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Next-Generation Battery Technologies for Electric Vehicles

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ABSTRACT

The worldwide move towards sustainable transport has seen electric vehicles (EVs) become the keystone to the mobility systems in the future. Battery technology is central in the performance, safety, affordability, and adoption of EVs. The domineering conventional lithium-ion batteries (LIBs), though, are becoming weaker due to their constraints around energy density, charging rates, thermal safety, lifecycle degradation, availability of raw materials, and environmental effects. Such issues have only served to drive more research into research on next-generation battery technologies that could support the power needs of the applications of EVs in the modern world. This paper comprehensively and systematically reviews the next-generation battery technologies in electric vehicles with solid-state batteries, lithium-sulfur battery, lithium-air battery, sodium-ion battery, and emerging multivalent and hybrid energy storage systems. The article starts with the description of the changes in EV battery performance as concept of energy density and power density, safety, cost, sustainability, and recyclability. A critical review of literature looks into the current developments, experimental innovations, and industrial developments on several battery chemistries. The suggested section of the methodology proposes a comparative techno-economic/performance analysis framework, which incorporates the electrochemical modelling, lifecycle analysis and systems-level optimization. The feasibility of every battery technology in the deployment of EVs is measured by using quantitative performance metrics, degradation models, and efficiency equations. Discussion and results point to the existing trade-offs between competing technologies with a specific focus on the balance between gravimetric energy density, volumetric efficiency, thermal stability, and supply chain resilience. The paper then summarises by identifying areas of research such as knowledge gaps, challenges to commercialisation and ongoing research such as artificial intelligence-assisted materials discovery, scalable manufacturing and standardisation driven by policies. The purpose of this work is to provide a full source of information to the researchers, automotive engineers, policy makers, and those stakeholders in the industry interested in the development of next generation EV battery systems.

KEYWORDS

Electric vehicles, next-generation batteries, solid-state batteries, lithium–sulfur, sodium-ion batteries, energy storage systems, battery management systems.

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1. INTRODUCTION

1.1. Background

Electrification of transport has become one of the key pillars in the worldwide campaign to cut greenhouse gasses, fight climate change and limit reliance on non-renewable fossil fuel reserves. The rising emission regulations and a rise in environmental awareness are making governments, industries and research institutions world wide increasingly turn to electric vehicles (EVs) as a viable alternative vehicle to replace the internal combustion engine vehicles. The EV sector has experienced a fast-paced technological change over the last 10 years based on major technological innovations of power electronics, high-efficiency electric drives, and high-speed-charging infrastructure, as well as intelligent energy management systems. All these advances have made cars perform better, have a longer range and are more accepted by the consumers enhancing a shift to electric mobility. Regardless of these developments, the battery pack is the most problematic and demanding aspect of an electric car. Not only it is the main source of energy, but also the most costly and the heaviest subsystem commonly, which makes about 30-40 percent of the total vehicle price. The driving range, charging time, safety and the overall cost of the life cycle of any given vehicle are directly affected by battery performance hence it has become a major topic of industrial innovation and also in research. In turn, the cost-effective, high-performance and widely accessible electric cars cannot be attained without enhancing battery technology. The current market associated with EV has been conquered by lithium-ion batteries (LABs) which have a relatively high energy density, prolonged cycle life, and established global manufacturing environment. Nevertheless, with the increase in EV deployment on the international basis, a number of inherent constraints of LIB technology have become more evident. These comprise limitations to theoretical energy density, fire hazards posed by the use of liquid electrolytes that are combustible and decline in performance over very high temperatures. Also, the lengthy charging cycles and strong dependence on hard to find raw materials including lithium, cobalt and nickel pose challenges with regard to suppliers chain security, environmental effects and sustainability in a long term perspective. These issues highlight why next-generation battery technologies are urgently needed to address the disadvantages of existing lithium-ion technology and to enable the further realization of electric transportation.

1.2. Need for Next-Generation Battery Technologies

The blistering growth of the electric vehicles adoption has already revealed the inherent drawbacks of the traditional lithium-ion battery technologies, which generated an excellent necessity to develop the next-generation battery types. Although there has been a tendency in improving chemistries progressively to make them viable, future mobility needs seek to perform disruptive improvements that surpass what is achievable using current lithium-ion platforms.

Fig 1 - Need for Next-Generation Battery Technologies

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1.2.1. Limitations of Energy Density and Driving Range

Among the main reasons that led to the development of next-generation batteries is the fact that the energy density requirements must be more intense to enable longer vitability of cars fueled by EV. The traditional lithium-ion batteries are nearing their real energy density limits, which constrains the further advancements in the vehicle range and design flexibility. The systems of higher capacity batteries will be required to reduce the range anxiety and allow traveling of longer distances as in internal combustion engines vehicles.

1.2.2. Safety and Thermal Stability Concerns

Existing battery technologies involve the use of flammable liquid electrolytes making the issue of safety a serious problem. Cases of thermal runaway, fire and explosion incidents have caused concerns amongst both the consumers and the regulators. Emerging new battery technologies, especially the use of solid electrolytes or intrinsically stable chemistries, are expected to go a long way to promote thermal, and operational safety, which is a primary requirement of a widespread EV adoption.

1.2.3. Fast Charging and Performance Reliability

The practicality of the electric vehicles is limited by the long charging time as well as they deteriorate when not operated at low current or extreme temperatures. The battery systems in the future should be able to support ultra-fast charging and retain structural and electrochemical stability. To ensure uniform performance in different working conditions, enhanced ion transport, lower internal resistance, and strong electrode architectures are required.

1.2.4. Resource Availability and Cost Reduction

Increasing reliance on key raw materials, i.e. lithium, cobalt and nickel has economic and geopolitical vulnerability. The ethical issues and the volatility of the prices based on the material extraction also add to the complexity of large-scale implementation. The second generation batteries place more importance on employing materials with low cost, which are largely available in the Earth, and facilitates more resistant supply chains, as well as lowering the total battery expenses.

1.2.5. Sustainability and Environmental Impact

The environmental impact of battery manufacturing and disposal tends to increase as the number of EVs is larger. The development of new technology in the battery should help in realizing sustainable manufacturing, improved service life as well as efficient recycle. Recycling of materials and lowering emission levels in their lifecycle is crucial to the formation that electric mobility can bring actual environmental advantages. All of them help indicate the necessity of the next-generation battery technologies that can provide improved performance, safety, economic viability, and long-term sustainability and, consequently, open the next chapter of adopting electric vehicles on the global level.

1.3. Next-Generation Battery Technologies for Electric Vehicles

The next-generation battery technologies are in focus of addressing the performance, safety, and cost-effectiveness constraints of traditional lithium-ion batteries and making the next step in the further development of electric vehicles (EV). Following the current trend in the rise of all-electric demand in the world, the creation of improved battery chemistries is on the way to provide higher energy density, quicker charging, enhanced safety, and lowered dependency on scarce raw materials. Solid-state batteries have become one of the most promising ones as they were shown to substitute flammable liquid ionic conductors with solid ones, which is critically important because the thermal

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conductivity and thus the thermal stability are highly increased, and lithium metal anodes may be used, allowing much more energy to be stored. Parallel to this, other technologies that are attracting interest are lithium-sulfur battery, which has a very high theoretically achievable energy density and potentially has very high-density due to the availability of the sulfur material and its low cost. These batteries can potentially radically increase the range of any car, and keep their costs down; issues around cycle life, polysulfide shuttling and electrode depreciation, however, require solutions before mass market use. Another alternative that can offer a resource-rich solution that can decrease reliance on lithium or cobalt entails sodium-ion batteries, which are a cost-effective and resource-rich solution. Sodium-ion batteries have a lower energy density than lithium-based systems, so they are not suitable in long-range electric vehicles or long-distance stationary energy storage applications, but are excellent in short range EVs and stationary energy storage applications where cost and safety are considered important. In addition to these technologies, other studies on multivalent batteries, including magnesium-ion, zinc-ion, and aluminum-ion, are currently growing in size because of their large volumetric capacity and automatic safety benefits. Also, newer technologies like lithiumair batteries are offering very high energy densities, with the potential of approaching fossil levels, but are still largely just in crime because of substantial technical challenges. Taken together, these advanced battery technologies describe a need to shift to more diverse energy storage solutions which are specialized to particular EV applications, with a focus on optimizing performance, sustainability, and scalability in the long term in order to help the world start adopting electric mobility.

2. *LITERATURE SURVEY*

2.1. Evolution of Lithium-Ion Battery Technologies

The progress of the lithium-ion battery (LIB) technology has primarily been predetermined by the necessity to increase the energy density, cycle life and safety to address the increasing requirements of portable electronics and electric vehicles. Investigations of the LIB early focused on layered cathode compounds, including lithium cobalt oxide (LCO) that was promising in terms of good electrochemical excellence but also had a high cost, limited temperature stability and an unethical cobalt sourcing issue. To overcome these shortcomings, other cathode chemistries including lithium manganese oxide (LMO) and lithium iron phosphate (LFP) were created and had focused on the reduction of costs, safety, and the life cycle. Later developments incorporated nickel-based layered oxide, such as nickel-magnesium-cobalt (NMC) and nickel-cadmium-aluminum (NCA) systems, that improved energy density by a large margin and reduced the amount of cobalt content. Simultaneous development in anode materials and especially the addition of silicon in graphite anodes has further enhanced specific capacity considering that silicon has a high theoretical storage capacity of lithium. However, issues including volume expansion, degradation of electrodes and safety hazard which are inherent to the liquid electrolytes still limit the LIB performance. Although there is operational and engineering optimization, many studies have shown that the traditional LIBs are close to their own practical and theoretical energy density constraint of about 300 350 Wh/kg, thereby creating an interest in the development of newer battery chemistry.

2.2. Solid-State Batteries

Solid-state batteries (SSBs) are a potentially viable next-generation energy storage technology as they have the capacity to eliminate the safety and performance shortfalls of liquid electrolyte-based LIBs. SSBs offer a limited number of hazards related to leakage, thermal runaway, and internal short circuits by substituting flammable organic liquid electrolytes with solid ionic conductors. In addition, lithium metal anodes can be used with the help of solid electrolytes, and they have a much higher theoretical capacity relative to traditional graphite anodes, which results in a higher energy density. Recent studies have shown that significant advancements in solid electrolyte materials are noticed, such as sulfide based electrolytes with high ionic conductivity, oxide electrolytes with high chemical stability and polymer electrolytes with high mechanic flexibility and easy processing. This notwithstanding, there are still a number of challenging limitations, especially, high interfacial resistance between electrodes and solid electrolytes, mechanical degradation through cycling and the ability to scale and produce processes that are cost effective. This therefore implies that, although solid-state batteries have great potential in future electric cars and grid scale uses, more investigations are necessary to overcome such interfacial, mechanical, and industrialization challenges.

2.3. Lithium–Sulfur and Lithium–Air Batteries

Batteries based on lithium should, but is not confined to the LiS and LiO 2 types because they have both very large theoretical energy densities. Lithium-sulfur batteries take advantage of the fact that sulfur has a high specific capacity and is naturally abundant; hence, it is a cheap and environmentally friendly solution. Nevertheless, their practical implementation is challenged by the fact that they are weak to polysulfide shuttle effect that causes loss of active material, low coulombic efficiency, and fast capacity decay. Massive research is conducted on cathode architecture development, optimization of electrolyte, and use of host material to entrap polysulfides and enhance cycle stability. Lithium-air batteries, on the contrary, have similar energy densities as gasoline hence are extremely appealing to long-range electric vehicles. Regardless of this potential, Li-air systems are mostly experimental because such severe challenges as the diffusion of oxygen, decomposition of electrolytes, clogging of electrodes, and low round-trip efficiencies exist. Consequently, both Li-S as well as Li-air batteries have the potential of transformation, yet significant technological advancements are needed before the two can be reduced to commercial scale.

2.4. Sodium-Ion and Alternative Chemistries

SIBs are also considered more as an alternative to lithium-ion batteries as a way of reducing carbon emission since the resources of lithium-ion are limited and the cost of materials is on the rise. Natural abundance and affordability of Sodium make SIBs particularly appealing to large-scale stationary energy storage and low- to medium-range electric vehicle applications. In spite of the fact that sodium-ion batteries are typically less efficient in terms of energy density compared to Li-ion ones because of higher atomic weight and larger ionic radius of sodium, recent developments in cathode and anode materials have provided demonstrable rate performance, enhanced cycle life and reasonable energy performance. In addition to sodium-ion system, there are also other battery chemistries currently being explored including magnesium-ion, zinc-ion and aluminum-ion batteries. Such multivalent systems have such advantages as high volumetric capacity, slower rate of dendrite formation and greater safety. Nonetheless, issues of slow diffusion of ions, electrolyte compatibility and electrode stability remain as a problem on their practical performance. All of these alternative chemistries are key directions of research that can help diversify energy storage technologies and eliminate reliance on lithium-based systems.

3. METHODOLOGY

3.1. Comparative Evaluation Framework

The next generation battery technologies need to be evaluated using a wide multi-criteria based evaluation system because no performance index alone can simply reflect their viability in practice. The developed framework rates the emerging battery systems on five key dimensions that

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are critical in scale and that involve technical performance, safety, economic factors, and the potential to deploy them on a long-term basis.

Fig 2 - Comparative Evaluation Framework

3.1.1. Electrochemical performance

One of the key requirements is electrochemical performance and incorporates variables relating to energy density, power density, cycle life, coulombic efficiency and rate capability. Driving range and storage capacity are determined by high energy density and fast-charging and high-load operation are determined by power density. The stability of the cycles during the long past charge-discharge cycles, and capacity retention are important aspects of the operational stability and minimized replacement cost. The dimension is a direct measure of the ability of a battery technology to convert and store electrical energy in compromised real-world operating conditions.

3.1.2. Thermal and operational safety

Thermal safety and operational safety tests the resistance of a battery to thermal runaway, short circuiting, overcharging and mechanical abrasion. This is a criterion that determines how flammable electrolytes, thermal stability of electrode material, and extreme operating temperature. Important to electric vehicles and large-scale energy storage systems, the chemistries of safer batteries have inherent thermal stability, whose failures can be extremely unsafe and very costly.

3.1.3. Economic feasibility

Economic feasibility looks at the cost related factors of the battery technologies such as the availability of the raw material used, complicated process of synthesizing, cost of manufacturing and cost per kilowatt-hour. Supply chain stability and reliance on materials that are critical or scarce like cobalt and lithium is also viewed in this dimension. The technological approaches that are based on the large quantities of low-cost materials and processes that are scalable, have more chances to become commercialized and competitive in the market.

3.1.4. Environmental sustainability

Environmental sustainability considers the environmental effects of the battery technologies through their life cycle, starting at the material extraction and processing, through usage and at end of life disposal, or recycling. Carbon footprint, material toxicity, recyclability, and environmental degradation of the mining activities are some of the factors taken into consideration. The vision of sustainable battery systems is to reduce the negative impact on the environment and help the transition to the concept of the circular economy due to the efficient recycling and recovery of materials.

3.1.5. Scalability and manufacturability

Scalability and manufacturability measure how readily a battery technology can be created to industrial scale and ensures quality and consistency in the produced technology. This factor takes into consideration compatibility to the available manufacturing infrastructure, process complexity,

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yield rates and reliability in mass manufacturing. Technologies based on batteries that can easily be integrated into existing production lines and be scaled quickly have higher chances of coming out of the laboratory research to commercial services.

3.2. Electrochemical Modeling

Electrochemical models form the basis of a quantitative evaluation and comparison of the operation of next-generation battery technologies, as they connect the properties of materials with metrics, a quantifiable aspect of the system. To determine the gravimetric energy density in this work we use the formula (E d = V nom x QM)/m), and (E d) is the energy density of the cell in Wh/kg, (V nom) is the nominal operating voltage of a cell, (Q) is the attainable capacity in ampere-hours and (m) is the total mass of a battery cell. This expression reflects the fact that the electrochemical properties and the physical architecture interrelate, with an increase in voltage or capacity of the electrode material or the electrolyte stability, it is necessary to decrease the mass such that the relationship is not linear. Consequently, through this model, it is possible to make a direct comparative analysis between the various chemistries (e.g. lithium-ion, solid-state and lithium 3-sulfur systems) on a single performance criterion.

Besides the energy density, long-term reliability is represented by the cycle life degradation modeling, which is essential with the electric vehicles and grid-scale storage. The decay of capacity with repeated cycles of charging and discharging is modeled as an exponentially decaying curve (C n = C 0 times e -kn) in which (C n) represents the remaining capacity after (n) cycles, (C 0) represents the initial rated capacity and (k) represents degradation coefficient which characterizes the rate of capacity loss. This parameter integrates various degradation processes, which include the structural change of electrode, decomposition of electrolyte, the increase of the interfacial resistance, as well as the active material loss. With variations in the degradation coefficient, the model is able to indicate various operating conditions, materials, and thermal conditions. When combined, these electrochemical models offer a simplified but powerful model used to predict the performance trends to allow a systematic comparison of the new battery technologies. They do not exhaust the list of microscopic electrochemical phenomena, but they do provide good information on the trade-offs between energy density, durability and the material design and thus aid in making informed choices in battery research and development.

3.3. Lifecycle and Cost Assessment

Lifecycle and cost assessment is a key element in ascertain the workable viability of next generation battery technologies aside of their electrochemical capability. Here, it is the total cost of a battery system that is estimated by relying on the formula (Ctotal = Cmaterials + Cmanufacturing + Crecycling) that reflects the total cost of the entire economic cost in the life cycle of a battery. Material costs are related to the prices and prices of the availability of raw materials (active electrode compounds, electrolytes, current collectors and packaging components) and their price elasticity. Some production costs include manufacturing of electrode, manufacturing of cell, quality control, energy usage, and capital expenditure on production infrastructure. The recycling expenses are end-life processing (with the form of collecting, dismantling, recovering materials and waste treatment) that gains more significance in accordance with the regulations and sustainability objectives. The combined assessment of these cost elements would be more accurate in estimating the economic real footprint of a battery technology as opposed to concentrating on the initial manufacturing cost only. Simultaneously, the environmental impact is determined by the lifecycle analysis in terms of carbon footprint associated with the amount of energy stored or delivered per kilowatt-hour. This measure works on green house gas emissions produced in the extraction of raw materials, material processing,

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cell manufacturing, operational use, and recyclings or disposal at the end of the life of the product or device. The mining and refining of lithium, cobalt, and nickel, which demand high energy requirements, can also have high energy demand contributions to the total carbon footprint. Battery technologies that consume many materials, have reduced temperature processing and recycling with low energy demand tend to have low environmental impacts. The assessment allows comparison of different chemistries and application scales, through normalization of the level of emissions per kilowatt-hour. In general, lifecycle cost and environmental impact analysis is to be incorporated so that the development of the battery meets the economic feasibility and sustainability goals. This integrative approach helps prior informed decision making among researchers, manufacturers and policymakers aiming at finding scalable, cost-effective, and environmental friendly energy storage solutions.

4. RESULTS AND DISCUSSION

4.1. Comparative Performance Analysis

Table 1: Comparative Performance Analysis

Technology	Energy Density (%)	Safety (%)	Cost Potential (%)	Maturity (%)
Li-ion (NMC)	60%	65%	60%	90%
Solid-State	80%	85%	65%	60%
Li–Sulfur	90%	60%	40%	35%
Sodium-Ion	40%	80%	85%	65%
Li–Air	100%	30%	20%	20%

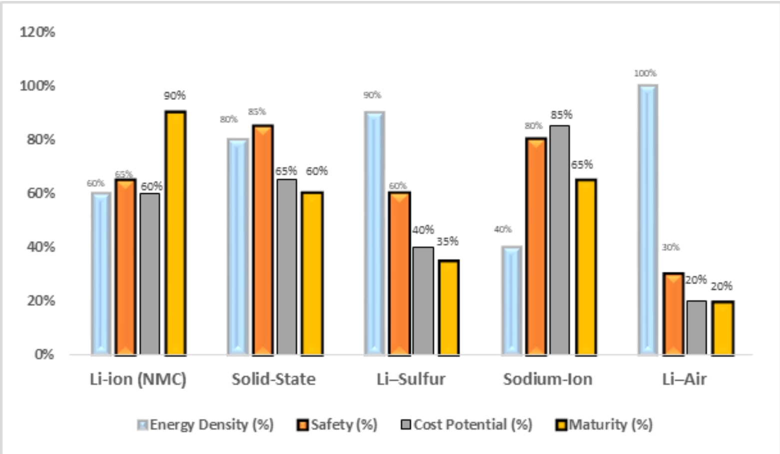

Fig 3 - Comparative Performance Analysis

4.1.1.Li-ion (NMC)

NMC chemistry-based lithium-ion batteries have a balanced performance scheme, including moderate-to-high energy density and well-known safety features. They have the longest level of maturity compared to the other technologies being compared; a certain sign of their high level of maturity is the massive commercial implementation, standardized manufacturing operations, and successful reliability of electrical vehicles and consumer electronics. Although their cost potential is of a moderate nature because of its use of nickel and cobalt, the large continuous material optimization and recycling are what have helped to stabilize supply chains and low long-term costs.

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4.1.2. Solid-State Batteries

Solid-state batteries are highly effective with regard to the energy density and safety because they have solid electrolytes that sharply decrease the risks associated with fires and leakages. Their benefit in energy density is due to the possibility of its use of lithium metal anode, whereas the high score of safety is intrinsic to a higher level of thermal stability. Their medium maturity, however, is a signal that the issues associated with interfacial resistance, material durability, and scalable manufacturing are still actively being studied, before it can be possible to permit a wide commercialization.

4.1.3. Lithium–Sulfur Batteries

Lithiumurn Sulfur battery has potential to be very high energy density, thus suitable to the future high range electric vehicles and aerospace applications. Although they have this merit, their safety and cost potential is moderate to low owing to problems like polysulfide shuttling, instability of the electrolyte and a low cycle life. The small maturity scale indicates that the largest number of lithiumsulfur systems is on laboratory or pilot level and this needs the major breakthrough to be guaranteed to result in long-term stability and commercial viability.

4.1.4. Sodium-Ion Batteries

Sodium-ion batteries are safer and have a cost potential because of the availability and cheapness of sodium materials, and their nature of being naturally stable. Though they have lower energy density than lithium-based systems do, their middle-stage maturity aids in the gradual progress to commercialization, especially in the use of storage of stationary energy and in the short range of electric vehicle use. Their positive cost model makes them a competitive option when it comes to large scale, and cost intensive deployments.

4.1.5. Lithium–Air Batteries

Among all technologies considered, lithium-air batteries have the highest theoretical energy density, which demonstrates their potential to be used in the storage of ultra-high energy in the long term. Nevertheless, they can be characterized by low scores (safety, cost potential, and maturity) because there are still many unresolved issues, such as oxygen control, electrolyte decay, low round-trip efficiency, and complexity of the system. Consequently, the lithium air batteries are also mostly experimental and are most likely going to need a significant technological breakthrough to sufficiently allow their practical application.

4.2. Discussion of Trade-Offs

When comparing the next-generation battery technologies, it could be said that all systems imply their own trade-offs in terms of performance, safety, costs, and technological readiness. Solid-state batteries are the most promising in the nearest future due to the ability to find a good compromise in several criteria. They are highly energy dense due to use of lithium metal anodes directly overcoming the range limitations that are present with current electric vehicles and solid electrolytes are also much safer regarding thermal and operational safety due to the lack of flammable liquid components. Notably, a variety of solid-state battery designs do not entirely replace existing lithium-ion manufacturing infrastructure, and therefore can be gradually industrialized instead of necessitating wholesome changes in the processes. This is a compatibility that minimizes risks of commercialization and solid-state batteries represent a viable transition technology to the next generation of electric mobility. In contrast, lithiumsulfur-based batteries focus on energy density with little consideration to stability and maturity over the long-term. They have such a high

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theoretical capacity as to be used in applications where weight is a critical criterion, e.g. long-range electric vehicles, aviation, and space systems. Nevertheless, their use is limited by recurring problems with polysulfide shuttle effect, high fading cycle capacity and short cycle life. The resolution of such problems will need enormous breakthrough in cathodes fabrication, electrolyte development, and interfacial deposit. Consequently, lithium–sulfur batteries constitute a high-reward, high-risk direction that should be considered in a long-term research investment than in a commercial one. Another example of a trade-off that involves trying to focus more on the cost efficiency and sustainability of resources, instead of improving the energy density of the battery is sodium-ion batteries. Their dependence on a large amount of sodium resources and a relatively easy way to process materials makes them quite suitable to a cost-sensitive market as well as high scale stationary energy storage systems. Sodium-ion systems present an appealing alternative in new economies and short-range use of electric vehicles where affordability and safety are less important than maximum driving range. The overall effect of these trade-offs is to emphasize that there is no universally best battery technology, and anything with an energy storage ecosystem in the future will almost certainly be a diversified portfolio based on application-specific needs.

5. CONCLUSION

New battery technologies are a crucial factor that can define the future of EVs and the general move towards a sustainable system of transportation. Despite years of research and industrial optimization, lithium-ion batteries will remain predominant in the near future as they have already proven reliability and established supply chains, as well as incremental performance and cost improvements. Nevertheless, with the increasing pace of the adoption of electric vehicles and rising performance demands, the natural constraints of traditional lithium-ion technology, especially when it comes to energy density and safety, and the dependency on resources, are becoming more evident. These limitations have inspired the world to conduct studies in advanced battery chemistries capable of providing increased performance in addition to the long term sustainability issues. Solid-state batteries are the most promising of the emerging technologies that could be used in near- and mid-term deployment. The fact that they can contribute greatly to safety, by substituting flammable liquid electrolytes with solid ionic conductors, as well as allowing energy density potentially to be increased by using lithium metal as anode, puts them as a revolutionary step forward over existing lithium-ion designs. Concomitantly, other chemistries, including lithiumsulfur, sodium-ion, and multi-valent battery systems, have complementary benefits, such as ultra-high theoretical energy density, less dependence on critical materials, and better cost-effectiveness. The existence of many of these technologies in their initial phase of development does not mean that their future contribution to electric mobility and grid-scale energy storage may be immense. In the future, the research directions should be holistic and interdisciplinary, meaning that materials science, electrochemistry, data science, and manufacturing engineering will be combined. Machine learning and artificial intelligence will be instrumental in improving the rate of materials discovery, electrode architecture optimization, and long-term degradation behavior prediction to reduce the time and cost of development. Between these, it will be necessary to focus on scalable and efficiency-oriented manufacturing processes to warrant that the laboratory scale of the innovations can be translated into manufacturing. The speech regarding the creation of closed-loop recycling systems allowing effective value recovery, decreasing the toll on the environment, and responding to the principles of the circular economy is also vital. The speed with which innovations will be followed ultimately depends on policy support, standardization activities, and good cooperation between academia, industry, and government. These combined measures will assist in creating a robust, sustainable, and high-

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performance battery ecosystem that will enable the mainstream following decades to come to enact electric cars.

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