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How to improve the lifespan of electric vehicle batteries using chemistry?

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Abstract: Improving the battery lifespan is really important. Improving the battery lifespan can lower the cost reduce the waste and support the future of Electric Vehicles (EVs) and clean energy. The study focuses on existing chemical methods and new system methods that can help solve battery ageing. The study focuses on world use, in China. I think the study uses a literature review as the research method. I focus on studying system-level methods which consist of cell balancing and Battery Management Systems (BMS). I also consider chemistry-based methods such as additives, surface coatings, doping, high-entropy cathodes, single-crystal cathodes, anode pre-litigation, ionic liquids and fluorinated electrolytes. Then, I start to argue two ideas. The main claim says that the current infrastructure and the chemistry knowledge can help battery lifespan development. The counterarguments point out gaps, in the technology the cost, the data sharing, the safety and the uneven access. The findings show that electrolyte additives and smart charging control is the most practical and logical. The future of battery life appears to be within reach through the development of advanced coatings and electrolytes and new cathode designs. The development of advanced coatings together with solid electrolytes and new cathode designs faces challenges because they remain expensive to produce and their manufacturing processes are slow. The conclusion matters in life. In my point of view, rebuilding new factories is unnecessary. The extended lifespan of EV batteries enables car owners to reduce their expenses. The extended lifespan of EV batteries which last longer serves to minimize damage. The better EV battery lifespan supports EV use.

Keywords: Electric Vehicle (EV) batteries, battery lifespan, Lithium-Ion Batteries (LIB), chemical modification

1. Introduction

Nowadays, as the deterioration of the environment and the worrying trend of green-house effect, finding another source of energy to replace fossil fuel becomes more and more important. In the past few years, the popularity of Energy Vehicles (EVs) has given us a new inspiration about it. This kind of renewable energy is considered to be environmentally friendly when it is generated by nature like wind and water [1, 2].

To reach the goal of sustainable development, many famous companies like Tesla and BYD concentrate on developing electric vehicles, and the most important part of the electric vehicle is the Lithium-Ion Battery (LIB), which is the energy storage part in the car, just like the fuel tank in internal combustion locomotive [3].

Up till now, although the energy density of batteries and the efficiency of charging have developed well, lifespan limitation is still a problem that will not be ignored. Due to the lifespan of battery, a lot of the new energy vehicles are needed to change their batteries. It will cost a large sum of money because of supply pressure and high price of lithium and waste a lot of rare Lithium-ion compounds. This dissertation aims to solve lifespan problem of electric vehicle battery in a chemical way [4, 5].

The battery needs replacement because its operational period exceeds its designated lifespan according to Smith et al. [6]. A large number of studies show that the capacity of battery will decrease to about 70% of their previous capacity after 8 years [5, 7]. Besides, the possibility of firing will also increase significantly [8]. The standard implementation will create major effects which will affect both safety and convenience aspects of new energy vehicle operation [9]. In consideration of the problem of excessive price change the battery and the waste of scarce resources, finding a way to improve the lifespan to avoid replacing the battery frequently is becoming more and more important. The aim of this dissertation is not only focusing on the price problem but also aims to achieve the carbon neutrality and sustainable development goal to delay the greenhouse effect and avoid the risk of resource depletion [10, 11].

To solve this problem, some researchers change the material of battery [12]. For example, sodium-sulfur batteries are much cheaper than lithium-ion batteries. However, this kind of battery is used on big machines, the advantage will only be shown when they are working over 300–350 ℃, so they are hard to be applied on domestic vehicles [13]. The lithium-sulfur battery represents an alternative material which could be used. The theoretical specific energy of it is 5 times lithium-ion batteries, and it has lower prices than lithium-ion batteries [12, 14]. However, the development of it is only at the beginning. The energy density of this battery system reaches only half the level of lithium-ion batteries while it experiences rapid deterioration during its operational period [15].

In the following part of the project. The author continue to study how to increase the lifespan of battery and take other factors into consideration. The study will evaluate the safety threats which emerge when people try to extend their battery life and demonstrate methods which boost performance while upholding safety standards [6, 9]. The study will analyze the price problem through the lens of customer response types which Zhang et al. had studied [16].

In literature review part. I will cite some references about the batteries of electric vehicles, from the structure of electric batteries to the possible way to improve their lifespan [3, 17].

In the discussion part. I will summary the references and come up with my own ideas about the method, like changing the electrolyte and material inside the battery [2, 7, 17].

2. Research Review

2.1. Introduction of battery and electric vehicle

To introduce the lifespan of the battery in electric vehicles, the basic structure of battery is need to be told firstly. For most kinds of electric vehicles, Lithium Iron Phosphate (LFP) and ternary lithium are used for the power supply. Batteries usually consisted of 5 parts: cathode, anode, electrolyte, separator and cooling system.

For the cathode which uses ternary materials, the cathode can provide energy with high density which is better when long time working is needed. For cathode made of lithium iron phosphate, they are more stable and have longer cycle life, which suits equipment that requires more safety and durability. About the anode aspect, most of the battery used graphite to make anode, because graphite can accept and release lithium ions. Another potential alternative is silicon-based materials. This kind of material is higher in capacity which can hold more lithium ions, but its expansion characteristics are larger, so more improvement is needed to make it spread. Another component is the electrolyte. The electrolyte is mainly made of lithium salts and other organic solutions. The purpose of them is to pass through the lithium ions to form the lithium flow inside and outside the circuit. The fourth part is the separator. The function of the separator is separating the cathode and anode in order to prevent the happening of short circuit [18], another main function of this structure is that it allows lithium ions to flow freely through the liquid electrolyte [18]. The last component is the cooling system. The function of this is obvious. The aim of them is maintaining temperature stability inside the battery. Most of the batteries in the electric vehicles have equipped the liquid cooling system

The most popular kind of battery is Lithium-Ion Battery (LIB) because it has the best comprehensive properties up to now. For example, the energy density, power, charge–discharge rate, cost, cycle life, safety, and environmental impact. Presently, lithium ion technology is significantly depended on cell with gravimetric energy densities which are smaller than 650W h L -1 [19]. In other industries, energy density is not that important, but in electric vehicles or other portable electronic devices because of the limit of batteries' volume.

Another thing is the electric vehicles. The definition of this kind of machine is automobiles that use electricity as their power source, or that adopt new on-board power devices (such as electric drive systems, batteries, motors). There are also some different types of electric vehicles. According to laws in China, there are mainly three kinds of electric vehicles: 1 Battery electric vehicle; 2 Plug-in hybrid electric vehicle and 3 Fuel cell electric vehicles.

2.2. Reason for the lifespan limitation of batteries

In order to introduce the reason for the lifespan of batteries, definition of lifespan is necessary. The lifespan of battery can mainly be divided into two types: Cycle life and Calendar life. The cycle life of a battery refers to the total number of complete charge-and-discharge cycles which it can perform before its capacity drops to a specific level. The duration of battery life which indicates how long a battery operates beyond its typical usage period.

The number of charge and discharge cycles which a battery can withstand until it reaches its end of life defines its cycle life. As Pinson and Bazant explained [20], "cycle life is critically important in applications of re-chargeable batteries" and much of the lifetime prediction is still based on empirical trends rather than fully understood models.

They show that capacity fading during cycling is driven by slow chemical processes such as growth of the Solid-Electrolyte Interphase (SEI) film on the negative electrode. The battery experiences minor damage and internal modifications during each operational cycle. The electrode materials would experience three possible failures which include cracking and losing electrical contact and detaching from their positions. Over many cycles these changes accumulate and the battery's ability to hold charge declines.

Calendar life, on the other hand, relates to ageing over time and storage rather than active cycling. Wright and Motloch performed tests which involved cell storage at different temperature settings and battery States of Charge (SOC) and their results demonstrated performance deterioration from minimal usage [21]. They found that "both the discharge and regen resistances have a non-linear increase with respect to time at test temperature". This shows that simply being stored under certain conditions still causes capacity to fade; high temperature and high SOC accelerate the process.

Why do these batteries have limited life? There are several main reasons. First, loss of active lithium. The study by Pinson and Bazant shows that SEI layer formation leads to permanent lithium-ion depletion which decreases the battery's usable lithium reserves [20].

The second factor which affects battery performance stems from electrode material degradation. The process of lithium-ion insertion and removal creates mechanical stress which leads to electrode material degradation through active material loss and electrical contact disruption. Third, electrolyte and interface ageing: The electrolyte decomposes while interface layers (SEI or CEI) become thicker which results in performance deterioration and internal resistance increases. The system experiences two main influencing factors which include temperature and State of Charge (SOC): The research by Wright and Motloch demonstrated that resistance growth became faster during calendar-life tests when tests ran at elevated temperatures while the State of Charge rose [21].

2.3. History of the electric vehicles' development

In order to better understand the necessity of improving battery lifespan in electric vehicles today, a short review of the history of electric vehicles is needed. Many studies have dis-cussed the early invention of electric vehicles. The Hungarian physicist Ányos Jedlik built one of the first electric motors in 1828 which he used to drive a miniature vehicle [22].

Then, in 1834, the American blacksmith Thomas Davenport developed a more advanced electric motor system. The design used a basic commutator system which allowed the vehicle to move at 6.4 km/h while carrying heavy loads [23]. However, because early batteries had limited capacity, these vehicles could not be widely used. Gaston Planté from France created the lead–acid battery in 1859 which brought rechargeable storage capabilities to the world and dramatically improved energy storage possibilities [24]. The invention enabled mass battery manufacturing which led to the development of functional electric vehicles.

After that, during the late 1890s and early 1900s, public interest in electric vehicles increased rapidly. For example, the Samuel's Electric Carriage and Wagon Company launched a fleet of electric taxis in New York City in 1897 [25]. The early electric vehicles provided several benefits to consumers when compared to the first petrol cars because they operated without vibration and produced no exhaust smells and made minimal noise while eliminating the need to shift gears. Because of these advantages, the early 1900s later became known as the "Golden Age" of electric vehicles.

However, this Golden Age only lasted about 20 years. The main reason was the improvement of road infrastructure, which made long-distance travel more common. People chose to drive petrol vehicles because these vehicles allowed them to travel longer distances before needing to refuel. The low cost of gasoline became possible because of extensive petroleum extraction operations which reduced fuel prices to levels where most people could purchase petrol cars. The initial electric vehicles operated at low speeds because their batteries allowed them to complete short distance journeys. As a result, most electric-vehicle manufacturers stopped production. By the 1920s, electric vehicles almost disappeared from the market [25].

New construction projects started to emerge in the area during the following thirty years. The 1950s brought Sonotone and other companies to create sintered-plate nickel–cadmium batteries which offered both quick recharging capabilities and reduced weight compared to lead–acid batteries according to Rand et al. [26]. The first battery made with lithium-based chemistry which American Motors Corporation and Gulton Industries developed in 1967 laid the essential base for building contemporary lithium-ion batteries [27].

The California Air Resources Board (CARB) established rules during the early 1990s to promote the purchase of vehicles which emitted minimal pollutants. The policy initiative brought electric vehicles back into public awareness.

Modern electric vehicles have returned to mainstream popularity during the present day. The Tesla Model S launch brought about a fast growth in sales numbers. The vehicle became one of the top electric vehicle sellers in North America during 2013 while annual worldwide sales exceeded 150,000 units in 2016 [28]. The research shows electric vehicles have gained substantial market acceptance yet battery life extension remains essential to progress electric vehicle technology.

2.4. Necessity of improving the lifespan of battery

As the fast popularity of electric vehicles, the safety aspect is becoming more and more important. Using batteries that exceeded their lifespan has many kinds of disadvantages. The most serious one is safety issues. For example, it will cause leakage of chemical liquid like HF in lithium-ion batteries which is extremely corrosive [29]. Leakage of this liquid will not only corrode other electronic components inside the vehicles but also hurt passengers who touch it. Besides, batteries may bulge because of the resistance of ageing batteries increased and more gas is produced inside the battery. Bulge of battery is always considered to be the prognostic of more serious accident's happening because pressure on the coat of battery will increase significantly and easily cause burst of battery splashing out of harmful chemical compound inside the battery. The third danger is that it may lead to fire even explosions. Because lithium dendrites will form inside the battery and pierce the separator between anode and cathode, then cause internal short circuit. The internal short circuit will also produce huge heat energy inside the battery and cause thermal runway and lead to fire or explosion at last.

However, the safety issue is not the only problem. When the battery reaches its lifespan, the performance will deteriorate significantly. Firstly, the capacity of battery will attenuate sharply which will extremely shorten the use time. This will deteriorate the user experience and waste a lot of time on charging. Secondly, the battery in vehicles will face the problem of hard being charged. Ageing batteries may not get charged or have an extremely low charging rate and cost a large amount of time, money and resources on charging. Thirdly, ageing battery will provide current that have unstable voltage because the internal resistance of battery will increase as it is aging. For electric vehicles, unstable voltage may cause unsmooth driving experience and abnormal functions. It can even harm other precision circuit components in the vehicles.

After the introduction of the dangers of using ageing batteries, main reasons why to improve the lifespan of battery instead of changing to another new battery can be concluded as follows. Firstly, about the economic part, nowadays, changing a new battery for electric vehicle requires 20 to 120 thousand yuan in China (£3,207 to £12,830 and $4,215 to $16,860), which takes up 40% to 50% of the rest part of vehicle. However, repairing them only needs 520 yuan on insurance. Secondly on environmental aspect, improving the lifespan of battery can solve the problem of the production of waste batteries which can extremely reduce the stress on environmental pollution. In comparison with changing a new one, producing a new battery will increase carbon emission and the old batteries also have the risk of leaking and giving out corrosive liquid like HF. Thirdly, in the long run, changing a new battery will extremely rely on rare or precious metals like lithium, cobalt and nickel.

2.5. Factors to consider when improving the batteries' lifespan

When considering the methods of improving the batteries' lifespan, there are also a lot of factors to be considered, and I will list them out in the following paragraphs.

2.5.1. Technical limitations

Firstly, material inside the battery will experience necessary attenuation in chemical areas which cannot be avoided. For example, graphite cathode may break apart in the long run because it will shrink and expand when charging and discharging. More importantly, metal lithium will form on the surface of cathode. The process both removes active lithium from electrode materials and creates safety risks according to Chen [30]. The anode also has attenuation. The system will experience structural failure which will lead to metal ion leakage. The electrolyte will also decompose on the surface of electrode to form a layer. The layer will keep consuming lithium ions and electrolyte, which will cause increase of the internal resistance and capacity attenuation [20].

2.5.2. Safety factors

Secondly, for improving the battery lifespan, the normal threshold of temperature must be loosen in order to make batteries working at the materials' limit. It means the battery will suffer higher possibility to run runaway. Besides, ageing batteries also have higher possibility of causing accidents. Things like lithium dendrites and lighter separators will make the battery become less stable when facing accidents like collisions [9]. Do the improvement on lifespan of battery overwhelms the increasing possibility of danger? It remains a question.

2.5.3. Economic factors

Thirdly, the development of batteries with longer lifespan like more precise BMS, thermal control system or new material of batteries will cause high investment on it. The rising expenses for basic materials will drive vehicle prices higher according to McKinsey & Company [31]. How to balance the customers' acceptance of increasing price and the increasing cost will become a new problem.

2.5.4. Environmental factors

Fourthly, it's clear to see that increasing the lifespan of battery can be a most effective way to protect the environment. The method prevents the production of environmentally damaging waste products which include HF and other acidic substances [4]. Increasing the lifespan also means that it will decrease the production of batteries, which will produce the most carbon-containing substances that can pollute the environment. Besides, mining and extracting precious metals like lithium, cobalt and nickel will also be reduced. The mining process of extraction leads to environmental contamination which becomes less severe when this extraction method is used [1].

2.5.5. Operational & Behavioral Dimension

Except for the three general factors above, there are also three dimensions that should be taken into consideration. This dimension is about the human and systematic impacts during the maintenance and use.

In this dimension, user behavior and operation both have their effect on lifespan respectively. The user behavior pattern which includes regular battery charging and both excessive battery charging and complete battery discharge will cause battery deterioration to happen faster [32]. Storage habits like long-term storage at full or low charge will both result in capacity loss [33]. Another aspect is related to the operation. The battery system will show uneven aging patterns and heat distribution because the machine does not have a thermal management system inspection feature and self-cleaning ability [34].

2.5.6. Institutional & Market Dimension

The research dimension will study how external policies together with consumer environment elements lead to longer product lifespan through their indirect impacts. About the policies, up to now, different countries have inconsistent definitions about battery life. The definitions which include cycle count and capacity retention exist with different meanings across various countries and business organizations. This may cause producers to choose an evaluation system that benefits themselves during life testing, thus affecting the actual performance and comparability of their products [34].

About the consumer environment, because of the fast pace of technological advances, consumers' pursuit of "new performance" is always blind, and this will cause the decrease of average lifespan of vehicles [35]. This will also cause the producers to focus on energy density and charging speed instead of lifespan and durability. The current market conditions which offer quick financial gains will create various obstacles for electric vehicle manufacturers to build their products from start to finish [36].

2.5.7. Manufacturing & Supply Dimension

The last dimension is about the manufacturing part. The unbalanced rate of side reactions happens because raw materials containing electrolyte and conductive agents which do not meet purity standards result in quick partial aging according to Li et al. [34]. The production lines of each factory operate under their own separate quality standards. The small producers lack both complete cycling tests and aging verification processes according to Wang et al. [36]. All of this will cause different quality of each battery.

3. Discussion

3.1. Real-world factors supporting extended battery lifespan in electric vehicles

3.1.1 Whether the customers' response supporting the improvement of lifespan

The success of battery lifespan extension depends on how customers feel about this development. Factories can support research and innovation activities because their customers will purchase extended lifespan technologies at higher price points. A previous survey by McKinsey [31] reported that around 67% of EV buyers consider battery longevity one of the top three factors when choosing an electric vehicle, showing that lifespan clearly matters to most users [31].

The level of support depends heavily on customer identity and daily usage needs.

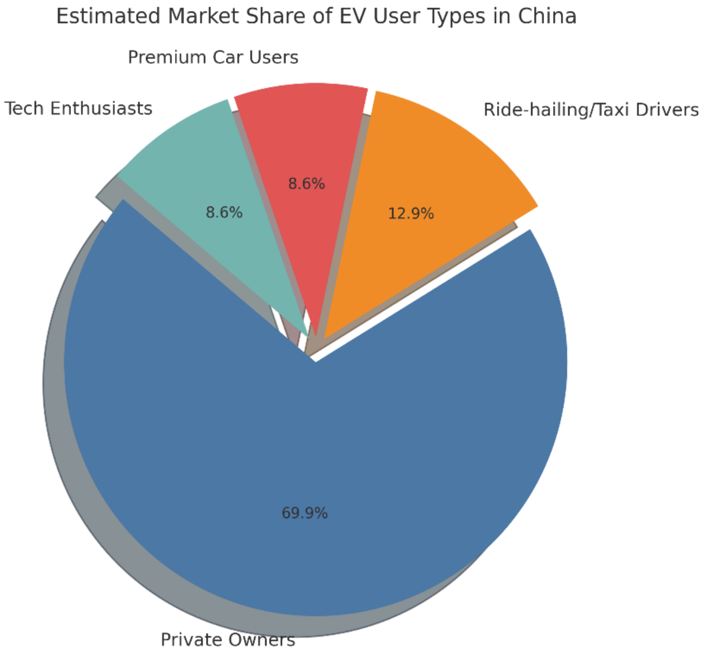

Figure 1. Estimated market share of EV user types in China

As Figure 1 shows, customers can be divided into four main groups: private car owners, ride-hailing/taxi drivers, high-end car users, and technology enthusiasts. Private car owners need their vehicles to last many years while their batteries remain functional and their vehicles maintain their market worth. A survey from Deloitte shows that 58% of private EV users worry that battery ageing reduces resale value. The system needs to maintain safety functionality during any extension of its operational period. Therefore, this group is likely to support longer lifespan technology. The market faces a major problem because customers remain highly responsive to price changes. If the increase in prices from new technology is too large, some owners may hesitate.

High-end car owners consider brand reliability and vehicle performance to be their most important factors. Research shows luxury EV owners do not consider expenses because they select vehicles which provide dependable operation and longer battery life [37]. The main focus of their organization deals with technology readiness and manufacturer warranty clarity rather than expenses. The group members endorse the goal to extend human lifespan. The third group is ride-hailing/taxi drivers, who rely on vehicles as income sources. Their support level is extremely high because improved lifespan directly increases profits. The average ride-hailing EV operates at 300–400 km per day according to CATARC but its battery capacity will decrease to 75–80% after five years which shortens its daily range to 240–320 km. The longer charging time results in reduced total operating time which produces negative effects on business financial performance. Therefore, taxi drivers strongly prefer longer-lasting batteries.

The first payment for electric taxis does not seem to provide enough financial advantages for taxi drivers according to some of them. The premium battery technology requires drivers to pay higher monthly leasing fees for their vehicles because they need to pay now instead of getting future benefits which could create financial problems. The group will maintain their backing for lifespan extension because costs remain affordable and they qualify for financial help through subsidy programs and fleet discount initiatives.

The last group consists of technology enthusiasts who represent 8–10% of the total EV market based on Deloitte. The organization dedicates its resources to buying new technology systems instead of working on user-friendly solutions and budget management. The main requirement of their group demands manufacturers to provide open access to their data which enables members to track advancements in materials and algorithms and battery technology. Although they verbally support lifespan improvement, they are usually unwilling to pay extra for it. Their limited market position makes it impossible for them to use financial influence to direct industry choices.

3.1.2. Whether the infrastructure supporting the improvement of lifespan

The response of the market is not the only thing that needs to be considered. Infrastructure may be an important part in some ways, because it forms the foundation for development.

Firstly, up to now, China has built one of the largest networks of Electric Vehicle (EV) infrastructure in the world. The system includes millions of charging stations together with national battery recycling programs and sophisticated management systems. By the end of 2023, China already had over 8.6 million charging points, and this number is expected to pass 9 million by 2025. Research into electric vehicle battery life extension needs to occur because electric vehicle ownership continues to rise. Next, both the arguments in favor of and against the idea that China's infrastructure supports battery lifespan improvement will be present. The conclusion will show that the current infrastructure system extends battery life but it encounters particular operational problems.

One reason to believe that China's infrastructure can support battery lifespan improvement is the rapid growth of charging stations across the country. The new stations use smart charging systems which monitor temperature and voltage conditions to defend batteries from stressful conditions which cause cycle ageing according to Wang et al. [38]. The systems defend batteries from high charging speeds and hot temperatures because these environmental factors speed up battery deterioration [39]. The EV owners who use this network will experience both practical benefits and receive protection for their battery together with extended battery lifespan.

The basic operational requirement of modern electric vehicles depends on Battery Management Systems (BMS) because these systems enable their operation. The cloud-based BMS system of BYD and NIO and XPeng enables manufacturers to track battery temperature and voltage and state of health. BMS systems which operate with cloud technology integration according to research data will extend battery lifespan because they identify essential system events right away to modify their charging methods [40]. The Chinese BMS systems operate with national data platforms which enable safety monitoring to achieve better management of large EV fleets according to MIIT.

China maintains a complete system for battery recycling and reuse which handles batteries from their start until their end of use. The Ministry of Industry and Information Technology has verified more than 200 licensed battery recycling facilities which operate throughout the entire country. The practice of using EV batteries for energy storage after their vehicle standards become obsolete helps to increase the overall battery lifespan and minimizes the amount of waste produced. Research shows that second-life batteries retain between 70% to 80% of their original capacity which makes them appropriate for stationary energy storage systems [4].

The Chinese battery swapping station system operates as a factor which helps users achieve longer battery life. The battery-swapping facilities of NIO operate more than 2,400 locations which conduct automated battery health checks before and after each usage. The study by Zhang and Qin [16] shows that scheduled maintenance combined with swap charging system management helps decrease battery deterioration when compared to using home fast-charging. The system protects batteries from fast capacity reduction which enables them to operate for extended periods.

However, there are also challenges. The charging stations located in rural areas and less developed regions do not have sophisticated charging control systems. The speed at which batteries lose their capacity during hot weather vehicle charging depends on both the quality and stability of the charging system infrastructure [34]. Major cities have achieved substantial development but their regional development disparities continue to be substantial.

Another limitation is that battery data management is not fully standardized across the industry. Although major automakers use strong BMS, there is no unified national standard for cross-brand battery health data sharing. The organizations fail to track market-wide population aging because their data integration systems do not function correctly according to Chen et al. [30]. The current system restricts the ability to achieve optimized battery life across the entire country.

Battery recycling infrastructure is also uneven. The majority of licensed recycling facilities operate in eastern provinces which include Jiangsu and Zhejiang and Guangdong but central and western areas have limited recycling facilities. Research indicates that communities which do not have enough recycling facilities become more vulnerable to waste disposal violations because they cannot process their waste properly [4]. The public lacks understanding about battery maintenance because EV owners show they do not know how to charge their vehicles properly [17].

The infrastructure which works to enhance battery lifespan maintenance shows positive development despite facing various obstacles. The Chinese charging network together with BMS systems and battery recycling programs and battery-swapping facilities create an effective system which enables battery life extension for EVs. The problems with data distribution and uneven regional development require administrative and technical solutions which can be solved through additional funding and better policies.

In conclusion, although the infrastructure is not perfect, China's current systems can support the improvement of battery lifespan. The advancement of technology together with standard unification will make

China's infrastructure essential for battery life extension of electric vehicles which will create environmental advantages for consumers in the future.

3.2. Existing methods to solve lifespan problems and their advantages and disadvantages

The evaluation of different lifespan-extension methods reveals that particular methods show effectiveness in actual EV battery applications but other methods exist only in laboratory settings. The commercial lithium-ion cells use FEC as an electrolyte additive because this substance provides affordable and simple implementation which results in stable cycle life extension [17]. The application of coating techniques offers better protection but needs complex machinery and longer production periods which makes them unsuitable for big battery manufacturing needed for electric vehicle production. The present EV pack requirements favor the use of additives and charging control methods instead of alternative solutions.

The comparison becomes easier to understand because coating technologies exist in various forms which demonstrate distinct advantages and disadvantages. High-entropy cathodes represent a modern approach which combines multiple metal elements throughout the cathode structure. The design achieves stability at high voltage operation but it does not solve the material cost problem which makes industrial production impossible [30]. High-nickel cathodes receive doping treatment through Mg-doping and Al-doping as one of their strategies. The addition of doping materials to cathode materials enhances their operational stability in batteries while protecting against oxygen loss but high doping levels decrease battery capacity so researchers must find the best doping concentration.

Scientists have also studied single-crystal cathode particles, which do not have grain boundaries that normally crack during cycling. The manufacturing process allows batteries to run for long times but the creation of single-crystal particles requires costly production methods and particular fabrication procedures [41]. The anode prelithiation method represents a technique which adds lithium to the anode material before the battery's initial cycle to minimize its capacity reduction during the first cycle. The method generates successful results but factory implementation remains dangerous because prelithiation materials create dangerous reactions with air components which exist in the atmosphere [42].

The research team uses ionic liquid electrolytes because these substances show stability in SEI layers and they do not evaporate rapidly. The materials operate safely because they decrease chemical reactions but their high cost and insufficient electrical conductivity at normal temperatures prevent their application in electric vehicle technology [43]. Scientists develop strong SEI and CEI films through fluorinated electrolytes which defend battery components from deterioration yet these electrolytes cost more and generate gas when batteries charge rapidly [44].

The laboratory tests show that these coating-related methods produce encouraging results which result in exceptional performance. The majority of these materials need expensive components and they need extended manufacturing periods and they require specific manufacturing environments to function. For this reason, they are not yet widely used in real EV batteries, even though they may become popular in the future.

When comparing all methods, the most important factor for EV batteries is whether the method can be used at large scale, low cost, and with stable results. The production of EV packs requires thousands of cells which causes the total battery pack price to rise when manufacturers face any cost escalation. The current manufacturing methods which include coating and doping and single-crystal production provide excellent technical advantages but they do not fulfill the requirements of EV production facilities. Solid electrolytes demonstrate promising development prospects according to [45] but their current conductivity levels remain low and they lack readiness for mass car adoption.

The battery industry can implement electrolyte additives and charging-control methods as affordable solutions which match current manufacturing capabilities and EV charging infrastructure. The chemical aging process inside cells becomes delayed because of [17] who studied additives. The system achieves intelligent charging which minimizes both heat and voltage-related stress according to Gonzalez-Moreno et al. [46]. The combination of these two methods provides a functional and robust extension of system lifespan at a reasonable price increase. The research by Sultan et al. [7] system offers useful features yet requires more hardware elements which drive up EV production costs for car manufacturers.

Based on all of these comparisons, the best current solution for EV batteries is the combination of electrolyte additives and smart charging control. The methods provide affordable solutions which deliver safety features and have demonstrated their success through scientific studies and business market adoption. The battery systems in modern EVs enable these vehicles to reach their best performance while maintaining the most cost-effective solution.

3.3. Future of the improvement of battery lifespan

The upcoming years will bring multiple innovative solutions which will extend battery operational time. The search for new materials depends on an essential path which AI technology enables. AI models analyze thousands of chemical structures to identify which compounds will maintain stability through multiple cycles of operation. The method allows scientists to identify both strong cathodes and anodes through quick laboratory tests which eliminate the requirement for multiple extended tests. Scientists have studied self-healing materials as an innovative concept. These materials contain special parts that can close small cracks in the electrode when the battery is used. Because cracks are a major cause of ageing, self-healing materials may help the battery keep its shape for more cycles. But they must stay stable and must not slow lithium movement [47]. Many researchers also focus on solid-state batteries. The batteries function through solid electrolytes instead of using conventional liquid electrolytes. A solid electrolyte functions as a barrier which prevents multiple unwanted chemical reactions while it helps to decrease temperature levels and provides protection to the battery system. The electrodes of this battery type experience slower aging which results in extended battery life. The production expenses of solid-state batteries remain high because their interface connections do not function properly [48]. The coating process can achieve better results through the implementation of Atomic Layer Deposition (ALD) as an advanced method. ALD can create very thin and even layers on electrode surfaces. These layers protect the material from breaking or reacting with the electrolyte. The process of ALD operates at a slow pace while being costly so its implementation in big manufacturing facilities remains uncertain for the future. The development of enhanced electrolytes shows promise to become a future advancement path. The electrolyte solution contains fresh compounds which form protective SEI and CEI layers that protect electrodes from damage during battery charging cycles. The development of stable layers becomes possible through the use of fluorinated additives and ionic-liquid additives which simultaneously decrease gas permeation and heat transfer and side reaction occurrence. The deployment of advanced Battery Management Systems (BMS) serves as a vital answer which will create substantial advancements. The BMS system employs machine learning technology to track battery health during operational use while it operates the charging system to reduce battery degradation. A smart BMS system protects batteries through its ability to stop over-voltage and high temperature and deep discharge which helps extend battery lifespan [49]. The upcoming development of battery lifespan improvement will combine advanced materials with enhanced coatings and electrolytes and sophisticated control systems. The developed concepts show promise to improve EV battery safety performance and extend their battery lifespan.

4. Conclusion

This study concludes that the most practical and effective way to improve electric-vehicle battery lifespan today is a combined approach that uses electrolyte additives inside the cell together with smart charging control at the system level. The two methods work together to support each other because additives establish stable interfaces which extend chemical degradation time and software-based charging methods minimize heat and voltage stress during actual vehicle operation. The two methods already function in current commercial EVs because they need no substantial modifications to existing manufacturing systems which results in excellent lifespan enhancement at affordable prices without production disruptions.

In addition, the contribution of this study is that it brings together chemical and engineering research and shows that real progress can be made through methods that are simple, scalable, and suitable for China's fast-growing EV industry. The research provides improved practical knowledge about battery aging mechanisms through its evaluation of system-level management against chemical ageing-control methods which identify the most suitable solutions for present-day battery applications.

The research contains multiple essential restrictions which need to be addressed. The implementation of high-performance methods including ALD coatings and single-crystal cathodes and high-entropy materials helps minimize fracture and oxygen loss but these methods require costly materials and time-consuming coating processes which make them unsuitable for industrial mass production. The absence of standardized national battery health data between EV manufacturers makes it impossible for them to conduct extended monitoring which restricts their ability to improve their predictive models. The prelithiation process serves as an initial step to reduce lithium consumption at the beginning but it needs dangerous air-sensitive materials to function. The recycling system in China operates with inconsistent coverage because its processing facilities mainly exist in eastern regions which do not provide sufficient support for battery recycling in central and western parts of the country. The implementation of chemical methods which extend battery life results in higher internal resistance and increased production expenses which prevent their use in affordable electric vehicles.

The research results include particular boundaries which need to be studied in future investigations. Factories need to investigate how fast-spray coatings and other inexpensive surface techniques can substitute for ALD technology to enable mass production of protective layers. The government needs to work with businesses to develop a national policy which allows different BMS systems to share health data for enhanced battery reliability throughout their operational period. The research into prelithiation needs to focus on air-stable salts because these materials minimize the safety threats which occur during typical factory production processes. China needs to establish recycling facilities throughout central and western regions to develop an equitable and enduring recycling framework. The development of future electrolytes requires researchers to discover protective electrode additives which will not increase production expenses or electrical resistance during mass EV manufacturing.

The described method enables China to obtain longer battery lifespan through safe and expandable procedures which work for actual deployment.

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