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İSTANBUL KÜLTÜR UNIVERSITY
INSTITUTE OF GRADUATE STUDIES

Implementation of Advanced Battery Technologies for Electric Mobility, Renewable Energy Storage, and Electronic Devices Using the TOPSIS Method

Master of Science Thesis

MUHAMMED AKKARI
2100006455

Department: Industrial Engineering
Program: Engineering Management

Supervisor: Assist. Prof. İBRAHİM ETHEM TARHAN

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Date   Name SURNAME

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Table of Contents

LIST OF TABELS

List of Figures

Üniversite	**: İstanbul Kültür Üniversitesi**
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ÖZET

Muhammed AKKARI

Katı haldeki piller, özellikle elektrikli araçlar, yenilenebilir enerji depolama ve akıllı telefonlar ve giyilebilir cihazlar gibi küçük cihazlar olmak üzere birçok sektörde devrim yaratmaya hazırlanıyor. Bu, çevre koruma yasalarının yürürlüğe girmesinden sonra enerji depolama sistemlerine olan artan talep ve mevcut lityum iyon pillerindeki güvenlik sorunlarından kaynaklanmaktadır. Sıvı elektrolit kullanan mevcut lityum iyon pillerden farklı olarak, katı haldeki piller katı bir elektrolit malzemesi kullanır. Bu çalışma, İdeal Çözüme Benzerlik Sırasına Göre Tercih Sıralaması Tekniği (TOPSIS) yöntemini kullanarak en iyi katı hal pil türünü belirlemeyi amaçlamaktadır. Polimer bazlı, sülfür bazlı ve oksit bazlı katı piller olmak üzere üç alternatif karşılaştırılmaktadır. Maliyet, verimlilik, kullanım ömrü, güvenlik, kar marjları ve çevresel etki olmak üzere altı temel kriter dikkate alınmıştır. Her ne kadar katı hal piller hakkındaki araştırmalar ve çalışmalar hala nadir olsa da, kapsamlı bir değerlendirme sağlamak için her kriter dikkatlice değerlendirilmiştir. Daha sonra TOPSIS yöntemi, pil türlerini ideal bir çözüme göre göreceli yakınlıklarına göre sıralamak için uygulanmıştır. Sıvı elektrolitli mevcut pillerle rekabet edebilmek için katı hal pillerin verimliliğini ve kapasitesini artırmak için daha fazla çalışmaya ihtiyaç duyulmasına rağmen, sonuçlar sülfür bazlı katı hal pillerin ideal seçenek olduğunu ve değerlendirilen tüm kriterlerde en uygun dengeyi gösterdiğini ortaya koymaktadır. Bu, sülfür bazlı pillerin enerji depolama teknolojisinde ilerlemeleri sağlamada önemli bir potansiyele sahip olduğunu düşündürmektedir. Verimlilik ve güvenlik gibi kritik alanlarda mükemmellik gösterirken makul maliyetleri ve minimum çevresel etkiyi koruyan sülfür bazlı katı hal piller, çeşitli uygulamalarda enerji depolama alanının geleceği için umut verici bir çözüm olarak öne çıkmaktadır.

Anahtar Kelimeler: Katı halde piller, Elektrikli araçlar, Yenilenebilir enerji depolama, TOPSIS yöntemi, Polimer esaslı katı halde piller, Sülfür esaslı katı halde piller, Oksit esaslı katı halde piller.

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ABSTRACT

Solid-state batteries are poised to revolutionize multiple industries, especially electric vehicles, renewable energy storage, and small devices such as smartphones and wearables. This is due to the increased demand for energy storage systems after the enactment of environmental conservation laws and the safety problems in current lithium-ion batteries. Unlike current lithium-ion batteries that use liquid electrolytes, solid-state batteries utilize a solid electrolyte material. This study aims to identify the best type of all-solid-state battery using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method, comparing three alternatives: polymer-based, sulfide-based, and oxide-based solid batteries. Six key criteria were considered: cost, efficiency, lifetime, safety, energy densities, and ionic conductivity. Although the researches and studies about all solid state batteries are still rare. Each criterion was carefully evaluated to ensure a thorough assessment. The TOPSIS method was then applied to rank the battery types based on their relative closeness to an ideal solution. Although more studies are needed to enhance the efficiency and capacity of solid-state batteries to compete with current batteries with liquid electrolytes, the results indicate that sulfide-based solid-state batteries are the ideal option, demonstrating the most favorable balance across all evaluated criteria. This suggests that sulfide-based batteries have significant potential to drive advancements in energy storage technology. By excelling in crucial areas such as efficiency and safety while maintaining reasonable costs and minimal ionic conductivity, sulfide-based solid-state batteries stand out as a promising solution for the future of energy storage across various applications.

Keywords: Solid-state batteries, Electric vehicles, Renewable energy storage, TOPSIS method, Polymer-based solid batteries, Sulfide-based solid batteries, Oxide-based solid batterie

1. INTRODUCTION

The advancements of sustainable energy solutions have reached a peak in recent years, driven by the need to strive against climate change, reduce fossil fuel dependency and environmental impact. Rechargeable lithium-ion batteries (LIBs) have been used for portable electronic devices so far and have recently expanded to mid-large-scale electrochemical energy storage applications, including electric vehicles (EVs) and power grid stations. But to succeed in EVs industry, battery technology must exceed current limitations in driving ranges by achieving larger capacity. A worldwide technical goal for the year 2030 requires secondary batteries to have a specific energy of 500 Wh kg−1, much higher than the 246 Wh kg−1 of typical EV batteries. A Li-metal anode is considered a top-ranking component for this high energy density. However, current LIB technology using liquid electrolytes cannot meet the requirements for a Li-metal anode or safety.

Lithium-ion batteries (LIBs) are a popular choice for electric vehicles and portable electronics. But due to their safety issues, such as flammable liquid electrolytes and limited energy density there are chances for numerous incidents, particularly in electric vehicles and portable electronics. The energy density limitations of LIBs also affect the efficiency of renewable energy storage systems, which require large-scale, high-capacity storage solutions. Environmental and economic concerns also complicate the widespread use of LIBs. The extraction and processing of lithium, cobalt, and other materials used in LIBs have significant ionic conductivities, including habitat destruction, water pollution, and high carbon emissions. Recycling and disposal of LIBs also pose environmental challenges leading to resource wastage and the geopolitical distribution of these resources raises concerns about supply chain security.

In contrast, All-solid-state batteries (ASSBs), which use inorganic solid-state electrolytes (SSEs), have emerged as a promising alternative to conventional Lithium-Ion batteries (LIBs) having liquid electrolyte. SSEs offer several advantages over liquid electrolytes, including stability in extreme environmental conditions such as high pressure, temperature, overcharge, or external shock etc., and improved volumetric energy density. They can be designed through bipolar stacking, eliminating the need to pack each cell, and reducing the volume of the battery, thereby reducing the risk of ignition or explosion. ASSBs offer superior safety, energy density, and longevity compared to conventional lithium-ion batteries.

All-solid-state batteries (ASSBs) eliminate leakage risks and thermal explosion. The solid electrolyte is more stable at higher temperatures and less reactive, making ASSBs safer and more reliable for various applications. ASSBs utilize high-capacity electrode materials like lithium metal anodes, which have a higher energy density than graphite anodes used in conventional LIBs. This overcomes the challenge of longer driving ranges for electric vehicles and renewable energy storage systems. The improved energy density will lead to advanced, high-performance, and smaller size portable electronic devices which aligns with the growing consumer demands.

ASSBs, or Advanced Solid-State Batteries can resolve environmental and economic issues associated with lithium-ion batteries. They can be made from more abundant and environment friendly materials, and their improved stability and longevity will reduce battery replacement frequency. The development of efficient recycling methods for ASSBs is expected to be easier due to the steadiness of solid-state materials. These batteries hold transformative potential across sectors like electric mobility, renewable energy storage, and electronic devices.

In summary, while lithium-ion batteries have been useful in the advancement of energy storage technologies, their limitations highlight the need for next-generation solutions. All-solid-state batteries represent a significant step forward, offering improved safety, higher energy densities, and potential environmental benefits. Currently, lithium-ion batteries (LIBs) dominate the energy storage systems due to their high energy density, long cycle life, and mature production processes. However, these batteries have several limitations that restrict their validity for future energy demands and applications. ASSBs are gaining attention due to their potential applications in electric mobility, renewable energy storage, and electronic devices. However, they also present challenges such as high material costs, precise control over solid-solid interfaces, and scalable production techniques. Despite these challenges, research and development is progressing in manufacturing cost-effective solid electrolytes, optimizing electrode-electrolyte interfaces, and scaling down manufacturing processes.

This thesis investigates the implementation of advanced ASSB technologies in these areas using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

method to evaluate and prioritize technological options based on performance metrics. Through this research.
All-solid-state batteries (ASSBs) have a long history dating back to the mid-20th century. The discovery of silver iodide's high ionic conductivity in the 1960s provoked interest in solid-state ionic materials, leading to broad research on sulfides, oxides, and polymers. Early studies focused on understanding their fundamental properties and potential energy storage applications. In the late 20th century, the development of Advanced Solid-State Battery (ASSB) made progress due to the limitations of traditional lithium-ion batteries and the growing demand for safer, more efficient energy storage solutions. Researchers aimed to address safety concerns with liquid electrolytes in LIBs, which were disposed to leakage, flammability, and thermal explosion. The solid-state nature of ASSBs inherently eliminates these risks, as solid electrolytes are non-flammable and can resist higher temperatures, making them safer and efficient. Advancements in material science and nanotechnology in the 1990s and early 2000s led to the development of new materials with improved ionic conductivity and stability, such as lithium garnet oxides and sulfide-based electrolytes with improved ionic conductivities, bringing ASSBs closer to practical application.

In parallel, significant efforts were made to address the interfacial challenges in ASSBs. The interfaces between the solid electrolyte and the electrodes play a crucial role in the overall performance of the battery. Issues such as high interfacial resistance, mechanical stress, and chemical instability at these interfaces cause potential hurdles to the practical deployment of ASSBs. To overcome these challenges, researchers implemented various strategies, including surface coatings, interface engineering, and the development of composite electrolytes, which combine different materials to enhance performance.
Over the past decade, there has been significant progress in the development and commercialization of ASSBs, with tycoons, entrepreneurs and research institutions investing heavily in this technology. Prototype ASSBs have indicated high energy density, long battery life, and enhanced safety, making them feasible for various applications. Research is now focused on scalability and fabrication of ASSBs, using techniques like thin-film deposition, 3D printing, and advanced manufacturing processes. Researchers have also explored cost-effective materials to reduce production costs. These efforts are crucial for transformation of ASSBs from the laboratory to commercial markets, where they can compete with and eventually replace conventional Lithium-Ion batteries. Regardless of these

remarkable advancements, challenges like high solid electrolyte material costs, manufacturing process difficulty, and need for ionic conductivity and interfacial stability still exist. Addressing these issues requires a multidisciplinary approach involving material science, engineering, and economics.

Even though lithium-ion batteries (LIBs) seem like the best option right now, they come with some scary safety risks. This is because they use liquid electrolytes, which can leak, catch fire, or even explode, especially in electric vehicles (EVs). The limited energy density of LIBs also restricts the driving range and efficiency of EVs. In the field of renewable energy storage, LIBs are unable to provide durable and high-capacity energy storage solutions. In electronic devices, the demand for longer battery life and improved safety remains unfulfilled due to the limitations of LIB technology.

Advanced Solid-State Batteries (ASSBs) are encouraging solutions for battery safety and thermal stability in electric vehicles (EVs) and electronic devices as they eliminate risks associated with liquid electrolytes. ASSBs are non-flammable and can bear higher temperatures without degradation and explosion. ASSBs can also offer higher energy density through advanced materials like lithium metal anodes, extending the range of EVs and improving renewable energy storage efficiency. However, practical implementation faces challenges like high material costs and manufacturing difficulties.

This study aims to evaluate and prioritize the implementation of advanced all-solid-state battery (ASSB) technologies in electric mobility, renewable energy storage, and electronic devices. Despite their advantages, worldwide adoption of ASSBs faces challenges. The research aims to identify these challenges, explore ASSBs' potential, and use the TOPSIS method to determine effective strategies for their implementation. The study uses the TOPSIS method, a multi-criteria decision-making (MCDM). This method compares various ASSB technologies based on safety, battery life, energy density, cost, and scalability.

Research Problem: The ultimate research problem is articulated as: How can advanced all-solid-state battery technologies be ideally implemented in various sectors like electric mobility, renewable energy storage, and electronic devices, to maximize their benefits and overcome existing challenges?

All-solid-state batteries (ASSBs) are evaluated for their suitability in electric mobility, renewable energy storage, and electronic devices. This evaluation will be achieved by identifying analytical performance metrics for ASSB assessment in each sector. Additionally, the TOPSIS method will be applied to prioritize and assess different ASSB technologies based on the identified metrics. Finally, the challenges hindering large-scale ASSB implementation, including technological, economic, and environmental factors, will be analyzed. Aligned with this evaluation process, the research objectives are defining performance metrics for ASSB assessment in each target sector, developing a TOPSIS-based framework for technology evaluation, analyzing the aforementioned challenges, and proposing solutions and recommendations for stakeholders in the electric vehicles, energy storage, and electronic device manufacturing industries.

This study aims to improve understanding and implementation of all-solid-state battery (ASSB) technologies across various sectors by addressing research gaps and challenges. It provides insights to accelerate the transition from conventional LIBs to safer, more efficient, and higher-performance energy storage solutions. The findings will contribute significantly to academic research and industrial applications, offering a comprehensive framework for evaluating and prioritizing ASSB technologies.

The study uses the TOPSIS method to evaluate ASSBs based on performance metrics which provide a comprehensive evaluation of various ASSB technologies and act as a reference for future research. The analysis of technological, economic, and environmental factors influencing ASSB implementation offers a holistic understanding and informed future decisions.

From an industry perspective, the insights gained from this study can urge innovation and strategic decision-making in sectors such as electric mobility, renewable energy storage, and electronic devices. For manufacturers and developers of electric vehicles (EVs), the study emphasizes the potential of ASSBs to overcome the safety and energy density limitations of LIBs, leading to the development of safer, longer-range, and more efficient EVs.

ASSBs are game changers in renewable energy storage due to their ability to operate at higher voltages and store more energy per unit volume than conventional batteries. Their higher energy density opens ways for more renewable energy sources like solar or wind power to be more reliable than before. For example, Solid-state lithium-ion batteries have proven their potential for grid energy storage, providing a stable and reliable way to balance electricity supply and demand. ASSBs can also be used in electric vehicles (EVs) to extend driving range per charge due to higher energy capacity and reduce battery-related issues, aligning with the global transition to reduce carbon emissions and tackle climate change. ASSBs also have applications in the automotive industry, particularly in electric vehicles

(EVs). They can reduce the overall weight of the battery pack, improving vehicle efficiency and performance. A lighter battery pack leads to better handling and acceleration and overall EVs design for passenger space and convenience can be improved.

ASSBs are ideal for electronic devices, such as smartwatches, fitness trackers, laptops, and portable devices due to their thinner, lighter, and more flexible design. In computing and mobile technologies, ASSBs offer longer battery life for smartphones and tablets due to their higher energy density. Companies are exploring ASSBs to extend usage times between charges, a significant improvement over current lithium-ion battery. This could enhance user convenience and reduce the need for frequent charging. They also offer increased stability in harsh environments, making them ideal for research and exploration.

The implementation of all-solid-state batteries (ASSBs) is composed to revolutionize sectors such as electric mobility, renewable energy storage, and electronic devices. The scope of this implementation incorporates extensive research and development techniques aimed at optimizing the performance metrics of ASSBs, identifying suitable applications, and solving technical challenges.

Electric Mobility: ASSBs are expected to significantly impact electric vehicles (EVs) by providing higher energy densities and improved safety compared to conventional lithium-ion batteries. The population of study includes the latest EV models and prototypes designed for ASSB integration. A proposed sample size would involve multiple vehicle types, ranging from passenger cars to commercial vehicles, to assess the performance across different automotive applications. Research methodology will focus on real-world driving range cycles, battery life, and safety testing under various environmental conditions. Inclusion criteria will be vehicles that can integrate ASSBs without significant redesign. Control variables such as temperature and charging time must be standardized to ensure consistent results.

Renewable Energy Storage: ASSBs have the potential to enhance the efficiency and reliability of storing energy from renewable sources like solar and wind energy. The population of study here includes grid-scale storage systems and residential storage solutions. The sample size would be determined by the capacity of the storage systems, ranging from small home batteries to large utility-scale installations. Research methodology involves long-term cycling tests, efficiency analysis, and grid simulation models to evaluate performance under fluctuating renewable energy inputs. Inclusion criteria are storage systems that can be directly connected to renewable energy sources, while exclusion criteria are those dependent on non-renewable energy sources. Control variables like charge/discharge rates and discharge depth must be carefully monitored to avoid biased results.

Electronic Devices: The application of ASSBs in electronic devices aims to extend device lifetime and reduce charging times. The population of study includes smartphones, laptops, and wearable technology and sample size of diverse range devices with different power requirements. Research methodology will involve user experience analysis, battery longevity, and performance tests under different usage patterns. Inclusion criteria will be devices that use rechargeable batteries, excluding the devices designed for single-use batteries. Control variables such as usage intensity and charging habits are crucial to consider, as they significantly affect battery performance metrics.

In all these applications, performance metrics such as energy density, power density, cycle life, and safety will be key indicators of ASSB feasibility. Currently available ASSBs include prototype EVs with extended travel range, home energy storage systems installed with solar panels, and smartphones with rapid charging.

Despite the wide scope, this study concedes several limitations that can affect the results. The availability of up-to-date and comprehensive data on advanced ASSB technologies may be limited, which could impact the accuracy of the evaluation and prioritization process. Additionally, ASSB technologies are still under development, and their performance metrics may evolve rapidly. The study's findings are based on current technology, which may change as new advancements are made. Furthermore, the economic factors affecting the commercialization of ASSBs, such as material costs and market demand, are subject to fluctuations. These variations could affect the study's recommendations and their implementations over time. Lastly, the environmental benefits of ASSBs are evaluated based on available data and assumptions, but actual ionic conductivities may vary depending on specific production practices and lifecycle management strategies.

This thesis is organized into five chapters, each providing a comprehensive analysis of the research topic. Chapter 1 introduces the research topic, outlines the context and background, defines the research problem, research questions and objectives, and highlights the scope and significance of the study. Chapter 2 showcases the previous research done on all-solid-state batteries, their implementation in electric mobility, renewable energy storage, and electronic devices, along with the application of the TOPSIS method in technology evaluation. Chapter 3 explains the chosen research design, data collection methods, and the application of the TOPSIS method to evaluate and prioritize ASSB technologies based on multiple performance metrics such as cost, battery life, energy density, and charging speed. Chapter 4 thoroughly presents the results evaluated, including a discussion on the implications for each of the three sectors. Finally, Chapter 5 summarizes the key findings, discusses the limitations of the study, and provides recommendations for future research and practical implementation.

2. LITERATURE REVIEW

Electric mobility and renewable energy sources are rapidly growing sectors with the potential to provide more sustainable transportation and power solutions. However, the integration and efficiency of these technologies relies heavily on energy storage solutions, with batteries being the main option (Eseye et al., 2019).With various new battery chemistries and technologies being developed, assessing their viability across multiple performance criteria poses a significant challenge. Multi-criteria decision analysis (MCDA) techniques provide a structured approach for such complex priority-setting and selection between alternatives. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is one popular MCDA method adopted in technology evaluations across domains. This literature review analyses existing research on battery technologies, their applications in mobility and renewables, use of MCDA methods particularly TOPSIS for technology assessments, and identifies research gaps for implementing TOPSIS in the evaluation and selection of advanced battery technologies across the focused sectors.

Numerous scholars have conducted investigations into emerging battery technologies such as lithium-ion, zinc-based, sodium-ion, and solid-state batteries, considering them as potential options for sectors such as electric transportation and the integration of large-scale renewable energy sources, each of which imposes strict technical performance criteria (Hirsh et al., 2020). These studies have emphasized enhancements in parameters such as energy density, lifetime, and safety features, while also pointing out the technological constraints and development time phases associated with alternatives to the predominant lithium-ion batteries. Through detailed examinations of the implementation and obstacles encountered with current lithium-ion batteries in electric cars and stationary energy storage systems for solar power generation, researchers have delved into crucial aspects including production scalability, opportunities for secondary usage, and the imperative of environmental sustainability, all of which serve as fundamental considerations that novel chemical compositions and supply networks need to confront (Ahmadi et al. 2014). Analyses of trends in battery usage and the evolution of standards in electronics such as laptops, and mobile devices serve to further depict the key characteristics that are in demand, such as faster charging times, resilience to varying temperatures, and the implementation of modular designs, which could potentially be applied to a wide array of other applications (Lu et al., 2022). These aspects play a crucial role in establishing the criteria that need to be considered when comparing newly developed battery solutions with those that are already established within the specific sectors under consideration.

Methods of Multi-Criteria Decision Analysis (MCDA) such as the Analytic Hierarchy Process (AHP), VIKOR, fuzzy set theory, and TOPSIS have been massively utilized for conducting evaluations of various technologies (Lamrini, Abounaima, & Talibi Alaoui, 2023). Even though these methodologies share a common focus on addressing subjective evaluations of criteria and managing uncertainties, which sets them apart from conventional financial or technical models, they differ in terms of the data inputs, such as the need for pairwise comparisons in the case of AHP, and their sensitivity to the different weighting schemes of criteria in the instance of VIKOR. TOPSIS, on the other hand, offers a straightforward computational method that is grounded in logic for selecting the best possible options based on their proximity to the ideal solution, a concept that remains valid even when dealing with incomplete datasets (Singha et al. 2022).

Recent research has illustrated the application of TOPSIS in a variety of contexts, including technology sustainability assessments, drug therapeutic selections, supply chain optimization models, and more complex hybrid MCDA frameworks (Chakraborty & Das, 2021). The versatility of TOPSIS in various evaluation scenarios and its ability to accommodate various performance indicators is crucial for prioritizing technological alternatives in areas like electric mobility and renewable energy. Although existing literature focuses on sustainability and technical feasibility in emerging technologies, TOPSIS's use in such applications is still in its early stages. There is a lack of studies conducting simultaneous multi-sector comparisons involving electric mobility, renewable energy integration, and consumer electronics requirements. Addressing these gaps presents an opportunity to develop a structured MCDM-based evaluation framework that defines sector-specific evaluation criteria and evaluates battery technology progress (Mishra et al., 2023)

Liquid electrolyte lithium-ion batteries face various failure mechanisms that limit their efficiency and longevity. The anode side faces challenges due to the growth of lithium dendrites, which can breach the separator, causing internal short circuits. The cathode experiences structural instability due to the dissolution of active materials, causing a decline in capacity and deteriorating performance. Brittle cathode-electrolyte interphases (CEIs) can fracture due to swelling and shrinking, increasing impedance levels, further reducing the battery's performance and operational efficiency. Addressing these issues is crucial to enhance the reliability of lithium-ion batteries. Solid-state electrolytes have been studied for their ability to suppress lithium dendrites, act as a separator layer, and prevent cathode dissolution, enabling stable cycling (Sun et al., 2017). However, these electrolytes present interfacial challenges such as weak carbon black conduction agents, gaps between electrolyte and cathode particles, and the degradation of solid electrolytes over time by transition metals in the cathode.

All-solid-state lithium batteries (ASSBs) are future battery technology, offering increased safety and higher energy densities. However, their universal commercial application faces challenges due to internal failure mechanisms (Sun et al., 2017). Wang et al. (2020) focuses on ASSBs that use high-voltage cathodes and reveals two main failure mechanisms: irreversible chemical reactions and mechanical exposure issues. Reversible chemical reactions occur due to thermodynamic and kinetic divergence between the electrolyte and high-voltage cathode materials, leading to performance degradation over time. To overcome these issues, the review suggests exploring cathodes that operate at lower voltages and creating electrolytes with enhanced chemical stability. Mechanical failures, which often manifest at the interface between the solid electrolyte and electrodes, can lead to increased resistance within the battery, reducing overall performance. Resolving these issues requires continuous research to identify techniques that enhance interfacial contact between components. By understanding these failure mechanisms, researchers and manufacturers can successfully integrate ASSBs into various fields.

Researchers emphasize the importance of understanding the electrode-electrolyte interface and tailoring cathode microstructure to mitigate degradation. In-situ testing probes provide insights into reaction mechanisms at the interface (Unocic et al., 2020). Reducing the active material's weight, currently around 60% of the total battery weight, is crucial for optimum performance. Recent advancements include 10mm thick electrolytes and polymer-based solid-state electrolytes, improving flexibility and ionic conductivity. However, more work is needed to address challenges and enable widespread adoption of solid-state batteries, particularly lithium-based systems.

2.1. Types of All-Solid-State Batteries

2.1.1. Oxide-based Solid-State Batteries:

Oxides, compounds formed through the reaction of oxygen with other elements, demonstrate remarkable diversity in their structures, properties, and applications. The nature of the bonding between oxygen and the other element significantly influences the oxide's characteristics. Metal oxides often exhibit basic tendencies, readily forming hydroxide solutions in water, making them valuable in applications such as catalysis, neutralization reactions, and energy storage (Figen & Filiz,2019). Additionally, certain oxides possess unique electronic and optical properties. Silicon dioxide (SiO2), for instance, serves as a vital insulating material in the fabrication of electronic devices, while other oxides like titanium dioxide (TiO2) find use in solar cells and photocatalysis (Parussulo et al., 2009). The structural diversity of oxides also contributes to their wide range of applications, with some used as pigments, coatings, ceramics, and high-temperature refractory materials. This versatility continues to drive extensive research into oxides within materials science, chemistry, physics, and engineering.

Oxide-based solid-state batteries hold immense promise due to their use of a ceramic oxide material as their solid electrolyte. Leading candidates for this electrolyte include garnets (with lithium lanthanum zirconium oxide, or LLZO, being particularly promising), perovskites (such as lithium lanthanum titanate), and the older NASICON-type family (Hou et al., 2020). The advantages of this technology lie in its inherent safety and stability. The non-flammable nature of oxides dramatically reduces the risk of fire or thermal issues compared to traditional liquid electrolyte batteries (Janek & Zeier, 2016). Furthermore, their chemical and thermal stability ensures reliable performance across diverse temperature ranges and contributes to an exceptionally long battery lifespan (Wen et al., 2022). The ability of oxide electrolytes to work with high-voltage cathodes unlocks the potential for significantly increased energy density, boosting the amount of energy stored within a battery (Kim et al., 2019).

Despite these benefits, oxide-based solid-state batteries face significant hurdles. The brittleness of ceramic materials poses challenges in manufacturing, increasing the risk of cracks and internal damage that can compromise performance (Zhang et al., 2020). Additionally, ensuring robust contact between the solid oxide electrolyte and the electrode materials is complex; any imperfections at this interface introduce resistance and limit the battery's power output (Kerman et al., 2017). Current manufacturing techniques for oxide electrolytes often involve intricate and expensive processes, driving up the overall cost of these batteries (Park et al., 2020).

The scientific community is heavily invested in addressing these challenges. Researchers are investigating doping strategies, where small amounts of other elements are added to the oxide electrolyte to boost its ionic conductivity and overall performance (Li et al., 2019).

Thin-film fabrication techniques offer the potential to create more flexible oxide layers, improving their contact with electrodes (Wen et al., 2022). Simultaneously, the development of novel, cost-effective, and scalable manufacturing methods is a crucial area of research to make oxide-based solid-state batteries commercially viable (Park et al., 2020).

Oxide-based solid electrolytes, such as garnet-type Li7La3Zr2O12 (LLZO), are known for their stability and high ionic conductivity. They are often used in Advanced Solid-State Battery (ASSBs) due to their compatibility with lithium metal anodes. However, challenges include integrating LLZO into composite cathodes and addressing interfacial resistance issues. The main challenge is achieving a good interface between the solid electrolyte and electrodes, as poor contact can lead to increased resistance and reduced battery performance. Researchers are exploring composite cathode architectures to improve interfacial contact and overall battery efficiency (Kravchyk, Karabay, & Kovalenko, 2022).

2.1.2. Sulfide-Based Solid-State Batteries:

Sulfides, containing the sulfide ion (S^{2-}), are a remarkably diverse class of inorganic compounds with far-reaching implications in environmental remediation, advanced materials, and biological systems. The environmental significance of sulfides lies in their role as both metal reservoirs and potential sources of contamination. Sulfide minerals bind various heavy metals, but their oxidative weathering can release these toxic elements into the environment, emphasizing the need for careful management (Lindsay et al., 2015). In the realm of materials science, the focus shifts to the desirable properties of sulfides like transition metal sulfides. Their high theoretical capacities and favorable redox behavior make them promising candidates for next-generation battery electrodes (Wu et al., 2021). Furthermore, certain metal sulfides display exceptional catalytic activity, potentially revolutionizing processes within the energy and chemical industries (Nagaraj & Farinato, 2016). Biologically, hydrogen sulfide (H_2S) has gained recognition as a crucial signaling molecule within the body. H_2S modulates physiological processes ranging from blood pressure regulation and inflammation to neurotransmission, prompting interest in its therapeutic applications (Szabo, 2018).

Sulfide-based solid-state batteries hold the potential to revolutionize energy storage with their unique sulfide-based solid electrolytes. Families like thio-LISICONs, argyrodites (such as Li6PS5Cl), and glass-ceramic sulfides offer advantages that could outperform traditional lithium-ion batteries (Tao et al., 2022). The most striking feature of sulfide electrolytes lies in their extraordinarily high ionic conductivity. This translates into the potential for lightning-fast charging speeds and exceptional power output, potentially exceeding the capabilities of conventional liquid electrolyte batteries (Zhang et al., 2018). Their softer composition compared to ceramic oxides also hints at benefits for battery design; sulfides may enable better contact with electrodes and could facilitate more flexible and adaptable battery structures (Wen et al., 2022).

However, unlocking the full potential of sulfide-based batteries demands overcoming their inherent challenges. Sulfides are susceptible to chemical reactions, especially with atmospheric moisture and lithium metal anodes. These reactions lead to electrolyte degradation and the formation of harmful byproducts that compromise battery performance (Wen et al., 2022). Additionally, Blanc et al. (2021) explored the development of a high-voltage Mg cathode using a chromium sulfide host, presenting their findings in ACS Materials Letters..

The scientific community is heavily invested in finding solutions to these limitations and harnessing the advantages of sulfide-based solid-state batteries. One promising strategy involves developing specialized protective coatings that shield the sulfide electrolytes from environmental exposure, thereby enhancing stability and longevity (Wen et al., 2022). Altering the chemical composition of sulfides through doping or other modifications is another active area of research aimed at improving stability and widening their compatibility with a broader range of cathode materials (Busche et al., 2016). Furthermore, researchers are dedicating significant efforts to optimizing the interfaces between sulfide electrolytes and electrodes. Meticulous interface engineering seeks to minimize resistance and maximize the power and efficiency of these batteries (Kato et al., 2016).

Sulfide-based solid electrolytes, like argyrodite (Li6PS5Cl), are being explored due to their higher conductivity and potential to enhance energy density and safety. However, ongoing research focuses on their performance at subzero temperatures and mechanical stability due to sulfur volume change. These electrolytes can surpass traditional liquid electrolytes and can be used as an anode, increasing battery energy density. However, they are sensitive to moisture and may require more complex manufacturing processes. Researchers are focusing on the degradation of the electrolyte and the mechanical stability of the cathode due to sulfur volume change during cycling.

2.1.3. Polymer-Based Solid-State Batteries:

Polymers are ubiquitous materials with a profound impact on modern society. These macromolecules, consisting of long chains of repeating monomer units, exhibit a remarkable range of properties dependent on their chemical composition and structure (Elias, 2012). Synthetic polymers, such as polyethylene and polystyrene, revolutionized industries from packaging to construction due to their versatility, durability, and cost-effectiveness (Long et al., 2016). Natural polymers, including DNA, proteins, and cellulose, form the basis of life and offer unparalleled functionalities (Klemm et al., 2005). Continued research in polymer science focuses on developing advanced materials with tailored properties for applications in medicine, energy, and environmental sustainability.

Polymers are indispensable components in the design and manufacture of industrial batteries, where they contribute to a wide range of essential functions. As active electrode materials, specialized polymers can directly participate in energy storage and release mechanisms, enhancing battery capacity (Scrosati & Garche, 2010). Polymeric binders, such as polyvinylidene fluoride (PVDF), are crucial for maintaining the structural cohesion of electrodes, ensuring their stability during repeated charge-discharge cycles (Zhang, 2007). In addition, polymers serve as the foundation for separators and electrolytes within batteries. These components must possess tailored properties like selective permeability and excellent ionic conductivity to facilitate efficient ion transport (Costa, Lizundia, & Lanceros-Méndez, 2020). Researchers are actively developing novel polymer-based electrolytes, both solid and gel-like, to address safety concerns associated with traditional liquid electrolytes and push the boundaries of battery performance (Stephan, 2006). The ongoing advancement of polymer chemistry holds the key to unlocking industrial batteries with superior energy density, fast charging capabilities, and exceptional safety for demanding applications.

Polymer-based solid-state batteries offer a distinct approach to energy storage, utilizing flexible polymer materials as their solid electrolyte. The most prevalent choice is polyethylene oxide (PEO), though researchers are actively exploring alternative polymer families to optimize performance (Zhang et al., 2022). Polymers excel in several key areas. Their inherent flexibility opens doors for adaptable battery designs, potentially enabling integration into wearable or bendable electronic devices (Hallinan Jr & Balsara, 2013). Additionally, polymers generally lend themselves to more straightforward processing and thin-film fabrication compared to brittle ceramic materials, offering the promise of streamlined and cost-effective manufacturing (Mindemark et al., 2018). From a safety perspective, while not entirely non-flammable, polymer electrolytes reduce fire risks compared to the liquid electrolytes found in conventional lithium-ion batteries.

However, polymer-based solid-state batteries face notable challenges. A significant drawback is their lower ionic conductivity when compared to oxide or sulfide-based electrolytes. This translates into limitations on overall power output and potentially slower charging times (Mindemark et al., 2018). Furthermore, the performance of polymer electrolytes is heavily influenced by operating temperature. Ionic conductivity becomes particularly problematic at room temperature, often necessitating elevated temperatures for adequate functionality (Hallinan Jr & Balsara, 2013).

To address these limitations, the scientific community is pursuing several research avenues. Modifications to the polymers themselves, such as incorporating ceramic fillers, creating polymer blends, or altering polymer chain structures, aim to boost ionic conductivity and broaden the suitable temperature range (Mindemark et al., 2018). Composite electrolytes, strategically combining polymers with oxide or sulfide components, seek to strike a balance between the flexibility of polymers and the superior ionic conductivity of inorganic solid electrolytes (Zhang et al., 2017). Finally, the ongoing exploration of fundamentally new polymer families with intrinsically higher conductivity and wider operating temperature windows holds the potential to further improve the performance of polymer-based solid-state batteries.

Polymer-based solid electrolytes offer flexibility and mechanical stability, making them suitable for various applications. Recent advancements focus on improving ionic conductivity and compatibility with lithium metal anodes. Sustainable solid polymer electrolytes using natural polymers are being explored. Polymer-based ASSBs use solid polymer electrolytes (SPEs), which can be processed at lower temperatures and offer greater design flexibility. While SPEs are less conductive than ceramic or sulfide electrolytes, recent developments aim to improve their performance.

2.1.4. Hybrid Solid-State Batteries:

Hybrid solid-state batteries seek to create a more balanced battery system by strategically combining traditional liquid electrolytes with solid electrolytes. This design approach aims to capture the advantages of both types of electrolytes while seeking to mitigate their limitations. A common configuration involves employing a thin layer of solid electrolyte at the electrode interface, alongside a liquid electrolyte filling the rest of the cell. Hybrid solid-state batteries offer benefits such as enhanced safety, as the solid electrolyte layer acts as a protective barrier, reducing the risks associated with flammable liquid electrolytes (Randau et al., 2020). They also open the door to using lithium metal anodes and high-voltage cathodes, which often encounter stability issues in purely liquid systems. This has the potential to significantly increase energy density (Wang et al., 2020). Furthermore, hybrid batteries could facilitate the transition towards full solid-state technology, allowing researchers to address some immediate challenges while continuing to improve solid electrolyte performance (Tan et al, 2022).

However, hybrid solid-state batteries also face challenges. The complexity of managing the interface where the liquid electrolyte, solid electrolyte, and electrodes interact is a critical design hurdle, as efficient operation depends on compatibility within this zone (Randau et al., 2020). Additionally, while power output is improved compared to completely solid-state batteries, the presence of a solid electrolyte layer still introduces some restriction to ion movement compared to purely liquid systems (Park et al., 2020).

Research is actively addressing these challenges and unlocking the potential of hybrid solid-state batteries. Key research areas include developing ultrathin, highly conductive solid electrolytes specifically optimized for hybrid systems to minimize resistance (Park et al., 2020). Understanding and managing the dynamic interactions between the different components at the interfaces is crucial for boosting compatibility and overall performance (Randau et al., 2020). Continued exploration of innovative battery architectures and tailored hybrid electrolyte compositions will aid scientists in finding the optimal balance between energy density, power output, and safety (Wang et al., 2020).

Hybrid solid-state batteries combine solid electrolytes with liquid components to offer improved safety and energy density, while addressing manufacturing and battery life challenges. These transitional technologies aim to combine the advantages of solid-state batteries with liquid electrolyte batteries, potentially offering higher energy densities and better safety profiles than conventional batteries. Hybrid batteries are seen as a final destiny towards fully solid-state technologies, with ongoing research focusing on optimizing the solid-liquid interface and improving battery longevity (Bubulinca et al., 2023)

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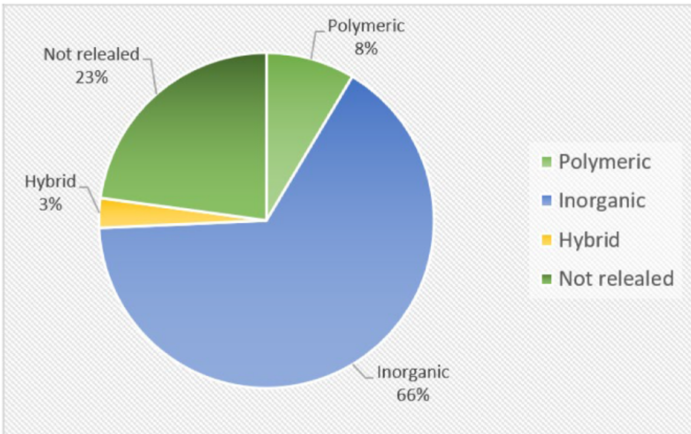

Figure 2.1: Classification of ASSBs based on the material used in the fabrication of SSE. (Bubulinca et al., 2023)

2.2. Challenges Associated with All-Solid-State Batteries

The growing demand for energy storage devices and issues related to liquid electrolytes (LIB) have led researchers to explore alternative solutions, such as solid-state electrolytes (SSEs) and all-solid-state batteries (ASSBs). SSEs are considered as the best approach for solving lithium dendrite formation in batteries, as they create a solid barrier to lithium dendrites, allowing the use of a metal lithium anode. However, fabrication of efficient ASSBs has been proven difficult due to side interfacial reactions, low ionic conductivity, poor physical contact at the cathode interface, and space charge formation layers.

Interfacial issues in the manufacturing and scaling up of ASSBs mainly arise from the instability of SSEs. The chemical potential of the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) determines the stability of the electrolyte. Three types of ASSB interface exist: thermodynamically stable (no chemical reactions), non-passivated mixed-conductive interphase, and passivated kinetically stable interphase. The mixed-conductive interphase shows high electronic and ionic conductivity, promoting spontaneous decomposition and reduction in the electrolyte. However, even in the kinetically stable interphase, reduction in SSE is spontaneous.

The formation of thermodynamically and kinetically stable interfaces could improve the long-term performance of the battery. On the anode side of the solid electrolyte, a kinetically stable, mixed-conductive interface is frequently found; yet the majority of reported solid electrolytes are thermodynamically unstable. Low ionic conductivity is a major problem affecting a solid-state electrolyte, as the ion conduction mechanism in SSEs is different than liquid electrolytes. The interface between cathode and the solid electrolyte is thermodynamically unstable due to chemical reactivity and the restricted electrochemical window of the electrolyte. The formation of a space charge layer (SCL) at the solid-solid interface, triggered by a substantial difference in the electrochemical potential of the cathode and the solid-state electrolyte, is another matter for consideration in the rational design of ASSBs.

2.2.1. Global Overview of ASSB-Producing Solid-State Battery Companies

The global demand for All-State Solid-State Battery (ASSB) has increased due to its worldwide application in various industries, including electric mobility, renewable energy storage, industrial, consumer, and portable electronics. These batteries are safer, more environmentally friendly, and have a higher energy density and longer service life than lithium-ion batteries with a liquid electrolyte. Several international companies have been focusing on developing and producing solid-state batteries, with developers of EV batteries, companies, universities, and government agencies at the forefront of innovation.

To provide an overview of major players in the global solid-state battery market, a list of major players was compiled using Google Ads and Google Trends search tools. Keywords such as "solid-state electrolyte," "all-solid-state battery," "solid-state battery," and "solid-state lithium-ion battery" were used to identify leading countries involved in ASSB development. Google searches were conducted to access current data on entities participating in ASSB activities.

The image below shows the countries that claim to manufacture ASSBs or to have their prototypes.

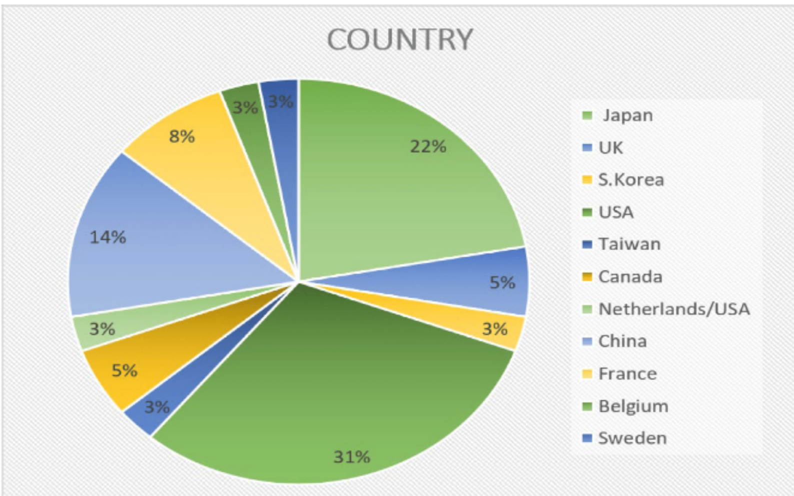

Figure 2.2: Pie chart of companies that claim to have an ASSB prototype or device.

2.3. History and Key Writers

The development of all-solid-state batteries (ASSBs) has its roots in the broader field of solid electrolytes, which gained significant attention in the 1960s. But the development of solid ionic conductors began with silver-ion conductors, discovered by Faraday in 1833. The most conductive solid electrolyte was Agl-type solid electrolyte, with a low ionic conductivity of 10-6 S/cm at 25°C. However, in the 1960s, a high ionic conductive Ag^3SI solid electrolyte was developed, with an ionic conductivity of 0.015 S/cm at room temperature. This solid electrolyte was incorporated into an $Ag|Ag^3SI|I^2$ SSB (Takahashi & Yamamoto, 1970). In 1967, $RbAg^4I^5$ was independently discovered with an ionic conductivity higher than 0.1 S/cm, with values of 0.12 S/cm and 0.21 S/cm. The early work on the theory of mixed phases laid the preliminary work for understanding ionic conduction in solid materials. The discovery of high ionic conductivity in solid electrolytes like silver iodide marked a pivotal moment, opening new possibilities for energy storage technologies (Wagner and Schottky, 1969).

Throughout the 1970s and 1980s, researchers explored various solid electrolytes, with significant contributions from Goodenough and colleagues, who investigated lithium cobalt oxide (LiCoO2) as a cathode material. Their research emphasizes the need for a nonflammable electrolyte to prevent lithium plating on the carbon anode during fast charging. This could involve a larger window between the lowest unoccupied molecular orbital (LUMO) and the highest occupied molecular orbital (HOMO) or a constituent that can rapidly form a solid/electrolyte-interface (SEI) layer. High Li-ion conductivity is required in both the electrolyte and across the electrode/electrolyte interface to ensure the battery's power capabilities. Increasing energy density, which is the product of voltage and capacity of reversible Li insertion or extraction through the electrodes, is a significant challenge. The authors propose a cathode made of low-cost materials that allows access to two Li atoms per transition-metal cation, increasing energy density (Goodenough & Kim, 2010). This work was crucial in demonstrating the potential of solid-state components in batteries, setting the stage for further advancements.

Bruce et al.'s research on lithium-air ($Li\text{-}O^2$) and lithium-sulfur (Li-S) explores the mechanisms governing and limiting the electrochemical operation of $Li\text{-}O^2$ and Li-S batteries. The study analyzes charge transfer across lithium peroxide, Li^2O^2, and investigates electron transfer exchange rate, film thickness, and the dominant charge transfer process through Li^2O^2. The study reveals that hole tunneling is the dominant process for charge transfer through Li^2O^2. The research also determines diffusion coefficients and concentrations of redox shuttles and superoxide ions in a 1,2-dimethoxyethane-based electrolyte. For Li-S batteries, the study highlights the need for advanced battery systems with high energy density, including lithium-sulfur (Li-S) energy storage. The study presents realistic conditions above 3 mgS, highlighting the potential benefits of Li-air (O^2) and Li-S batteries. This study emphasizes the potential of ASSBs to overcome the limitations of traditional LIBs, such as flammability and limited energy density.

Research on solid-state electrolytes increased suddenly in the early 2000s. Takada et al (2013) indicated the feasibility of using sulfide-based electrolytes, a combination of high ionic conductivity with chemical stability. In 2013, Takada et al. conducted innovative research on graphite anodes in sulfide-based all-solid-state batteries (ASSBs). However, the electrochemical performance of graphite anodes in solid-state lithium batteries was not well-understood at the time. In 2013, they published a study on the performance of a coin-type solid-state battery with a solid electrolyte, a significant development in the field of all-solid-state lithium batteries (Takada et al, 2013).

Other significant contributions from researchers like Sakuda et al. (2018), who conducted research on the interfacial stability between solid electrolytes and electrodes, a critical factor for the practical deployment of ASSBs.

In recent years, the research landscape has expanded to include comprehensive reviews and meta-analyses of various solid electrolyte materials. Bachman et al. (2016) provided a detailed comparison of inorganic solid-state electrolytes, highlighting the mechanisms and properties governing ion conduction. Their work emphasized the diverse material options available and their respective advantages and challenges.

The research by Bachman et al. explores the ion-transport mechanisms and fundamental properties of inorganic solid-state electrolytes for use in electrochemical energy storage systems. Their research analyzes the impacts of the nature of the ligand and metal comprises the framework on the performance of solid-state electrolytes. The research helps identify candidate migrating species and structures and introduces the concept of tuning conductivity through interfacial effects, such as controlling grain boundaries and strain at the interfaces. High-frequency dielectric constants and frequencies of low-energy optical phonons are discussed as examples of properties that correlate with activation energy across many classes of ionic conductors. The research gives insight into the physical parameters affecting the diffusion process, allowing for more efficient and target-oriented research on improving solid-state ion conductors (Bachman et al. 2016).

Another research on the application of ASSBs in electric mobility focuses on the challenges in developing solid-state batteries along with their safety and energy density. The challenges include achieving high ionic conductivity in solid electrolytes, strong interfacial contact between the electrolyte and electrodes, and costly manufacturing processes. Researchers have suggested strategies to address these challenges, such as developing new solid electrolyte materials with higher ionic conductivity, improving the interface between the electrolyte and electrodes, exploring composite electrolytes and architectures, and evaluating cost-effective fabrication techniques (Janek and Zeier, 2016).

Similarly, Kato and colleagues (2016) focused on the integration of ASSBs in EVs, improving their thermal stability and long cycle life. They developed lithium superionic conductors with high conductivity and stability, which were used to create an all-solid-state cell with very small internal resistance, especially at 100°C. The all-solid-state cell demonstrated high specific power and stable cycling with a high current density of 18℃, charging and discharging in just three minutes. The high performance of this all-solid-state battery is attributed to the sulfide-based lithium superionic conductors. This research represents a significant advancement towards safe and high energy density energy storage implications, such as electric vehicles and grid-scale energy storage. The ability to achieve high power and stable cycling at high current densities suggests the potential for these batteries in applications requiring rapid charging and discharging processes (Kato et al. 2016).

The renewable energy sector has also seen significant interest in ASSBs. Zhang et al. (2018) evaluated the suitability of these batteries for large-scale energy storage, highlighting their potential to manage the variability of renewable energy sources. Hitz et al. (2018) further investigated the scalability of ASSBs, identifying key technical challenges and proposed potential solutions to enhance their application in renewable energy storage systems.

The table 2.1 represents the work done by key writers along with their research title and methodology utilized.

Table 2.1: Work done by key writers in ASSB technologies.

Sr.	Researcher Names	Research Title	Methodology
1	Wagner & Schottky	Theory of regular mixed phases	Theoretical analysis
2	Goodenough & Kim	Challenges for rechargeable Li batteries	Experimental and theoretical
3	Bruce et al.	Li-O2 and Li-S batteries with high energy storage	Experimental research
4	Takada et al.	Solid-state lithium battery using graphite anode	Experimental study
5	Sakuda et al.	Favorable composite electrodes for all-solid-state batteries	Interface stability analysis
6	Bachman et al.	Inorganic solid-state electrolytes for lithium batteries	Comparative review
7	Janek & Zeier	A solid future for battery development	Review of applications in electric mobility
8	Kato et al.	High-power all-solid-state batteries using sulfide superionic conductors	Experimental evaluation
9	Zhang et al.	New horizons for inorganic solid state ion conductors	Review of material properties
10	Cheng et al.	High-energy-density flexible ceramic-based Li-ion batteries	Experimental and scalability analysis
11	Koerver et al.	Capacity fade in solid-state batteries: Interphase dynamics and protocol dependence	Experimental and interface analysis
12	Banerjee et al.	Interfaces and interphases in all-solid-state batteries with inorganic solid electrolytes	Review of material advancements
13	Funke et al.	Mechanisms of ion conduction in solid electrolytes	Theoretical and experimental

14	Phillip et al.	Lithium cobalt oxide and its applications in solid-state batteries	Experimental study
15	Takada et al.	Sulfide-based solid electrolytes for high performance ASSBs	Experimental evaluation
17	Janek et al.	Safety improvements in electric vehicle batteries using ASSBs	Review and experimental
18	Kato et al.	Thermal stability and cycle life of ASSBs in electric vehicles	Experimental study
19	Yildiz et al., 2024	A Comparative Review of Models for All-Solid-State Li-Ion Batteries.	Experimental and review
20	Yildiz, 2021	Evaluation of the performance of batteries used in electric vehicles using TOPSIS method	Experimental study

2.4. Methodologies and Methods Applied

The methodologies and methods applied in ASSBs' research are diverse, reflecting the multifaceted nature of the research filed. Experimental approaches often involve the synthesis and characterization of solid electrolytes and electrode materials. Techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and electrochemical impedance spectroscopy (EIS) are commonly used to analyze the structural and electrochemical properties of materials (Zhang et al., 2017).

Computational modeling has also played a significant role in ASSBs research. Research by (Kato et al. 2016; and Banerjee et al. 2020) utilized density functional theory (DFT) to predict the ionic conductivity and stability of solid electrolytes. These theoretical models provide insights into the fundamental mechanisms regulating ion transport and material stability.

For the assessment of ASSB performance in practical applications, researchers have utilized various evaluation methods. The TOPSIS method, for example, has been used to prioritize different ASSB technologies based on multiple performance metrices i.e. safety, cost, and energy density (Bachman et al., 2016). These multi-criteria decision-making tools help in evaluation of alternative technologies and facilitate the selection of the most suitable technologies.

For the literature review the general methodologies utilized are listed below:

2.1.5. Experimental Analysis and Material Characterization

Several of the reviewed studies, including those by Koerver et al. (2018) and Takada et al. (2013), utilized comprehensive experimental setups to analyze the properties and behaviors of materials used in all-solid-state batteries (ASSBs). Techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX) were applied to characterize the microstructure and composition of solid electrolytes and electrode materials. These methods enabled researchers to gain detailed insights into the atomic and molecular structures, which are crucial for understanding and improving ionic conductivity and stability in ASSBs.

1.1.2. Electrochemical Testing

Electrochemical characterization methods were prominently featured across the studies, including cyclic voltammetry (CV), electrochemical impedance spectroscopy (EIS), and galvanostatic cycling. For example, Sakuda et al. (2018) employed these techniques to evaluate the ionic conductivity, interfacial resistance, and overall performance under various operating conditions. These methods are essential for assessing the efficiency and durability of ASSBs, especially in relation to their potential applications in electric vehicles and grid storage.

2.4.3. Interface Analysis Techniques

The focus on interfaces and interphases in ASSBs, as explored by Banerjee et al. (2020), required specialized analytical techniques that could probe the complex interactions at the electrode-electrolyte boundary. Techniques such as transmission electron microscopy (TEM) and atomic force microscopy (AFM) were utilized to visualize and assess the stability and integrity of interfaces. These methodologies are critical for developing strategies to mitigate interface degradation and enhance the lifespan of ASSBs.

2.4.4. Theoretical Modeling and Simulations

Research by Wagner et al. (1969) and subsequent studies often integrated theoretical models and computational simulations to predict the behavior of ions within solid electrolytes and across interfaces. These models help in understanding the fundamental mechanisms of ion transport and interfacial reactions, which are difficult to measure directly. Density functional theory (DFT) and molecular dynamics (MD) simulations were particularly useful for exploring ionic pathways and predicting material performance before practical experiments.

2.4.5. Thermal Analysis

Thermal analysis methods, including differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), were applied in research by Kato et al. (2016) to study the thermal stability of solid electrolytes. These methods assess how materials decompose or react under varying temperatures, providing essential data for evaluating the safety and operational limits of ASSBs, especially in high-demand applications like electric vehicles.

2.4.6. Long-Term Cycling and Stress Tests

Long-term performance testing, including charge-discharge cycling and accelerated life testing, were methods particularly noted in the studies by Zhang et al. (2017) and Hitz et al. (2018). These tests are critical for assessing the endurance of ASSBs under prolonged or extreme conditions. They help in identifying degradation patterns and the lifespan of battery components, which are crucial for their commercial viability and reliability in energy storage applications.

2.4.7. Safety Evaluation Procedures

Finally, safety evaluation, as discussed in Janek et al. (2016), involved methodologies such as nail penetration tests, crush tests, and thermal runaway tests under abusive conditions. These methods are vital for assessing the risk factors associated with ASSBs, particularly in comparison to liquid electrolyte-based systems. They provide valuable data on how ASSBs react under failure modes, which is critical for their application in sensitive environments like electric vehicles and portable electronics.

3. METHODOLOGY

As mentioned in section one, the general research problem can be defined as follows: How will the new, advanced all-solid-state battery technologies be best deployed in electric mobility, renewable energy storage, and electronic devices to maximize their benefits and address the many challenges prevailing, which include dangers caused by liquid electrolytes?

This research assesses ASSBs for their applicability in electric mobility, renewable energy storage, and electronic devices. In so doing, it identifies analytical performance metrics to use in estimating these ASSBs in each of the three sectors. Various ASSB technologies will then be prioritized and assessed using the TOPSIS method. Also included will be an analysis of the challenges towards large-scale implementation of ASSBs, including technological, economic, and environmental factors, with emphasis on dangers from liquid electrolytes.

Guided by that evaluation, the objectives of this research include the definition of the performance metrics for the assessment of ASSBs in each of the target sectors; the development of a TOPSIS-based framework to evaluate technologies; analysis of identified challenges; and the presentation of solutions and recommendations for stakeholders within the electric vehicle, energy storage, and electronic device manufacturing industries.

3.1. TOPSIS

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a multi-criteria decision-making (MCDM) method introduced by Hwang and Yoon (1981), shows promise for systematically addressing the challenges of material selection and evaluation in all-solid-state batteries (ASSBs). Its ability to rank alternatives based on their similarity to ideal characteristics across multiple criteria aligns well with the complex decision-making processes inherent in ASSB research (Behzadian et al., 2012).

TOPSIS could be particularly valuable within ASSB development for selecting solid electrolyte materials. This involves prioritizing and balancing key properties like ionic conductivity, electrochemical stability, mechanical strength, and ease of fabrication (Lu et al., 2022). Criteria weights would require careful determination, likely involving input from experts in materials science, electrochemistry, and battery engineering.

The comparative nature of TOPSIS method holds a significant consideration in ASSB material selection. Researchers must be mindful of how trade-offs between different performance metrics can influence rankings of different battery types (Yildiz, 2021). Moreover, the sensitivity of TOPSIS to assigned performance metrics weightage highlights the need for a precise and transparent weight determination process within the specific context of ASSBs.

Developing techniques of TOPSIS offer ways to address uncertainties frequently encountered in ASSB research. For example, Fuzzy TOPSIS method is appropriate to handle imprecise or qualitative performance data associated with advanced materials by utilizing fuzzy sets (Bottani & Rizzi, 2006). Additional potential applications of TOPSIS in ASSBs include Ranking potential ASSB fabrication processes based on factors such as scalability, cost-efficiency, reliability, and environmental sustainability (Chen et al., 2018).

Evaluating and comparing ASSB cell designs, considering energy density, power density, cycle life, and safety parameters (Liu et al., 2022).

While TOPSIS presents an effective decision-making framework for ASSBs, it has its own limitations. The potential for rank reversal, reliance on subjective weight assignments, and its compensatory nature impose significant precautions. Combining TOPSIS with compatible MCDM methods or simulation tools could provide a more comprehensive and robust evaluation approach (Yazdani et al., 2019).

For using TOPSIS, six steps must be followed:

3.1.1. Making a normalized decision matrix.

A normalized decision matrix can be created from a decision matrix by dividing each entry in the decision matrix by the maximum value in its column. This ensures that all entries in the normalized decision matrix are on a common scale.

Creating a normalized decision matrix rij $(i = 1, 2, \dots, m; j = 1, 2, \dots, n)$ can be achieved by utilizing the decision matrix (x_{ij}).

$$\left[r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i}^{m} x^2{}_{ij}}} \right] \tag{1}$$

when $A_i = (xi_1, xi_2, \dots, xi_n)$ which n is quantity of criteria. And m is quantity of alternatives.

3.1.2. Determining the weighted normalized decision matrix.

Assigning weights to each criterion represents its relative importance. The weights should sum up to one. These weights can be determined based on the preferences and priorities of the decision-maker. To determine the weighted normalized decision matrix, the following equation must be used.

$$\left[t_{ij} = w_j r_{ij} = w_j \frac{x_{ij}}{\sqrt{\sum_i^m x^2{}_{ij}}} \right] \qquad (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \ (2)$$

3.1.3. Determining positive ideal and negative ideal solutions.

The (TOPSIS) is a multi-criteria decision-making (MCDM) method that generates two creates two best possible options as benchmarks to compare the alternatives under consideration. The positive ideal alternative (a_i^+) is a hypothetical alternative that has the best possible attribute values for all criteria. The negative alternative (a_i^-) is a hypothetical alternative that has the worst possible attribute values for all criteria.

The best alternative is the one that is closest to the positive ideal alternative and farthest from the negative ideal alternative.

$$a^+ = \begin{cases} \max a_{ij} & if \quad n \ \ is\, a\, benefit \quad criterion \\ \min a_{ij} & if \quad n \ \ is\, a\, non-benefit \ \ criterion \end{cases} \qquad (3)$$

$A_i^+ = (a_1^+, a_2^+ \cdots a_n^+)$

Which A_j^+ is the best value for j criterion for each alternative.

$$a^- = \begin{cases} \min a_{ij} & if \quad n \ \ is \ \ a \quad benefit\, criterion \\ \max a_{ij} & if \quad n \ \ is\, a \quad non-benefit \ \ criterion \end{cases} \qquad (4)$$

$$A_i^- = (a_1^-, a_2^- \cdots a_n^-)$$

Which A_j^- is the worst value for j criterion for each alternative.

3.1.4. Calculating the separation measures for each alternative.

The numbers d_i^+ of the column $d^+ = (d_1^+ \ d_2^+ \ \cdots d_3^+)$ are the distances from the points A_i, to the point A^+, which is calculated by the formula:

$$d_i^+ = d(A_i, A^+) = \sqrt{\sum_{j=1}^n (a_{ij} - a_j^+)^2} \qquad (5)$$

The numbers d_i^- of the column $d^- = (d_1^- \ d_2^- \ \cdots d_3^-)$ are the distances from the points A_i, to the point A^+, which is calculated by the formula:

$$d_i^- = d(A_i, A^-) = \sqrt{\sum_{j=1}^n (a_{ij} - a_j^-)^2} \qquad (6)$$

3.1.5. Calculating the relative closeness to the ideal solution.

The TOPSIS method evaluates the gap of a specific alternative to both the ideal solution (D^*) and the negative ideal solution (d^-) by considering their relative closeness. This is done by calculating the Euclidean distance, which results in a positive value (d^+) for the ideal positive solution and a simultaneous calculation of the ideal negative solution.

$$D^* = \frac{d^-}{d^- + d^+} \quad (7)$$

3.1.6. Finding the ideal solution

Lastly, according to the proximity of how closely the alternatives resemble the ideal solution answer, the TOPSIS ranks the options. The most desirable alternative is the one with the highest value of (D^*).

3.2. Data Collection Methods

The evaluation of all-solid-state batteries (ASSBs) for applications in electric mobility, renewable energy storage, and electronic devices needed a comprehensive and systematic approach to data collection. This thesis primarily relies on secondary data sources, including industry reports and research publications available online, to gather relevant performance metrics for various types of solid-state batteries. These data collection methods are chosen to ensure a thorough understanding of the batteries' performance characteristics, which are crucial for their successful implementation in the targeted fields of study.

The first step in data collection involves literature review of academic journals, conference papers, and industry white papers that focus on ASSBs, their applications and challenges. This review helps synthesize existing knowledge on the selected performance metrics i.e. ionic conductivity, energy density, cost, efficiency, safety, lifetime, and cycle count. Databases such as Research Gate, ScienceDirect, IEEE Xplore, and Google Scholar are utilized to access peer-reviewed articles that provide experimental data on these metrics. By compiling quantitative data from multiple studies, this thesis presents a comprehensive overview of the current ASSBs and highlight areas where further research is needed.

Along with academic sources, industry reports from battery manufacturers and market research firms are consulted to gather data on the commercial feasibility and real-world performance of ASSBs. Reports from organizations such as the International Energy Agency (IEA), Bloomberg New Energy Finance (BNEF), and various battery consortia provide valuable insights into the scalability, manufacturing costs, and market trends associated with solid-state batteries.

The data collected will be evaluated for reliability and validity through a critical evaluation of the sources, including methodologies, sample sizes, and credibility of authors and institutions. Prioritizing studies with rigorous experimental protocols and detailed descriptions will be made. Meta-analyses and systematic reviews will be used to synthesize findings from multiple studies, enhancing the robustness of conclusions. Cross-referencing data from different sources will identify discrepancies or variations for further investigation. The data is presented using visualization techniques like graphs, charts, and tables, and a comparative analysis highlights the strengths and weaknesses of each ASSB type, providing insights for future research and development.

3.3. Evaluation Criteria for All-Solid-State Batteries

The evaluation of all-solid-state batteries (ASSBs) needs a rigorous and multi-dimensional approach, considering the complex interaction of various performance metrics. The selected performance metrics i.e. energy density, ionic conductivity, cost, efficiency, safety, lifetime, and cycle count serve as critical evaluation criteria to determine the feasibility of ASSBs for applications in electric mobility, renewable energy storage, and electronic devices.

Energy Density is the amount of energy stored per unit volume or weight of the battery. High energy density is particularly crucial for electric vehicles and portable electronic devices, where space and weight constraints are significant. The evaluation of energy density involves measuring the specific capacity (mAh/g) and the voltage range of the battery materials. Comparative analysis of ASSBs with existing technologies, like lithium-ion batteries, using TOPSIS method is applied to evaluate the performance of ASSBs and identify potential improvements in material design and cell architecture.

Ionic Conductivity is another critical metric, representing the ability of the solid electrolyte to conduct lithium ions. High ionic conductivity is essential for ensuring efficient ion transport and minimizing internal resistance, which directly impacts the battery's overall performance and efficiency. Ionic conductivity tests are often conducted over different temperatures to assess the conductivity behavior under different operating conditions. The results are analyzed to optimize the electrolyte composition and structure, aiming to achieve conductivity levels comparable to or exceeding those of liquid electrolytes.

Cost is a vital consideration for the commercialization of ASSBs. The cost analysis involves the raw materials, manufacturing processes, and scalability of production. Manufacturing cost is desired as low as possible as quality products under affordable prices are more likely to be adopted by customers and business industry. This research aimed to explore the high performance ASSBs with low manufacturing cost.

Efficiency or energy efficiency is the ratio of energy output during discharge to the energy input during charging. High efficiency is desired for applications of all-solid-state batteries in targeted areas and especially in renewable energy storage, where energy losses need to be minimized. Efficiency evaluation involves conducting charge-discharge cycling tests under controlled conditions and analyzing the Coulombic efficiency (the ratio of charge output to charge input) and energy efficiency. This research compares the efficiencies of selected ASSB types using TOPSIS method.

Safety is a criterion that cannot be compromised, particularly considering the problems such as thermal explosion and flammability that come with conventional lithium-ion batteries. ASSBs are inherently safer due to their solid electrolytes, but comprehensive safety evaluations are still required. This involves thermal stability tests, overcharge and short-circuit tests. The results are compared against safety standards and regulations to ensure the batteries can withstand real-world operating conditions without compromising user safety.

Lifetime and Cycle Count are critical for determining the longevity and durability of ASSBs. Lifetime refers to the total operational period before the battery capacity falls below a usable threshold, while cycle count measures the number of complete charge-discharge cycles the battery can endure before significant capacity degradation occurs. Long-term cycling tests are conducted to gather data on capacity retention, internal resistance growth, and any structural changes in the battery materials. These tests simulate real-world usage patterns and help predict the battery's performance over its intended lifespan.

By carefully evaluating these performance metrics, a more suitable SSB technology can be identified for each application, ensuring optimal performance, economic viability, environmental responsibility, and a smooth transition from existing Li-ion battery technology.

3.4. Data Collected for evaluation of ASSBs:

The research focused on the evaluation of current ASSBs and the data collection for selected performance metrics is done through recent research publications and industry reports.

Oxide-based solid-state batteries

The table 3.1 represents a comparative overview of data collected for three types of oxide-based solid-state batteries: LLZO (Lithium Lanthanum Zirconium Oxide, a Garnet), LLTO (Lithium Lanthanum Titanate, a Perovskite), and LISICON (Lithium Superionic Conductor).

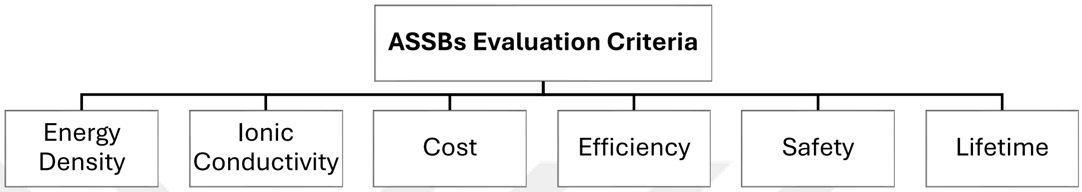

Table 3.1: Data gathered for Oxide-based solid-state batteries.

Performance Metric	LLZO (Garnet)	LLTO (Perovskite)	LISICON
Ionic Conductivity	10^{-3} S/cm	10^{-4} S/cm	10^{-3} S/cm
Energy Density	300 Wh/kg	250 Wh/kg	280 Wh/kg
Cost	$130-170/kg	$100-140/kg	$120-160/kg
Efficiency	90%	85%	88%
Safety	High thermal stability	Moderate thermal stability	High thermal stability
Lifetime	>10 years	8 years	9 years
Cycle Count	1000 cycles	800 cycles	900 cycles

LLZO has a high ionic conductivity of 10^{-3} S/cm (Meesala et al., 2019), making it suitable for efficient ion transport. Its energy density is 300 Wh/kg, making it suitable for high energy storage applications like electric vehicles. LLTO has the lowest energy density at 250 Wh/kg, making it less efficient in energy-intensive applications. The cost is the most economical option at $100-140/kg, while LLZO is the most expensive at $130-170/kg. Efficiency is 90%, with LISICON at 88% and LLTO at 85%. Both LLZO and LISICON have high thermal stability, making them suitable for safety-critical applications. LLTO has moderate thermal stability, requiring additional safety measures. The battery's lifetime and cycle count are also important factors. LLZO has a lifetime of over 10 years and can endure around 1000 cycles, while LISICON has a 9-year lifetime and 900 cycles. LLTO has the shortest lifetime at 8 years and a cycle count of 800 cycles.

Sulfide-based solid-state batteries

The table 3.2 represents the data collected for three types of sulfide-based solid-state batteries: Crystalline Sulfides, Glassy Sulfides, and Glass-Ceramic Sulfides.

Table 2.2: Data gathered for Sulfide-based solid-state batteries.

Performance Metric	Crystalline Sulfides	Glassy Sulfides	Glass-Ceramic Sulfides
Ionic Conductivity	10^{-2} S/cm	10^{-3} S/cm	10^{-2} S/cm
Energy Density	350 Wh/kg	300 Wh/kg	320 Wh/kg
Cost	$180-220/kg	$160-200/kg	$170-210/kg
Efficiency	92%	88%	90%
Safety	High thermal stability	Moderate thermal stability	High thermal stability
Lifetime	>10 years	10 years	>10 years
Cycle Count	1200 cycles	1000 cycles	1100 cycles

Crystalline and Glass-Ceramic Sulfides are two types of batteries that are suitable for various applications. Crystalline Sulfides have high ionic conductivity, making them efficient for fast ion movement and overall battery performance. They have an energy density of 350 Wh/kg, making them suitable for high-energy applications like electric vehicles. Glassy Sulfides have a 320 Wh/kg, providing a balance of high energy storage. They are cost-effective at $160-200/kg, while Glass-Ceramic Sulfides are moderately priced at $170-210/kg. Crystalline Sulfides are the most expensive at $180-220/kg, reflecting their superior performance metrics but potentially limiting their use to applications where higher costs can be justified by performance benefits. They demonstrate the highest efficiency at 92%, making them ideal for renewable energy storage. They also have high thermal stability, making them ideal for applications where safety is a critical concern. Both Crystalline and Glass-Ceramic Sulfides have lifetimes of over 10 years, with Glassy Sulfides having a slightly lower lifetime. They offer substantial longevity, although slightly less than the other two types.

Polymer-Based Solid-State Batteries

The table 3.3 represents the data gathered for three types of polymer-based solid-state batteries: PEO (Polyethylene Oxide) with LiTFSI, PAN (Polyacrylonitrile) with LiTFSI, and PVDF (Polyvinylidene Fluoride) with LiTFSI.

Table 3.3: Data gathered for Polymer-based solid-state batteries.

Performance Metric	PEO with LiTFSI	PAN with LiTFSI	PVDF with LiTFSI
Ionic Conductivity	10^{-4} S/cm	10^{-5} S/cm	10^{-4} S/cm
Energy Density	250 Wh/kg	220 Wh/kg	230 Wh/kg
Cost	$130-170/kg	$100-140/kg	$125-165/kg
Efficiency	85%	82%	84%
Safety	Moderate thermal stability	High thermal stability	Moderate thermal stability
Lifetime	8 years	7 years	7 years
Cycle Count	800 cycles	700 cycles	750 cycles

The polymer electrolyte (PEO) with LiTFSI and PVDF with LiTFSI have varying ionic conductivity, energy density, cost, efficiency, safety, and cycle count. PEO with LiTFSI has a higher ionic conductivity of 10^{-4} S/cm, suggesting better performance in high-power applications. PVDF with LiTFSI has a higher energy density of 230 Wh/kg, making it suitable for high energy storage applications like electric vehicles. PAN with LiTFSI has the lowest energy density at 220 Wh/kg and it is the most cost-effective at $100-140/kg, while PEO with LiTFSI is the most expensive at $130-170/kg. PVDF with LiTFSI balances cost with performance, making it a moderately priced option with good overall characteristics. Efficiency is 85%, with PEO with LiTFSI showing moderate energy losses during charge-discharge cycles. PAN with LiTFSI is noted for its high thermal stability, making it preferable for applications where safety is a primary concern. Both PEO and PVDF with LiTFSI exhibit moderate thermal stability, suggesting additional safety measures may be needed. The battery's lifetime and cycle count are 8 years and 750 cycles, respectively.

4. IMPLEMENTATION AND RESULTS

4.1. Results for Electric Vehicles

The table 4.1 presents a weighted evaluation of all-solid-state batteries (ASSBs) for their feasibility in electric vehicles (EVs). The calculation in this table is based on the average of all parameters listed in tables (3.1, 3.2, 3.3). The table focuses on six performance metrics: Cost, Efficiency, Lifetime, Safety, Energy densities, and Ionic conductivity. Cost is the most critical factor, followed by Efficiency and Safety, while Energy densities and Ionic conductivity are less critical but still important.

Table 4.1: Performance metrics weightage of ASSB types for Electric Vehicles

	Non-Benefit	Benefit	Benefit	Benefit.	Benefit.	Benefit.
weightage	0.25	0.2	0.15	0.2	0.1	0.10
	Cost ($)	Efficiency	Lifetime (years)	Safety	Energy density (Wh/Kg)	Ionic conductivity (S/cm)
Oxide-Based	136.67	87.67%	9.67	8	276.67	7E-04
Sulfide-Based	190	90%	11.33	8	323.33	7E-03
Polymer-Based	138.33	83.67%	7.33	7	233.33	7E-05

Cost has the highest weightage (0.25) because the upfront cost of EVs remains a significant barrier to widespread adoption. Therefore, reducing battery costs is crucial for making EVs more affordable. Efficiency has a weightage of 0.20, crucial for evaluating the per charge range of EVs. High efficiency ensures that EVs can travel longer distances on a single charge, making them more practical for daily use. Battery lifetime, weighted at 0.15, directly impacts the long-term ownership costs and the range of EVs. A longer battery life suggests better replacements and value over time. Safety, with a weightage of 0.20, is paramount for any vehicle. Strong safety features are essential for consumer confidence. The evaluation of safety criterion is between 1 and 10. Energy density has a weightage of 0.10. Energy density is essential for manufacturers to invest in research and development, but for consumers, affordability is more important. Ionic conductivity is also weighted at 0.10, making it an important consideration for determining the power output of a battery. EVs are generally cleaner than gasoline vehicles, but their environmental benefits depend on the electricity grid.

Oxide-based ASSBs have a high-cost, moderate Efficiency and Safety, lower weightage in Lifetime, Energy densities, and Ionic conductivity; indicating they are less suitable. Polymer-based ASSBs have the lowest cost and the highest Safety score, indicating them as the most affordable. But they have lower performance in Efficiency, Lifetime, Energy densities, and Ionic conductivity, thus not feasible for electric vehicles. Sulfide-based ASSBs have high scores in Efficiency, Lifetime, and Safety, and moderate cost scores. Therefore, sulfide based ASSBs are the most suitable choice for EV applications.

Normalized decision matrix is a method for evaluating and prioritizing the results calculated. This matrix normalizes each metric to provide a comparable scale for assessing the relative strengths and weaknesses of each battery type in the context of their application in electric vehicles (EVs).

The table 4.2 represents the values of key factors for assessing ASSBs.

Table 4.2: Normalized decision matrix results of ASSBs for Electric Vehicles

Normalized decision matrix (EVs)	Cost	Efficiency	Lifetime	Safety	Energy density	Ionic conductivity
Oxide-Based	0.5027	0.5808	0.5825	0.6013	0.5701	0.0995
Sulfide-Based	0.6989	0.5962	0.6825	0.6013	0.6662	0.9950
Polymer-Based	0.5088	0.5543	0.4415	0.5262	0.4808	0.0099

The normalized decision matrix value have been calculated by using the equation (1)

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i}^{m} x^2{}_{ij}}}$$

For example, to calculate the normalized value for oxide based solid states batteries cost (0.5027).

$$r_{11} = \frac{136.67}{\sqrt{136.67^2 + 190^2 + 138.33^2}}$$

Then, in step 2, calculating weighted normalized decision matrix extract from the equation (2) by Multiplying the normalized value with the weightage

$$t_{ij} = w_j r_{ij} = 0.5027 * 0.25$$

The results shows that cost of electric vehicles (EVs) is a key factor for their commercialization. Sulfide-based batteries have the highest cost (0.6989), making them less suitable. Polymer -based batteries are more affordable, and Oxide-based batteries are the most cost-effective option. But sulfide-based batteries are the highest in efficiency, indicating superior performance. Efficiency is crucial for EV owners, as high efficiency leads to longer driving ranges per charge. The lifetime of the battery impacts the overall ownership cost and the vehicle's range. Sulfide-based batteries have the highest score (0.5962), indicating strong safety features. Both Sulfide based and Polymer-based batteries score higher than Polymer-Based batteries, suggesting they may provide the best safety performance. Energy densities are important for manufacturers, as they impact their ability to invest in further research and development. Sulfide-based batteries have the highest score (0.6662), indicating better energy densities. The ionic conductivity of EVs is a significant factor, with Sulfide-based batteries having the best impact. The table 4.3 below presents an ideal solution analysis for three types of all-solid-state batteries (ASSBs) Oxide-Based, Sulfide-Based, and Polymer-Based against selected performance metrics. This analysis involves comparing each battery type to the ideal (a+) and anti-ideal (a-) solutions, calculating the distance (d+ and d-) from these ideal points, and determining a composite distance score (D) to rank the battery types. The battery type with the highest value of D is considered the most preferable.

Table 4.3: Ideal Solution analysis of ASSB battery types for Electric Vehicles

Ideal solation	Cost	Efficiency	Lifetime	Safety	Energy density	Ionic conductivity	d+	d-	D
Oxide-Based	0.126	0.116	0.087	0.120	0.057	0.010	0.091	0.057	0.385
Sulfide-Based	0.175	0.119	0.102	0.120	0.067	0.099	0.049	0.108	0.688
Polymer-Based	0.127	0.111	0.066	0.105	0.048	0.001	0.108	0.048	0.306
a+	0.126	0.119	0.102	0.120	0.067	0.099			
a-	0.175	0.111	0.066	0.105	0.048	0.001			

For calculating positive ideal and negative ideal solutions, the equation 3 have been implemented

$$a^{+} = \begin{cases} \max a_{ij} & if \quad n \quad is\ a\ benefit \quad criterion \\ \min a_{ij} & if \quad n \quad is\ a\ non-benefit \quad criterion \end{cases} \tag{3}$$

In Our example, minimum value among the normalized values was choosen because our criterion (Cost) is non-benefit.

For continuing to calculating the ideal distance, the equation 5 have been implemented

$$d_i^{+} = d(A_i, A^{+}) = \sqrt{\sum_{j=1}^{n} (a_{ij} - a_j^{+})^2}$$

For example, to calculate the positive ideal distance (d^{+}) for oxide-based batteries (0.091)

$$d^{+} = \sqrt{(0.126-0.126)^2 + (0.116-0.119)^2 + (0.087-0.120)^2 + (0.120-0.120)^2 + (0.057-0.067)^2 + (0.010-0.099)^2}$$

And for calculating the relative distance (D), the Equation 7 have implemented

The implementation of equation 6 for highest value (0.688) is showing below

$$D^{*} = \frac{d^{-}}{d^{-} + d^{+}} = \frac{0.108}{0.108 + 0.049}$$

The calculations above have been implemented in the same way for all the following sections. This ensures that everything is kept consistent and accurate, allowing for easy comparison and understanding of the results throughout the document.

Cost is a significant factor for EVs, and Oxide-Based batteries are the most cost-effective option, with a proximity to the ideal solution (0.126), followed by Polymer-Based (0.127) and Sulfide-Based (0.175). Sulfide-Based batteries have the best efficiency (0.119), outperforming Polymer-Based (0.111) and Oxide-Based (0.116), making EVs more practical for everyday use and addressing the challenge of distance covered per charge. Sulfide-Based batteries indicate the highest lifetime value (0.102), as compared to Oxide-Based (0.087) and Polymer-Based (0.066), indicating their superior durability. Safety is crucial for consumer satisfaction, Both Sulfide-Based and Oxide-based batteries offer the best safety features (0.120), while Polymer-Based batteries scores (0.105), indicating strong but slightly lesser safety features compared to Sulfide and Oxide-Based batteries. Proximity to energy densities is the highest for Sulfide-Based batteries (0.067), while oxide-based and polymer-based batteries have lower scores (0.057 and 0.048 respectively). The ionic conductivity of electric vehicles (EVs) is significant, with Sulfide-Based batteries having the highest near-ideal impact value (0.099), while Oxide-Based and Polymer-Based batteries have lower scores (0.010 and 0.001), respectively.
The ideal solution analysis reveals that Sulfide-Based batteries are the most suitable type of ASSB for EV applications due to their balanced performance across efficiency, lifetime, safety, energy densities, and ionic conductivity. Oxide-Based batteries have the second-highest D value due to safety features, while Polymer-Based batteries have the lowest D value (0.272) due to higher costs and lower efficiency and lifetime performance. This is also shown in below figure:

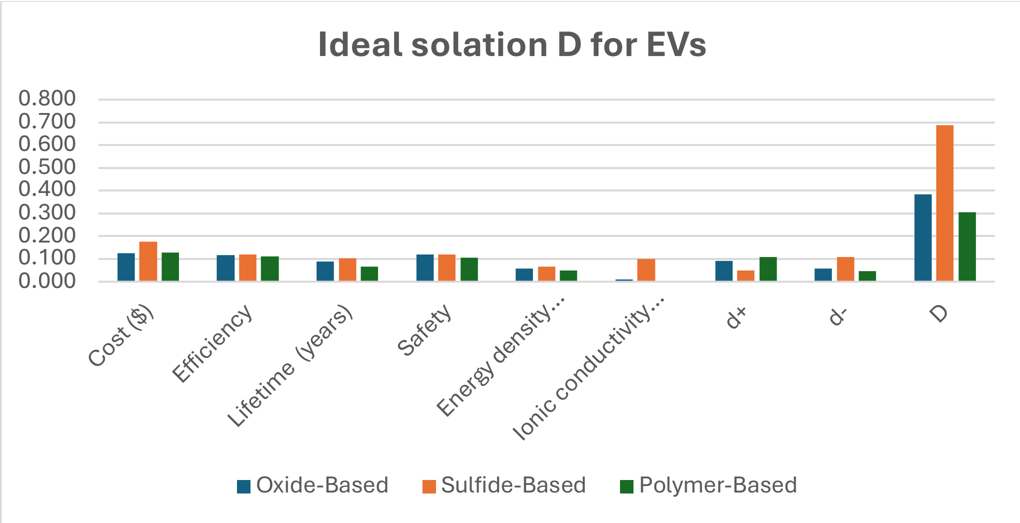

Figure 4.1. Ideal solation (D) for EVs.

4.2. Results for Renewable Energy Storage

The calculation in this table is based on the average of all parameters listed in tables (3.1, 3.2, 3.3). The table 4.4 evaluates the performance of three types of all-solid-state batteries (ASSBs) for renewable energy storage applications based on six performance metrics. Each metric is assigned a weightage reflecting its importance in the context of renewable energy storage.

Table 4.4: Performance metrics weightage of ASSB types for Renewable Energy Storage

	Non-Benefit	Benefit.	Benefit.	Benefit.	Benefit.	Benefit.
weightage	0.30	0.2	0.15	0.1	0.08	0.17
	Cost ($)	Efficiency	Lifetime (years)	Safety	Energy density (Wh/Kg)	Ionic conductivity (S/cm)
Oxide-Based	136.67	88%	9.67	8	276.67	7E-04
Sulfide-Based	190	90%	11.33	8	323.33	7E-03
Polymer-Based	138.33	84%	7.33	7	233.33	7E-05

Cost (0.30): The cost of renewable energy storage is a major challenge to its worldwide implementation. Therefore, it is given the maximum weight. Oxide-Based batteries the cheapest (136.67 $), indicating as the most cost-effective option, while Sulfide-Based and Polymer-Based batteries are less favorable.

Efficiency (0.20): Efficiency is critical for the economic feasibility and long-term performance of renewable energy systems. Sulfide-Based ASSB technology scores highest in efficiency (90%), making them the best option when efficiency is desired as compared to Oxide-Based batteries and Polymer-Based batteries.

Lifetime (0.15): A longer battery life directly impacts the sustainability and cost-effectiveness of renewable energy storage. Sulfide-Based batteries score highest (11.33), indicating maximum battery life. Safety (0.20): Safety parameters are critical to ensure the protection of people and the environment. Oxide and sulfide-Based ASSBs take the lead in safety with a score of 8, suggesting the best safety features. Polymer-Based ASSBs score 7, indicating high safety but slightly less as compared to other batteries.

Energy densities (0.08): Energy densities are beneficial for manufacturers but in the case of renewable energy projects energy density is less critical as compared to public benefit. Sulfide-Based ASSBs score highest (323.33), indicating better energy densities while Oxide-Based and Polymer-Based batteries have less energy density.

Ionic conductivity (0.17): High ionic conductivity facilitates faster movement of ions within the electrolyte, leading to improved charge and discharge rates in batteries, which enhances overall performance. Sulfide-Based ASSBs score highest ($7*10^{-3}$), which means they have high overall performance. While Oxide-Based and Polymer-Based ASSBs score, disclosing a high ionic conductivity.

Conclusively, Oxide-Based batteries are the most cost-effective, making them highly suitable for applications where cost is a major consideration. Sulfide-Based ASSBs having high efficiency and lifetime are suitable for long-term energy storage, despite their high costs. Polymer-Based ASSBs offer low cost, efficiency, and lifetime. So, they are less suitable compared to the other types for renewable energy storage applications.

The table 4.5 below presents the performance results of all-solid-state batteries (ASSBs) renewable energy storage applications based on a normalized decision matrix.

Table 4.5: Normalized decision matrix results of ASSBs for Renewable Energy Storage

Normalized decision matrix	Cost ($)	Efficiency	Lifetime (years)	Safety	Energy density (Wh/Kg)	Ionic conductivity (S/cm)
Oxide-Based	0.5027	0.5808	0.5825	0.6013	0.5701	0.0995
Sulfide-Based	0.6989	0.5962	0.6825	0.6013	0.6662	0.9950
Polymer-Based	0.5088	0.5543	0.4415	0.5262	0.4808	0.0099

This table indicates that Oxide-Based batteries are the most cost-effective, but they offer moderate efficiency, lifetime, safety, and ionic conductivity.
Sulfide-Based batteries offer better efficiency, lifetime, energy densities, and ionic conductivity, making them the best option even with higher costs.
Polymer-Based batteries are highest in safety but are less suitable in terms of cost, efficiency, lifetime, and energy densities.
The following figure clearly indicates the feasibility of Sulfide-Based ASSBs for renewable energy storage. The table 4.6 presents a detailed evaluation of three types of all-solid-state batteries (ASSBs) based on key performance metrics. The analysis uses a normalized decision matrix and the concept of ideal solutions (considering the highest value of D) to determine the most suitable battery type for renewable energy storage.

Table 4.6: Ideal Solution analysis of ASSB Battey types for Renewable Energy Storage

Ideal solation	Cost	Efficiency	Lifetime	Safety	Energy density	Ionic conductivity	d+	d-	D
Oxide-Based	0.151	0.116	0.087	0.060	0.046	0.017	0.153	0.065	0.299
Sulfide-Based	0.210	0.119	0.102	0.060	0.053	0.169	0.059	0.172	0.745
Polymer-Based	0.153	0.111	0.066	0.053	0.038	0.002	0.172	0.057	0.249
a+	0.151	0.119	0.102	0.060	0.053	0.169			
a-	0.210	0.111	0.066	0.053	0.038	0.002			

In the case of renewable energy storage, Oxide-based ASSBs have the ideal cost (a+) with score 0.151. Polymer-Based batteries have the closest proximity to the ideal cost as compared Sulfide-Based batteries. The ideal efficiency (a+) is 0.119. Sulfide-Based batteries rank highest in efficiency, making them highly suitable for long-term energy applications. An ideal battery lifetime value (a+) is 0.102. Again, Sulfide-Based batteries have the ideal value. Safety is most important to protect both people and the environment and the ideal safety value (a+) is 0.060. Here, Oxide and Sulfide-Based batteries offer the highest safety score, while Polymer-Based ASSBs also provide slightly less level of safety. The ideal energy density value (a+) is 0.053. Once again, Sulfide-Based batteries are a better choice as they have equal value to the ideal solution. The positive ideal solution (a+) for ionic conductivity is 0.169. It can be seen in the above table that Sulfide-Based batteries are the most environmentally friendly option.

Conclusively, the proximity to ideal solution for renewable energy storage is indicated by the values of D, the battery type having highest value of D is the most suitable battery type. Here, Sulfide-Based batteries have the highest D value (0.745), indicating as the most suitable option for renewable energy storage. Oxide-Based batteries, with a D value of 0.299, are also a great option, especially in terms of cost and safety. But Polymer-Based batteries, having higher costs, lower efficiency, and the lowest D value of 0.249, are not preferred to be used in renewable energy projects.

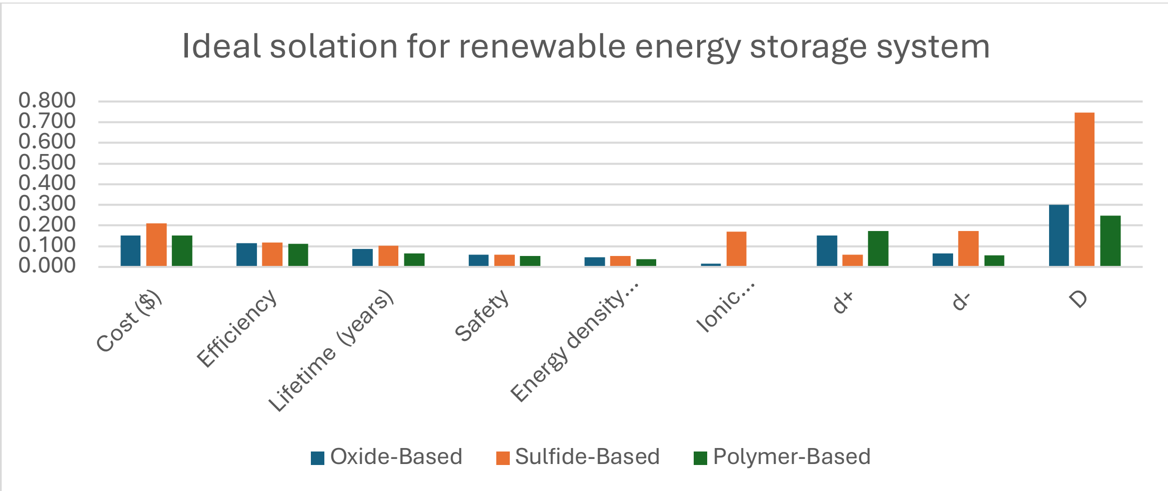

Figure 3.2. Ideal solation (D) for renewable energy storage system

4.3. Results for Electronic Devices

Electronic devices are mostly portable and carried close to the body therefore users prefer an efficient and safe device having longer battery life. High efficiency means longer battery life which reduces the need for frequent charging. Safety is to minimize overheating and explosion or burnout risks. Cost and energy densities are significant factors that decide the final price of the device, but it is often integrated into the device's price. Users might prioritize a slightly higher cost if they desire better battery performance. Despite the small size of electronic devices, proper battery recycling and ethical material sourcing are essential to reduce their negative environmental effects.

The table 4.7 below presents the weightage of selected performance metrics for all-solid-state batteries (ASSBs) relevant to electronic devices i.e. laptops, mobile phones, smartwatches, and other wearables. The calculation in this table is based on the average of all parameters listed in tables (3.1, 3.2, 3.3).

Table 4.7: Performance metrics weightage of ASSB types for Electronic Devices

	Non-Benefit	Benefit	Benefit	Benefit	Benefit	Benefit
weightage	0.22	0.23	0.12	0.25	0.1	0.08
	Cost ($)	Efficiency	Lifetime (years)	Safety	Energy density (Wh/Kg)	Ionic conductivity (S/cm)
Oxide-Based	136.67	87.67%	9.67	8	276.67	7E-04
Sulfide-Based	190	90.00%	11.33	8	323.33	7E-03
Polymer-Based	138.33	83.67%	7.33	7	233.33	7E-05

Table 4.7 indicates that Oxide-Based Batteries have low cost indicating their affordability, but they have low efficiency and less battery lifetime, safety ratio is same as sulfide-based ASSBs. Overall, these batteries provide a balanced performance but drop back in efficiency and ionic conductivity compared to Sulfide-Based batteries.

Sulfide-Based Batteries offer high efficiency (90%), longer battery lifetime with approximately 11.33 years, sharing a superior safety with Oxide-based batteries (8), high cost (190 $), and decent energy densities (323.33 Wh/Kg). These characteristics indicate that Sulfide-Based batteries are the most efficient and suitable option for electronic devices, especially when high efficiency and long lifespan are desired.

Polymer-Based batteries offer lowest Safety and the moderate cost. However, they have are low in Efficiency, lifetime, and ionic conductivity. Their low efficiency and shorter lifespan might disrupt users who prioritize performance over price.

The table 4.8 below presents the normalized performance metrics for all-solid-state batteries (ASSBs) evaluated for their suitability in electronic devices such as laptops, mobile phones, smartwatches, and other wearables.

Table 3: Normalized decision matrix results of ASSBs for Electronic Devices

Normalized decision matrix	Cost	Efficiency	Lifetime	Safety	Energy density	Ionic conductivity
Oxide-Based	0.5027	0.5808	0.5825	0.6013	0.5701	0.0995
Sulfide-Based	0.6989	0.5962	0.6825	0.6013	0.6662	0.9950
Polymer-Based	0.5088	0.5543	0.4415	0.5262	0.4808	0.0099

Oxide-Based batteries have cheapest cost among other alternatives, as indicated by their normalization score (0.5027). They have high ratings for safety (0.6013), moderate rates for ionic conductivity (0.0995), lifetime (0.5825), and efficiency (0.5808). The energy density of (0.5701) is not the highest, but it is acceptable.

Sulfide-Based batteries perform better having highest scores for efficiency (0.5962), lifetime (0.6825), and efficiency (0.5962). They offer the greatest energy density (0.6838), highest cost (0.6989) and moderate safety (0.6013).

Polymer-Based batteries offer the moderate cost (0.5088). their efficiency (0.5543) and lifetime (0.4415), safety (0.5262), ionic conductivity (0.099) and energy densities (0.4808) are not as favorable.

In summary, Sulfide-Based batteries stand out as the most suitable option for electronic devices due to their high efficiency, extended lifetime, and positive ionic conductivity but are relatively more expensive. Oxide-Based batteries offer a balanced performance with low price. The Polymer-Based batteries are low in safety, efficiency and lifetime. But it is having low cost, which is not desirable for users who prioritize performance.

Table 4.9: Ideal Solution analysis of ASSB Battey types for Electronic Devices

Ideal solation	Cost	Efficiency	Lifetime	Safety	Energy density	Ionic conductivity	d+	d-	D
Oxide-Based	0.111	0.134	0.070	0.150	0.057	0.008	0.073	0.052	0.413
Sulfide-Based	0.154	0.137	0.082	0.150	0.067	0.080	0.043	0.089	0.672
Polymer-Based	0.112	0.127	0.053	0.132	0.048	0.001	0.089	0.042	0.321
a+	0.111	0.137	0.082	0.150	0.067	0.080			
a-	0.154	0.127	0.053	0.132	0.048	0.001			

The table provides comparative results for evaluation of all-solid-state batteries (ASSBs) based on their suitability for electronic devices such as laptops, mobile phones, smartwatches, and other wearables. This analysis considers crucial factors including cost, efficiency, lifetime, safety, energy densities, and ionic conductivity, with the highest value of D indicating the most suitable battery type.

Ideal Solutions (a+ and a-):

The ideal solutions (a^+) represent the best possible scores across all metrics: Cost (0.111), Efficiency (0.137), Lifetime (0.082), Safety (0.150), Energy densities (0.067), Ionic conductivity (0.080). The negative ideal solutions (a^-)are present the worst possible scores: Cost (0.154), Efficiency (0.127), Lifetime (0.053), Safety (0.132), Energy densities (0.048), Ionic conductivity (0.001).

Distance to Ideal Solution (d+ and d-):

d^+ (Distance from a+): Lower values indicate closer proximity to the ideal solution. Scores: Oxide-Based (0.073), Sulfide-Based (0.043), Polymer-Based (0.089).

d^- (Distance from a-): Higher values indicate closer proximity to the worst-case scenario. Scores: Oxide-Based (0.036), Sulfide-Based (0.097), Polymer-Based (0.084).

Relative distance (D):

Higher values of D indicate the most suitable battery type for electronic devices. Scores: Oxide-Based (0.413), Sulfide-Based (0.672), Polymer-Based (0.321).

Sulfide-Based batteries are the most suitable option for electronic devices, having the highest value of D (0.672). They are superior in efficiency (0.137), lifetime (0.082), and ionic conductivity (0.080), which are critical factors for users seeking long-lasting and efficient batteries. Additionally, their high cost (0.154) and strong safety (0.150) make them a balanced choice. Polymer-Based batteries have a lowest D value (0.321), indicating worst suitability. Oxide-Based batteries having the moderate D value (0.413), they are the acceptable alternative among the three ASSB types.

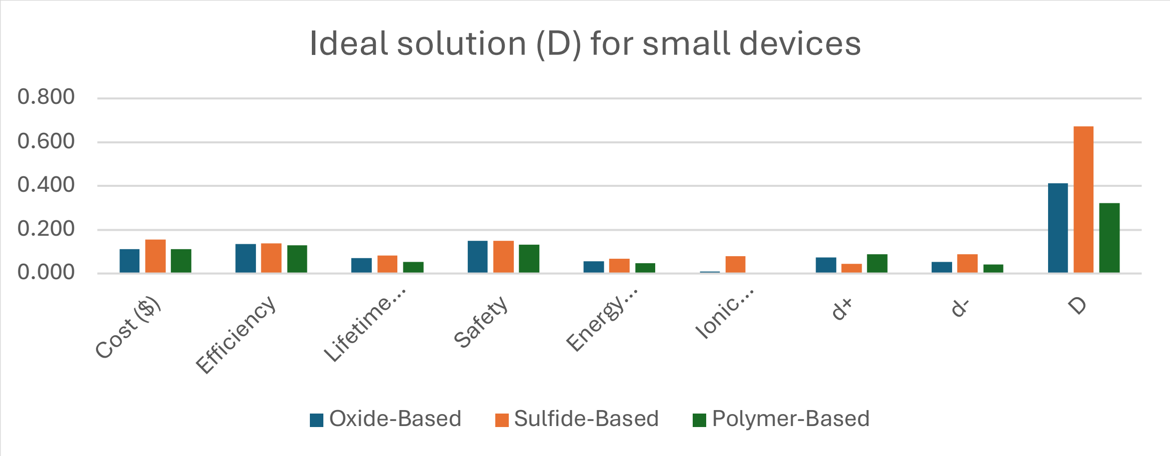

Figure 4.3. Ideal solution (D) for small devices

Conclusively, for electronic devices such as laptops, mobile phones, smartwatches, and wearables, Sulfide-Based batteries are the most suitable option due to their high efficiency, long lifetime, and positive ionic conductivity. Oxide-Based batteries are a safe alternative but do not provide the best performance. Polymer-Based batteries are the least preferable choice as they have low efficiency, lifetime.

5. CONCLUSION

This research investigates the implementation of all-solid-state battery (ASSB) technologies across three major sectors: electric mobility, renewable energy storage, and electronic devices, using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. The study was conducted to address the serious issues associated with current lithium-ion battery (LIB) technologies, which include safety and explosion risks due to flammable liquid electrolytes, low performance, and lower energy density in the targeted research areas. ASSBs, with their non-flammable solid electrolytes and higher energy density, present a promising alternative. However, their practical adoption has limitations such as high costs and manufacturing complexities. The aim of this research was to systematically evaluate and prioritize different ASSB technologies to provide actionable recommendations for their implementation in the targeted sectors.

The literature review for this research encompassed a wide array of sources, including academic journals, industry reports, and case studies. These sources provided insights into the current state of LIB and ASSB technologies, highlighting the limitations of the former and the potential advantages of the latter. Additionally, the literature review covered the methodologies used in previous studies for evaluating ASSB technologies, with a focus on multi-criteria decision-making (MCDM) methods like TOPSIS along with other methodologies i.e. experimental analysis and material characterization, electrochemical testing, interface analysis techniques, theoretical modeling and simulations, thermal testing, and safety evaluation procedures. This background established a foundation for the research by identifying key performance metrics and decision-making frameworks applicable to ASSBs.

The central research problem in this study was: How can advanced all-solid-state battery technologies be ideally implemented in various sectors such as electric mobility, renewable energy storage, and electronic devices to maximize their benefits and overcome existing challenges? The first approach to address this problem, was identification of the critical performance metrics for ASSBs in the context of each targeted sector. The metrics included cost, efficiency, lifetime, safety, energy densities, and ionic conductivity, which were chosen based on their relevance to the functional and economic adoption of ASSBs.

Data collection methods involved gathering qualitative data for analyzing different ASSB types and quantitative data for evaluation of best battery type. The study focused on the peer reviewed research papers, industry reports and the companies that claim to manufacture to ASSBs. This data was evaluated through normalized decision matrix and suitability value (D) to facilitate comparison and fed into the TOPSIS framework. The TOPSIS method was chosen for its ability in handling multiple performance metrics and to rank them based on their proximity to an ideal solution. Each ASSB type was evaluated against the performance metrics, with weights assigned to each metric based on their importance in the respective sector.

The evaluation using the TOPSIS method yielded clear rankings for each ASSB type in the three sectors. In case of electric mobility, quantitative results indicate that sulfide-based batteries have the highest suitability value of D (0.680) for EV applications, and their superior efficiency, long lifetime, and good ionic conductivity, making them the most favorable choice for enhancing the performance and adoption of electric vehicles. The findings address the major concerns of driving range per charge and battery degradation in electric vehicles. For renewable energy storage, the research indicates that sulfide based ASSBs were again identified as the most suitable option due to the highest value of D (0.674), high efficiency and durability. Which are essential factors for the stability and economic feasibility of renewable energy storage systems. In the context of electronic devices, sulfide-based batteries were identified as the best option having the highest value of D (0.682), providing a high efficiency, safety, and long lifespan, which are critical for user satisfaction and device performance.

The interpretation of these results suggests that sulfide based ASSBs are currently the most optimistic technology across all three targeted sectors. This conclusion is based on their superior performance metrics, which align closely with the needs and challenges of each sector. The study also highlights the importance of ongoing research and development to address the remaining challenges of ASSB implementation, particularly in reducing raw material costs and improving manufacturing processes.

In conclusion, this research successfully applied the TOPSIS method to evaluate and prioritize advanced all-solid-state battery technologies for electric mobility, renewable energy storage, and electronic devices. The findings indicate that sulfide-based ASSBs hold the greatest potential for their widespread adoption, offering significant improvements in efficiency, safety, and ionic conductivity over current lithium-ion technologies. The study provides a clear framework for stakeholders to appraise the feasibility of ASSB technologies and emphasizes the need for constant innovation to overcome the economic and technical barriers to their implementation. As ASSB technology progresses, it is expected that these batteries will play an important role in the future of sustainable energy production and advanced electronic devices.

5.1. Recommendations for Future Study (in future)

This study has laid the groundwork for understanding the potential and challenges of implementing advanced all-solid-state battery (ASSB) technologies in electric vehicles, renewable energy storage systems, and electronic devices. However, given the complexity and evolving nature of this field, further research is essential to address the unresolved issues and enhance the practical viability of ASSBs. Future studies should explore new materials, improve manufacturing techniques, long-term performance for practical implications, and develop comprehensive economic models.

Electric Mobility:

Material Innovation: Research on advanced materials for anodes, cathodes and electrolytes that can enhance the energy density and lifetime of ASSBs, particularly focusing on lithium metal electrolytes and sulfur-based cathodes.

Thermal Management: Investigate thermal management solutions to maintain optimal operating temperatures for ASSBs in electric vehicles, ensuring safety and performance.

Charging Infrastructure: Study the development of fast charging technologies compatible with ASSBs, to reduce charging times without compromising battery lifetime.

Safety Protocols: Develop and standardize safety protocols for the use of ASSBs in electric vehicles, addressing potential risks such as overheating, short circuits, and thermal explosion.

Economic Models: Create accurate economic models to calculate the cost-effectiveness of ASSBs in the electric vehicle market, focusing on factors such as raw material costs, production scalability, and market demand.

Renewable Energy Storage

Grid Integration: Future work should focus on the research and integration of ASSBs into the power grid to enhance the stability and reliability of renewable energy systems, focusing on energy storage capacity and discharge rates.

Durability Testing: Conduct extensive durability tests under various environmental conditions and extreme temperature to ensure that ASSBs can withstand the demands of renewable energy storage over long periods.

Hybrid Systems: Explore hybrid energy storage systems that combine ASSBs with other technologies, such as supercapacitors, to enhance their performance and efficiency.

Economic Feasibility: Assess the economic feasibility of installing ASSBs in large-scale renewable energy storage projects, including cost-benefit analyses and return on investment.

Energy Density Optimization: Investigate methods to optimize the energy density of ASSBs for renewable energy applications, ensuring that storage solutions are both compact and efficient.

Electronic Devices

Miniaturization: Research on miniaturization techniques for ASSBs to make them suitable for small electronic devices such as smartphones, wearables, and medical implants.

Performance Enhancement: Investigate methods to enhance the performance of ASSBs in electronic devices, focusing on extended battery life and reducing the need of frequent charging.

Safety Standards: Develop rigid safety standards and testing protocols for ASSBs in electronic devices, addressing issues such as overheating and leakage.

User Experience: Study the impact of ASSBs on user experience, particularly in terms of device’s battery time, charging convenience, and overall performance.

Recycling Technologies: The future research should focus on advanced recycling technologies for ASSBs in electronic devices to promote environmental sustainability and reduce electronic waste.

Prototype Development: Encourage the development and testing of ASSB prototypes for electronic devices, yielding real-world data and user feedback for continuous improvement.

Energy Efficiency: Investigate the energy efficiency of ASSBs in electronic devices to maximize performance and minimize power consumption.

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