

# Solid-state / Semi-solid Li-ion Battery Innovation & Patent Review

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## About the Author

**Pirmin Ulmann** obtained a diploma in chemistry from ETH Zurich (Switzerland) in 2004 and a PhD from Northwestern University (USA) in 2009. Thereafter, he was a JSPS Foreign Fellow in an ERATO academic-industrial project at the University of Tokyo (Japan). From 2010 to 2016, while working at a major battery materials manufacturer in Switzerland, he was a co-inventor of 7 patent families related to lithium-ion batteries. He was also in charge of a collaboration with the Paul Scherrer Institute, evaluated outside technologies for corporate strategy, and made customer visits to battery manufacturers in East Asia, North America & Europe. He holds the credential Stanford Certified Project Manager (SCPM) and has co-authored scientific articles with more than 2,000 citations.

## Introduction

### Focus of this Review

In this review, technical options are discussed that are being evaluated by key solid-state / semi-solid lithium-ion battery companies towards the launch of commercial products for various applications, in particular electronics and EVs. The analysis is based on a unique AI-supported screening approach for the identification of patent filings with high prospective commercial relevance, which are compared with public statements (incl. at conferences).

Comprehension of solid-state / semi-solid Li-ion battery technology decision trees allows for the identification of promising product development directions that have not yet been explored.

Patent portfolios by key commercial players have been classified into 6 categories:

- Level 1) **Electrolyte & electrode patents**
- Level 2) **Cell patents (chemistry & architecture)**
- Level 3A) **Pack / form factor / packaging patents**
- Level 3B) **Application patents**

- Level 3C) Reliability patents (e.g. mitigation of short circuits / heat & gas formation)
- Level 3D) Manufacturing patents (electrolytes, electrodes, cells)

A patent portfolio that covers all of these categories generally reflects a substantial product development effort that addresses all aspects necessary for a successful launch.

For tailored patent searches, the AI model used for preparation of this review is available to users on [b-science.net](https://b-science.net).

Table 2: (projected) market launches for solid-state / semi-solid battery EVs; color labels: midnight blue: oxide / phosphate-based electrolytes (may contain polymers); mocha: sulfide-based electrolytes (may contain halides, polymers); teal: halide-based electrolytes (without sulfur); plum: polymer-based electrolytes (predominant component)

Company	Country	Year	Possible Electrolyte / Negative Electrode Type / Other Info
20 entries			

## Benchmarking & Product Launch Risk Factors – Cells with Liquid vs. Semi-Solid vs. Solid Electrolytes

A battery fails commercially if any performance & safety characteristic or costs do not match the requirements of the corresponding application. Outperformance in one dimension usually does not compensate for the biggest weakness.

Table 6: targeted energy density

Companies (approximate cell capacity)	Approximate volumetric / gravimetric energy density (for >1 Ah cells unless if mentioned otherwise)	Positive electrode	Negative electrode
20 entries			

## Technology Decision Trees

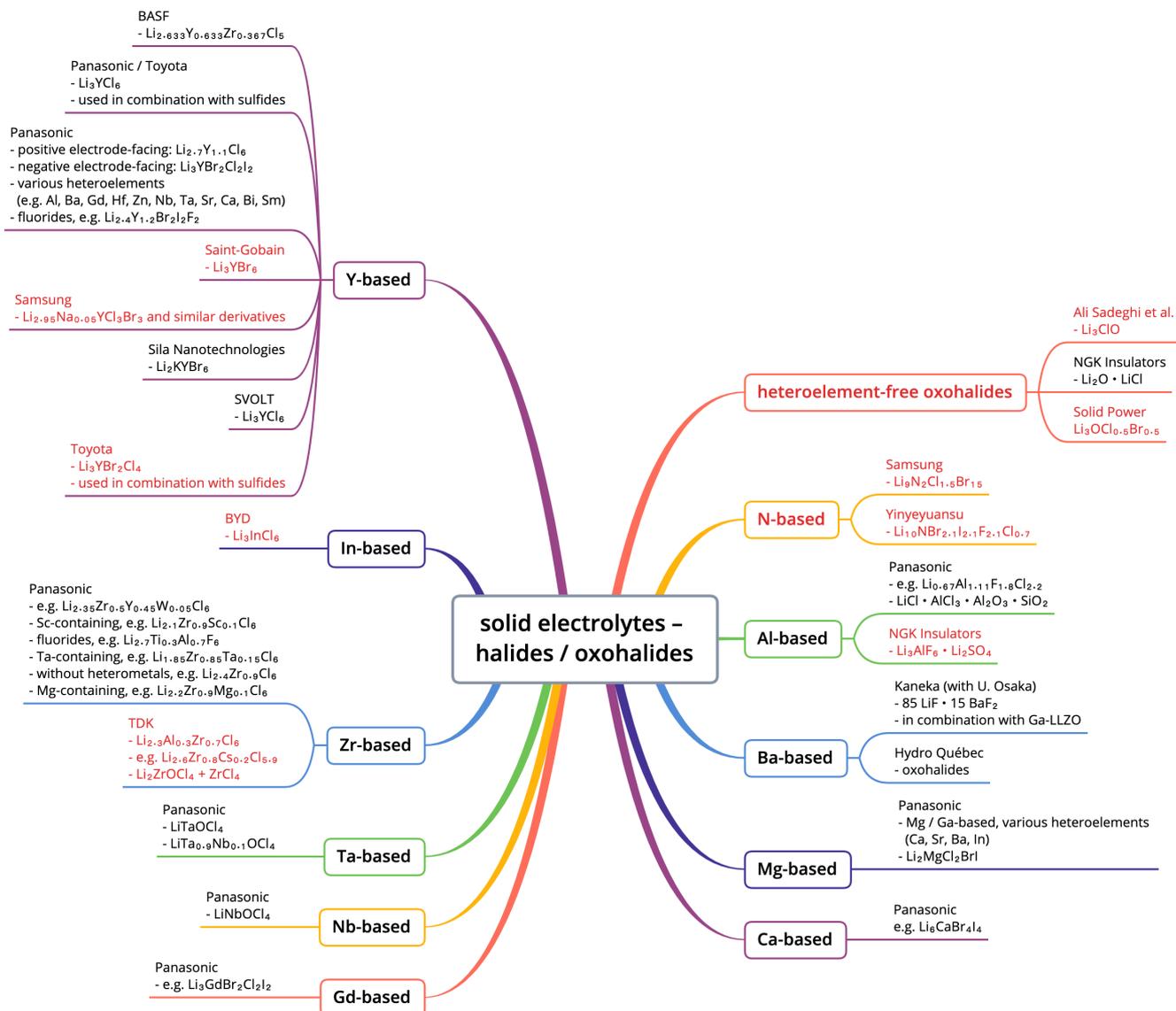
Table 7: ion conductivity of solid electrolytes (as identified in patent applications, in public statements, or by reference to an academic publication); color labels: **midnight blue**: oxide / phosphate-based electrolytes (may contain polymers, may contain minor amount of halide); **mocha**: sulfide-based electrolytes (may contain halides, polymers); **teal**: halide-based electrolytes (without sulfur, may contain oxygen); **plum**: polymer-based electrolytes (predominant component)

Companies	Possible electrolyte	Approximate ion conductivity at 25 °C unless if otherwise mentioned
Škoda (VW)	'Li-glasses' based on complex mixture, e.g. P <sub>2</sub> O <sub>5</sub> / LiCl / Li <sub>2</sub> O / Al <sub>2</sub> O <sub>3</sub> / B <sub>2</sub> O <sub>3</sub> / LiI	5.5 × 10 <sup>-2</sup> S/cm
<u>Hydro Québec (licensed from Texas University / Porto University / Laboratório Nacional de Energia e Geologia)</u>	'Li-glasses' based on dried LiOH, LiCl, Ba(OH) <sub>2</sub>	4 × 10 <sup>-2</sup> S/cm
<u>Toyota</u>	Li <sub>9.54</sub> Si <sub>1.74</sub> P <sub>1.44</sub> S <sub>11.7</sub> Cl <sub>0.3</sub>	2.5 × 10 <sup>-2</sup> S/cm
<u>SVOLT</u>	Li <sub>5.85</sub> P <sub>0.8</sub> Bi <sub>0.1</sub> Sn <sub>0.1</sub> S <sub>4.4</sub> O <sub>0.15</sub> Cl <sub>1.45</sub>	1.5 × 10 <sup>-2</sup> S/cm
<u>Ampcera</u>	'sulfur-stuffed' argyrodite, Li <sub>8</sub> P <sub>3</sub> S <sub>11+n</sub> Cl or Li <sub>8+2n</sub> P <sub>3</sub> S <sub>11+n</sub> Cl, n > 0	>1.2 × 10 <sup>-2</sup> S/cm (public statement that presumably corresponds to the electrolyte on the left)
<u>Dynanonic</u>	Supramolecular siloxane-PEO, coupled with click chemistry	1.2 × 10 <sup>-2</sup> S/cm
<b>118 additional entries</b>		

Table 10: raw material / process aspects that could impact costs

Companies	Critical raw material or process aspects
<b>19 entries</b>	

Figure 12: technology decision tree – solid electrolytes – halides / oxohalides  
(in red: newly added branches as compared to prior review)



## Assessment of Companies

Author comments are displayed in maroon.

### Contemporary Amperex Technology (CATL) – China

#### Organization profile

Contemporary Amperex Technology Limited (CATL, <https://www.catl.com/en/>) is the world's largest Li-ion battery producer. CATL was founded in 2011 in Ningde, China. In 2017, CATL has completed a split from its parent company ATL/TDK. With BRUNP Recycling (subsidiary), CATL

jointly develops positive electrode active materials.

**Unique capability:** 1) supramolecular ionic liquid / polymer / lithium salt electrolyte membranes with very favorable ionic conductivity (up to  $2.4 \times 10^{-3}$  S/cm) and high boiling point ( $>438$  °C), along with corresponding cells with lithium metal negative electrodes; 2) sulfide electrolyte-based lithium metal cells based on  $\geq 5$  complementary concepts to mitigate various failure modes.

**Leap of faith:** 1) the toxicity of triphenylene-containing electrolytes will be acceptable; 2) the risk of toxic hydrogen sulfide gas emissions when sulfide electrolytes are in contact with water or moisture will not be a showstopper during production, operation and / or recycling.

**Comment:** approaches 1) and 2) could finally enable the operation of lithium metal negative electrodes at room temperature and below with favorable fast charge / discharge characteristics (along with favorable energy density).

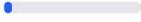
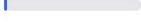
## News reports & press releases

[This information is included in the full version.](#)

## General patent portfolio characteristics

68 new patent families by CATL related to semi-solid or solid-state Li-ion batteries have been published since 2022 (level 1: 42, level 2: 46, level 3A: 9, level 3B: 1, level 3C: 32, level 3D: 11, see adjacent Excel file). Polymer / oligomer and sulfide electrolytes constitute key patenting focus areas (Figure CA-1).

Figure CA-1: AI-based classification of patent families by CATL published since 2022 related to solid electrolytes categories 1-6. Patents without direct relation to one category (e.g. because of solid-state cell packaging focus) were excluded.

CATEGORY	PATENT COUNT	PERCENTAGE	VISUAL
Category 4: sulfides	23	43.4%	
Category 5: polymers / oligomers	22	41.5%	
Category 6: halides / oxyhalides	4	7.5%	
Category 2 & 3: oxide / polymer composites	3	5.7%	
Category 1: oxides	1	1.9%	

## Key Polymer Electrolyte Product Development Concepts

Figure CA-2: AI-based polymer electrolyte product development concept identification (CATL)



Figure CA-2 illustrates how CATL pursues a range of polymer / oligomer-related product development approaches, among which 2 concepts appear complementary, even though no patent has been identified yet that confirms their simultaneous use.

**Concept 1: Supramolecular Ionic Liquids**, WO 2022021231 A1 ([EPO](#) / [Google](#))

### KEY FINDINGS

$2.4 \times 10^{-3}$  S/cm ionic conductivity in membranes based on supramolecular assembly of ion-channels, comparably low density, based on abundant precursors.

## TECHNICAL DESCRIPTION

Benzophenanthrene-based supramolecular ionic liquids with  $\pi$ - $\pi$  stacking creating ordered ion transport pathways. Ether side chains (1-16 carbons, see Figure CA-3) balance molecular assembly with ion mobility. Synthesis via Williamson reaction and  $\text{FeCl}_3$  cyclization, resulting in  $6.5 \times 10^{-3}$  S/cm bulk conductivity at  $25^\circ\text{C}$ .

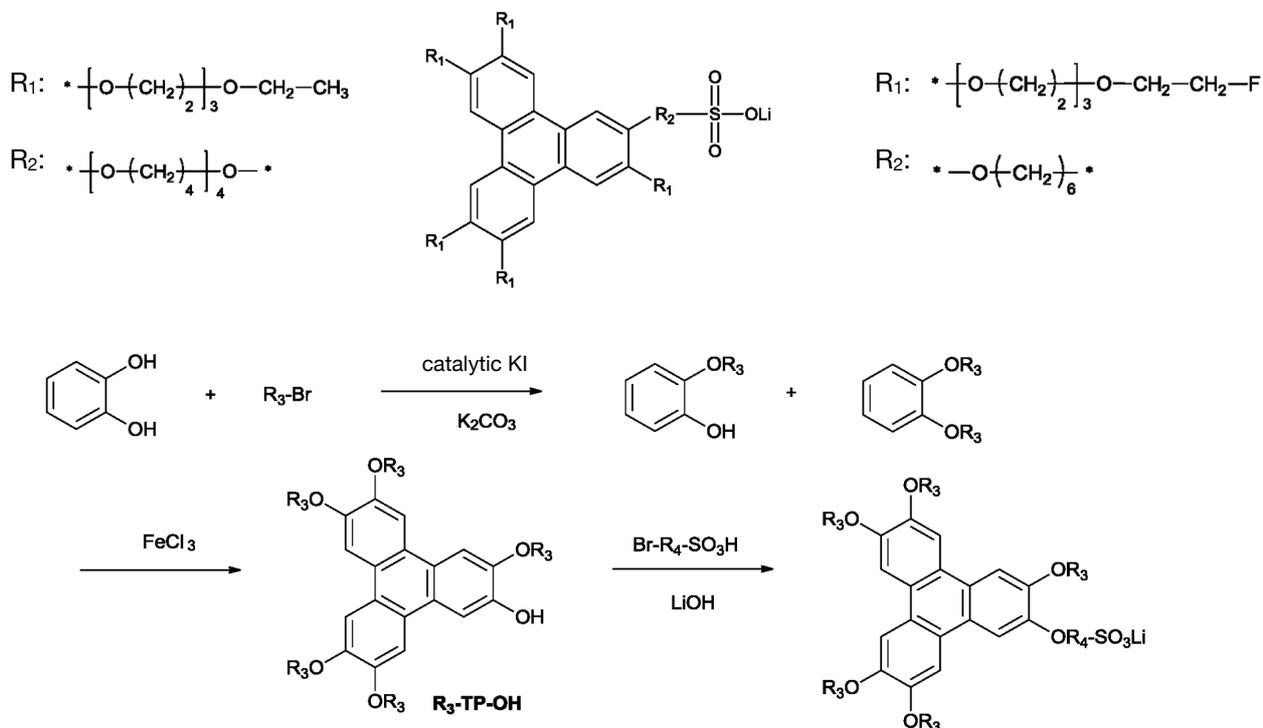
## BACKGROUND INFORMATION

Patent WO 2022021231 A1 addresses the polymer ionic conductivity bottleneck. A self-assembly approach results in near-liquid conductivity ( $2.4 \times 10^{-3}$  S/cm in membrane), while offering safety advantages for which solid-state Li-ion batteries are known (triphenylene shown in Figure CA-3 exhibits a boiling point of  $438^\circ\text{C}$ ). Manufacturing is based on organic chemistry and comparably abundant precursors.

## ELECTRODE CONFIGURATION

Negative electrode: lithium metal | Positive electrode: NMC811.

Figure CA-3: top – two triphenylene derivatives with (optionally fluorinated) ethylene oxide / lithium sulfonate groups. The derivative on the left exhibits particularly favorable ion conductivity ( $6.5 \times 10^{-3}$  S/cm), while the derivative on the right exhibits particularly favorable cycling stability, bottom – synthesis procedure,  $\text{OR}_3 = \text{R}_1$ ,  $\text{OR}_4 = \text{R}_2$  (CATL)



**The full version includes a discussion of polymer electrolyte product development concepts 2-5.**

## Potential Synergies Between Concepts

R&D concepts 1 (supramolecular ionic liquids) and 3 (gradient crosslinking systems) offer synergies in terms of overcoming the fundamental trade-offs in solid-state battery development. Concept 1 addresses the critical ionic conductivity bottleneck that has limited solid-state batteries, achieving near-liquid ionic transport through self-assembled molecular architectures. Concept 3 solves mechanical integrity and safety challenges by providing spatially optimized structural reinforcement. The combination could enable solid-state batteries that achieve both liquid-like ionic conductivity and superior structural integrity – previously mutually exclusive characteristics.

## Possible Material / Cell / Process Characteristics (Projection Based on Public Information)

- **Electrolyte:** benzophenanthrene-based supramolecular ionic liquids with  $\pi$ - $\pi$  stacking architecture and ether side chains (1-16 carbons) that exhibit an ionic conductivity of  $6.5 \times 10^{-3}$  S/cm at 25°C (WO 2022021231 A1, Example 22). When integrated with a polymer matrix (PEO/PVDF/LiTFSI at 10-80 : 100 : 5-40 by mass), the composite electrolyte exhibits  $2.4 \times 10^{-3}$  S/cm conductivity. Gradient acrylate crosslinking systems (WO 2024243875 A1) might be incorporated into side chains to tune mechanical characteristics.
- **Negative electrode:** lithium metal on copper foil (WO 2022021231 A1).
- **Positive electrode:** NMC811 with conductive carbon (2 mass%) and PVDF binder (2 mass%) on aluminum current collector (WO 2022021231 A1).
- **Design:** prismatic stacked multilayer cells with favorable deformation resistance (WO 2024243875 A1).
- **Process:**
  - 1) Supramolecular ionic liquid synthesis via Williamson reaction and FeCl<sub>3</sub> cyclization (WO 2022021231 A1).
  - 2) Sequential or parallel (such as with multi-slurry feeder) injection gradient crosslinking film formation (WO 2024243875 A1).
  - 3) Hot pressing (1-20 MPa, 50-100°C) with spatially controlled crosslinking density.
  - 4) Vacuum annealing (60-80°C, 1-8 h).
  - 5) Electrode and electrolyte layer lamination through cold-pressing (250 MPa, 25 °C, 2 min) to obtain multi-layer cells.
  - 6) Prismatic cell encapsulation.

Supporting inventions listed in Figure CA-2 (bottom) might additionally be employed in this context.

## Key Sulfide Electrolyte Product Development Concepts

The full version includes a discussion of sulfide electrolyte product development concepts 1-5, synergies and possible material / cell / process characteristics.

## Highly Relevant Inventions Covered in Recent Triweekly Patent Updates

The full version includes a summary and discussion of 3 additional highly relevant all-solid / semi-solid Li-ion battery electrolyte patents that have been identified during our triweekly patent screening process.

### AI-based Patent Summaries

The adjacent Excel file contains AI-based patent summaries for all patents mentioned in this chapter, classified in terms of electrolyte type (Figure CA-1) and level 1 (electrode / electrolyte patents) to level 3D (manufacturing patents).

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