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Advancing Electric Vehicle Technologies: A Comparative Analysis of Lithium-Ion and Emerging Solid-State Battery Systems

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Abstract— **This paper examines the evolving battery technology landscape within the electric vehicle (EV) industry, with a particular focus on the shift towards solid-state batteries as a promising alternative to the dominant lithium-ion technologies. While lithium-ion batteries currently lead the market, their inherent drawbacks such as flammability, dendrite growth, and thermal instability are significant impediments to the rapid adoption of EV technologies. Solid-state batteries are highlighted as a viable and superior alternative due to their enhanced energy density and safety profiles. The paper also explores modelling techniques instrumental in enhancing the performance and longevity of lithium-ion and solid-state solutions, potentially accelerating the shift towards EVs in pursuit of global net-zero objectives..**

Keywords—EV Batteries, Solid-State Technology, Battery Modeling, Energy Density

I. Introduction

The trajectory of greenhouse gas (GHG) emissions has seen a disturbing rise, primarily driven by burgeoning economies such as China and Brazil, accounting for 61.6% of the global emissions as of 2019 [1]. Despite a temporary decline by 3.7% during the COVID-19 pandemic, emissions rebounded with a 2.3% increase in 2022 compared to pre-pandemic levels, totaling 53.8 Gt CO2eq [2]. Specifically, the road transportation sector was responsible for 12% of these emissions globally in 2022, with the European Union witnessing a 5% surge in transport-related emissions from 2021 to 2022, the highest among all sectors [1].

The pressing need to mitigate these environmental impacts has intensified efforts towards sustainable transportation solutions, notably through the expansion of electric vehicle (EV) technology. Although over 10 million EVs were on the roads by 2022 [3], the adoption rate still lags behind the targets necessary to achieve global net-zero emissions. Central to this challenge is the advancement of battery technology. Lithium-ion batteries dominate the EV market but are hampered by significant drawbacks including high flammability, material scarcity, and thermal instability.

This paper aims to critically review the current landscape of battery technologies with a focus on evaluating sustainable alternatives that could hasten the transition to electric vehicles. Initially, we discuss the primary battery technologies employed in EVs, outlining their advantages and limitations. Subsequently, Authors explore advanced modeling that could enhance the performance and longevity of these battery systems, thereby supporting faster adoption of EVs to meet environmental goals. Particular attention is given to solid-state battery technology, which offers promising improvements in safety and energy density over traditional lithium-ion systems.

II. Review of EV Batteries

A. Lithium-Ion Batteries

Lithium-ion batteries possess a high power-to-weight ratio as well as a high temperature performance [4]. In the lithium family, lithium iron phosphate is the material used for the cathode due to its high power-to-weight ratio. This is due to its stable structure which allows for faster charging/discharging. Its use of advanced electrolytes, optimum designs and effective thermal management systems are other factors which make lithium-ion batteries feasible for EV technology [5].

Apart from that, lithium metal has a relatively high theoretical specific heat capacity of around 3860 mAh g^{-1} meaning that it has a greater ability to maintain temperature stability within the EV battery. In addition, its electrode potential is also the lowest with a difference of 3.04V against Hydrogen [6].

On the contrary, Lithium-Ion batteries do pose several challenges like its limited energy density as well as Li dendrite formation. Li dendrite formation is usually the result of excess lithium ions forming on the anode surface during times of overcharging or low temperature charging as well. This leads to safety issues such as short circuits and even risk of fires. Reduced battery life is another possibility due to the decomposition of the electrolyte after reacting with the lithium dendrites [7]. Therefore, research is being carried out to introduce dendrite-free and high coulombic efficiency Li metal anode. Coulombic efficiency is the ability of the battery to operate at high current densities without short-circuiting. Investigations includes usage of electrolyte additives, even distribution of lithium-ion deposits, usage of solid electrolytes and stable Li-ion plating [6].

B. Lithium Iron Phosphate

A type of lithium-ion battery chemistry is known for its unique properties and has gained popularity in various applications, including electric vehicles and renewable

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energy storage. They are less prone to thermal runaway, which reduces the risk of fire or explosion, making them suitable for applications where safety is paramount. They also can endure a higher number of charge-discharge cycles before experiencing significant capacity degradation. They are also considered environmental friendliness as the materials used in these types of batteries, including iron and phosphate, are abundant and relatively environmentally friendly compared to other lithium-ion chemistries that may contain more scarce or toxic elements. They energy density is between 90 – 160 Wh/kg.

C. Nickel-Metal Hydride

Research on Nickel-based batteries is being carried out ever since 1967 and it was during the 1980s when hew hydride alloy discoveries enhanced battery stability. Nickel Metal Hydride batteries possess a 40% greater specific energy relative to Nickel Cadmium [8]. This is due to the utilization of nickel oxide hydroxide for optimum chemical reactions. In addition, by using a hydrogen-absorbing alloy for negative electrodes, NiMH (i.e., Nickel-Metal Hydride) batteries achieve double the volume of NiCd (i.e., Nickel Cadmium) batteries and a higher efficiency compared to Lithium-ion batteries. In earlier models of electric and hybrid vehicles, NiMH batteries were popular compared to lead-acid batteries due to high long-term performance, lower cost and better safety features [4]. Another advantage of NiMH includes the formation of water during the discharge process. Therefore, the product does not cause any harm to the environment. In fact, an extra electron is also formed to improve electrical conductivity [8]. Compared to Lithium-ion batteries however, NiMH batteries have a low gravitational energy density. This in turn means that the vehicle has to be charged after a shorter mileage. Even though, NiMH batteries' heavier weight might be useful for counteracting the vehicle inertia, the mileage might still be less due to reduced capacity caused by the battery memory effect. This happens when charging the battery after only being partially discharged [9]. In terms of durability however, NiMH batteries are better performing [4]. Further research is being carried out to overcome the energy density problem in United States., China, Japan and Europe [8].

D. Lead-Acid Batteries

Lead-acid batteries remained the most commonly used battery technology during the 1900s (ever since its invention in 1859). During this time period, increased popularity was also the result of modifications in its capacity as well as manufacturing methods. The main manufacturing procedure involves submerging individual lead alloy cells in an electrolyte. Within the electrolyte, lead oxide is involved in the charging and discharging of the Anode and cathode. In the late 1920s however, EVs were discontinued due to short mileage, long recharging times and insufficient number of charging stations. Furthermore, Lead-Acid batteries were also unable to dominate the market even after the rebirth of EVs in the mid-1990s. This was due to a relatively low specific energy between 30-50 Wh/Kg (as seen in table 1). In fact, ever since the introduction of lithium ion batteries in 1991, even Nickel Metal Hydride batteries were losing their market within the EV industry [10]. Additional disadvantages of lead-acid batteries include environmental and corrosion issues, acid fumes and Sulfation which have also further decreased their usage in the recent years. However, benefits such as its ability to operate under both high and low temperatures, low price and easy to manufacture may enable further improvements in its technology [8].

Table 1- Comparison of battery types

Battery Type	Energy Density (Wh/kg)
Lead-Acid Batteries	30-50
Nickel-Metal Hydride	60-120
Lithium Iron Phosphate	90-160
Lithium-Ion	150-250
Solid-State Technology	>500

E. Solid-State Technology

The latest advancements in solid-state battery (SSB) technology have focused on improving the mechanical and chemical properties of solid electrolytes, developing new materials for anodes and solid electrolytes, and overcoming challenges related to material stability and ionic conductivity. These innovations promise safer, more efficient, and potentially cheaper battery technologies for a wide range of applications, including electric vehicles. Generally, solid-state batteries have been projected to achieve energy densities significantly higher than conventional lithium-ion batteries. Some estimates [11] suggest that solid-state batteries could potentially reach energy densities exceeding 500 watt-hours per kilogram (Wh/kg). Solid-state batteries are becoming a popular area of research due to several benefits in areas of volumetric energy density, temperature stability as well as the elimination of fire risks. This technology employs an inorganic solid electrolyte instead of the organic liquid electrolyte found in the currently used lithium-ion batteries (i.e., organic liquid electrolyte is more flammable). Even regarding performance, Solid State batteries will enable greater driving range between charging periods as well as a longer life cycle. However, several challenges exist in its processing technology. This includes things like the development of electrode and electrolyte materials since changes in material volume can affect mechanical stability. In addition, solid-state electrolytes may not have high magnitudes of conductivity to liquid electrolytes. This is because mobile ions have to travel between ion lattice areas. Research is being carried on several materials such as sulfide and organic polymers. On the contrary, ensuring electrochemical stability at the electrodes will still prove to be challenging [12].

III. MODELLING OF EV BATTERIES

Modeling electric vehicle (EV) batteries involves creating mathematical and computational simulations to predict the performance, degradation, and operational behaviors of batteries under various conditions. These models are crucial for the design, optimisation, and management of batteries in EV applications. They encompass several aspects, from electrochemical processes and thermal management to the

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estimation of the battery's state of charge (SOC), state of health (SOH), and remaining useful life (RUL). These are the main types of models used in EV:

A. Modeling of Lead-Acid Batteries

Lead-acid batteries, known for their robustness and cost-effectiveness, have been widely used in automotive and backup power applications. Electrochemical models of lead-acid batteries focus on the reactions between lead dioxide (PbO_2), lead (Pb), and sulfuric acid (H_2SO_4), which constitute the charge and discharge processes. The Pseudo Two-Dimensional (P2D) model, adapted for lead-acid chemistry, captures spatial variations in ion concentrations and potential differences. Equivalent Circuit Models (ECM), featuring resistors and capacitors, mimic the battery's internal resistance and charge storage dynamics, effectively simulating its transient electrical behavior. [13].

B. Modelling of Nickel-Metal Hydride Batteries:

NiMH batteries offer a balance between cost and performance, with applications ranging from portable electronics to hybrid electric vehicles. Modeling NiMH batteries involves understanding the complex hydriding and dehydriding reactions within the metal hydride anode. Kinetic models describe the reaction rates and are crucial for predicting the battery's response to various loads. ECMs for NiMH batteries often include elements that represent the nickel hydroxide cathode's capacitive behavior and the anode's absorption characteristics. Thermal models are also vital, as NiMH batteries can exhibit significant heat generation during rapid charging or discharging. [14].

C. Modelling of Lithium Iron Phosphate Batteries:

Lithium Iron Phosphate Batteries are prized for their safety, long life, and thermal stability, making them suitable for energy storage and electric vehicles. Modeling these batteries typically focuses on the lithium intercalation process in the iron phosphate cathode. The Single Particle Model (SPM), which simplifies the electrode to a single spherical particle, can effectively capture the essential dynamics of lithium insertion and extraction. Advanced electrochemical-thermal coupled models account for the heat generated by internal resistances and reaction kinetics, aiding in the design of thermal management systems. [15].

D. Modelling of Lithium-Ion Batteries:

The versatility and high energy density of lithium-ion batteries have made them the standard for portable electronics, electric vehicles, and renewable energy storage. Comprehensive electrochemical models, such as the Doyle-Fuller-Newman (DFN) model, delve into the intricacies of lithium transport within electrodes and the electrolyte. These models can be computationally intensive, hence simplified models and ECMs are often employed for system-level simulations and Battery Management System (BMS) integration. Degradation models that simulate capacity fade and impedance rise over time are critical for predicting battery life and performance [16].

E. Modelling of Solid-State Batteries:

Solid-state batteries represent a transformative leap forward in energy storage technology, promising higher energy densities, improved safety, and longer lifespans compared to conventional liquid electrolyte-based lithium-ion batteries. Modeling solid-state batteries involves a comprehensive approach that incorporates electrochemical, thermal, and mechanical aspects to address the unique challenges posed by solid electrolytes and interfaces [17]. This detailed exploration goes into the key components of solid-state battery modeling which include the following:

- Electrochemical Modeling: It focuses on the movement of lithium ions through solid electrolytes, the intercalation mechanisms at the electrodes, and the reactions at the electrolyte-electrode interfaces. The complexity arises due to the solid nature of the electrolyte, which influences ion transport mechanisms and interface stability.
- Thermal Modelling: Thermal models for SSBs calculate the heat generated during operation due to ohmic resistance, reaction enthalpy, and interfacial phenomena. Effective thermal management is crucial to prevent localised hot spots that can degrade performance and safety.
- Mechanical Modelling: Solid electrolytes and electrodes can undergo significant volume changes during lithium insertion and removal, leading to mechanical stresses. These stresses can cause cracking or delamination at interfaces, affecting performance and durability.
- Interfacial Modelling: A critical aspect of SSB modeling is understanding the stability and reactivity of the interfaces between solid electrolytes and electrodes. These interfaces significantly impact ion transport, battery impedance, and overall performance.
- Multiphysics Models: Given the interdependence of electrochemical, thermal, and mechanical phenomena in solid-state batteries, comprehensive multiphysics models are necessary. These models integrate the various physical processes into a unified framework, allowing for accurate predictions of battery behavior under diverse operating conditions.

Modeling solid-state batteries requires a multidisciplinary approach to accurately capture the complex interactions within these systems. The ongoing development of these models is essential for optimising battery design, enhancing performance, and accelerating the commercial adoption of solid-state technology. As research progresses, these models will continue to evolve, incorporating new insights into material properties, interface dynamics, and system-level behaviors to pave the way for the next generation of energy storage solutions.

The flowchart in Fig. 1 illustrates structured approach to how a MATLAB code operates from setting up parameters and material properties, defining the function for differential equations, running the simulation and finally plotting the results.

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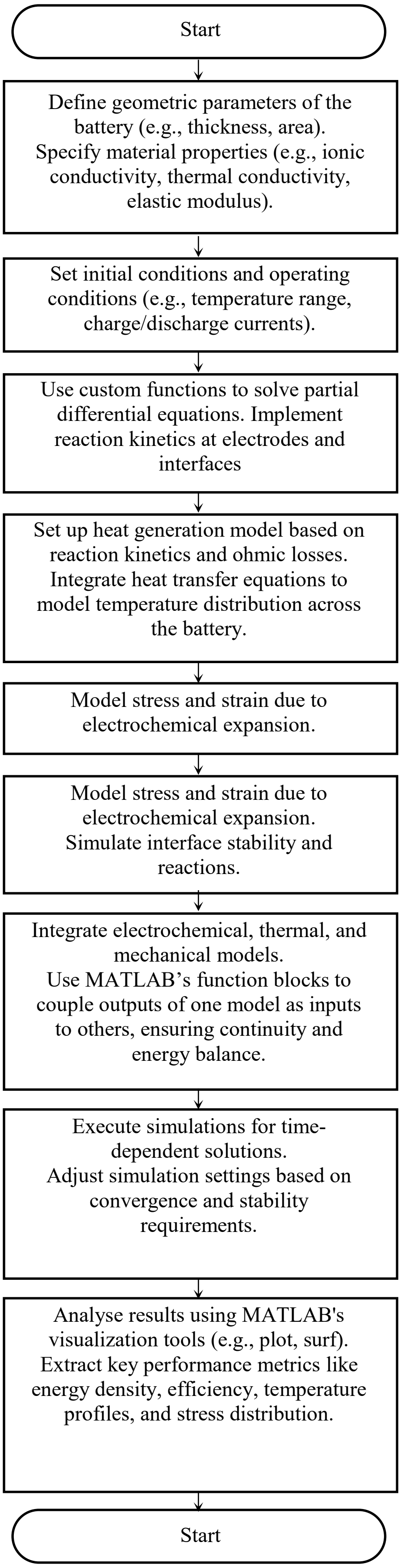

Fig. 1. Flow-chart for Modelling of Solid-State Batteries

IV. Solid -State Batteries in EVs

Solid-state batteries have the potential to significantly enhance the performance and safety of electric vehicles (EVs) compared to the currently dominant lithium-ion batteries. Some of the key advantages in EV applications are [18]:

A. *Increased Energy Density*

Solid-state batteries can store more energy per unit of weight than lithium-ion batteries. This means that electric vehicles equipped with solid state batteries could potentially have longer ranges on a single charge. This is crucial for making EVs more competitive with traditional internal combustion engine vehicles in terms of travel distance.

B. *Faster Charging Times*

Solid-state batteries can potentially be charged much faster than lithium-ion batteries. This could reduce the time EV drivers spend waiting at charging stations, making electric vehicles more convenient for longer journeys and daily use.

C. *Improved Safety*

One of the significant advantages of solid-state batteries is their safety profile. These batteries are less prone to catching fire or exploding in the event of damage or malfunction because they do not contain the liquid electrolytes that are used in lithium-ion batteries, which are flammable.

D. *Longer Lifespan*

Solid state batteries have the potential to last longer than their lithium-ion counterparts. They are less susceptible to issues like electrolyte degradation, which can extend their functional life. This would reduce the frequency and cost of battery replacements for electric vehicles, thereby lowering the total cost of ownership.

E. *Better Performance at Extremes*

Solid-state batteries can operate more efficiently in both very cold and very hot environments. This enhances the reliability and performance of electric vehicles under varying climatic conditions, which is a challenge for current lithium-ion technology.

F. *Cost Competitive*

While currently more expensive due to the early stage of their development and limited production, mass production and further technological advancements could eventually make solid state batteries cost-competitive with, or even cheaper than, lithium-ion batteries. This would help decrease the overall cost of electric vehicles.

While solid state batteries offer significant potential for the future of electric vehicles, several obstacles must be surmounted before they can be broadly implemented. Currently, these batteries are more expensive to produce than lithium-ion batteries due to complex manufacturing processes and high material costs. Additionally, escalating production to meet the demand of the electric vehicle market presents a substantial challenge. Manufacturers are tasked with developing efficient, cost-effective methods for the mass production of these advanced batteries.

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Despite these hurdles, progress in research and development of solid-state battery technology is advancing quickly. Numerous companies and academic institutions are investing significantly in this field to address current limitations and move the technology toward market readiness.

V. Conclusions

The paper concludes by reaffirming the crucial role of advanced battery technologies in the shift towards sustainable transportation. It argues that solid-state batteries are pivotal in this transition, given their potential to resolve many limitations of current battery systems, particularly regarding energy density and safety. The conclusion acknowledges the current economic and technical challenges but remains optimistic about future breakthroughs that could facilitate mass production and adoption. The final thoughts emphasise the importance of continued research and development, supported by both academic and industrial investments, to bring solid-state battery technology to a point where it can meet global demands and contribute effectively to reducing greenhouse gas emissions through enhanced EV adoption.

Future research work in solid-state batteries for electric vehicle (EV) applications is focused on addressing several key challenges and optimising various aspects of the technology. For example, improving the electrolyte materials, increasing energy density, reducing costs, improving cycle life and durability, environmental and sustainability consideration.

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