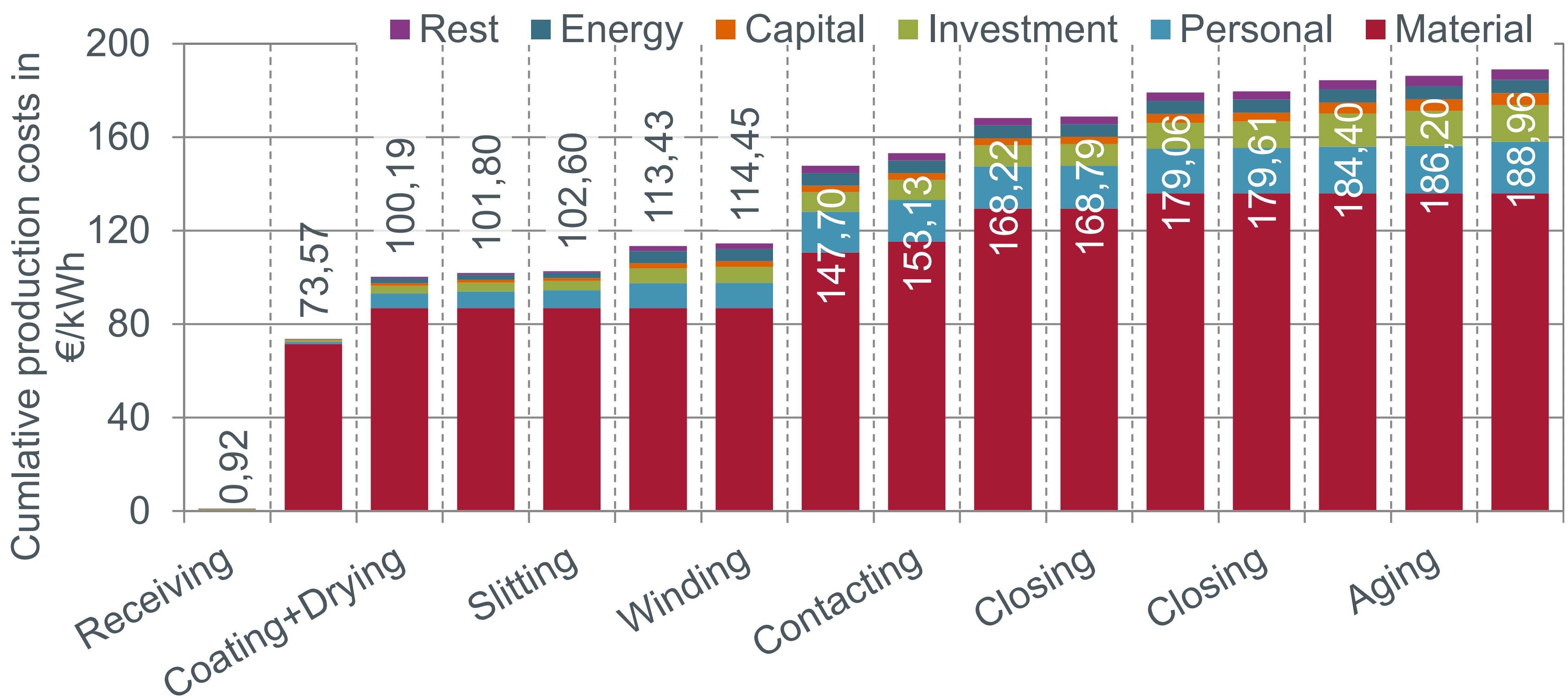
C//NMC 111, PHEV2, 36 Ah



J.-H. Schünemann – Modell zur Bewertung der Herstellkosten von Lithiumionenbatteriezellen, Dissertation, iPAT Schriftenreihe, Sierke-Verlag

Cumulative cost over production steps

C//NMC, PHEV2, 36 Ah



J.-H. Schünemann – Modell zur Bewertung der Herstellkosten von Lithiumionenbatteriezellen, Dissertation, iPAT Schriftenreihe, Sierke-Verlag

Requirements in process chain

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1st process step

efficiency per process step: 97 %

number of process steps: 18

$(0,97)^{18} = 0,578$

efficiency of entire process chain: 57,8 %

18th process step

Detailled knowledge to each process step and to the interaction of the process steps is required!

to secure fast ramp up of mass scale cell productions with minimal rate of production rejects

Competence Cluster Recycling & Green Battery
Action – Recycling of electrode production rejects

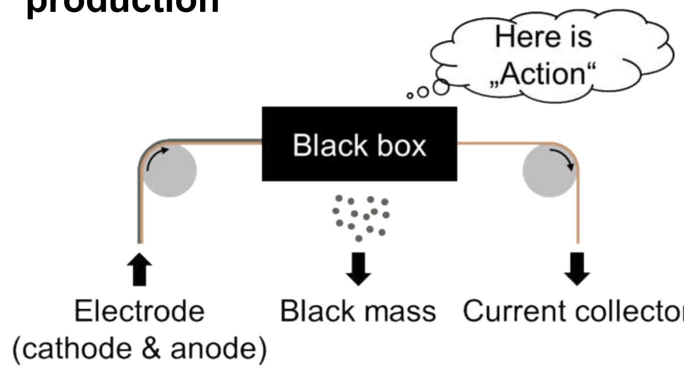
Electrode comminution and subsequent classification (reference process)

Improvement through adjustment of
- Process parameters
- Process control
- Electrode pretreatment

→ Cannot be integrated directly into electrode production

Comparison

Development of a new process that can be integrated into electrode production



Process and product characterization

e.g. yield, energy consumption, impurities, particle size, morphology, viscosity, electrochemical performance

greenBatt Action

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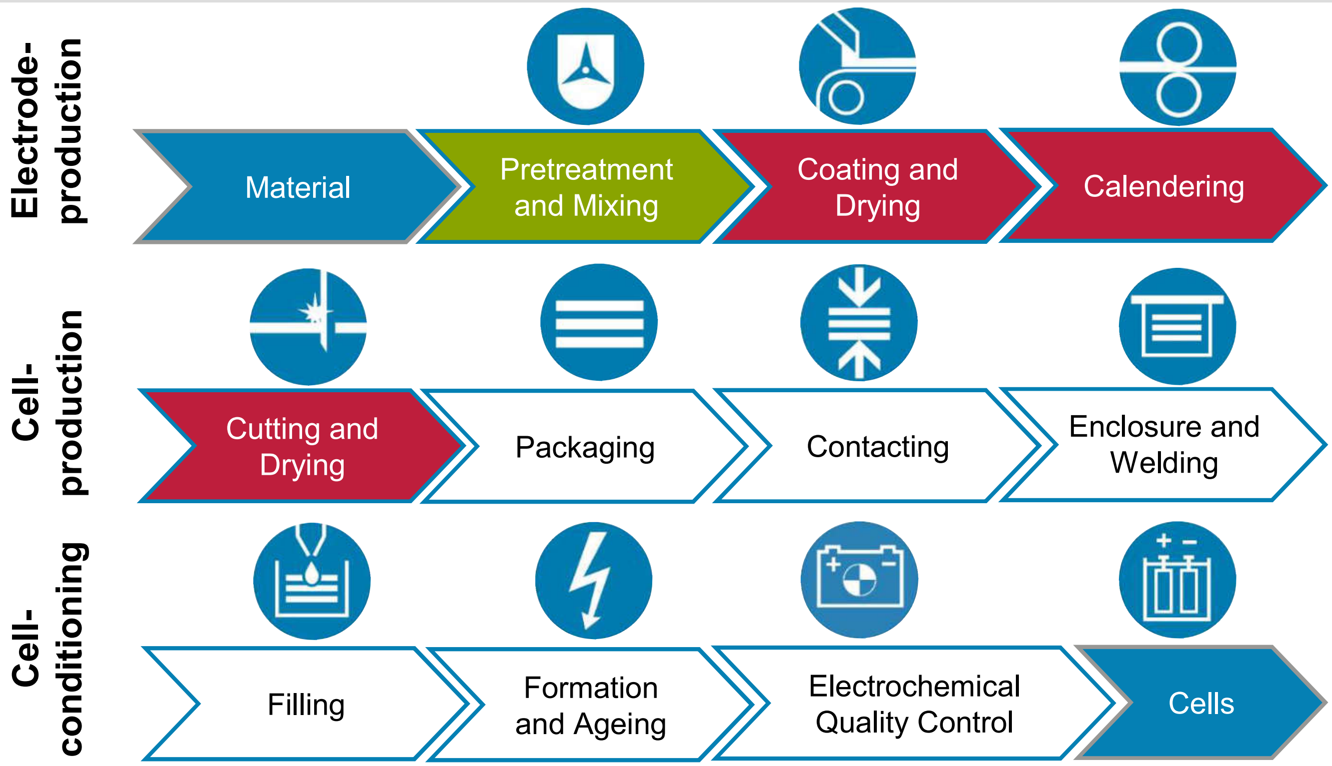
Reuse and recycling of production scrap
Electrode scrap



Coating, Drying & Calendering

- Ramp-up
- Coating defects

→ Electrode scrap

Cutting

- Projection

→ Electrode scrap

Reuse

Processing and direct return of the coating material

According to: Kwade, A. and Haselrieder, W. et al.: *Current status and challenges for automotive battery production technologies.* Nature Energy, vol. 3, pages 290–300 (2018)

Reuse and recycling of production scrap
Recycling of electrode scrap

Dry-mechanical

Milling → Fine Screening → De-Agglomeration → Re-Dispersing → Re-Coating

Cutting mill

Current collector and coating material

Sieve

Coating material

Current collector

Wet-chemical

Milling → Solvation in NMP at 90°C → Screening Foil Fraction / Filtration → Drying → Deagglo-meration → Re-Coating

C. Hanisch et al.: *In-Production Recycling of Active Materials from Lithium-Ion Battery Scraps.* ECS Trans, vol. 64, pages 131–145 (2015)

Reuse and recycling of production scrap

Cell scrap

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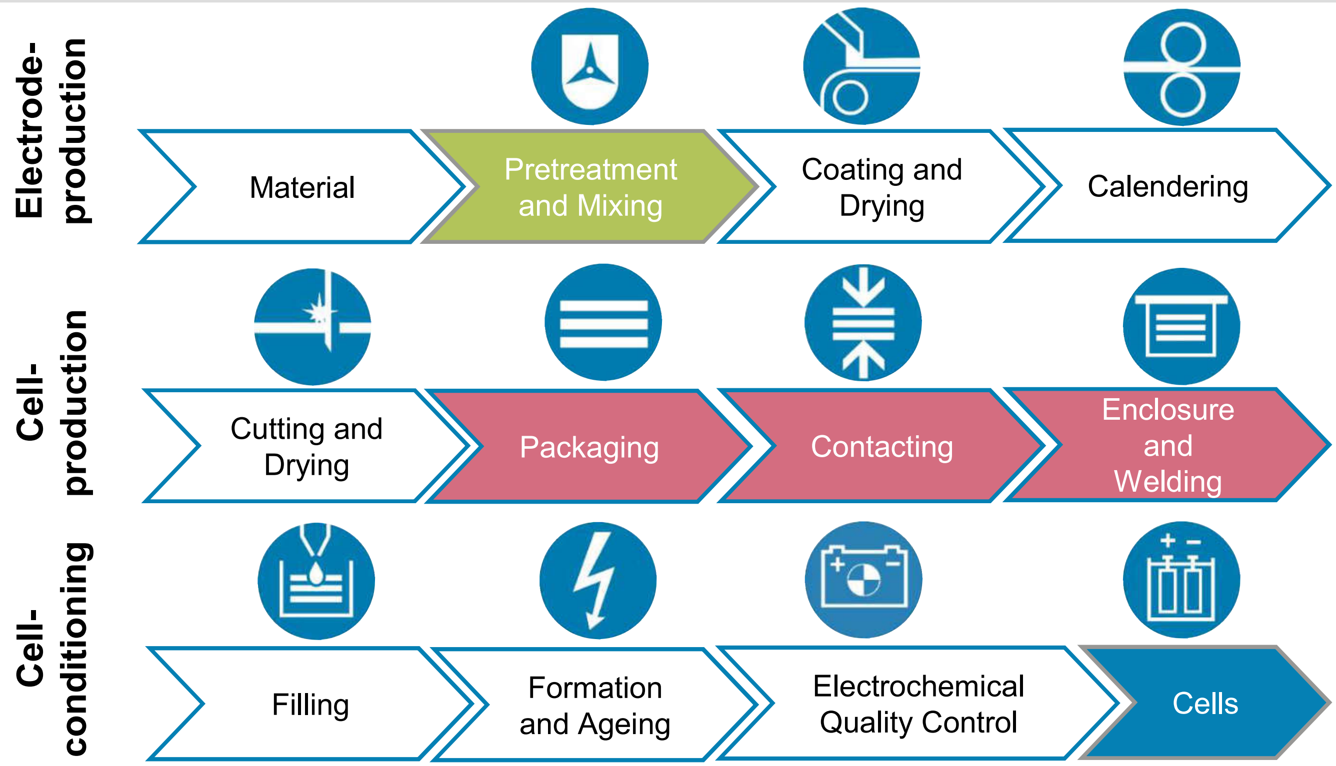
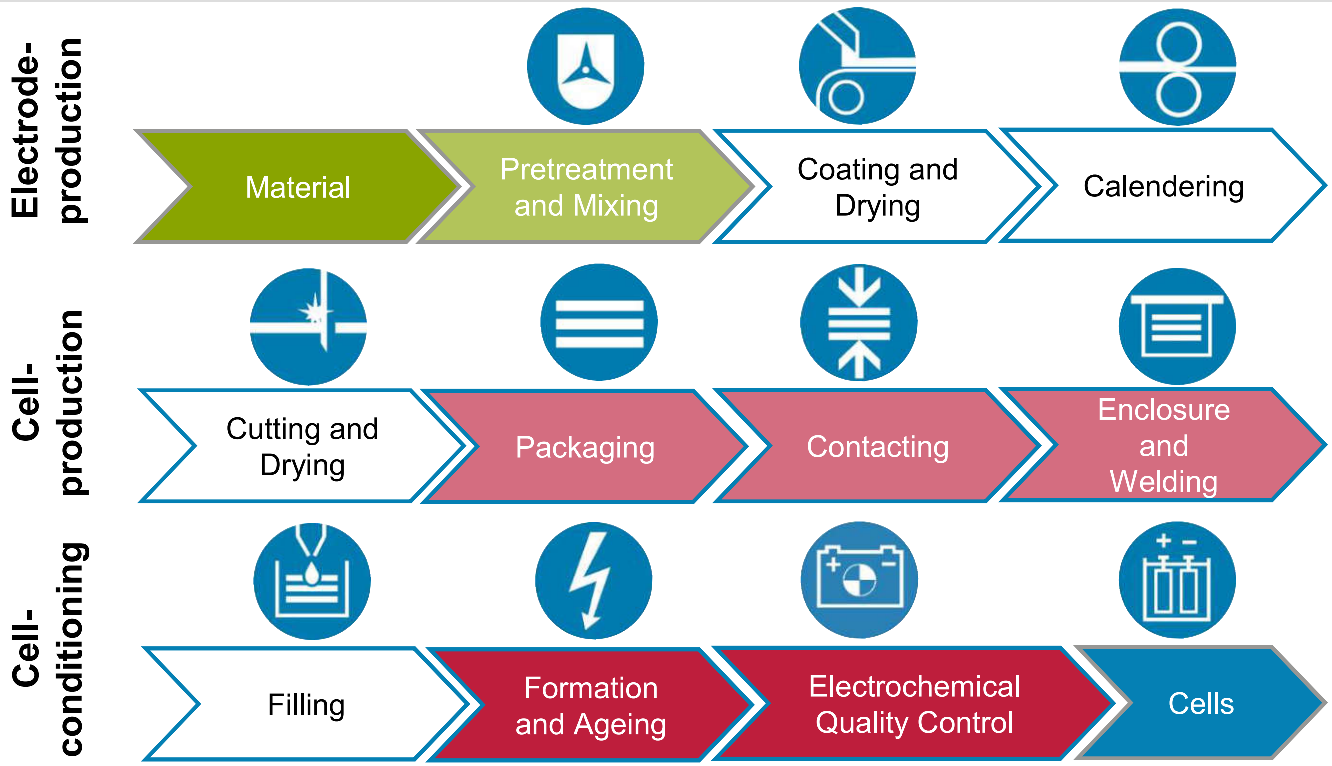


Dry cell assembling
- Process failures
- In production quality gates

Reuse
- Processing and direct return of the coating material as for electrode scrap

According to: Kwade, A. and Haselrieder, W. et al.: *Current status and challenges for automotive battery production technologies.* Nature Energy, vol. 3, pages 290–300 (2018)

Reuse and recycling of production scrap
Cell scrap



Electrochemical Quality Control
- not functional
- inadequate performance

Reuse
- Processing to raw materials
- alternative applications, e.g. stationary energy storage

According to: Kwade, A. and Haselrieder, W. et al.: *Current status and challenges for automotive battery production technologies.* Nature Energy, vol. 3, pages 290–300 (2018)

Circulating production scrap and EoL-Batteries Recycling Technologies

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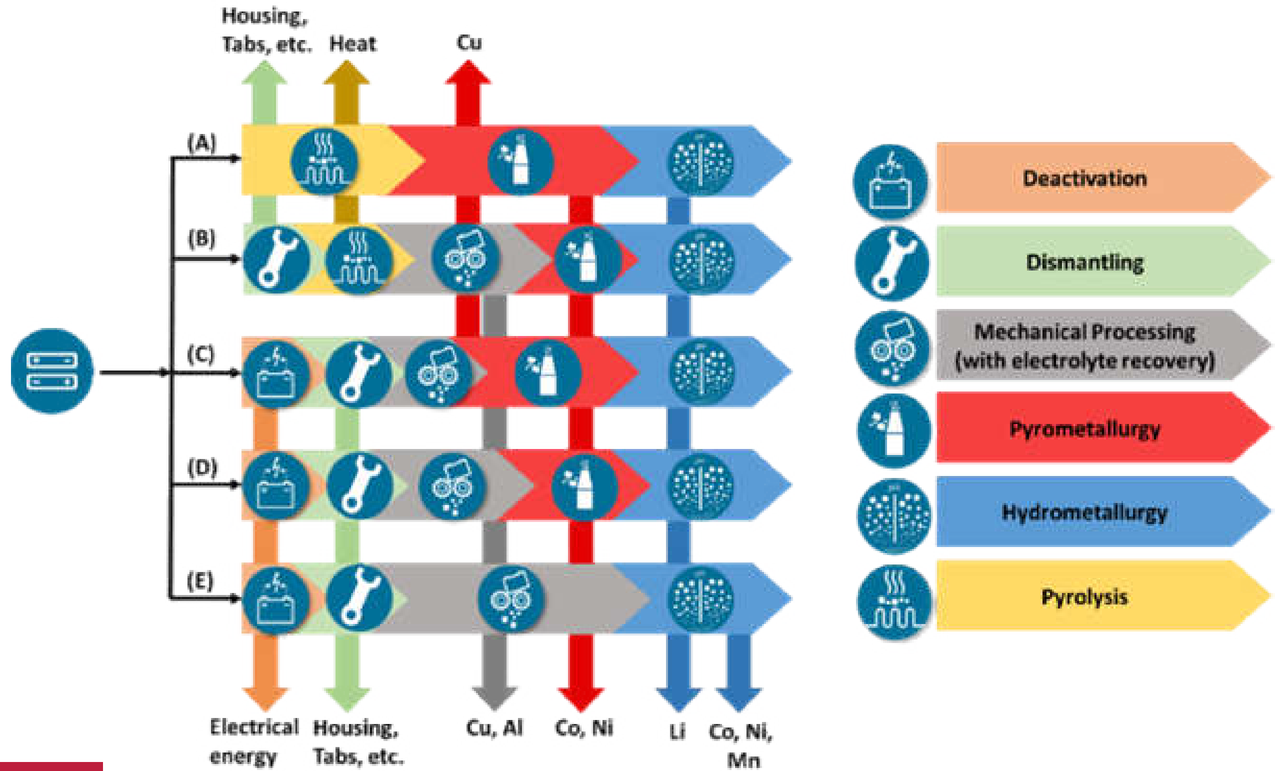
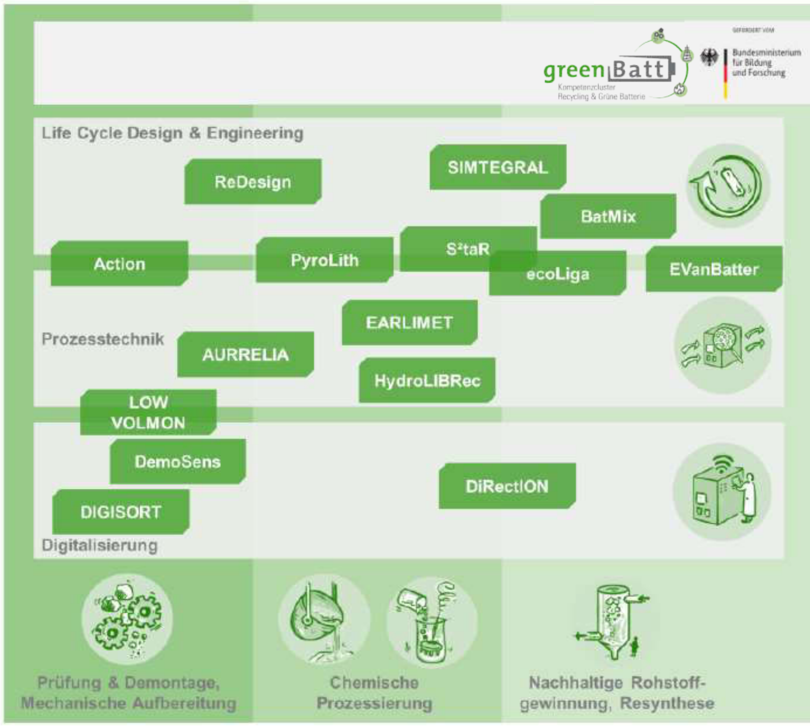


Competence Cluster Recycling & Green Battery



Mission:

Designing an energy and material efficient battery life cycle by closing material loops

Cluster goals:

- Development and application of innovative recycling and resynthesis processes
- Increasing the quality and availability of data for the development of multidisciplinary life cycle models and tools
- Recommendations for design for recycling and for end-of-use

Funding:

approx. 30 million €

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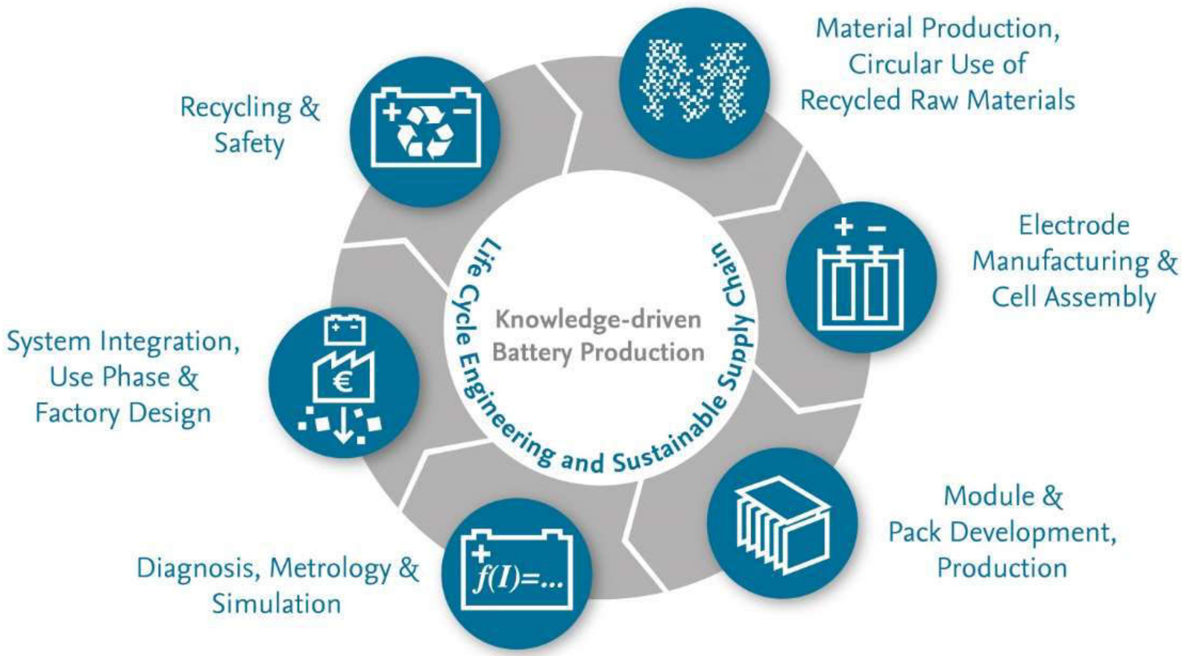
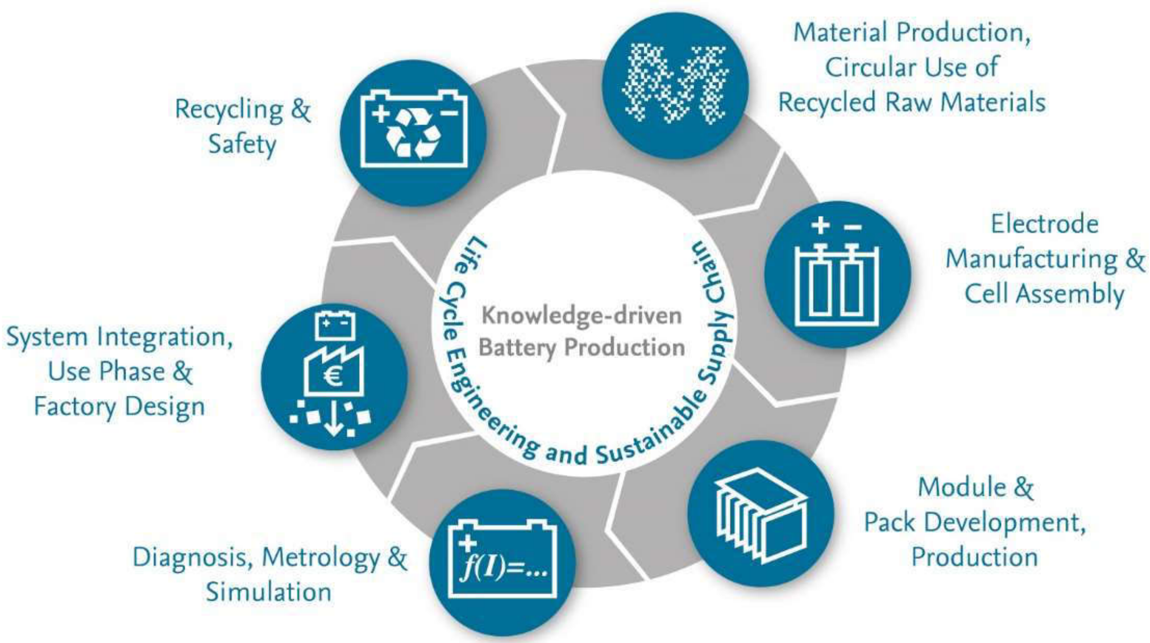
Battery Recycling and Circular Battery Production

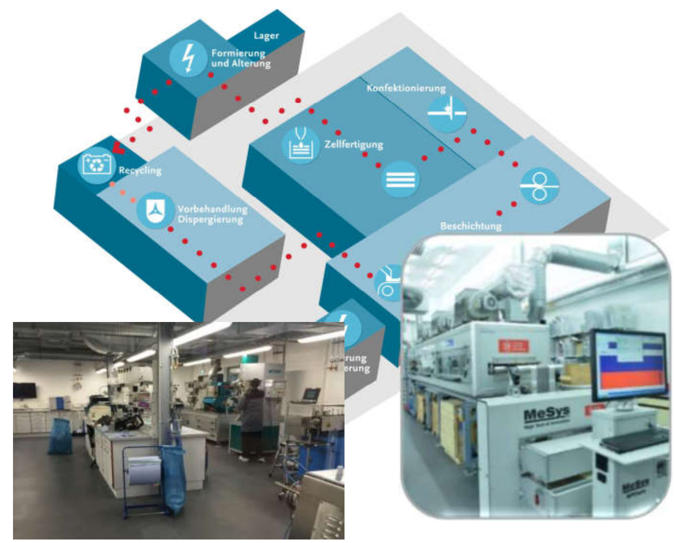


- Cycle materials and keep them in country – less CO_2, negative social impact and costs
- Be competitive in battery cell production by utilizing the 75% material cost portion
- Enable a sustainable future mobility

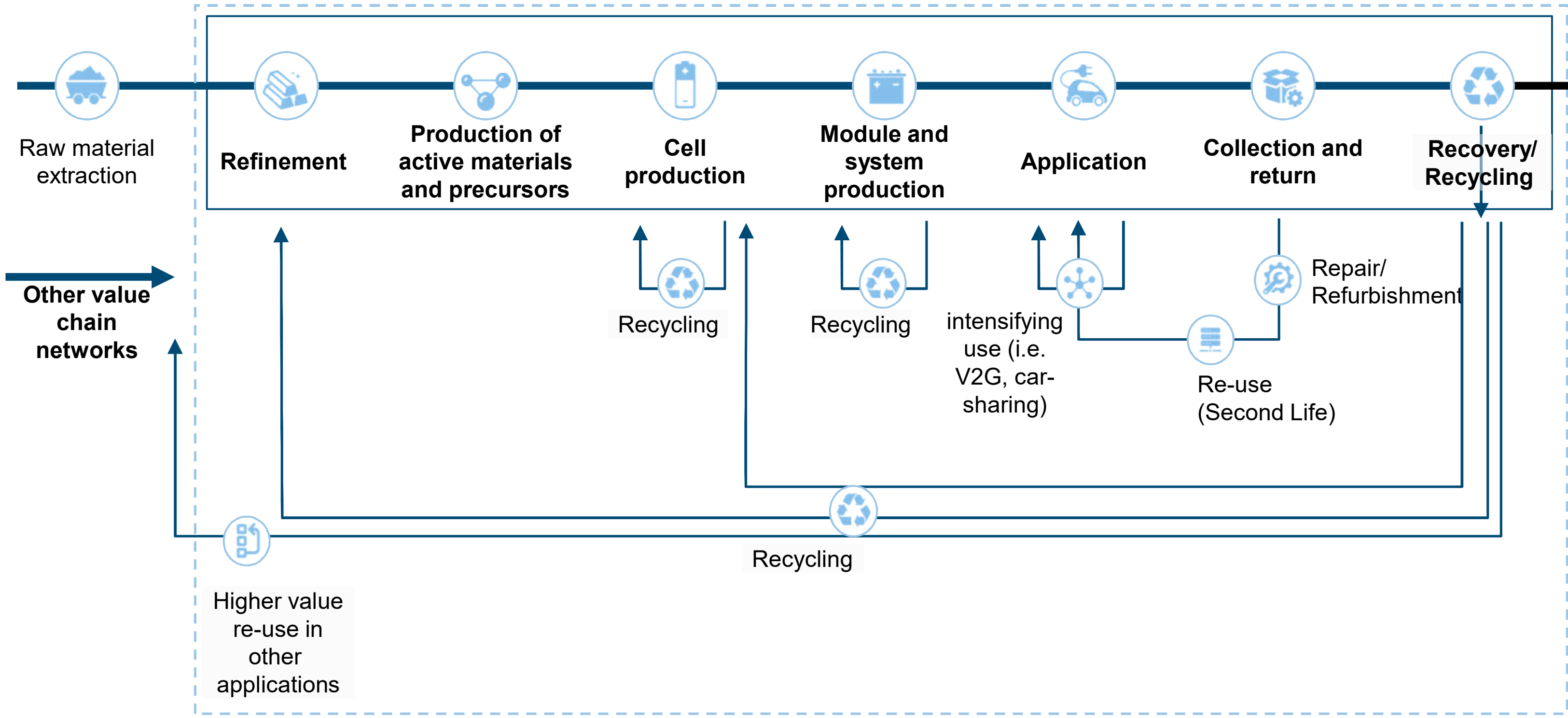
Battery LabFactory Braunschweig
Circular Battery Economy at BLB



Pilot scale circular battery production facility



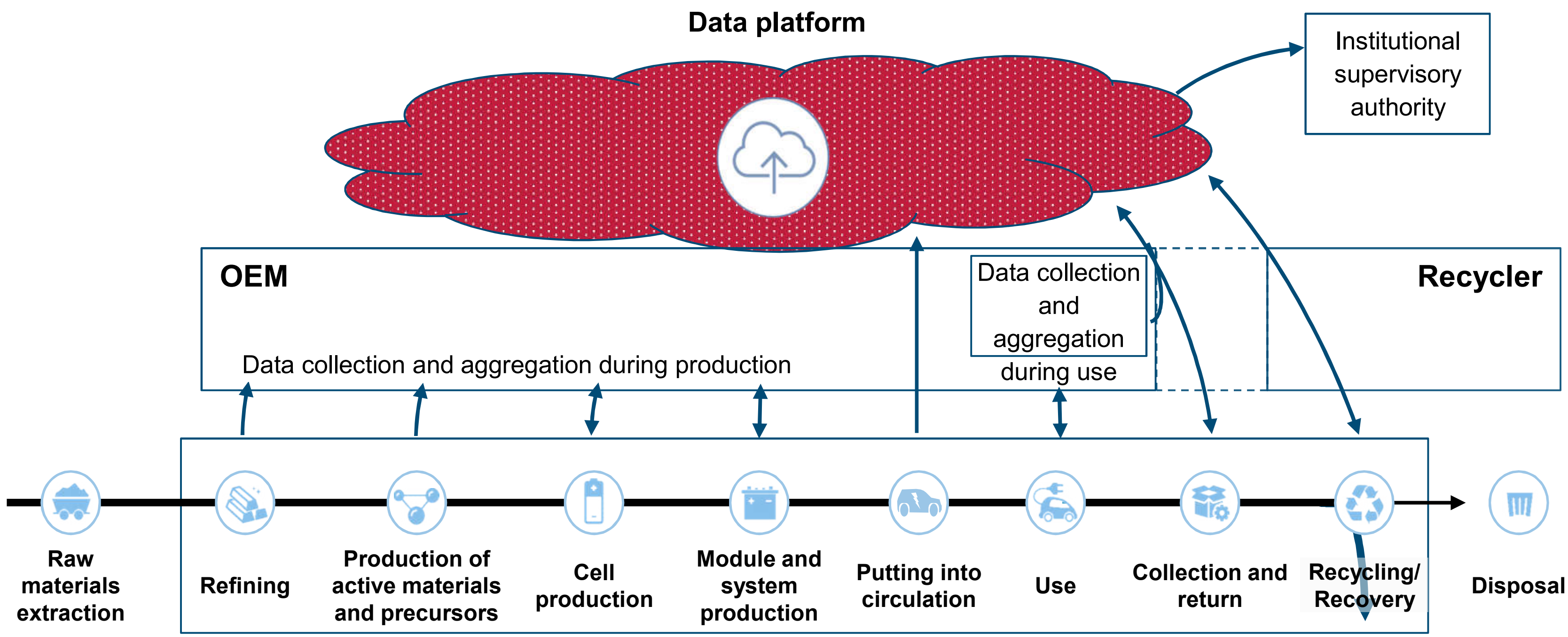
CEID Working Group Traction Batteries: Focus



Source: Circular Economy Initiative Deutschland; based on World Economic Forum 2019

www.circular-economy-initiative.de

Pilot Profile I:
„Knowledge of battery life“

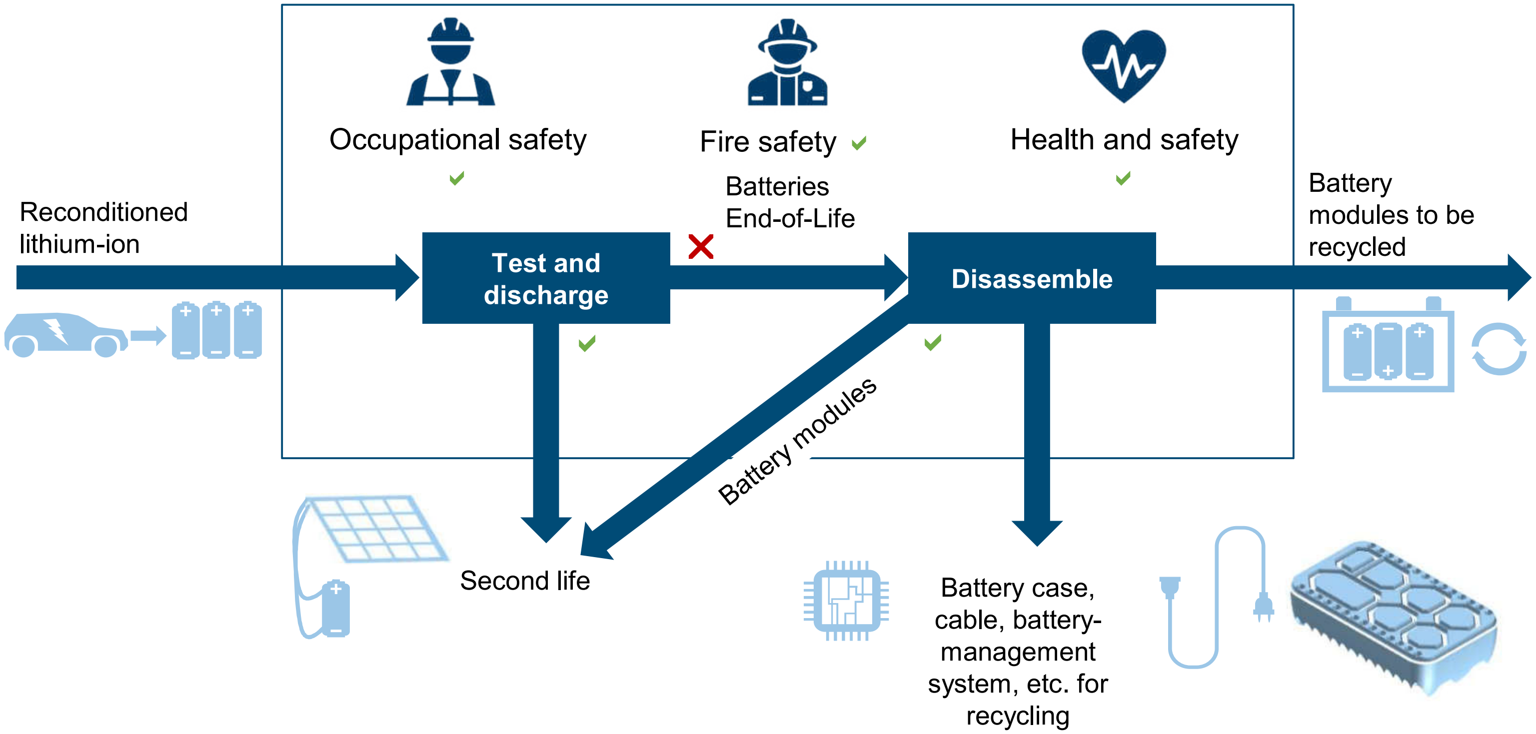


Information flows to promote the recycling of lithium-ion batteries

Source: Circular Economy Initiative Deutschland; based on World Economic Forum 2019

www.circular-economy-initiative.de

Pilot Profile III: „Disassembly network“



Source: Circular Economy Initiative Deutschland; based on World Economic Forum 2019

www.circular-economy-initiative.de

Source: Circular Economy Initiative Deutschland

Central recommendations for action

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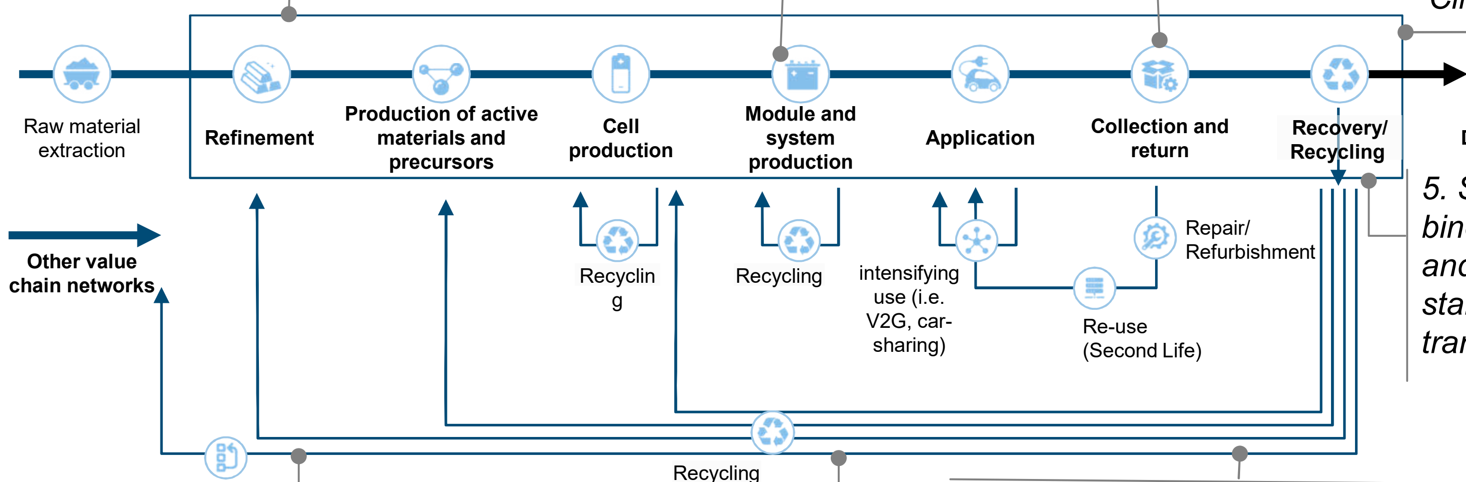
1. Provision of battery data over the entire life cycle of the battery ("battery passport")

2. Design for circularity including modularity, better recyclability and reuse

3. Building physical infratructure – network reverse logistics and disassembly of batteries.

4. Strengthening trans-/ interdisciplinary education, training, and research for Circular Economy



5. Setting ambitious, binding recycling quotas and further definitions and standards in the context of transnational regulation

8. Developing relevant metrics, measurement methods and tools for systemic evaluation of optimal CE.

7. Developing effective incentive systems to ensure transformation

6. Development of digital tools to support optimal end-of-life battery applications (decision support for second use).

www.circular-economy-initiative.de

BATTERY LABFACTORY BRAUNSCHWEIG

Source: Circular Economy Initiative Deutschland; based on World Economic Forum 2019

Recommendation of recovery rates

Circular Economy Initiative Deutschland

EU directive (proposal)

Material	Recommended Recovery rates*		EU directive (proposal)	
	2025 – binding	2030 – to be aspired to***, ****	2025	2030
Total battery**	60 %	70 %	65 %	70%
Lithium	50 %	85 %	35 %	70 %
Cobalt	85 %	90 %	90 %	95 %
Nickel	85 %	90 %	90 %	95 %
Copper	85 %	90 %	90 %	95 %
Steel	90 %	95 %	-	-
Aluminum (without Al foil)	90 %	95 %	-	-

Source: Circular Economy Initiative Deutschland; based on World Economic Forum 2019

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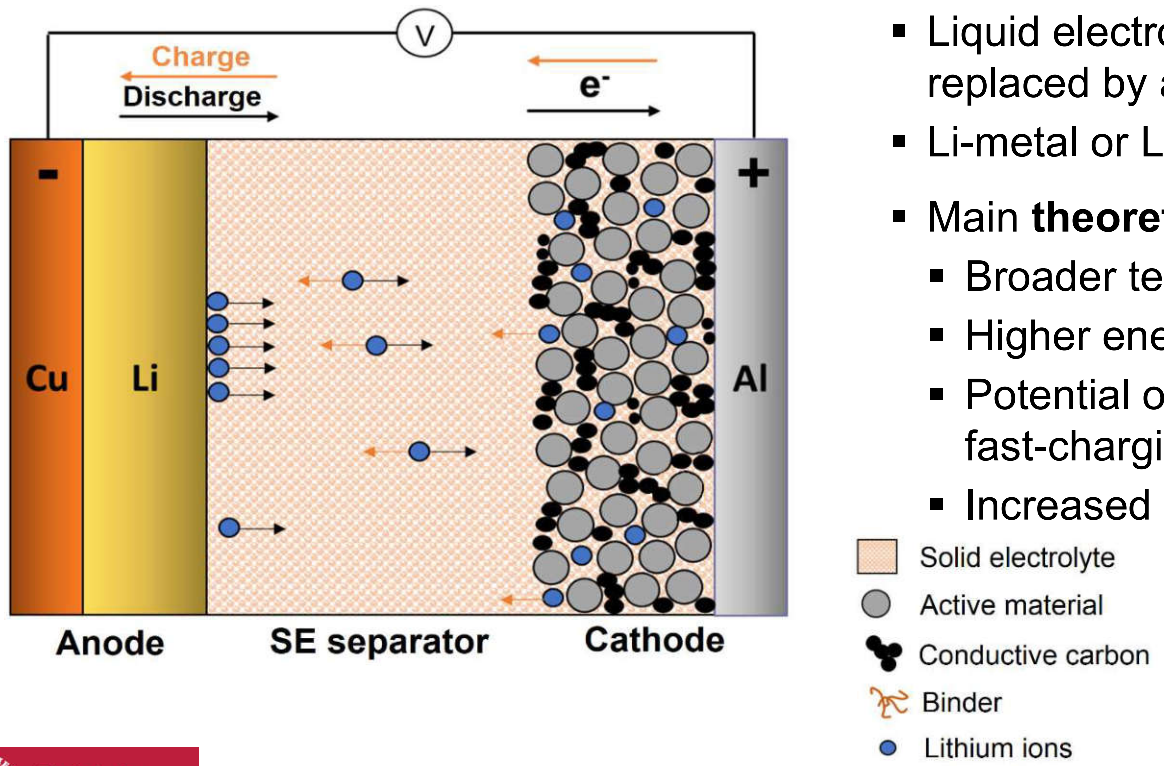
Content

Lithium-ion based all-solid-state-battery - basics



- Liquid electrolyte and porous separator are replaced by a solid electrolyte
- Li-metal or Li-free anode
- Main **theoretical/potential advantages**:
  - Broader temperature window
  - Higher energy density potential (Wh/L)
  - Potential of higher ionic conductivity for fast-charging capability
  - Increased safety

Performance potential of all solid state batteries

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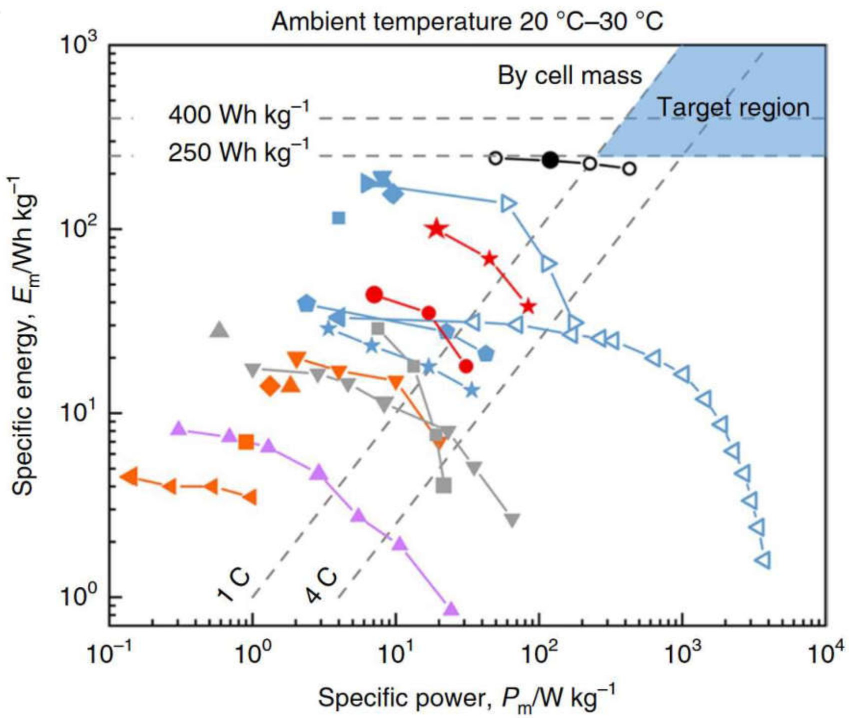

[1]

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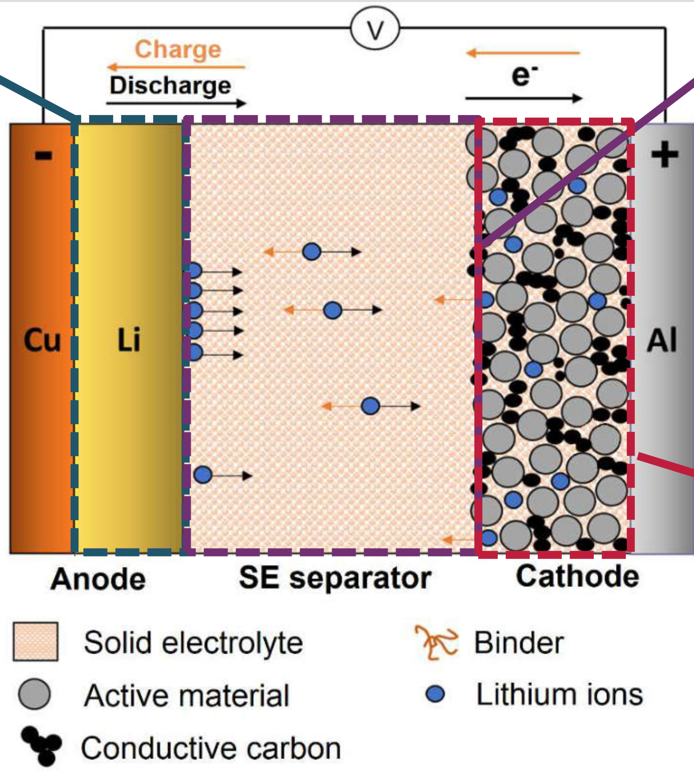
[1] S. Randau, D. A. Weber, O. Kötz, R. Koerver, P. Braun, A. Weber, E. Iver-Tiffée, T. Adermann, J. Kulisch, W. Zeier, F. H. Richter, and J. Janek, “Benchmarking the performance of all-solid-state lithium batteries” *Nat. Energy* **5**, S. 259-270, 2020.

Challenges of high-energy ASSB

Li-metal anode
- Thin (10 µm) for opt. energy density
- High surface area for good discharge rate
- Compensation for volume expansion
- Prevention of Li-dendrite formation



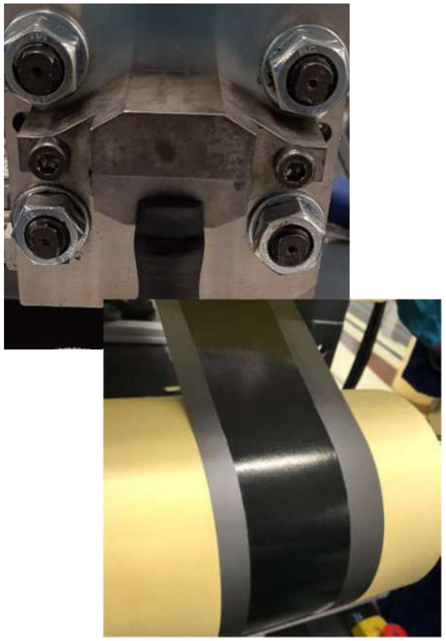
Separator
- Electrochemically stable against Li-metal
- High ionic conductivity
- Mechanically stable against Li-dendrites
- Thin enough for high energy density

Cathode challenges:
- Volume expansion of active material
- Electrical and ionic percolation
- Interface resistances (ionic and electric phases)

Production of solid state batteries

Challenges:

- Individual processing routes required for different solid electrolytes
  - Polymers: mechanical and thermal degradation of polymers limits processing windows for dispersion and extrusion
  - Sulfides: processing sensitive to water/ various solvents
  - Oxides: thermal processing window exceeds degradation threshold of active materials, conductivity decreased with decreasing sintering temperature
- Lithium-anode production is demanding and requires novel processing techniques



Solvent free production chains of polymer based composite cathodes for solid state batteries

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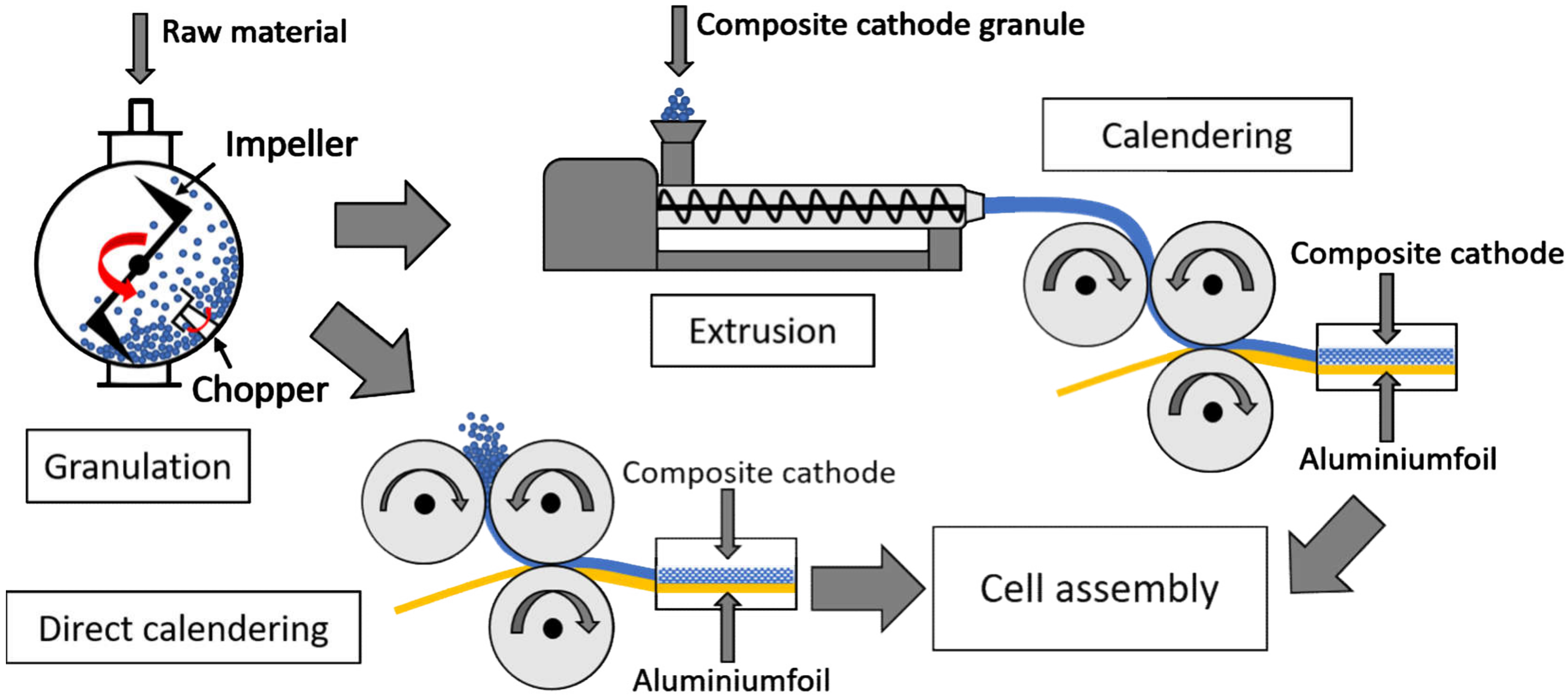

Electrochemical Performance

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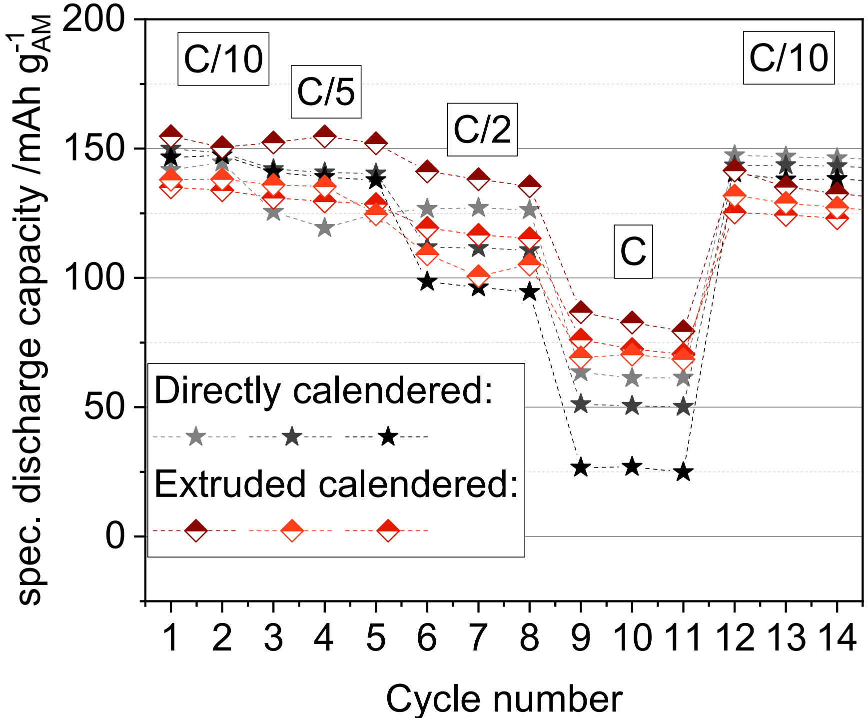

- Polymer electrolyte distribution shows strong influence on ion. conductivity
- Input PEO mol. weight effects viscosity during processing and therefore the carbon black distribution

LH1

Benchmarking the Perfomance

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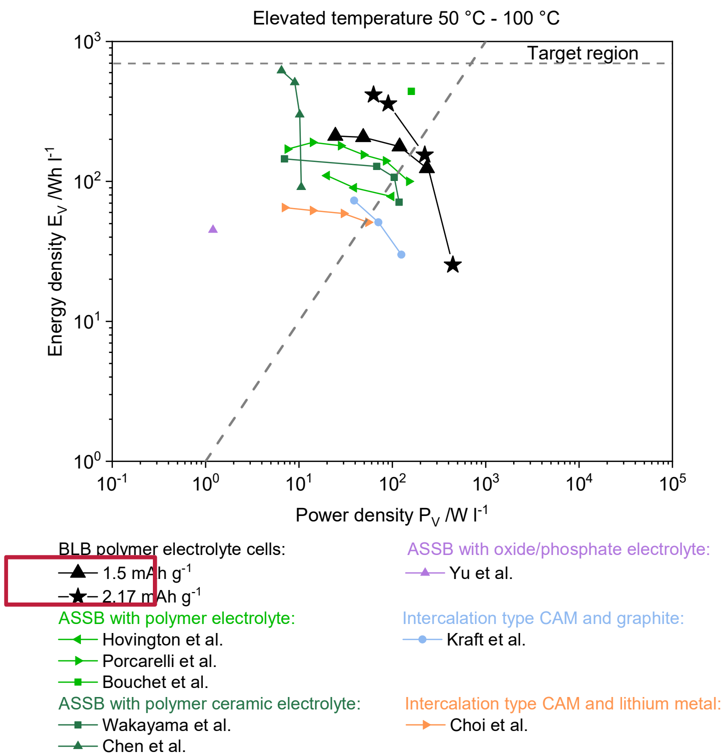

Reach Target region by:

- Increase area capacity and use multy-layer electrodes to reduce transport limitations
- Use hybrid electrolytes with low amount of oxides or sulfides to lower operating temperature and transport limitations
- Enable the use of NCM as cathode active material

Source: S. Randau, Benchmarking the performance of all-solid-state lithium batteries, 2020

Folie 50

LH1 Punkte BLB Zelle dicker
Laura Helmers; 05.10.2020

Circular economy and recycling of solid state batteries

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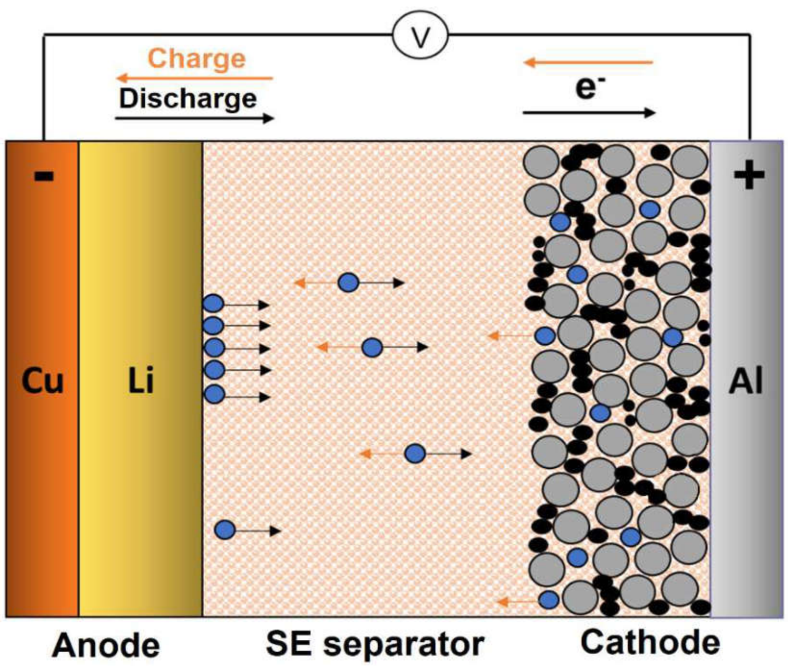

Recycling target:
Economically and ecologically efficient recovery of high quality products or precursors for battery production

Challenges:

- High number of materials used and lower material value reduces ecological incentive and increase the recycling effort
- High safety requirements for the processes due to reactivity of various components (Lithium, sulfide based SE)

Circular economy and recycling of solid state batteries

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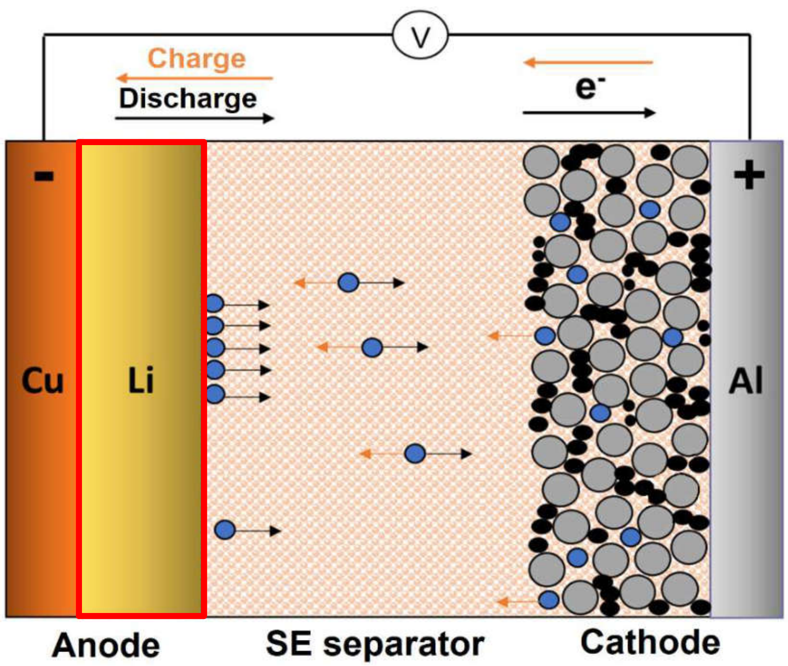

Anode:
Recovery of lithium or lithium salts

Challenges and opportunities:

- Reactivity of lithium with water and air
- ✓ Higher concentration of lithium in SSB
- ✓ Possible solution step to recover lithium salts
- ✓ In aqueous systems, formation of LiOH with release of H2
- ✓ lithum-free anodes lead to simplified recycling due to absence of metallic lithium

Circular economy and recycling of solid state batteries

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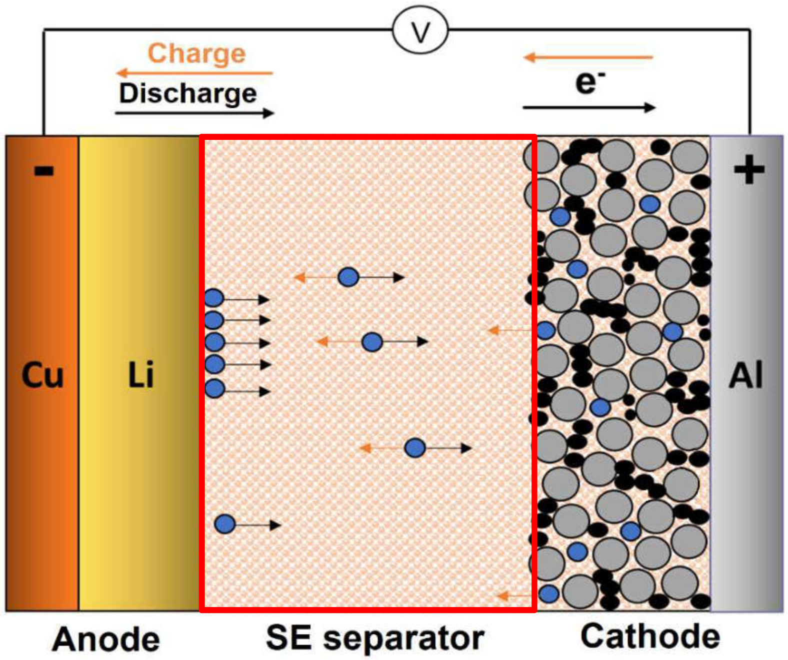

Solid Electrolyte (SE):
Direct Recovery of SE or Recovery of precursors

Challenges and opportunities:

- – Different cell chemistries require different recycling methods
- – Reactivity of sulfide based solid electrolytes
- – Hybrid SSBs increase the recycling effort
- ✓ Direct Recycling methods due to the absence of chemical degradation for oxide based SE
- ✓ Solution Processes for sulfide and polymer based SE

Circular economy and recycling of solid state batteries

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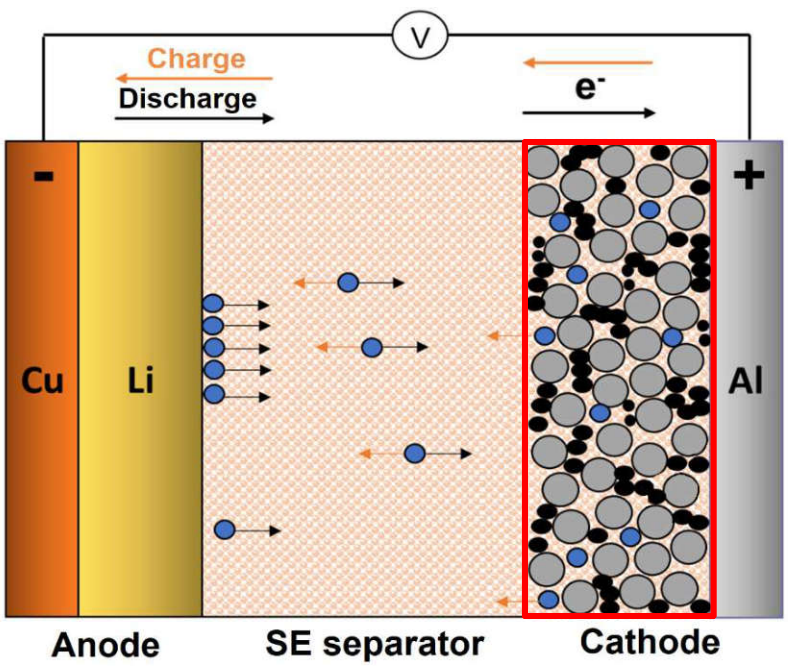

Composite cathode:
Recovery of active material and SE

Challenges and opportunities:

- Selective Separation necessary
- Solid-solid structure makes separation into pure fractions difficult
- Polymer SSB: low material values reduce ecological incentive
- ✓ Hydrometallurgical approaches to recover both, SE and active materials

Content

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Conclusion

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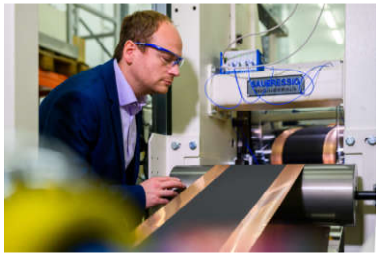
- Sustainable production processes and circluar battery production with closed material cycles are very important for long term success of electro mobility
- Environmental impact of battery systems (e.g. GWP in t CO_2/kWh) must be decreased to reduce distance before EV have a lower GWP than conventional cars
- Internal recycling of production scrap is a very important measure to improve CO2-footpring of cell production beside usage of energy efficient processes and green energy
- Battery materials should be chosen not only regarding their performance, but also regarding the environmental impact
- Solid state batteries have the potential to increase the cell performance further, but will increase the effort for recycling of production scrap and EoL batteries



Activities in Germany

- Development of new recycling and production processes
- Circular economy initiative Deutschland
- International Battery Production Conference

INTERNATIONAL BATTERY PRODUCTION CONFERENCE

1 to 3 November 2021

Thank you very much

.... for the support by

….for the great work of my
PhD-students and co-workers

… for your attention