

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

Table of Contents (in parentheses: date of latest version)	Page
<u>Executive Summary</u> (June 2023)	5
<u>About the Author</u> (June 2023)	6
<u>Introduction</u> (June 2023)	6
• <u>Focus of this Review</u>	
• <u>Solid-state / Semi-solid Li-ion Battery Components</u>	
• <u>The Solid-state / Semi-solid Li-ion Battery Market Today</u>	
• <u>(Projected) Market Launches – Solid-state / Semi-solid Li-ion Battery EVs</u>	
<u>AI-based Identification of Commercially Relevant Patents</u> (June 2023)	12
• <u>Number of Commercially Relevant Patent Families / Utility Models Since 2022</u>	
<u>Technology Decision Trees</u> (June 2023)	31
• <u>Solid Electrolytes – Types – Launched or Close to Market Launch</u>	
• <u>Solid Electrolytes – Types – Based on Patent Filings</u>	
• <u>Solid Electrolytes – Concepts</u>	
• <u>Solid Electrolytes – Oxides That Do Not Contain Phosphorus – (Probably) Crystalline</u>	
• <u>Solid Electrolytes – Phosphates / P-containing Oxides – (Probably) Crystalline</u>	
• <u>Solid Electrolytes – Oxide / Phosphates – (Probably) Glasses</u>	
• <u>Solid Electrolytes – Hydroxides</u>	
• <u>Solid Electrolytes – Sulfides</u>	
• <u>Solid Electrolytes – Mitigation of Hydrogen Sulfide Emissions</u>	
• <u>Solid Electrolytes – Polymers</u>	
• <u>Solid Electrolytes – Halides / Oxohalides</u>	
• <u>Solid Electrolytes for Thin-film Batteries</u>	
• <u>Solid Electrolytes – Boranes</u>	
• <u>Lithium (Sodium) Salts</u>	
• <u>Plasticizers</u>	
• <u>Liquid Electrolyte Components / Liquid Additives</u>	
• <u>Solid Electrolyte Additives / Support &amp; Filler Materials That Do Not Contain Li</u>	
• <u>Solid Electrolyte Binders</u>	
• <u>Negative Electrode Active Materials</u>	
• <u>Positive Electrode Active Materials</u>	
• <u>Negative Electrode Additives</u>	
• <u>Positive Electrode Additives</u>	
• <u>Negative Electrode Binders</u>	
• <u>Positive Electrode Binders</u>	

- [Cell Design](#)
- [Cell Design – Concepts](#)
- [Pack Engineering](#)
- [Reliability](#)
- [Applications](#)
- [Electrolyte Film Deposition Processes](#)

#### Benchmarking & Product Launch Risk Factors –

Cells with Liquid vs. Semi-Solid vs. Solid Electrolytes (June 2023) 56

- [Inherent Safety – Key Risk Factors](#)
- [Energy Density – Positive & Negative Electrode Active Material Selections](#)
- [Power Density – Ion Conductivity of Solid / Semi-solid Electrolytes](#)
- [Longevity – Risk of Crack Formation & Chemical Instability](#)
- [Cell Size](#)
- [Raw Materials & Manufacturing Processes](#)

Predictions (June 2023) 70

Assessment of Companies 72

- [Blue Solutions](#) (2026-01-12)
- [BYD](#) (2025-11-18)
- [Contemporary Amperex Technology Ltd. \(CATL\)](#) (2025-11-18)
- [LG Energy Solution / LG Chemical](#) (2025-11-18)
- [Samsung](#) (2025-11-18)
- [Panasonic](#) (2025-11-18)
- [ProLogium Technology](#) (2025-12-08)
- [Toyota](#) (2025-11-18)
- [Ampcera](#) (June 2023)
- [BASF](#) (June 2023)
- [Blue Current](#) (June 2023)
- [BrightVolt](#) (June 2023)
- [Corning](#) (June 2023)
- [Enpower Greentech](#) (June 2023)
- [Factorial Energy](#) (June 2023)
- [FDK / Fujitsu](#) (June 2023)
- [Foxconn \(Hon Hai Precision Industry\) / SolidEdge Solution](#) (June 2023)
- [Ganfeng Lithium / Zhejiang Fengli / Zhejiang Funlithium](#) (June 2023)
- [GM](#) (June 2023)
- [Hydro Québec](#) (June 2023)
- [Idemitsu Kosan](#) (June 2023)
- [Ilika Technologies](#) (June 2023)
- [ION Storage Systems](#) (June 2023)
- [JX Nippon Mining and Metals / Eneos](#) (June 2023)
- [Maxell](#) (June 2023)
- [Mitsui Mining and Smelting / Mitsui Kinzoku](#) (June 2023)
- [Murata Manufacturing](#) (June 2023)
- [NGK Insulators](#) (June 2023)
- [Ohara](#) (June 2023)

• <a href="#">Piersica</a> (June 2023)	
• <a href="#">PolyPlus</a> (June 2023)	
• <a href="#">Qingtao Kunshan New Energy Materials / Suzhou Qingtao New Energy Technology / Yichung Qingtao Energy Technology</a> (June 2023)	
• <a href="#">QuantumScape</a> (June 2023)	
• <a href="#">Sakuú</a> (June 2023)	
• <a href="#">SES Holdings</a> (June 2023)	
• <a href="#">Soelect</a> (June 2023)	
• <a href="#">Solid Power</a> (June 2023)	
• <a href="#">SVOLT Energy Technology / Fengchao Energy Technology / Honeycomb Technology</a> (June 2023)	
• <a href="#">Taiyo Yuden</a> (June 2023)	
• <a href="#">TDK</a> (June 2023)	
• <a href="#">TeraWatt Technology</a> (June 2023)	
• <a href="#">Toshiba</a> (June 2023)	
• <a href="#">WeLion</a> (June 2023)	
<a href="#">Deep Dive – Oxide Electrolyte Options &amp; Selection Trade-offs</a> (2025-05-30)	384
• <a href="#">Introduction</a>	
• <a href="#">‘Decision Maze’ Towards Oxide Electrolyte-containing Li-ion Battery Cells</a>	
• <a href="#">At Which Temperature Should Electrolyte Film Formation Occur?</a>	
• <a href="#">Crystalline vs. Glassy / Amorphous Electrolytes</a>	
• <a href="#">Dopant Selection / Defect Density / Defect Filling</a>	
• <a href="#">Modifications of Particle Surface Chemical Composition</a>	
• <a href="#">Combination with Other Electrolyte Classes</a>	
<a href="#">AI Patent Analysis Methodology</a>	397
<a href="#">List of Abbreviations</a>	397
<a href="#">Disclaimer</a>	400

## 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

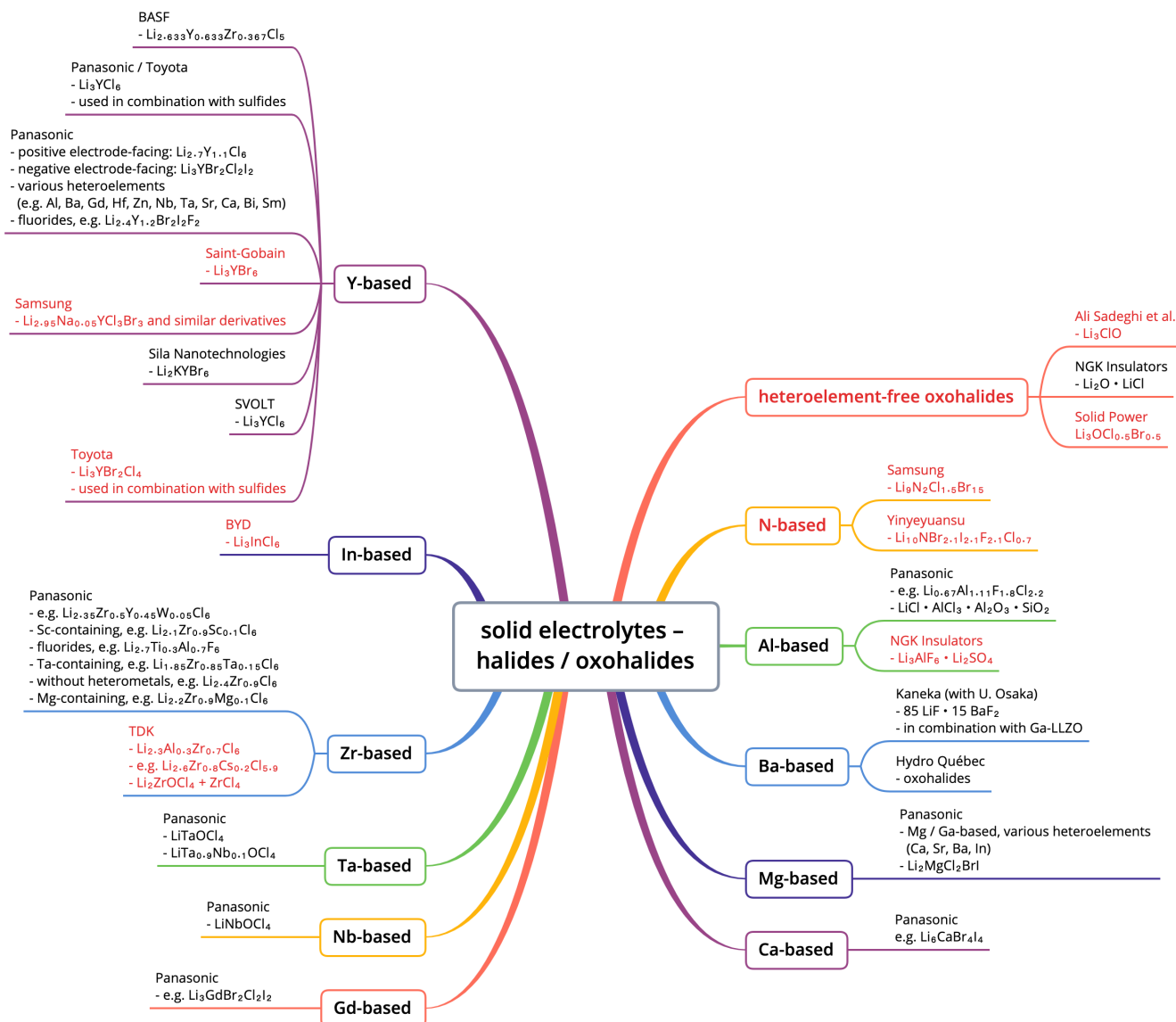
Table 7: ion conductivity of solid electrolytes (as identified in patent applications, in public statements, or by reference to an academic publication); color labels: **midnight blue**: oxide / phosphate-based electrolytes (may contain polymers, may contain minor amount of halide); **mocha**: sulfide-based 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. $P_2O_5$ / LiCl / $Li_2O$ / $Al_2O_3$ / $B_2O_3$ / LiI	$5.5 \times 10^{-2}$ S/cm
Hydro Québec (licensed from Texas University / Porto University / Laboratório Nacional de Energia e Geologia)	'Li-glasses' based on dried LiOH, LiCl, $Ba(OH)_2$	$4 \times 10^{-2}$ S/cm
Toyota	$Li_{9.54}Si_{1.74}P_{1.44}S_{11.7}Cl_{0.3}$	$2.5 \times 10^{-2}$ S/cm
SVOLT	$Li_{5.85}P_{0.8}Bi_{0.1}Sn_{0.1}S_{4.4}O_{0.15}Cl_{1.45}$	$1.5 \times 10^{-2}$ S/cm
Ampcera	'sulfur-stuffed' argyrodite, $Li_8P_3S_{11+n}Cl$ or $Li_{8+2n}P_3S_{11+n}Cl$ , $n > 0$	$>1.2 \times 10^{-2}$ S/cm (public statement that presumably corresponds to the electrolyte on the left)
Dynanonic	Supramolecular siloxane-PEO, coupled with click chemistry	$1.2 \times 10^{-2}$ S/cm
118 additional entries		

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

Companies	Critical raw material or process aspects
19 entries	

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).


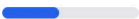
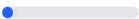
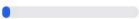
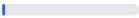
## News reports & press releases

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  $25^\circ\text{C}$ .

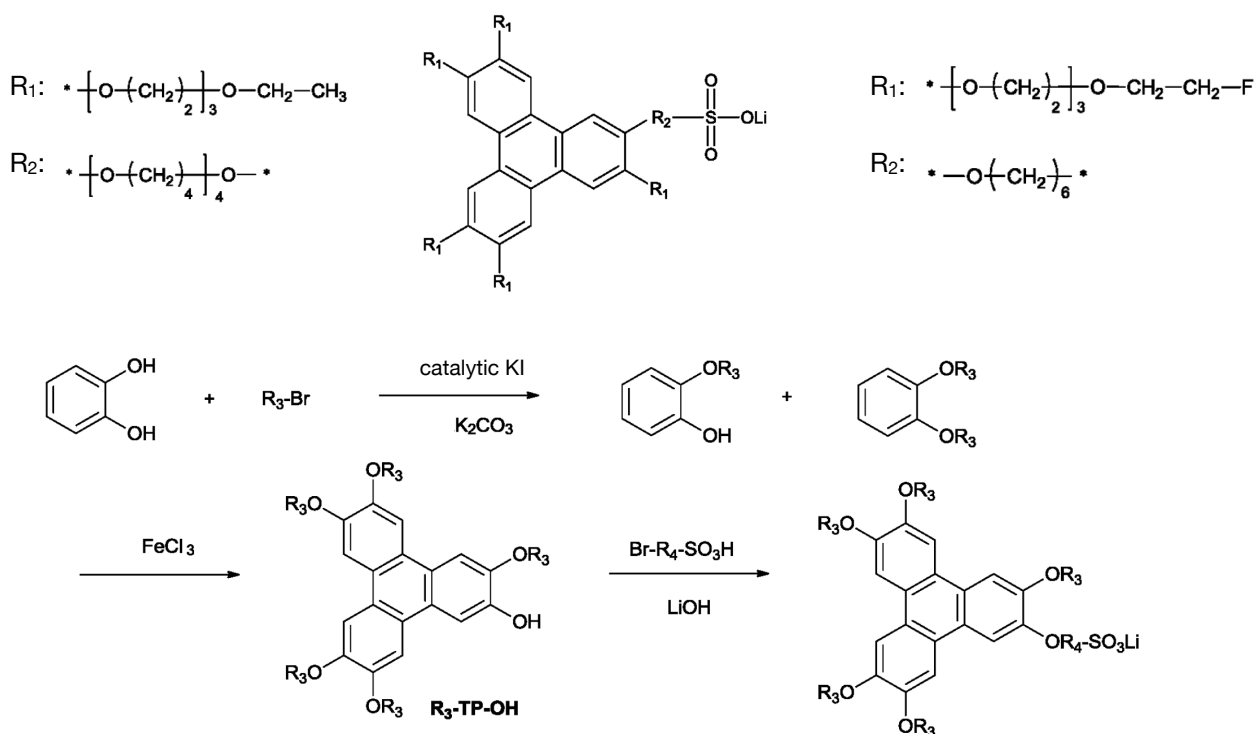
## BACKGROUND INFORMATION

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  $\text{FeCl}_3$  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).

## AI Patent Analysis Methodology

The patent information source for this review is the European Patent Office (EPO), which covers patent filings from more than 100 patent offices around the world. >3M patent documents are included in the b-science.net database that were published since 1980, which either contain the words 'battery' or 'batteries' in the title or abstract, or were assigned to one of the energy storage-related CPC (cooperative patent classification) or IPC (international patent classification) codes: H01M (batteries & fuel cells) or H01G (capacitors). An AI model was defined for commercially relevant Li-ion battery solid / semi-solid / gel electrolytes. Patent documents were grouped into patent families and scored with the AI model. An AI relevancy score cutoff value of 40 was applied (100: very relevant, 0: not relevant). For companies covered with a chapter, AI scores between 35 and 45 were checked manually and false-positives / false-negatives were corrected if necessary.

## Disclaimer

All warranties and liabilities on the part of b-science.net GmbH (LLC) and its affiliates are excluded, including, without limitation, guarantees as to fitness for a specific purpose, non-infringement, accuracy or completeness. Please check our Terms & Conditions and Privacy Policy, which apply to this document.

THIS SERVICE MAY CONTAIN TRANSLATIONS POWERED BY GOOGLE. GOOGLE DISCLAIMS ALL WARRANTIES RELATED TO THE TRANSLATIONS, EXPRESS OR IMPLIED, INCLUDING ANY WARRANTIES OF ACCURACY, RELIABILITY, AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT.