INSIGHT SERIES

FROM EXPERTISE TO IMPACT

HyLiST

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What Is the Winning Formula for Scalable Solid Polymer Batteries?

Abstract

The race for next-generation solid-state batteries is accelerating, driven by the demand for safer, higher-energy storage. Success requires crossing key milestones: high-voltage cathodes, high-energy-density anodes, and stable electrolytes capable of operating at elevated voltages, all while ensuring that these components are scalable and industry-ready. The HyLiST project demonstrates this winning formula, bridging lab-scale innovation to pilot-scale production and setting the stage for safe, high-performance, and commercially viable solid polymer batteries.

The Race Toward Safer, High-Energy Batteries

Lithium-ion batteries have driven decades of innovation, powering everything from consumer electronics to electric vehicles. Yet their liquid electrolytes carry inherent drawbacks, including flammability, leakage, and thermal runaway, which limit energy density, fast-charging capability, and long-term reliability.

Solid-state batteries promise to overcome these limitations by replacing the liquid phase with thermally stable, non-flammable solid electrolytes, offering enhanced safety, mechanical robustness, and thermal stability.

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Among solid electrolytes, solid polymer electrolytes (SPEs) offer unique advantages: mechanical flexibility, low density, and compatibility with scalable coating methods. The challenge lies in determining which combination of materials and manufacturing methods can turn polymer-based solid-state batteries into an industrial reality capable of competing with today's lithium-ion chemistries.

Recent research points to a clear conclusion: a high-performance, scalable solid polymer battery requires:

- High-voltage cathodes
- High-energy-density anodes
- Thermally and electrochemically stable polymer electrolytes
- Manufacturing routes compatible with roll-to-roll processes

This combination addresses electrochemical, mechanical, and safety challenges, forming the foundation of the HyLiST project, which develops LNMO-based hybrid SIPE solid-state cells alongside scalable lithium-metal fabrication.

Component Selection and Scalability

High-Voltage Cathodes, why LNMO Leads?!

Achieving competitive energy density requires pairing polymer electrolytes with cathodes that remain stable above 4.5 V. LNMO ($LiNi_{0.5}Mn_{1.5}O_4$) stands out due to:

- High operating voltage (4.7–5.0 V vs. Li/Li^+)
- Cobalt-free composition, easing supply chain and cost concerns
- Stable spinel structure, enabling robust cycling at elevated voltages
- Compatibility with aqueous casting, supporting greener manufacturing

Conventional PEO-based SPEs oxidize at ~3.8 V, far below LNMO's voltage window. Modern single-ion polymer electrolytes (SIPEs) overcome this through chemically stable backbones and delocalized anionic groups, enabling the oxidative durability required for high-voltage operation.

Lithium Metal, Unlocking Maximum Energy

Replacing graphite with lithium metal anodes unlocks exceptional performance:

- Theoretical capacity of 3860 mAh g^{-1}
- Minimal anode mass, boosting gravimetric energy density
- Potential >400 Wh kg^{-1} when paired with high-voltage cathodes

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However, lithium metal introduces challenges, including dendrite formation, high reactivity, and interfacial instability. Overcoming these issues requires electrolytes with high Li^+ transference numbers, stable interfaces, and protective surface engineering. SIPEs are particularly well suited to address these challenges by facilitating uniform Li deposition and suppressing dendrites.

SIPEs, the Stability and Safety Factor

The electrolyte is often the most critical determinant of success in polymer-based solid-state batteries. A high-performance SIPE must provide:

- Ionic conductivity $\geq 10^{-4}$ S cm^{-1} at room temperature
- Li^+ transference number ≈1 (tLi^+ ~0.9–1.0)
- Electrochemical stability >4.5 V
- Chemical compatibility with LNMO and lithium metal
- Mechanical robustness to suppress dendrites
- Scalable, low-cost processing routes

SIPEs immobilise anions within the polymer backbone, eliminating concentration polarization and promoting uniform Li deposition. This single-ion transport mechanism makes them uniquely suited for pairing with both high-voltage LNMO cathodes and lithium-metal anodes.

Scalability, Bridging Lab Success and Industrial Reality

High-performance electrolytes often fail when transitioning from laboratory to industrial scale. A commercially viable polymer solid-state battery must support:

- Roll-to-roll, slot-die, or blade-coating compatibility
- Controlled drying or curing that preserves polymer integrity
- Processing in ambient or dry-room conditions
- Low-toxicity or solvent-free formulations
- Formation of thin, defect-free electrolyte layers (<50 μm)

Different polymer systems present trade-offs:

- PEO-based SPEs; Highly processable, but insufficient high-voltage stability
- Polycarbonates; Excellent amorphous conductivity, but require precise salt pairing
- SIPEs; Strong electrochemical performance, but synthesis must be optimized for industrial scalability

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HyLiST Connection: Industrializing the Winning Formula

The HyLiST project integrates advanced materials and scalable manufacturing to implement this winning formula:

LNMO Cathode

- High voltage, cobalt-free chemistry
- 3–4 mAh/cm^2 areal capacity
- Processed using water-based binders for sustainability

Hybrid SIPE (HSIPE)

- $tLi^{+} > 0.9$
- Ionic conductivity >0.5 mS/cm
- Mechanically robust and oxidation resistant
- Compatible with LNMO and lithium metal

Lithium-Metal Anode

- Ultrathin 5–10 µm layers
- Fabricated roll-to-roll via pulsed laser deposition (PLD)
- Surface alloying and barrier layers suppress dendrites

Interface & Cell Engineering

- In-situ characterization of lithium deposition
- Mechanical modeling to prevent fracture
- Digital twins to optimize coating and assembly
- Pilot-line 5 Ah pouch cells, validating industrial scalability

By unifying optimized materials, scalable processes, and digital manufacturing tools, HyLiST demonstrates polymer-based solid-state battery technology ready for real-world deployment.

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The Winning Formula

A scalable, safe, and high-energy solid polymer battery requires:

- High-voltage cathodes (LNMO, 4.7–5.0 V, cobalt-free, high areal loading)
- Lithium-metal anodes (ultrathin, dendrite-suppressed, polymer-compatible)
- Scalable manufacturing (roll-to-roll coating, thin-film formation, wet/dry electrode processing)
- Interface & digital tools (in-situ monitoring, mechanical modelling, digital twins)
- Sustainability (water-based systems, reduced solvent footprint, recyclable materials)

HyLiST embodies this formula, bridging the gap between lab-scale performance and industrial-scale deployment, paving the way for Europe's next generation of safe, high-energy solid-state batteries.

ABOUT THE AUTHOR

Meisam Hasanpoor is a scientist, project manager and scientific coordinator at the Battery Technologies division of the Austrian Institute of Technology. He received his Ph.D. in 2021 from the Institute for Frontier Materials at Deakin University, where he specialized in advanced lithium-based batteries. His research spans both liquid and solid-state battery systems, while his current work is dedicated to the development of advanced materials and scalable processes for high-energy solid-state batteries, targeting demanding applications in electric vehicles (EVs) and aviation. His overarching goal is to contribute to the advancement of environmentally friendly and sustainable energy storage technologies by improving cell component manufacturing, optimizing electrode-electrolyte interfaces, and enabling high-performance solid-state cell architectures.

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