SCALABLE AND SUSTAINABLE PILOT LINE BASED ON INNOVATIVE MANUFACTURING TECHNOLOGIES TOWARDS THE INDUSTRIALISATION OF SOLID-STATE BATTERIES FOR THE AUTOMOTIVE SECTOR

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SOLiD4B

Going solid for safer batteries

Funded by the European Union

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General Overview

of SPINMATE Project

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General Overview

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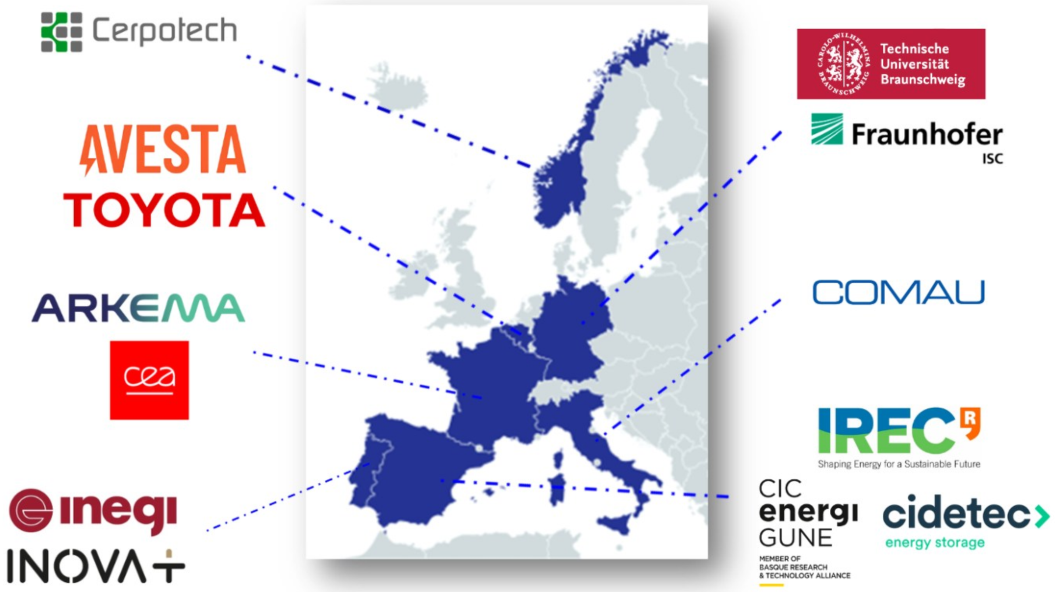
- 13 Partners from 7 European Countries
  - ✓ Resources required to secure access to **safer, durable, cost-competitive, sustainable, and higher-performance** batteries for **the EV sector**
  - ✓ Cover the whole value chain of the **SSB industry**
- 48-month project: from 01/08/2022 to 31/07/2026
- Total Budget of 6,976,600 EUR
- 9 Work Packages



Key Performance Indicators (KPIs)

Based on the Grant Agreement (pages 111-112)

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Materials/battery components

Expected KPIs of **Solid electrolyte:** ionic conductivity of around 10^{-3} S cm^{-1} at RT, performances kept up to 80 °C and no flammability under 130 °C, electrochemical stability >4.4 V, and no dendrite formation during plating/stripping experiments in Li symmetric cells; **Li metal anode (on Cu with a protection layer):** specific capacity of 3860 mAh g^{-1}, Coulombic efficiency >99.5%, cycling of >500 cycles at C rates >1C, and ΔV <100-200 mV and current density >1mA cm^{-2} during stripping and plating; **NMC811-based cathode:** discharge capacity of 200 mAh g^{-1}, average operating voltage of 3.6 V vs Li/Li^{+} and loading capacity of >4 mAh cm^{-2}.

Battery cell (10 Ah) performances

Expected KPIs for the **10 Ah Gen 4b SSB cells** are gravimetric and volume energy density of at least 450 Wh/kg and 1,200 Wh/l, respectively; Cycle life up to 3,000 (70% DoD); ability to operate at charging rate of 0.5-1 C (continuous) and 3-5 C during 5 seconds; Low-cost configuration <75 euro/kWh by the end of the project based on mass production assumptions and raw materials global markets.

Additionally, the expected battery performance KPIs, the number of cells for testing, and other essential requirements have also been available in the **SPINMATE Deliverable 2.1** (the public version is available here https://doi.org/10.5281/zenodo.10818344).

Other than that, it will follow the milestones.

There are only the collective KPIs available for the SPINMATE project, and segmented targets per WPs based on milestones.

Progress Results

of the SPINMATE Project from M1 to M46

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NMC811 Development in the SPINMATE Project

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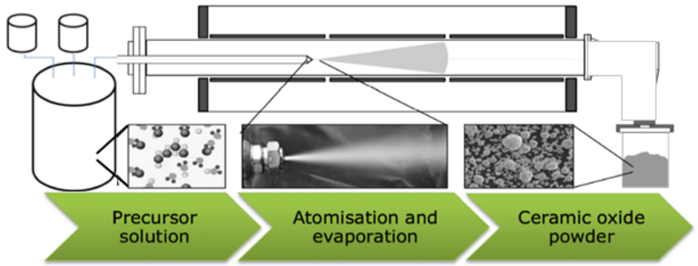
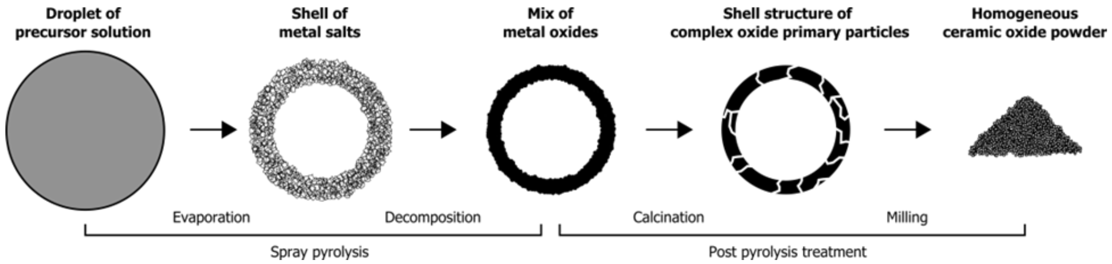
Spray pyrolysis process - Overview



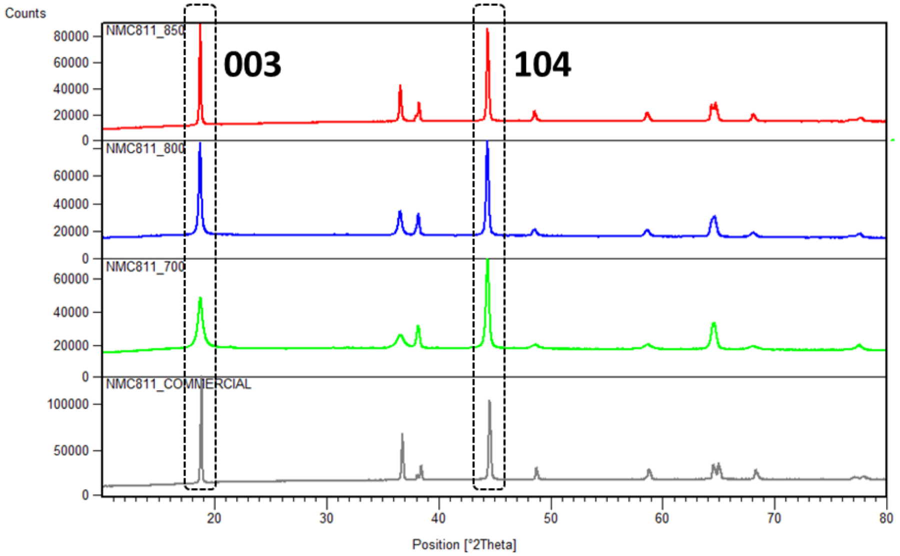
Continuous process with spraying of solution and collecting raw powder.



Complete process chain from feedstock chemicals to customized powders:

1) Solution, 2) continuous spray pyrolysis, 3) calcination, and 4) milling.

Cation Mixing (Li^+/Ni^{2+})
Ratio I(003)/I(104) ≥ 1.2



	Ratio I(003)/I(104)
MTI	1.6
NMC 850	0.9
NMC 800	0.8
NMC 700	0.5

NMC811 Development in the SPINMATE Project

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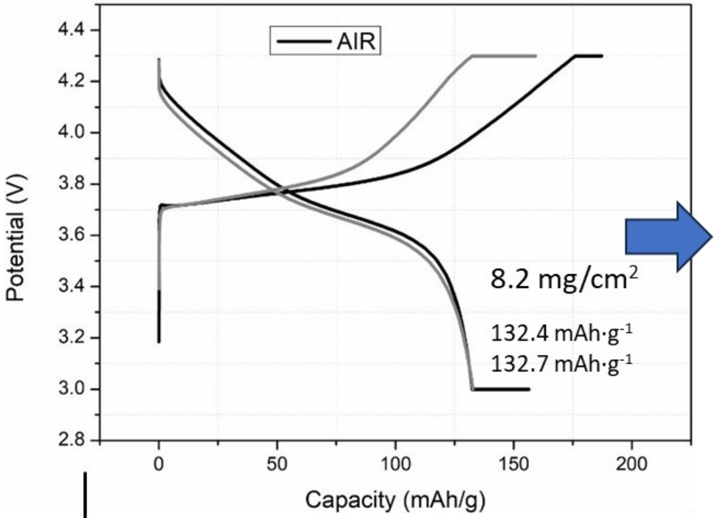
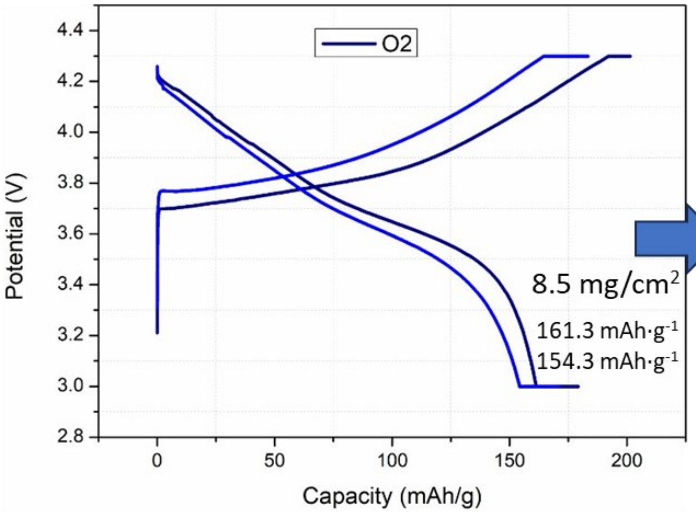
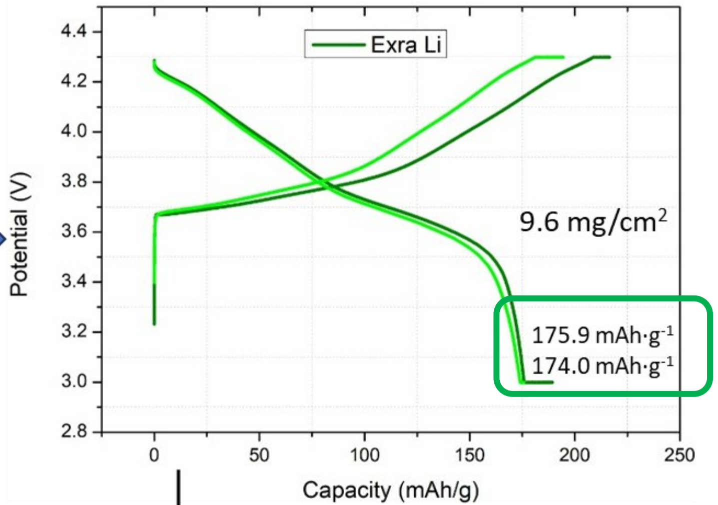
NMC811 calcined in air



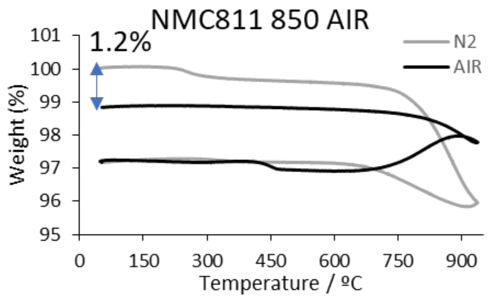
NMC811 calcined in O_2



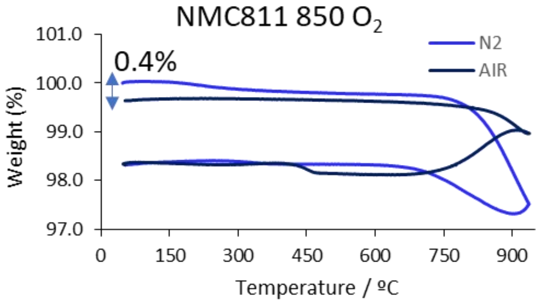
NMC811 calcined in O_2
+ 10% Extra Li Precursors



TGA
CO_3^{2-} QUANTIFICATION



I(003)/I(104) ≤ 1.2



I(003)/I(104) ≥ 1.2

I(003)/I(104) ≥ 1.2

ICP-OES	Co (0.1)	Mn (0.1)	Li (1.0)	Ni (0.8)
NMC811 850-6h AIR	0.106	0.111	0.914	0.800
NMC811 850-6h O_2	0.107	0.109	0.908	0.800
NMC811-10Li 850-12h O_2	0.111	0.116	1.033	0.800

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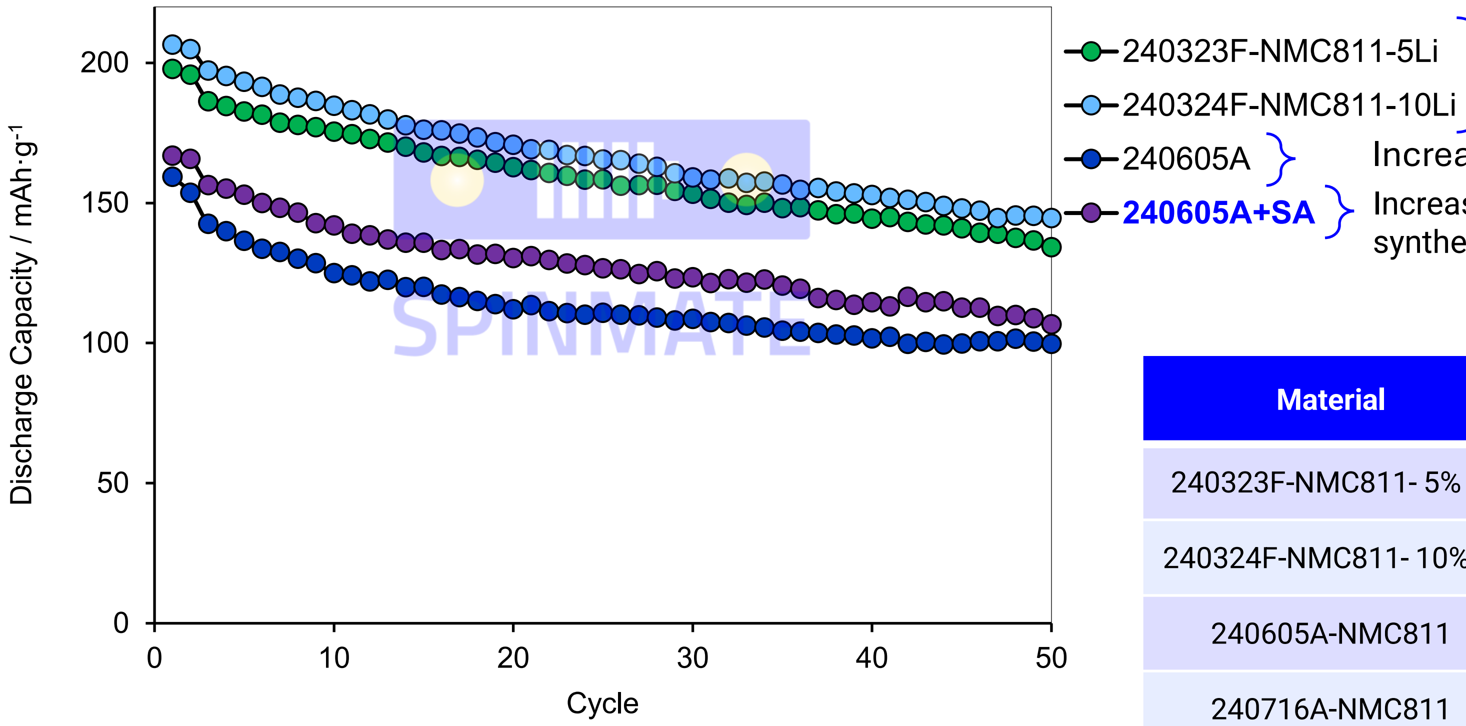
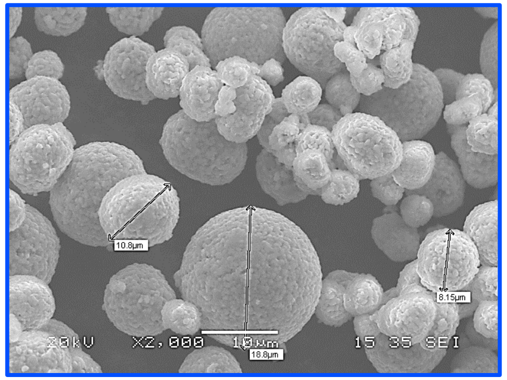


Small Powder Bed + 850 ºC – 12h in AIR

Increased Powder (~200 g) + 850 ºC – 16h in AIR

Increased Powder (~200 g) + 850 °C – 20h in AIR + 700 °C-6h in synthetic air

	ICP				XRD	
Material	**Co**	**Mn**	**Li**	**Ni**	**I_{003}/I_{104}**	**Li/Ni Disorder**
240323F-NMC811- 5% Li	-1.1%	-1.0%	-3.8%	0.8%	1.38	4.2%
240324F-NMC811- 10% Li	-1.7%	-1.5%	0.5%	0.3%	1.71	3.4%
240605A-NMC811	-0.9%	-1.7%	5.2%	-0.4%	1.24	8.4%
240716A-NMC811	0.6%	-2.2%	5.8%	-0.7%	1.28	6.6%
240716B-NMC811	0.8%	-2.2%	3.0%	-0.3%	1.40	5.9%



- ✓ Stoichiometry (+10% Li, NMC ratio / Spraying agent)
- ✓ Calcination time → 20h
- ✓ Powder bed → ~1.0-1.2 cm

Li-M on Cu Development in the SPINMATE Project

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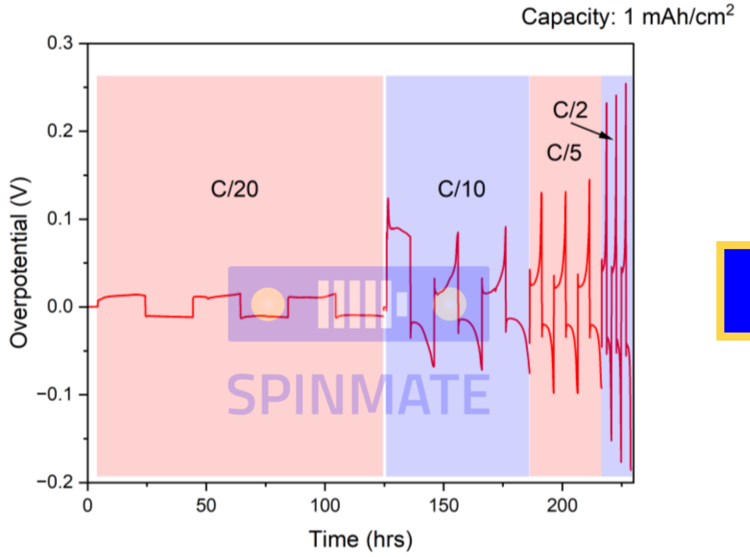
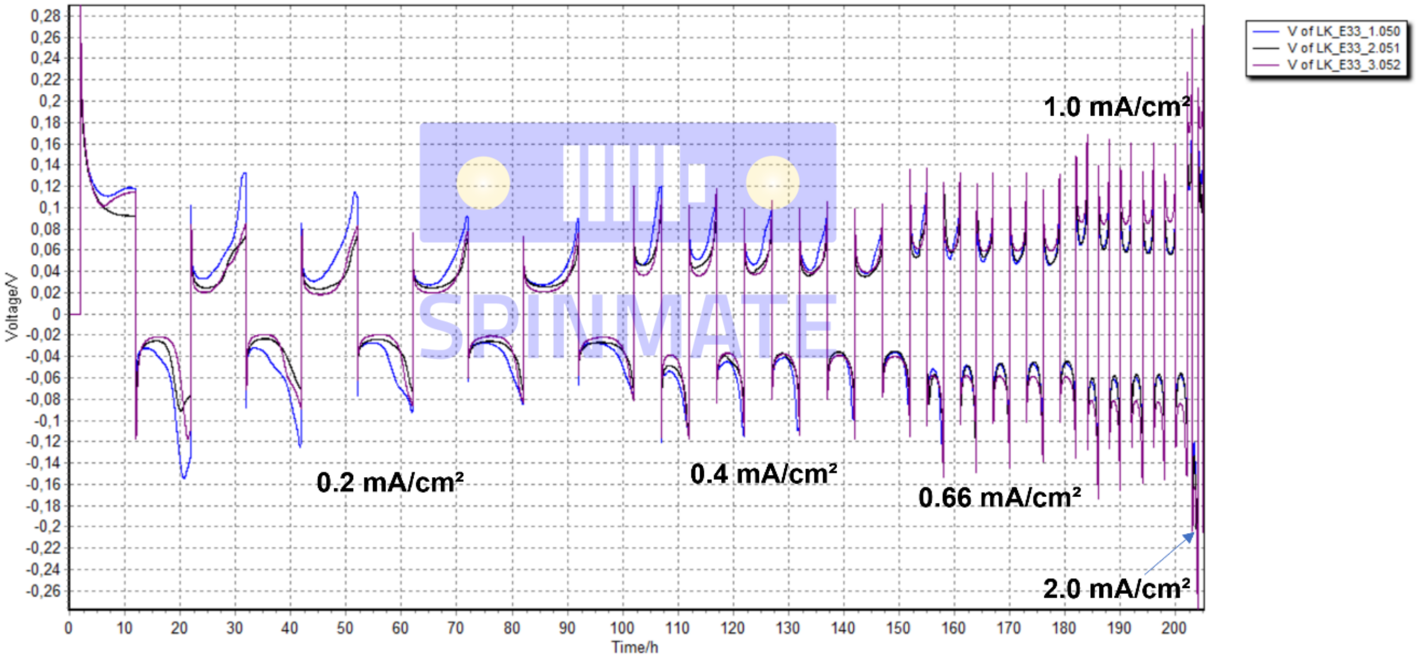
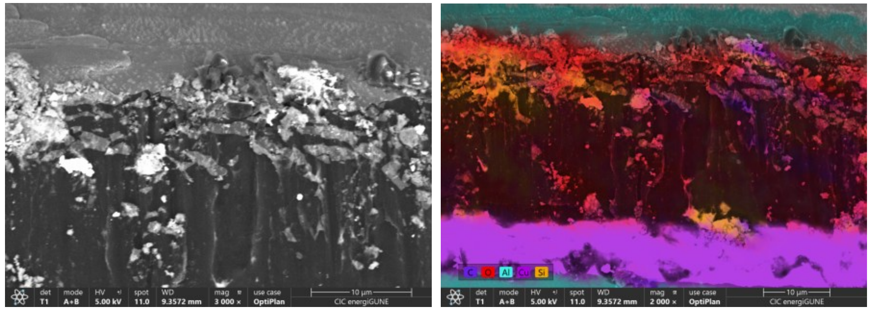
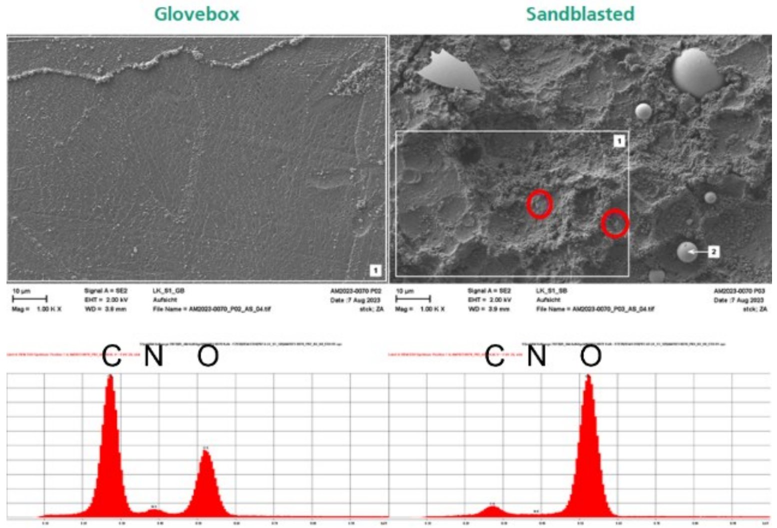


- Mechanical cleaning of Li surface
- Automated sandblasting drive
- Parameter optimization
- Symmetrical Li/Li cells w/ fluid electrolyte



Al_2O_3-coated Li – Cross section





SPE Development in the SPINMATE Project

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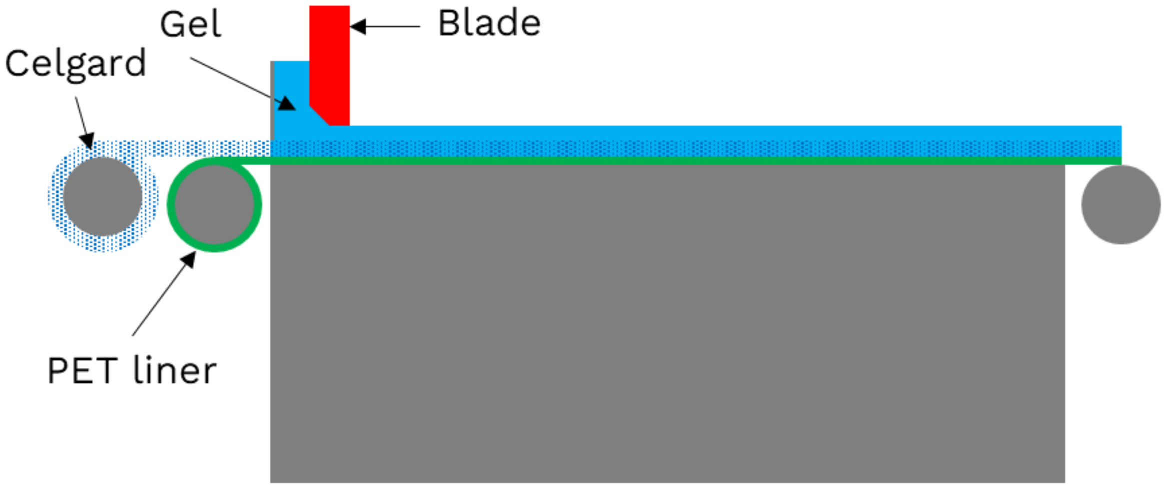
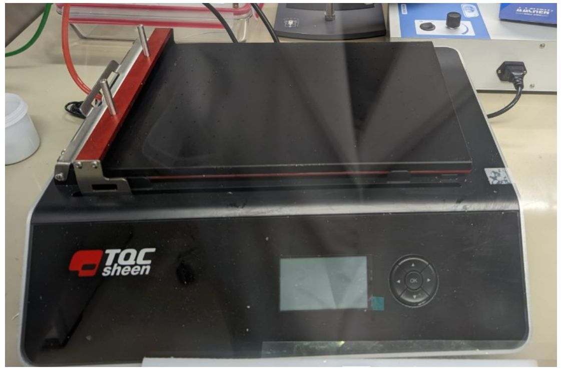
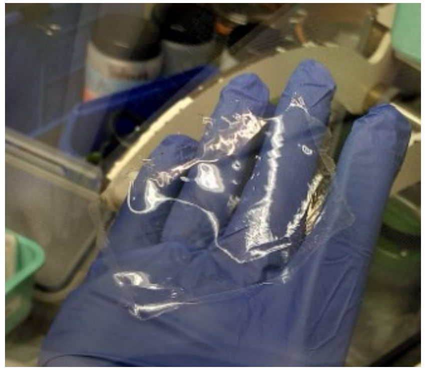


Processing

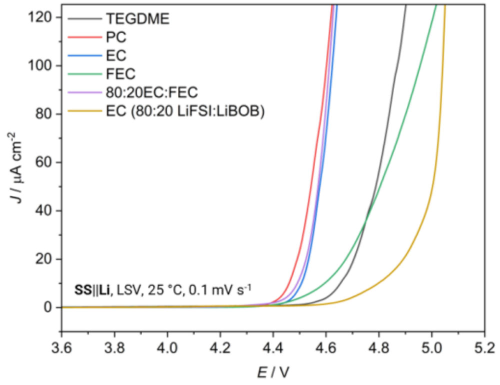
Prepare acetone solution (2 g in 5 mL) ⇨ Casting (200 cm^2, 250 µm gap) ⇨ Drying (RT, 500 mbar, 16 h)



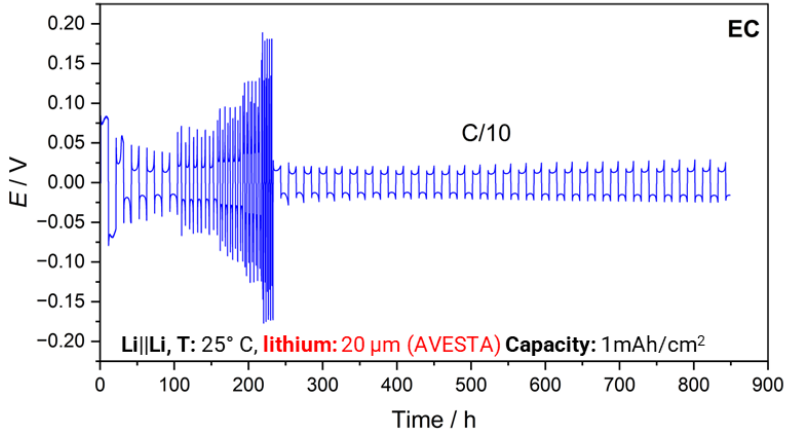


Plasticizer	$\sigma_{25\,°C}$ / S cm^{-1}
TEGDME	3.8 x 10^{-4}
PC	5.4 x 10^{-4}
EC	7.8 x 10^{-4}
FEC	5.3 x 10^{-4}

Membrane with **EC** have the highest ionic conductivity…



- PC, EC show the worst oxidative stability
  - ➢ E_{ox} ~ 4.3 V
- Addition of LiBOB improves the oxidative stability
  - ➢ E_{ox} ~ 4.5 V



… and the best plating-stripping performance

Dry Process Trials for Cathode Making

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- Polymers: PVDF-HFP, PEO
- Active material: NMC811
- Conductive agent: C45
- Conductive salt: LiTFSI
- Ionic liquid (IL): $PYR_{14}TFSI$

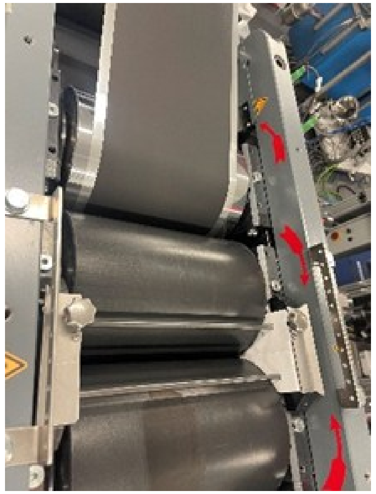
- Mixing all material in 3D-tumbling mixer
- Producing granulates in kneader (30 min, 120 rpm, 120 °C)

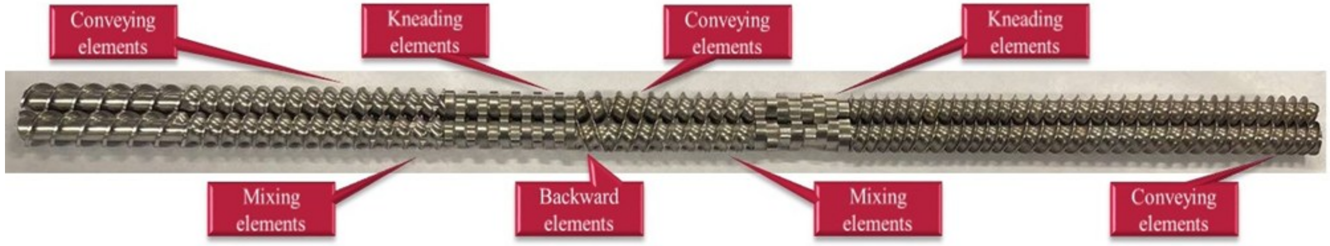
- Calendering and coating on C-coated Al-foil (0.5 m/min, 120 °C)

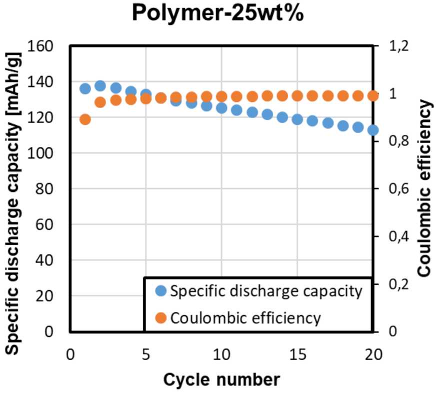
Poro SEM TPR Adhesion

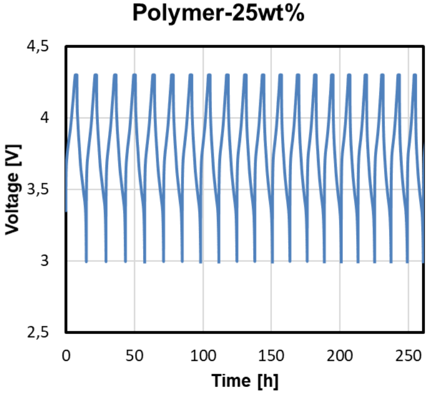
- Producing cell and cycling (0.1C, 80 °C, ~2 mg_{AM}/cm^2)

Cycling



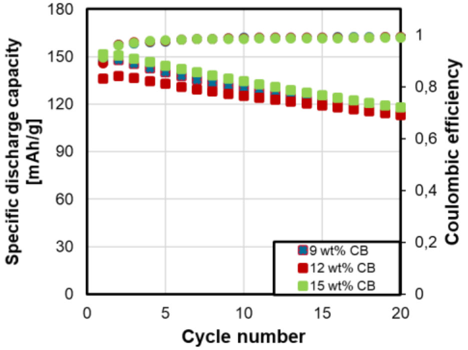


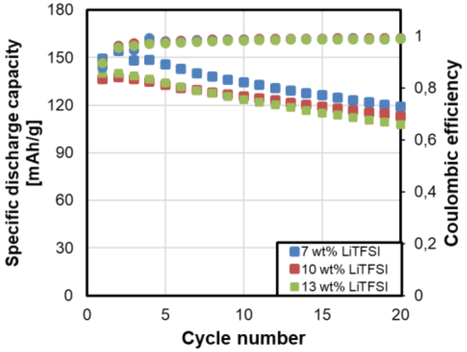


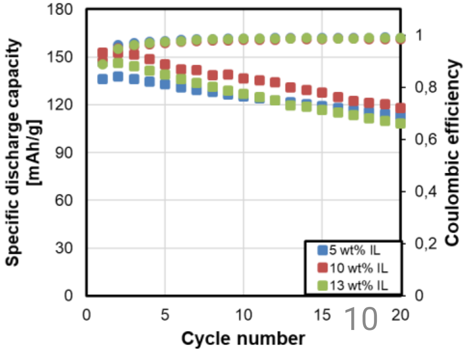


Cathode composed of 25wt% showed the best result. So further investigation was done.

Best performance based on cycling data: 15 wt% CB







Data-Driven Approach for Process Optimisation

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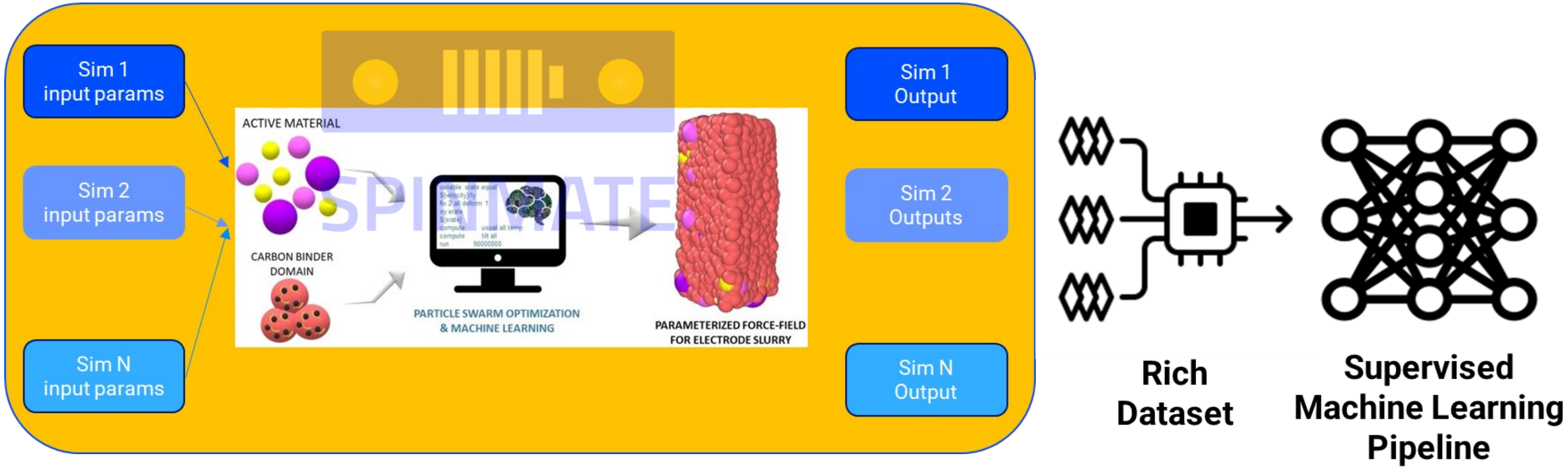
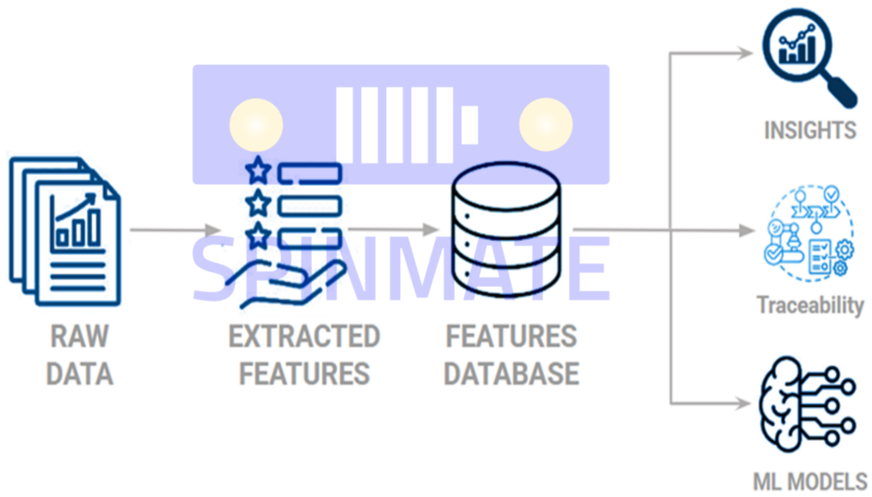
Cathode process modelling:





SPINMATE analytics tool to address cell testing data challenges:

- Unified processing of data from diverse partners and instruments.
- Extraction of a feature store from raw data for varied applications.
- Streamlining data analysis, allowing experts to focus on interpreting insights rather than manually comparing disparate files.
- Creation of a comprehensive dataset to enable advanced Machine Learning models.

Development of the Cell-Making Equipments

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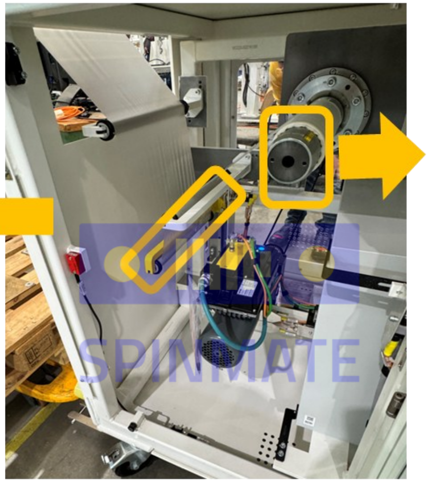
BOPP Rewinder

Feeding unit: BOPP as input from the cutting machine

Control panel

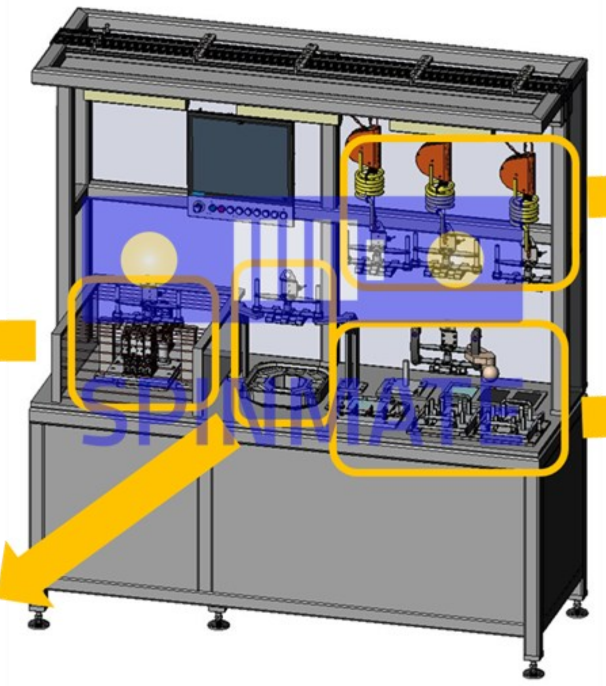
Tension roller: it is lifted down when BOPP is released. Motor is activated accordingly for rewinding.



Block Shaft: it is responsible for rewinding the BOPP film, following the motor movement.

Pick and Place Cell Assembly

Stacking stage: with proper fingers to assure to maintain the alignment among layers without damaging the surface of the materials.



Vacuum pads: for the 3 materials; different pads to avoid contamination and with characteristics tailored to handle the different materials.

Magazines: one per each material.

Vision system: controls the stacking stage.

Development of the Cell Testing Tool – Pressure Jigs

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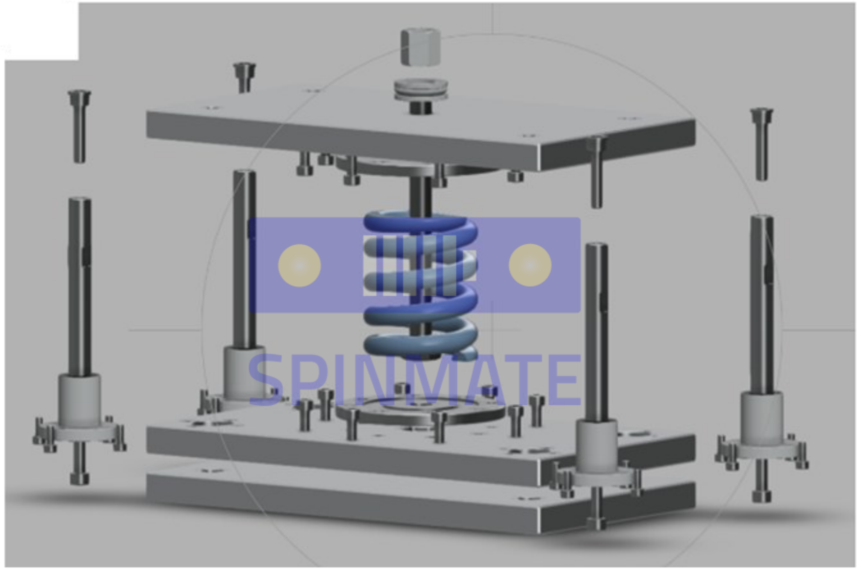


Improvements:

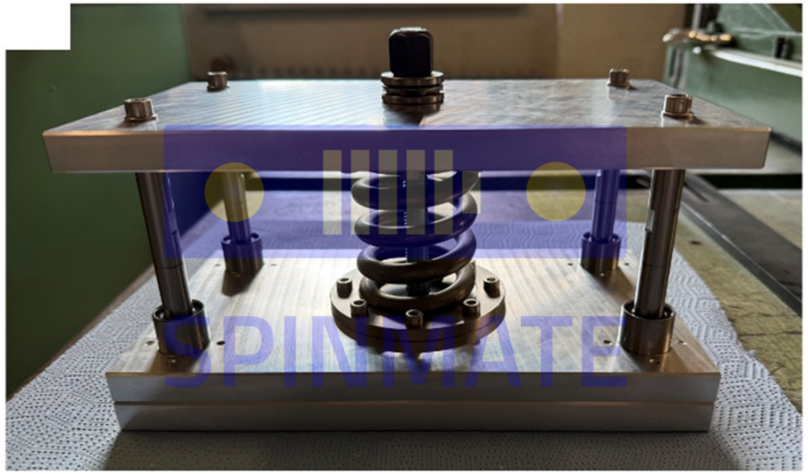
- *Thicker plates (no bending)*
- *Linear ball bearings (no tilting)*
- *Polished surfaces*
- *Larger spacers (adjust pressure)*

1 Ah jig

Maximum cell size: ~100 x 90 mm

-> **35** (incl. one prototype) of the small 1 Ah jigs have been produced and delivered to the consortium

10 Ah jig



Maximum cell size: ~175 x 140 mm

-> **8** (incl. one prototype) of the 10 Ah jigs have been produced and delivered to the consortium

Pouch Cell Testing (1 Ah)

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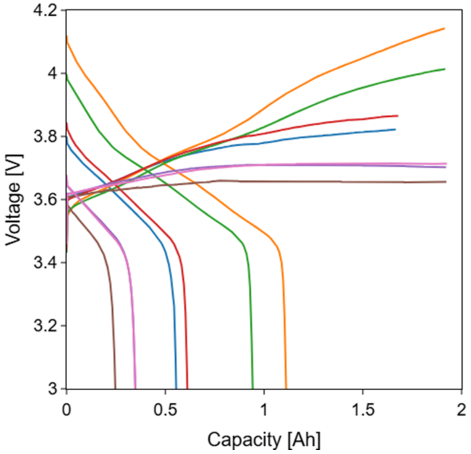
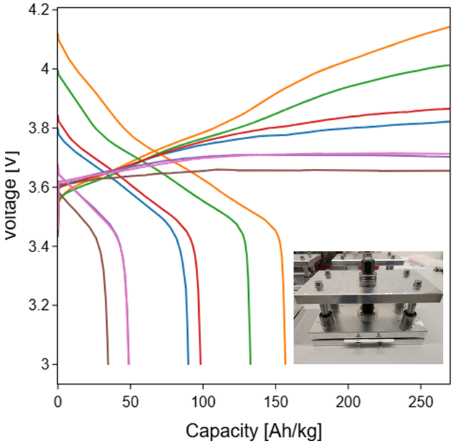
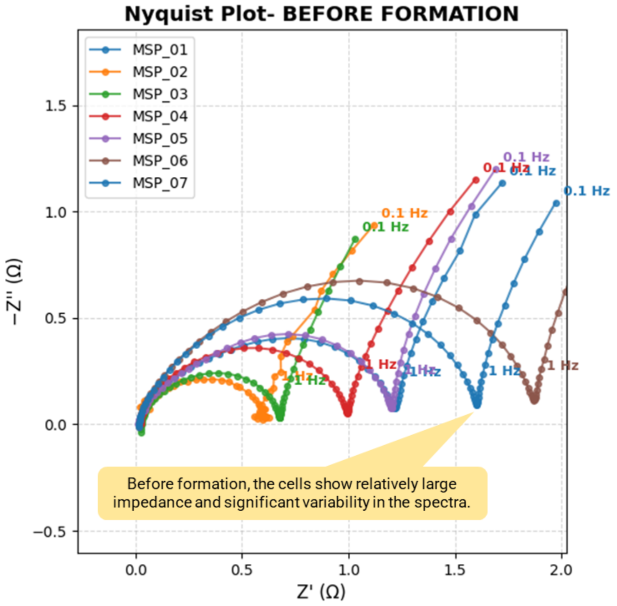
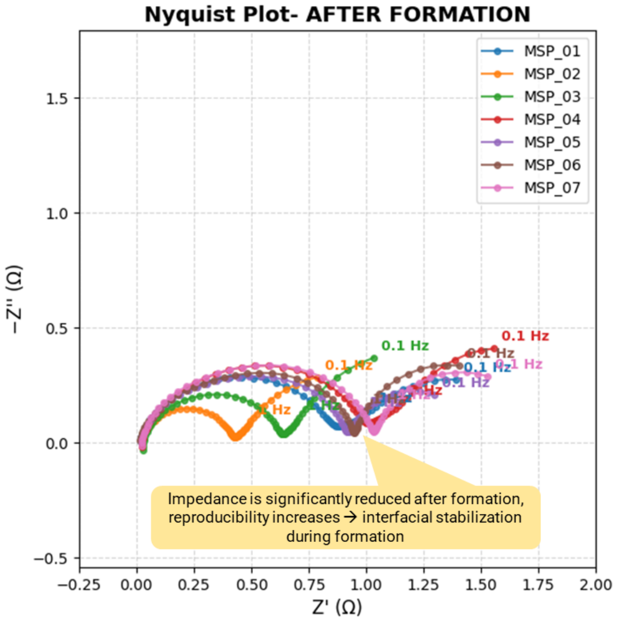
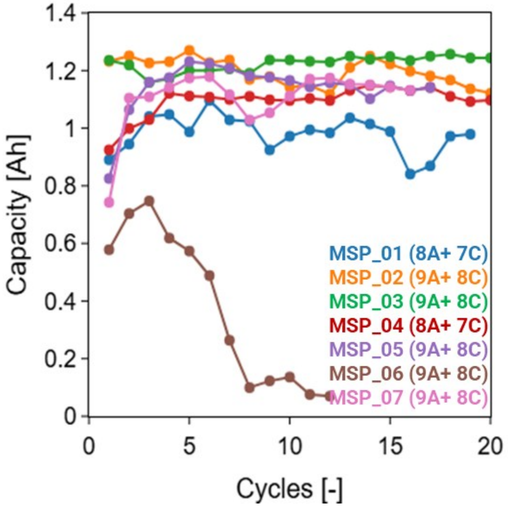


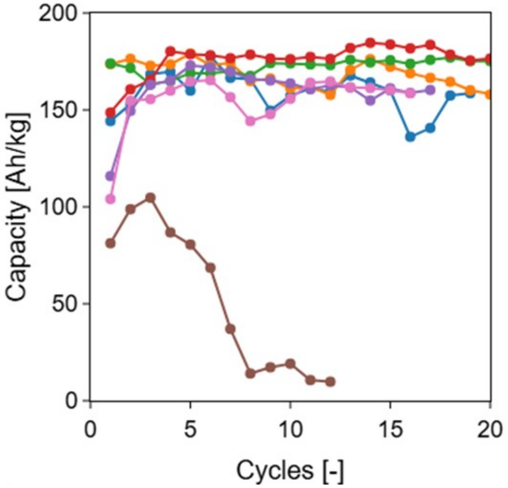


1x Formation cycle
0.05C | 0.05D, V=(2.8 – 4.2 V)
T= 45ºC, p = 300 kPa









- The formation cycle improves the electrodes - electrolyte interfacial contact.
- This may be explained by a mechanical accommodation of the polymer electrolyte.
- A stabilisation of the Li metal – SPE electrolyte interface may also contribute to the impedance decrease

Post-Mortem Analysis

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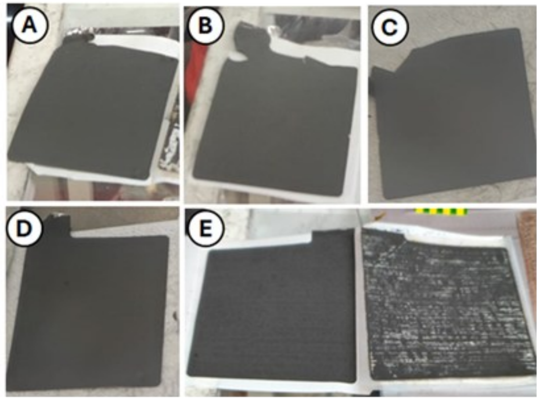
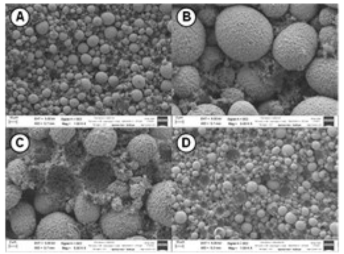
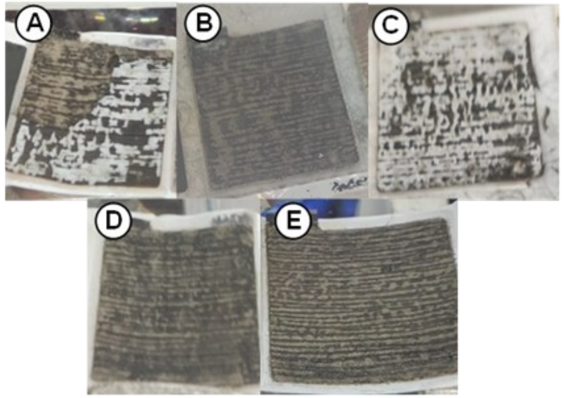
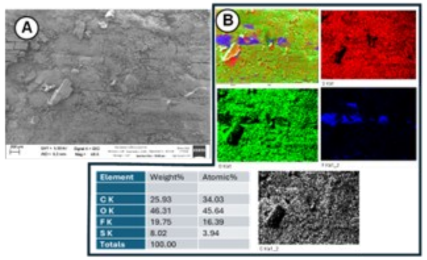
Cathode





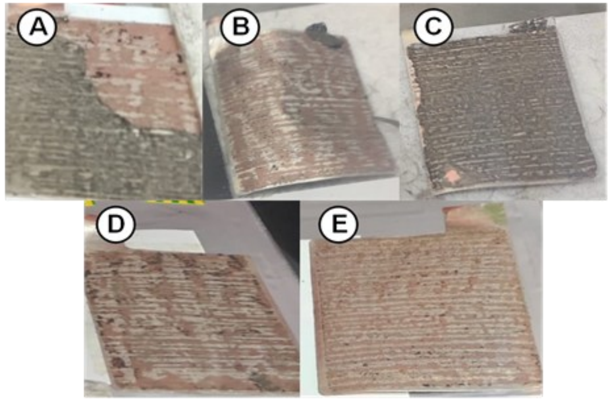
SPE

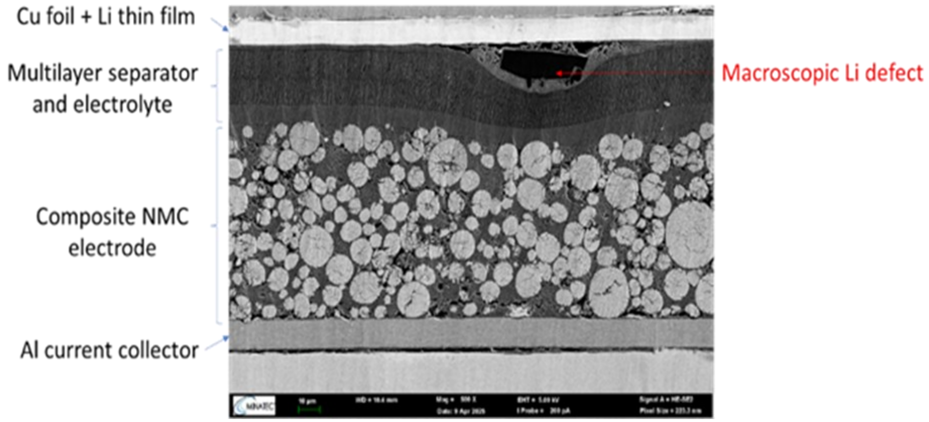




Element	Weight%	Atomic%
C K	25.93	34.03
O K	46.31	45.64
F K	19.75	16.39
S K	8.02	3.94
Totals	100.00	

Anode





- **Post-mortem analysis of cells:**
  - Disassembling
  - Macroscopic observations
  - SEM (Scanning Electron Microscopy) images
  - Material composition detailed analysis
  - Electrochemical characterisation of the different cell components (separately, and in combination)

Safety Analysis

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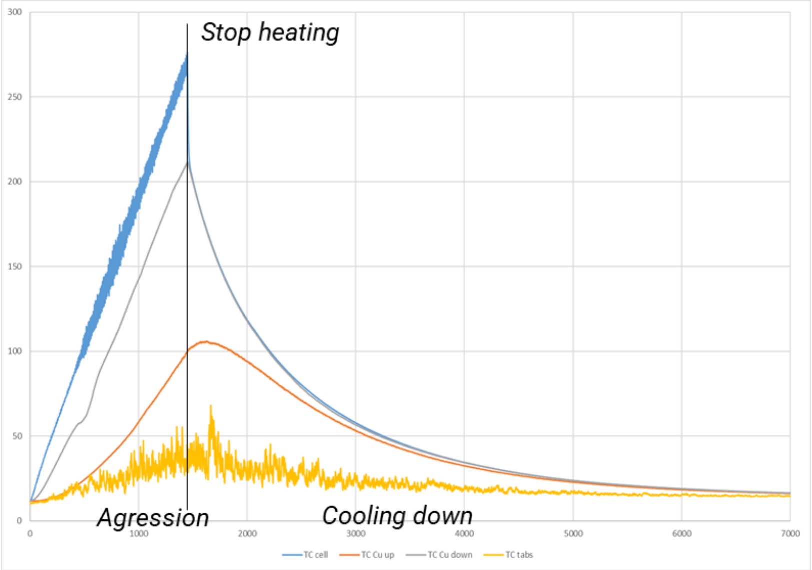
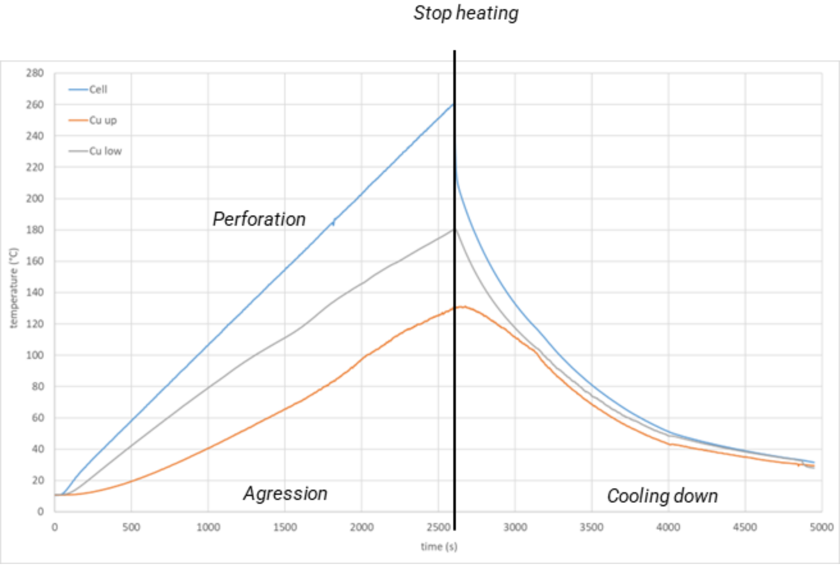


Fresh cell

➔ No visible thermal runaway

➔ Some observation, however: mini-casing perforations, small fumes.

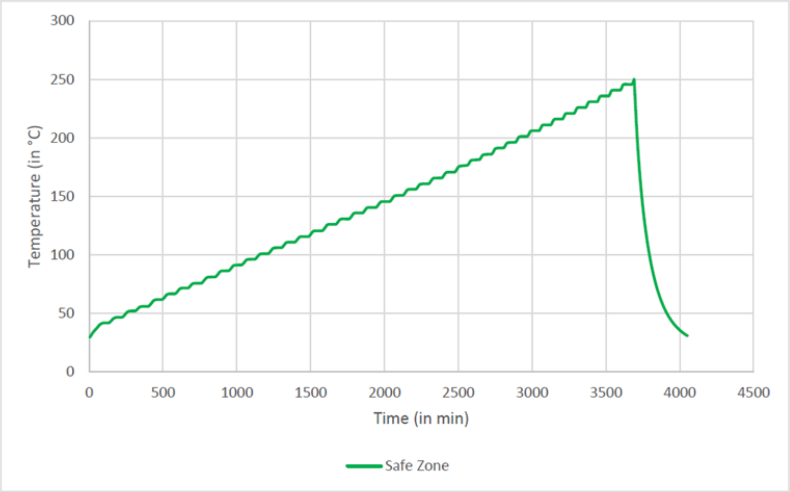


Aged cell

➔ No visible thermal runaway

➔ Some observation, however: mini-casing perforation, small fumes.

Cell temperature during ARC test:



Accelerating Rate Calorimeter test

➔ No visible thermal runaway

➔ The varnish on the pouch envelope has been melted because of the heat, but this is not representative of any flammable material

Preliminary Recycling Activity

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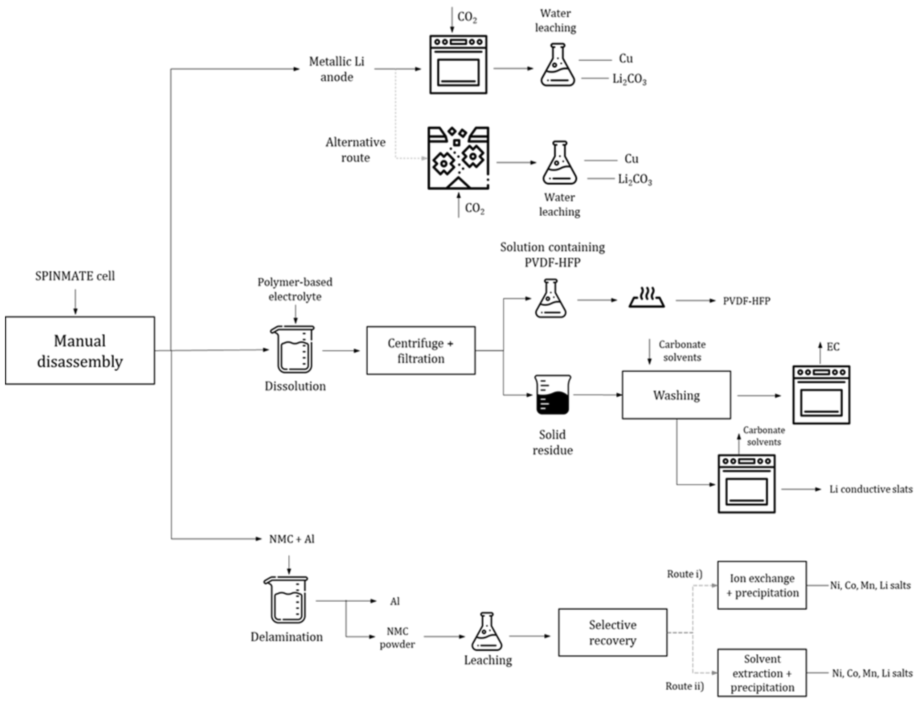
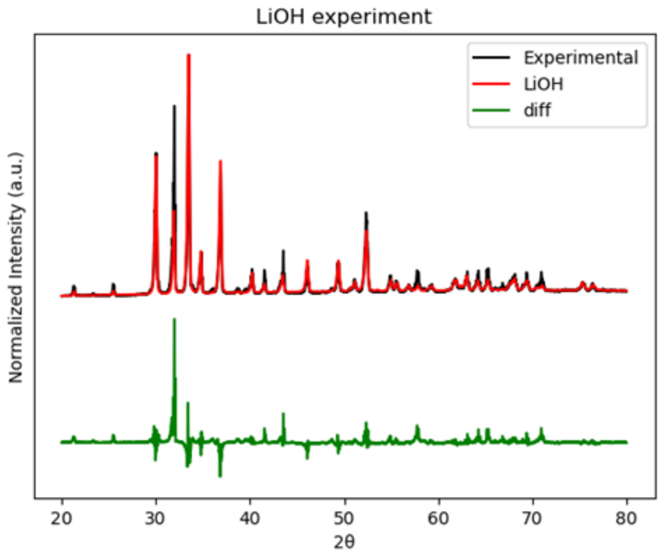
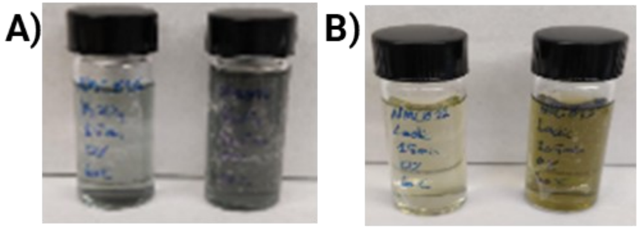
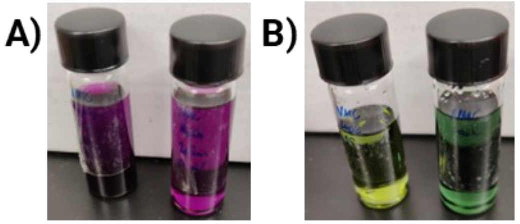




XRD of initial experimental LiOH compared with LiOH monohydrate. Impurities, either as unknown elements or crystalline impurities, are observed



NMC811 leaching at 60C, characterization is ongoing
A) H2SO4, 0 vol% H2O2, 15 min (left), 105 min (right)
B) Lactic, 0 vol% H2O2, 15 min (left), 105 min (right)



NMC811 leaching at 90C, characterization is ongoing
A) H2SO4, 0 vol% H2O2, 15 min (left), 105 min (right)
B) Lactic, 0 vol% H2O2, 15 min (left), 105 min (right)

Transition metals color:

- Li – transparent
- Ni – green
- Mn – pink/pink, brown, purple, green
- Co - pink

Preliminary Environmental & Cost Assessment Activity

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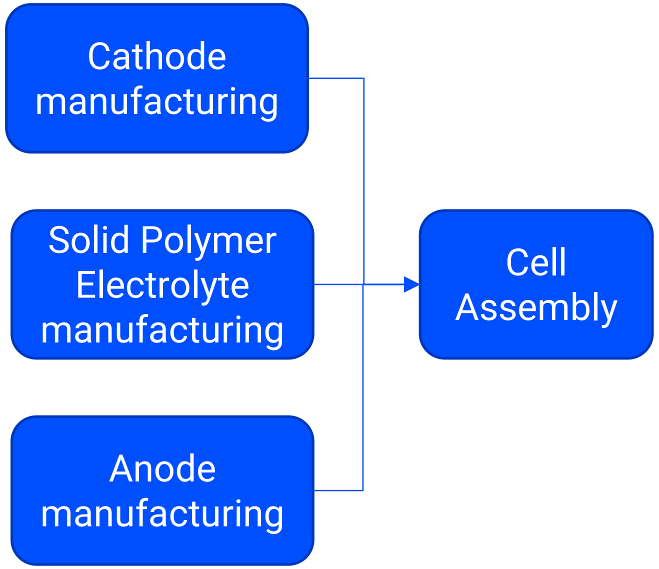
Case study: For 1 Monolayer Cell Battery Manufacturing Breakdown

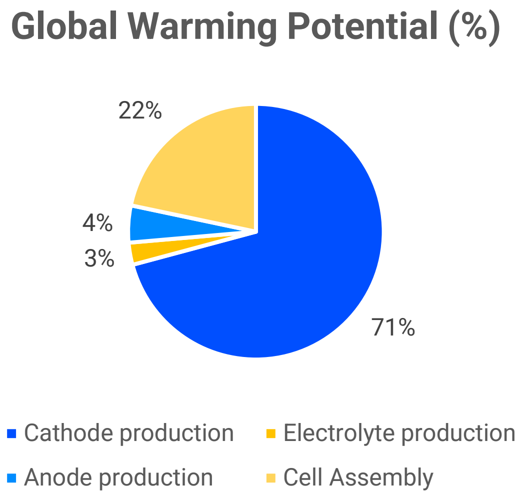


Boundaries:
Environmental: Cradle-to-gate
Costs: Manufacturing line

Functional unit: Manufacturing 1 monolayer cell

Environmental LC Assessment

Methodology: ISO 14040/44

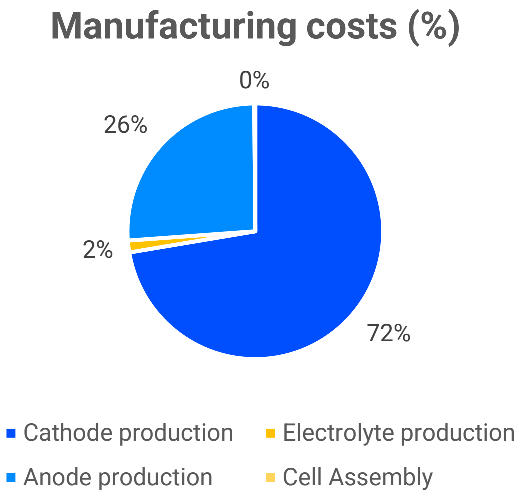


*Global Warming Potential of **manufacturing 1 monolayer cell** – ReCiPe 2016 Midpoint (H); Energy-mix: BE*

Key findings:
- The impact is primarily due to **cathode production (71%),** specifically due to CAM (NMC811): nickel, lithium, and cobalt.

Cost Assessment

Methodology: ISO 14051



*Cost results of **manufacturing 1 monolayer cell** Energy-mix: BE*

Key findings:
- The main responsible of the costs are associated to **the cathode production (72%),** due to CAM and ionic liquid

Eco-Design Regulations Approach

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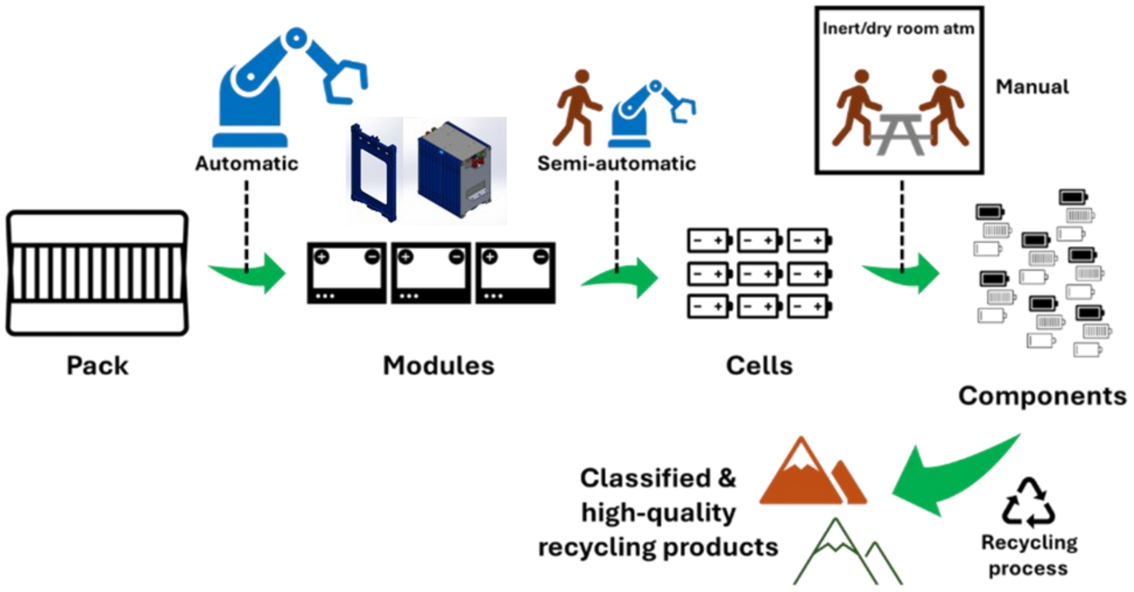

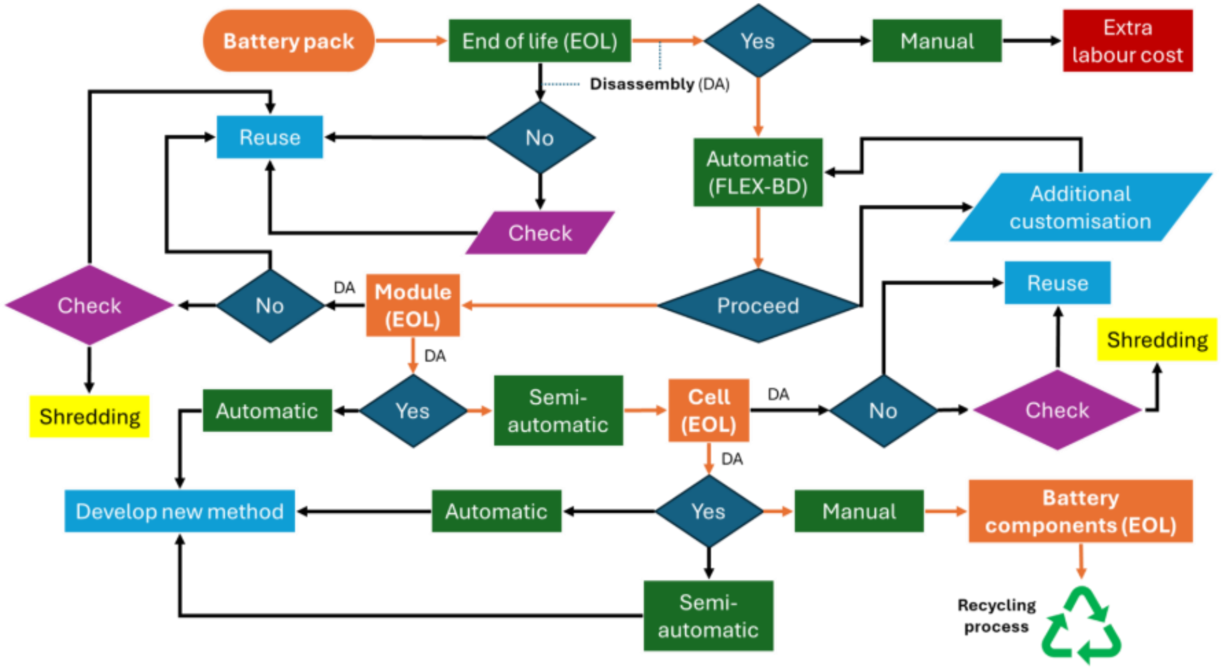

- Eco-design regulation for battery disassembly processing technology;
- Considering safety, chemical, electrical & thermal runway aspects, hazardous standards in IEC 62660-1/2/3, and cost & environmental efficiency;
- Include the guidelines, diagram, and decision tree in a scientific paper.

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Mid to long term expected impacts

of the SPINMATE Project from M1 to M46 and the designed impacts after M48

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Scientific, Technology, and Industrial

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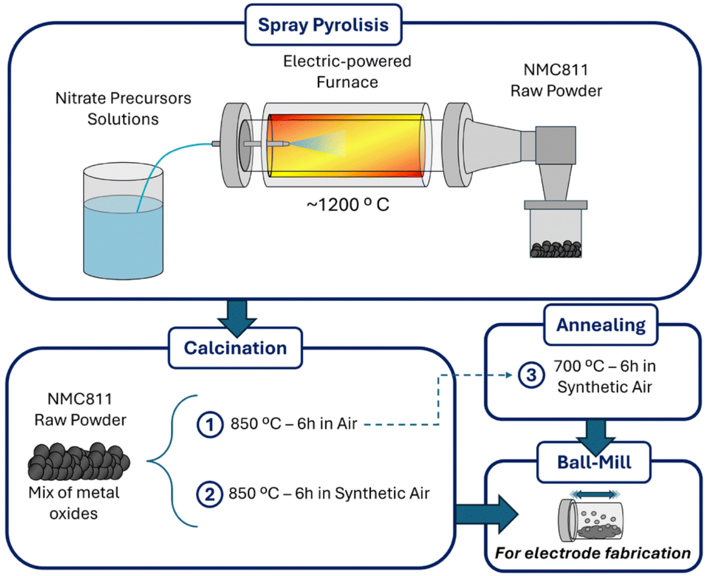
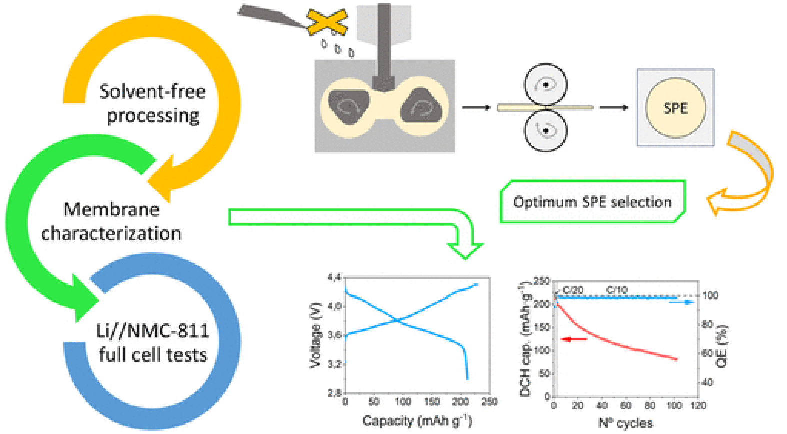
#	Section	Corresponding Questions	Type
1	Motivation–Why do projects cluster	i. What are the primary drivers for collaborating and clustering with other projects? ii. Do you collaborate because there are inherent benefits or because it is required by the EU? iii. Over the course of your project, what benefits does your organization expect to receive from collaborating with other projects? iv. Are there any specific challenges or barriers to effective collaboration and knowledge exchange with partners from other projects? v. Please reflect on question #4. Do you have any recommendations for the SOLID4B cluster to overcome the above-mentioned challenges?	Closed, multiple choice. Except question v., which is open, descriptive
2	Approach–How should projects cluster	vi. What is the optimum frequency, according to you, for a common cluster activity? vii. If there is a confidentiality agreement between all the cluster projects in place? What are you willing to share with other projects? viii. Do you think that a common repository of related projects with the following information would help collaboration and increase synergies?	Closed, multiple choice
3	Implementation–When should networking happen	ix. Do you actively seek opportunities to engage with partners from different projects in external events, conferences, or research networks to expand the cluster's reach and influence? x. The cluster leader has strived to organize events at the cluster level every 6 months. Are you aware of these events? Have you received regular updates about the progress? Would you like to participate actively in such events?	Closed, multiple choice
4	General–open questions	xi. From your experience, do you have any example of a successful collaboration/clustering across different projects? According to you, what are the factors contributing to its success? xii. When it comes to the SOLID4B cluster, are the expectations and opportunities arising from cross-project collaboration clear to you?	Open, descriptive

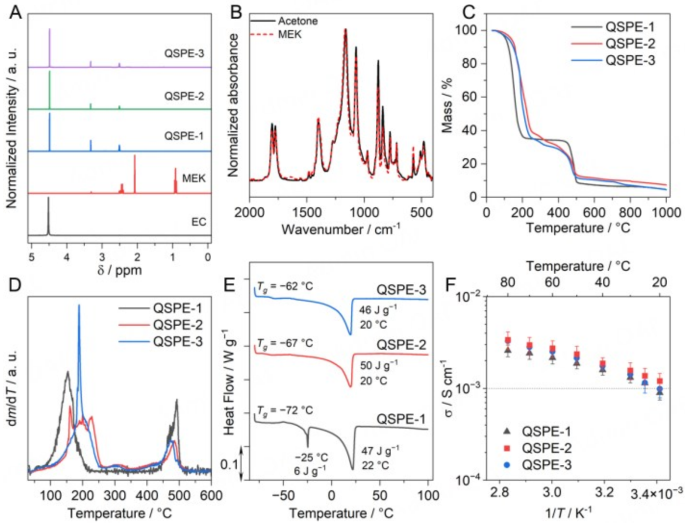
Adm. Sci. **2024**, 14(5), 104
[10.3390/admsci14050104]



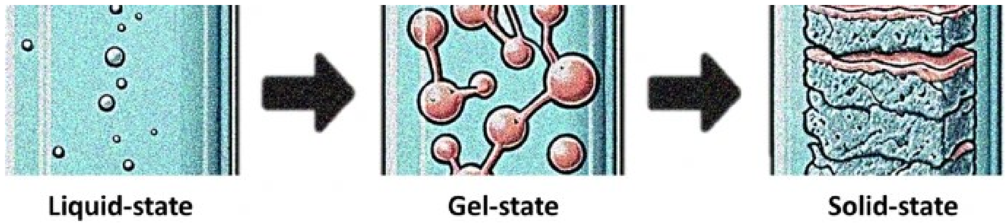
Nanoscale **2024**, 16, 22326-22336
[10.1039/D4NR04146A]



ACS Appl. Polym. Mater. **2025**, 7, 24, 16443−16456
[10.1021/acsapm.5c02544]
[10.5281/zenodo.17737512]



Energy Mater. **2025**, 5, 500040
[10.20517/energymater.2024.203]



Discov. Electrochem. **2025**, 2, 26
[10.1007/s44373-025-00040-y]

https://www.spinmate.eu/scientific-publications/

Economic, Societal, and Policy

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1. Strengthening Europe's leadership in industrial-scale production of **polymer-based SSBs** and related machinery.
2. Advancing scalable, low-emission, low-carbon, and cost-efficient solid-state battery manufacturing with enhanced safety, aligned with **the Made in Europe initiative**.
3. Enhancing **skills among researchers and industry professionals**, expectedly creating new high-skilled jobs in the medium term and multidisciplinary roles in the long term.
4. Contributing to **battery-related policy and regulatory decisions**, addressing EU priorities in electric vehicles, safety, recycling, performance, and durability.
5. Establishing **the Solid4B Cluster to drive innovation and collaboration among researchers, industry experts, and policymakers**. This cluster promotes joint R&D efforts in the EV sector. Alongside 15 projects, SPINMATE **fosters synergy across European SSB initiatives (Li-ion, Li-metal, Na-based, and beyond)**, transforming research into actionable insights for stakeholders. Together, they aim to develop safe, efficient, and sustainable battery technologies for future mobility. Solid4B also accelerates SSB market entry and raises awareness on carbon footprint reduction and environmental preservation.

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Summaries and Inputs

from the SPINMATE Project perspective

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Summaries and Inputs

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- ✓ The SPINMATE Project has a challenging approach to match the R&D activities of a **solid polymer electrolyte (SPE)-based solid-state electrolyte system** with the applicable implementation of **Li-metal anode** and **NMC811 cathode**. Promising results from the lab-based and pilot-line activities are presented. However, it still needs more collaboration and effort to move on to 10 Ah for industrial-scale proof of concepts (PoCs).
- ✓ Those extra efforts will be carefully handled together by all SPINMATE project consortium partners **during the 3rd phase of the project towards the end (~Mid 2026, to early 2027)**.
- ✓ The further series of R&D projects in solid polymer electrolyte (SPE)-based solid-state electrolyte batteries (e.g. application of the SPINMATE SPE for ongoing project or future proposals) will help **to drive the output of the current SPINMATE project to the next technology readiness level (TRL) even further**.

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