Asian Journal of Innovation and Policy (2023) 12.3:345-362
DOI: https://doi.org/10.7545/ajip.2023.12.3.345

Analysis of Secondary Battery Trends Using Topic Modeling: Focusing on Solid-State Batteries

Chunghyun Do*, Yong Jin Kim**

Abstract As the widespread adoption and proliferation of electric vehicles continue, the secondary battery market is experiencing rapid growth. However, lithium-ion batteries, which constitute a majority of secondary batteries, present high risks of fire and explosion. Solid-state batteries are thus garnering attention as the next-generation batteries since they eliminate fire hazards and significantly reduce the risk of explosions. Against this background, the study aimed to analyze research trends and provide insights by examining 2,927 domestic papers related to solid-state batteries over the past decade (2013–2022). Specifically, we used topic modeling to extract major keywords associated with solid-state batteries research and to explore the network characteristics across major topics. The changes in research on solid-state batteries were analyzed in-depth by calculating topic dominance by year. The findings provide an overview of the emerging trends in domestic solid-state battery research, and might serve as a valuable reference in shaping long-term research directions.

Keywords Secondary battery, Solid-state battery, Topic modeling, LDA, Latent dirichlet allocation

I. Introduction

Secondary batteries, rechargeable batteries capable of permanent use through repetitive charging and discharging, have evolved from lead-acid batteries over the past 120 years to nickel-based batteries and lithium-ion batteries (LIB) (Yu, 2020). LIBs that are widely used at present were invented in US in the 1970s and successfully commercialized by Sony in Japan in 1991 (S.K. Kim, 2023), rapidly replacing conventional nickel-based secondary batteries.

Submitted, December 12, 2023; 1st Revised, December 22, 2023; Accepted, December 28, 2023
* Senior Researcher, Office of R&D Planning, Korea Research Institute of Chemical Technology, Daejeon, Korea; dch125@krict.re.kr
** Corresponding, Principal Researcher, Office of R&D Planning, Korea Research Institute of Chemical Technology, Daejeon, Korea; koine@krict.re.kr

However, the critical disadvantages of LIBs include vulnerability to fire and high risk of explosion. For instance, the Tesla Model S exploded in 2018, and similar accidents involving Toyota Prius and Prius Prime plug-in hybrid models occurred in the same year. In 2022, Hyundai's electric car IONIQ 5 caught fire after colliding with an impact-absorbing barrier in front of a toll booth, resulting in the deaths of passengers.

As a result of these incidents, consumer concerns about LIBs have escalated (K.S. Kim, 2017), leading to increased interest in solid-state batteries as one solution to mitigate fire and explosion risks. Solid-state batteries refer to batteries where all components are in a solid state, with the conventional liquid electrolyte replaced by a solid electrolyte (KIST, 2023). LIBs with liquid electrolytes can lead to significant fires even with minor impacts and have a high possibility of fire and explosion accidents at temperatures above 60°C. On the other hand, solid-state batteries with solid electrolytes are capable of withstanding high impacts and are expected to address the stability issues inherent in LIBs, as they can be used up to approximately 170°C (See Table 1).

Table 1. Advantages and disadvantages of liquid and solid electrolytes

Classification	Liquid electrolyte	Solid electrolyte
Advantages	·High-speed charging and discharging · Suitable for mass production ·Excellent long-cycle properties	·Almost no risk of ignition or explosion ·Safe at high temperatures ·Extremely low self-discharge rate
Disadvantages	·High risk of ignition and explosion ·Significant environmental pollution in case of ignition or explosion ·Poor safety at high temperatures	·Low ion conductivity ·Compromised electrochemical properties ·Room for improvement in long-term performance

Source: Authors, based on Lee and Park (2022).

Due to the characteristics of solid-state batteries, the market is experiencing rapid growth. The solid-state battery market, as shown in Table 2, recorded approximately \$61.6 million in 2020 and is forecasted to grow at an average annual rate of 34.2%, reaching approximately \$482.5 million by 2027. Moreover, the domestic market size is projected to increase from approximately \$2.92 million in 2020 to around \$32.29 million by 2027, with an average annual growth rate of 41.0%.

Table 2. Market outlook for solid-state batteries in the world and Korea (Unit: $1 million)

Classification	World	Korea
2020	61.6	2.92
2021	63.5	3.03
2022	69.8	3.36
2023	82.4	4.4
2025	160.7	10.32
2026	265.1	17.99
2027	482.5	32.29
CAGR	34.2%	41.0%

Source: Authors, based on Kim et al. (2022).

With solid-state batteries emerging as one of the next-generation secondary batteries, researchers are continuously paying attentions to this area. Ha (2021) emphasized the need to develop sulfide solid electrolyte technology for the commercialization of solid-state batteries, while Hwang et al. (2022) conducted a study on the types and development trends of solid electrolytes, a key component of solid-state batteries. Kim (2022) stressed the importance of technology in enhancing solid-state battery performance and adapting to changing demands. Miura et al. (2019) highlighted the need for process technology development to produce solid-state batteries with high ion conductivity.

Previous research in the solid-state battery field primarily focused on qualitative studies, providing technical explanations and discussing R&D directions. However, despite the rapid shift in the paradigm of secondary batteries toward solid-state batteries, few studies have explored core areas that can set R&D directions at the national and corporate levels. Moreover, quantitative analyses utilizing techniques like keyword extraction from papers and patents remain vague.

This study aims to identify common topics of interest in the field of solid-state batteries using quantitative methods. Specifically, by applying topic modeling to papers derived from solid-state battery-related keywords, research trends and future research areas are identified. This study presents an overview of domestic research topics related to solid-state batteries and contribute to the formulation of policies by domestic companies and the government.

This study comprises five chapters. Chapter 2 presents an overview of solid-state batteries and analyzes research trends. Chapter 3 collects data and provides the analytic methodology of topic modelling. Chapter 4 describes the research trends of solid-state batteries that were derived through topic modeling analysis. Finally, Chapter 5 draws conclusions and implications based on the analysis results.

II. Background

As the secondary battery market grows rapidly, the Korean government has actively pursued technological development and implemented policies to foster related industries. Secondary batteries have been designated as one of the 12 national strategic technologies (see Table 3). Through the 2030 Secondary Battery (K-Battery) Development Strategies, the government aims to firmly establish Korea's position in the secondary battery industry by encouraging the development of solid-state batteries and other next-generation secondary batteries (Relevant government ministries, 2021).

Table 3. Secondary batteries in the context of national strategic technology

Key technology	Future materials
·LIB and core materials	·800-km range battery materials, high safety battery materials, etc.
·Next-generation secondary battery materials/cells	·Low-carbon, recyclable, reusable battery materials
·Secondary battery modules/ systems	·New materials for sustainable batteries
·Reuse/recycling of secondary batteries	·Free-form (robotics), biocompatible (medical), extreme environment (aerospace) battery materials

Source: Measures to Foster 12 Major National Strategic Technologies, Ministry of Science and ICT (MSIT) (2022)

Furthermore, during the 16th Emergency Economic Meeting in April 2023, the Ministry of Trade, Industry, and Energy (MOTIE) announced a national strategy aimed at strengthening the competitiveness of the secondary battery industry by mobilizing a total of 20 trillion won in public-private investments by 2030, targeting the world's first commercialization of solid-state batteries (MOTIE, 2023). The plan is to drive large-scale R&D investment for next-generation battery development, focusing on technology development for commercialization of solid-state batteries and lithium-sulfur batteries.

In addition, the MOTIE announced the Industrial Transformation Leading-Edge Project in April 2023, aiming to establish a goal-oriented, outcome-driven R&D system in the field of secondary batteries, including solid-state batteries (see Table 4).

Table 4. Solid-state batteries in the Industrial Transformation Leading-Edge Project

Mission	Project
Realization of technological leap in lithium secondary batteries	·Development of energy density-enhancing components for commercial lithium secondary batteries and driving innovation in DT-based processes
Fostering an ecosystem for battery-based new industries	·Development of biocompatible recycling technology for Battery as a Service (BaaS)
Dominating the next-generation battery market	·Development of high-safety, ultra-lightweight, high-density (solid-state, lithium sulfur, lithium metal) secondary batteries for future mobility

Source: Measures for the Implementation of the Industrial Transformation Leading-Edge Project, Ministry of Trade, Industry, and Energy (MOTIE) (2023)

The Ministry of Science and ICT (MSIT) has initiated the leading-edge R&D strategies for next-generation batteries, highlighting investments in fundamental research that connects materials to manufacturing (MSIT, 2023).

Other than the government, many companies aim to dominate the nascent solid-state battery market during its early stage. As part of South Korea's strategic core material development efforts, the Korea Electronics Technology Institute, Ulsan National Institute of Science & Technology, Sungkyunkwan University, and small and medium-sized enterprises have formed a solid-state battery-related R&D consortium and are conducting relevant research.

Currently, the development of solid-state battery technology among companies is primarily led by Samsung SDI, LG Chem, and SK On, as well as automotive companies like Hyundai Motor.

Samsung SDI is regarded as the most advanced among the three domestic companies in the solid-state battery field. It is focusing on sulfide-based solid-state battery development and has pioneered the world's first anode-only battery technology, securing industry-leading energy density and high safety levels (Maeil Ilbo, 2023).

LG Chem established the Advanced Materials Business Division in 2019 to bolster its R&D capabilities in secondary battery-related materials and is actively conducting research on solid-state batteries (Electronic Times, 2019).

SK On is currently constructing a next-generation battery pilot plant at its battery research institute in Daejeon, targeting completion by 2024. It plans to invest a total of 470 billion won by 2025 to expand the research facility, and establish the next-generation battery pilot plant and global quality management center (Maeil Ilbo, 2023).

Hyundai Motor Group seeks to accelerate the development and validation of next-generation batteries, including solid-state batteries, by establishing a next-generation battery research facility in 2024. Building upon its technology and expertise gained from battery design, it aims to commence pilot production of electric vehicles equipped with solid-state batteries by 2025 and achieve full-scale production around 2030 (Hyundai Motor Group, 2023).

KG Mobility, formerly SsangYong Motor, plans to secure various secondary batteries ranging from lithium iron phosphate and ternary lithium-ion ternary batteries through partnerships with major global secondary battery companies. Following this, its lineup of secondary batteries will be further diversified to include high-performance solid-state batteries (KG Mobility, 2023).

III. Data and Research Methodology

This study aims to identify research trends by applying topic modeling to domestic papers in the field of solid-state batteries. The process involved data collection, preprocessing, and the application of analytical methodologies.

1. Data Collection

To examine research trends in the field of solid-state batteries, this study collected papers using detailed searches in the citation index database provided by Clarivate Analytics, the Web of Science (WoS). Specifically, the search keywords in titles and abstracts included “all-solid-state battery,” “solid electrolyte,” “polymer electrolyte,” “hybrid electrolyte,” and “next-generation battery,” and the document type was set as published articles. The period of data collection ranges from 2010-2022 (10-year).

A total of 3,776 papers affiliated with institutions located in Korea were collected, and after removing 849 duplicates, 2,927 papers were used in the analysis.

2. Data Preprocessing

Data preprocessing refers to transforming unstructured text data into structured data suitable for text mining. In Python 3.10.12, WoS article data was structured into Excel format, with information such as topics and keywords arranged into a two-dimensional list.

To enhance the quality of data analysis, the collected data underwent the following preprocessing steps. Firstly, through tokenization, documents were processed into the smallest analyzable forms of information (Kang & Park, 2019). This involved breaking down the entire document into sentence forms and further dividing sentences into words. For instance, the sentence "All-solid-state battery market is expected to grow rapidly" would be segmented into eight pieces of information: "All-solid-state," "battery," "market," "is," "expected," "to," "grow," and "rapidly." Additionally, uppercase letters were converted to lowercase, and special characters were removed.

Next, words with a length of one character or less were excluded. In the process of removing unnecessary particles, conjunctions, prepositions, meaningless words, and numbers appearing within the document, the root forms of words were selected.

Taking into account the research topics and meaning of derived keywords, some adjectives were converted into noun forms. Additionally, duplicate keywords found in both the title and abstract were consolidated regardless of their frequency of appearance, considering them as occurring once.

Lastly, word stems were extracted using NLTK (Natural Language Toolkit) 3.8.1 and sklearn 1.2.2 within Python. Fig. 1 is an example of data before and after preprocessing.

- 1. Finally, current requisites and future perspectives for the composite solid electrolytes are suggested by help of some decent reviews recently reported.

Before preprocessing

⇩

- Finally current requisite future perspective composite solid electrolyte suggested help decent review recently reported

After preprocessing

Figure 1. Example of preprocessing

The data preprocessing step is related to the conversion of word-document matrices, which lays the foundation for LDA (Latent Dirichlet Allocation) analysis. It reduces the dimensions of matrices and prevents excessive weighting of elements in specific rows or columns. This is a crucial step as it enables clear topic extraction.

3. Analysis Methodology

LDA, initially proposed by Blei in 2003 (Blei et al., 2003), has widely accepted as a useful tool in topic modeling research (Bae et al., 2013). It facilitates analysis of large volumes of documents encompassing multiple topics, and is thus widely utilized in studies analyzing research trends (Kim & Noh, 2019) (see Table 5).

Table 5. Research employing LDA

Author (year)	Description of research
M. M. Kim (2015)	·Extracted keywords from a collection of papers, and analyzed the relationships among major keywords
J. S. Kim et al. (2012)	·Analyzed keywords with high frequency and research topics through topic modeling on titles and abstracts in the field of bioscience
H. J. Kim et al. (2015)	·Analyzed trends by using topic modeling analysis to categorize papers into specific topics
Chung and Lee (2018)	·Performed quantitative analysis on bibliographic data using LDA-based topic modeling to understand research trends in the field of artificial intelligence technology
Adnan et al. (2021)	·Applied LDA to identify technological trends and hotspots in smart factory
Griffiths and Steyvers (2004)	·Applied topic modeling to abstracts to identify hot topics and cold topics at various time periods
Mustak et al. (2021)	·Extracted citation data from WoS in the field of marketing and performed LDA-based topic modeling to objectively categorize major research topics

This study utilized LDA through the Python library sklearn (https://scikit-learn.org/stable/), which incorporates various machine learning algorithms and data preprocessing functions, simplifying the execution of topic modeling analysis (Choi & Park, 2020).

Visualizing the LDA algorithm as depicted in Fig. 2, M represents the number of documents, w is the observable words, and the box's lines denote their repetition. N stands for the count of words in the n-th document, θ refers to the topic distribution in documents, and Z signifies the topic number to which a specific word belongs. α and β represent parameters indicating the patterns of topics and words (Park et al., 2018).

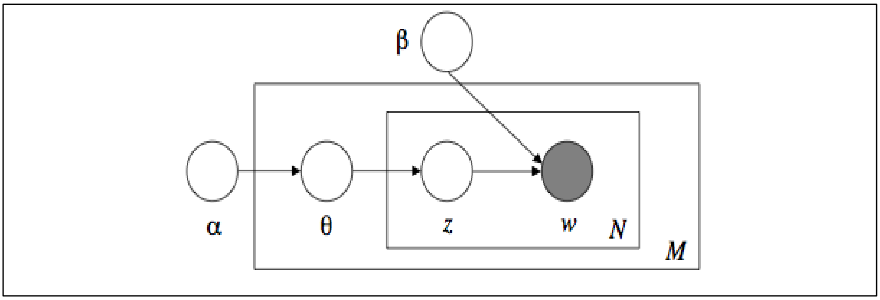

Figure 2. LDA algorithm

Based on the above, the estimation distribution of latent variables (θ, Z) for extracting topics can be expressed as follows (Lee & Lee, 2021).

$$\mathrm{p}(\theta, \mathrm{z}|\mathrm{w}, \alpha, \beta) = \frac{p(\theta, z, w \mid \alpha, \beta)}{p(w \mid \alpha, \beta)}$$

In this study, the parameter α used in LDA was the default value determined through the document set, while β was applied as the default value of 0.1.

The number of topics in this study was determined based on objective indicators such as Coherence and Perplexity to ensure the validity of the analysis. Coherence is a metric used to evaluate the degree of connection between words within the data, where higher coherence among words within a topic implies a better-formed topic (Lee & Lee, 2021).

The equation for the coherence of a given set of words is defined as follows.

$$\mathrm{Coherence(W)} = \sum_{w_1 w_2 \in W} \log \frac{D(w_1, w_2) + \epsilon}{D(w_2)}$$

D(w) is a function indicating the number of documents in which the word w appears at least once, while D(w1, w2) indicates the number of documents in which both words w1 and w2 appear at least once together. ε is a value typically set as 0.01 to prevent the base of the logarithm function from reaching zero (Arora et al., 2012).

A low perplexity is an indicator of a well-structured topic with low disorder. A stable number of topics can be found by identifying the number of topics with the lowest possible perplexity. The equation to calculate perplexity is as follows.

$$\mathrm{Perpexity}(D_{test}) = \exp - \frac{\sum_{d=1}^{M} \log \mathrm{P}(w_{d})}{\sum_{d=1}^{M} N_d}$$

The most suitable number of topics can be chosen as the number associated with the highest coherence before the gradient changes to zero or negative in the coherence curve (Prabbakaran, 2018).

In this study, the coherence was most appropriate when the number of topics was 4, as shown in Fig. 3. Meanwhile, considering the decrease in perplexity with increasing number of topics, and in alignment with the interpretability of the resulting topics, the final decision on the number of topics was made to be 4.

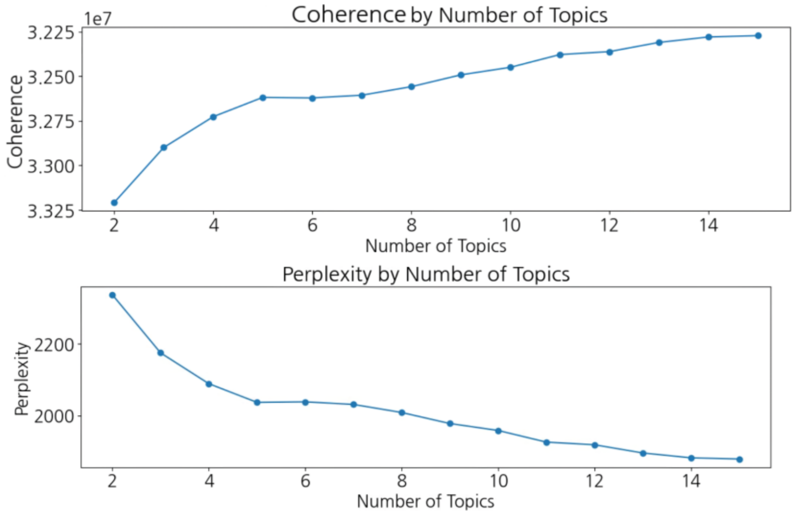

Figure 3. Coherence (top) and perplexity (bottom) in relation to number of topics

IV. Results of Analysis

This study identified the major research themes for each topic. Annual topic dominance was calculated to understand how research trends for individual topics have evolved. After determining the annual trends of each topic, the changes in solid-state battery research over time were analyzed.

1. Identification of Major Keywords

The major keywords derived based on their frequency of occurrence are as presented in Table 6. When arranged in descending order of frequency, the major keywords are “electrolyte,” “high,” “battery,” “cell,” “use,” “electrode,” “cycle,” “performance,” “conductor,” and “material” among others.

The top 10 keywords have shown a consistent increase in frequency since 2013. These top 35 representative keywords account for approximately 46% (29,178 out of 64,161 instances) of the total frequency. “Electrolyte” has the highest frequency at 5,350 instances, showing a substantial 178% increase from 327 instances in 2013 to 910 instances in 2022.

In particular, the keyword occurred 389 times in 2017, and surged by about 34% in the next year, reaching 520 instances in 2018.

Following “electrolyte,” the keywords with high frequencies are “high” (3,005), “battery” (2,884), “cell” (2,783), “use” (2,743), “electrode” (2,594), “cycle” (2,502), “performance” (2,468), “conductor” (2,453), and “material” (2,396).

Through the extraction of major keywords, three patterns were observed. First, keywords such as “energy,” “density,” and “device” emerged after 2017. Notably, all three keywords ranked higher in frequency in 2022 compared to their overall ranking (“energy” 18th → 12th, “density” 21st → 18th, “device” 31st → 26th).

Second, until 2017, keywords like “anode” and “oxid” had high frequencies, but after 2017, they decreased in importance or were replaced by other keywords.

Lastly, compared to 2017, keywords like “lithium” (17th → 2nd), “battery” (7th → 4th), “cycle” (10th → 5th), and “capacity” (16th → 8th) exhibited a sharp increase in frequency in 2022.

Table 6. Keyword frequency by year

Keyword \ Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
electrolyte	327	433	336	426	389	520	569	625	815	910	5,350
high	79	150	142	175	235	337	348	389	524	626	3,005
battery	0	118	159	154	197	332	324	384	592	624	2,884
cell	218	270	256	282	234	258	237	305	371	352	2,783
use	136	197	184	217	202	267	332	239	433	446	2,743
electrode	111	162	179	132	206	302	322	356	382	442	2,594
cycle	0	108	139	137	166	291	318	342	464	537	2,502
performance	121	170	168	177	159	261	289	288	394	441	2,468
conductor	104	138	181	190	210	238	202	250	427	513	2,453
materiel	73	129	131	139	197	265	289	325	380	468	2,396
solid	136	176	182	220	192	217	218	249	348	403	2,341
electrochemical	99	126	140	154	153	208	244	266	363	404	2,157
anode	93	151	137	192	144	222	221	257	327	355	2,099
capacity	0	115	113	0	143	238	237	294	360	450	1,950
lithium	0	0	111	0	139	0	0	248	618	759	1,875

cathode	92	119	0	158	154	180	187	208	296	362	1,756
stability	65	87	92	110	118	153	195	202	294	326	1,642
energy	0	0	0	0	129	261	220	212	347	417	1,586
result	73	93	87	109	111	131	152	163	238	262	1,419
oxid	88	127	113	155	123	141	130	143	176	182	1,378
density	0	0	0	118	0	205	220	205	278	342	1,368
surface	78	121	103	105	93	144	139	183	180	207	1,353
ion	55	71	96	74	103	179	135	174	201	246	1,334
layer	116	134	158	133	150	172	225	231	0	0	1,319
improve	69	95	79	86	85	115	139	164	231	246	1,309
composite	53	66	109	98	95	152	125	142	195	240	1,266
effect	46	105	87	88	78	109	132	139	215	259	1,258
metal	0	49	65	51	85	95	113	174	222	249	1,103
increas	67	124	67	91	88	113	110	125	133	165	1,083
polymer	69	87	74	92	89	109	105	137	153	117	1,032
device	0	0	51	0	83	155	156	137	202	228	1,012
power	54	57	55	88	89	107	107	97	121	137	912
mechanism	0	50	53	59	64	93	79	109	188	185	880
rate	30	0	58	58	67	96	95	104	145	140	793
sei	34	56	0	60	57	80	99	107	123	142	758

2. Topic Identification

After selecting keywords of high importance among the entire keywords, the selected keywords were combined to derive the four topics shown in Table 7.

The four topics were named “Solid Ion Conductors and Solid Electrolytes,” “High-Performance Materials and Nanotechnology,” “Energy Conversion and Storage Technologies,” and “Electrochemistry and Battery Technology.”

The topic “Solid Ion Conductors and Solid Electrolytes” revolves around solid-state electrolytes and ion conductors, which are substances crucial for facilitating the flow of electrical energy. This topic finds applications in diverse fields such as batteries, fuel cells, and electronic devices.

“High-Performance Materials and Nanotechnology” pertains to high-performance materials and nanotechnology. Nanotechnology is used to manipulate the microstructure of constituents in solid-state batteries, enhancing performance, stability, and energy density.

“Energy Conversion and Storage Technologies” focuses on energy conversion and storage. This topic covers efficient utilization and storage of renewable energy and sustainable energy supply technologies.

"Electrochemistry and Battery Technology" deals with electrochemistry and battery technology. It addresses topics associated with enhancing battery performance and efficiency in fields like electric vehicles and electronic devices.

Table 7. Topic identification

All keywords	Topic
electrolyte, solid, ion, solid-state, cell, anode, cathode, layer, composite, metal, oxide, surface, polymer, material, structure, conductivity, density, SEI, cycle, power, stability, result, effect, increase, rate, mechanism, improve, device, use, energy, battery, conductor	Solid Ion Conductors and Solid Electrolytes
high, performance, material, nanotechnology, solid, metal, oxide, polymer, composite, cell, battery, cycle, rate, mechanism, device, increase, improve, effect, result, capacity, use, electrolyte, density, solid-state, power, ion, layer, surface, stability, energy	High-Performance Materials and Nanotechnology
energy, storage, battery, cell, power, capacity, high, solid-state, electrolyte, cycle, rate, material, structure, device, composite, polymer, ion, layer, surface, metal, oxide, density, effect, increase, improve, result, use, stability	Energy Conversion and Storage Technologies
electrochemistry, battery, technology, lithium, lithium-ion, cell, electrolyte, electrode, cycle, performance, rate, high, stability, voltage, discharge, recharge, power, solid-state, material, metal, ion, surface, oxide, layer, composite, polymer, density, effect, increase, improve, use	Electrochemistry and Battery Technology

Upon examining the changes in the proportions of the four topics over time, it is evident that "Electrochemistry and Battery Technology" has gained the most attention since 2019. Among the four topics, research on "Solid Ion Conductors and Solid Electrolytes" and "Energy Conversion and Storage Technologies" have shown a declining trend (see Table 8).

On the contrary, "High-Performance Materials and Nanotechnology" has exhibited a consistent upward trend since 2013.

Table 8. Changes in annual proportion of the four topics

Topic	Proportion (%)									
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Solid Ion Conductors and Solid Electrolytes	30.2	29.2	35.3	32.1	22.5	21.5	20.9	9.6	21.0	9.6
High-Performance Materials and Nanotechnology	31.0	30.3	22.4	14.4	22.8	6.4	37.6	25.8	37.8	25.9
Energy Conversion and Storage Technologies	17.8	22.2	31.1	23.8	30.4	52.2	13.1	4.4	12.4	4.3
Electrochemistry and Battery Technology	21.0	18.3	11.2	29.7	24.3	19.9	28.4	60.2	28.8	60.2

3. Matching Between Major Keywords and Topics

The 35 major keywords identified in this study were matched to four topics, in consideration of topic meanings.

The topic “Solid Ion Conductors and Solid Electrolytes” is associated with keywords like “electrolyte,” “solid,” “ion,” “conductor,” and so forth. The topic “High-Performance Materials and Nanotechnology” is related to keywords such as “high,” “performance,” “material,” and “density.”

“Energy Conversion and Storage Technologies” is connected with keywords like “energy,” “capacity,” “cycle,” and “stability,” and “Electrochemistry and Battery Technology” is associated with “electrochemical,” “electrode,” “mechanism,” and the like (see Table 9).

Table 9. Matching between major keywords and topics

Major keywords	Topic
electrolyte, solid, ion, anode, cathode, layer, composite, conductor, polymer, SEI	Solid Ion Conductors and Solid Electrolytes
high, performance, material, density, surface, metal, device	High-Performance Materials and Nanotechnology
energy, battery, cell, effect, cycle, power, stability, result, use	Energy Conversion and Storage Technologies
electrochemical, electrode, lithium, oxid, improve, capacity, increase, mechanism, rate	Electrochemistry and Battery Technology

V. Conclusion and Implications

1. Research summary

This study aimed to examine the trends in solid-state battery research from 2013 to 2022, and provide insights for future research in this field. For this purpose, topic modeling analysis was performed on 2,927 solid-state battery articles published in the Web of Science (WoS) during 2013–2022. The findings are as follows.

First, the analysis revealed 35 major keywords such as “electrolyte,” “high,” “battery,” “cell,” “use,” “electrode,” “cycle,” “performance,” “conductor,” and “material.” The frequency of the top 10 keywords has steadily increased since 2013, and except for “electrolyte,” the rankings of most major keywords have changed over the analysis period. Moreover, new keywords like “energy,” “density,” and “device” emerged after 2017, and there was a significant increase in the frequency of keywords such as “lithium” (17th→2nd), “battery” (7th→4th), “cycle” (10th→5th), and “capacity” (16th→8th) from 2017 to 2022.

Second, the results of topic modeling revealed four distinct topics: “Solid Ion Conductors and Solid Electrolytes,” “High-Performance Materials and Nanotechnology,” “Energy Conversion and Storage Technologies,” and “Electrochemistry and Battery Technology.” These four topics verify the diverse range of research in related fields.

From examining the weights of the four topics by year, a distinct sharp increase was observed in research related to battery performance enhancement, efficiency, high performance, stability, and energy density improvement under the topics of “Electrochemistry and Battery Technology” and “High-Performance Materials and Nanotechnology” since 2019. Conversely, there was a relative decline in research associated with electrical conductivity and energy storage for the topics “Solid Ion Conductors and Solid Electrolytes” and “Energy Conversion and Storage Technologies.” By matching the 35 major keywords with the four topics, it was confirmed that the keywords and research themes of the topics are interacting with each other.

2. Implication

Based on these research findings, the implications of this study are as follows. First, “electrolyte,” “use,” “conductor,” “performance,” and “electrode” are consistently discussed as important keywords. Through topic modeling analysis, it was found that research related to battery performance enhancement, efficiency, high performance, stability, and energy density improvement is actively ongoing. This highlights the attention received by solid-state batteries as a type of battery capable of addressing the drawbacks of traditional LIBs.

This shift in keywords can be interpreted as a reflection of the evolving interest among related researchers in technological advancement and innovation. Furthermore, by recognizing these trends, this study is expected to lay a foundation for predicting the future direction of secondary battery research and exploring potential industrial applications.

Secondly, research focused on battery performance enhancement since 2019 accounts for approximately 60% of all solid-state battery research. On the other hand, studies related to renewable energy utilization and storage represent about 4%, the lowest proportion. This indicates that current trends in solid-state battery research emphasize enhancing battery performance, while research in renewable energy-related fields appears relatively limited.

These trends align with the efforts of major Korean secondary battery companies and automotive firms striving for the highest energy density and enhanced safety in solid-state battery development. It is anticipated that future investments by companies will continue in this direction.

Third, by matching major keywords with topics, primary themes and research content could be identified.

The “Electrochemistry and Battery Technology” topic, which has accounted for the largest proportion since 2019, is associated with keywords such as “electrochemical,” “electrode,” “lithium,” “oxid,” “improve,” “capacity,” “increase,” “mechanism,” and “rate.” These results reaffirm that solid-state battery research is predominantly focused on studies related to battery performance enhancement.

The above trends can be predicted to have a substantial impact on the establishment of research strategies for the development of safe, lightweight, and high-density solid-state battery technology. As mentioned earlier, such efforts are being made as part of the government's 2030 Secondary Battery Industry Development Strategies and the MOTIE's Industrial Transformation Leading-Edge Project.

3. Limitation

This study presents the following limitations. First, while this research aimed to address the limitations of conventional literature review methods and conduct a more objective analysis by using topic modeling analysis, it was challenging to entirely eliminate the researcher's subjectivity in reviewing the targeted studies, determining the topic names associated with the derived topics, and interpreting the research results. Regardless, the process of deriving keywords and topics in the actual analysis was performed as objectively as possible. Second, the papers included in the topic modeling analysis were limited to those from researchers affiliated with institutions located in Korea. This presents a limitation as it confines the discussions to domestic research without taking into account international research trends. More meaningful results can be obtained through follow-up studies that examine international research trends, allowing for comparative analysis with the current findings.

References

Blei, D., and Lafferty, J.D. (2009). Topic Models, Text Mining: Classification, clustering, and application, 10(71), 1-34.

Blei, D., Ng, M., and Jordan, M. (2003). Latent Dirichlet allocation, Journal of Machine Learning Research, 3, 993-1022

Griffiths, T.L., and Steyvers, M. (2004), Finding scientific topics, Proceedings of the National academy of Sciences, 101(1), 5228-5235

Ha, Y.C. (2021). Recent Trends in Sulfide Solid Electrolyte Technology for the Practical Development of All-Solid-State Batteries, Journal of the Korean Battery Society, 1(1), 76-80.

Hussain, A., Kim, C., Battsengel, G., and Jeon, J. (2021). Analyzing Technological Trends of Smart Factory using Topic Modeling. Asian Journal of Innovation & Policy, 10(3).

Joo, D.Y. (2018). The Current Status and Development Issues of the Domestic Secondary Battery Industry, Sejong: Korea Institute for Industrial Economics and Trade.

Kang, M.S., Park, J.H., Kim, H.O., and Kim, H.J. (2019). A Study on the Alignments Analysis Between Strategy and Budget of the Government R&D's Major Sectors, Seoul: Korea Institute of Science & Technology Evaluation and Planning.

Kim, G.C., and Noh, H.J. (2019). Research Trends of Regional Geography Education Using Topic Modeling", Journal of the Korean Social Studies Association, 58(4), 49-67.

Kim, H.J., Cho, N.O., and Shin, K.S. (2015). Text Mining-Based Emerging Trend Analysis for the Aviation Industry, Journal of Intelligence and Information Systems, 21(1), 65-82.

Kim, J.W. (2022). Solid-State Batteries as Next-Generation Batteries, Daejeon: Korea Institute of Science and Technology Information.

Kim, K.S. (2017). Research and Development Trends in Solid Electrolytes and Solid-State Batteries for Enhanced Safety in High-Energy Secondary Batteries, Journal of the Korean Institute of Electrical and Electronic Material Engineers, 30(7), 20-31.

Kwon, K.S., and Kim, S.Y. (2023). Analysis of socio-economic issues of ChatGPT based on LDA topic modeling, Journal of Korea Technology Innovation Society, 26(4), 593-612.

Lee, J.Y., and Lee, B.H. (2022). Sentiment Analysis and Issue Mining on All-Solid-State Battery Using Social Media Data, The Journal of the Korea Contents Association, 22(10), 11-21.

Lee, M.J., Han, J.H., Lee, K.B., Lee, Y.J., Kim, B.G., Jung, K.N., Kim, B.J., and Lee, S.W. (2022). Elastomeric electrolytes for high-energy solid-state lithium batteries, Nature, 601, 217–222

Lee, K.S., and Park, J.W. (2022). Solid-State Batteries, Seoul: Korea Institute of Science & Technology Evaluation and Planning.

Ministry of Science and ICT (2022). Measures to Foster 12 Major National Strategic Technologies, Sejong: Ministry of Science and ICT.
Ministry of Trade, Industry and Energy (2023). Measures for the Implementation of the Industrial Transformation Leading-Edge Project, Sejong: Ministry of Trade, Industry and Energy.
Park, J.H., Kang, M.S., Kim, Y.J., and Kim, H.H. (2018). A Study on Government R&D Strategy and Investment Using Text Mining Analysis, Korea Technology Innovation Society 2018 Fall Conference Proceedings, 648-694.
Park, S.B. (2022). Recent Advances in Interface Engineering for All-Solid-State Batteries, Journal of the Korean Ceramic Society, 25(1), 104-121.
Relevant government ministries (2021). 2030 Secondary Battery Industry (K-Battery) Development Strategies.