International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

A Review on Evolution of Batteries in Electric Vehicles

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ABSTRACT—

The evolution of battery technology has been a cornerstone of advancements in electric vehicles (EVs), transforming mobility and addressing environmental concerns. This paper reviews key milestones in battery development, from early lead-acid and nickel-metal hydride (NiMH) batteries to the widespread adoption of lithium-ion (Li-ion) batteries, which dominate today's EV market due to their high energy density, long lifespan, and environmental benefits. Emerging technologies, such as lithium-sulfur and solid-state batteries, are also explored for their potential to enhance energy efficiency, safety, and cost-effectiveness.

The study emphasizes the role of Battery Management Systems (BMS) in optimizing battery performance, safety, and thermal management while highlighting challenges such as cost, material sustainability, and limited charging infrastructure. Current research efforts focus on addressing these limitations through advancements in battery materials, recycling methods, and ultra-fast charging solutions.

This review provides a comprehensive analysis of the technical advancements and challenges in EV batteries, offering insights into future innovations necessary for improving range, efficiency, and sustainability. By examining past and emerging trends, the paper lays the groundwork for continued progress in sustainable transportation.

Keywords— *Battery control system, battery modeling, electric vehicle, cell balance, health status, charge level, and battery thermal regulation system*

Introduction

The need to switch to alternate transportation systems and renewable energy sources is growing as a result of the depletion of fossil fuels. The environmental impact is increased by intensive fossil fuel extraction and usage, which produces significant volumes of CO_2 and other pollutants. Because Energy Storage Systems (ESS) store extra energy produced during peak production and deliver it to the grid during periods of high demand or low renewable generation, they are crucial for enhancing the viability and dependability of renewable energy.

As the use of renewable energy increases, ESSs are essential to maintaining the stability of the grid. With advantages like lower greenhouse gas emissions, less air pollution, and improved energy efficiency, electric vehicles (EVs) and hybrid electric vehicles (HEVs) are quickly replacing internal combustion engine vehicles.

EVs and HEVs are powered by batteries, which are prized for their high energy density, low environmental effect, and extended lifespan. Improvements in battery technology, including continuous attempts to boost storage capacity, shorten charging times, and cut costs, are directly related to the wider acceptance of EVs. Because of their advantageous characteristics, lithium-ion (Li-ion) batteries currently control the majority of the EV market; nevertheless, scientists are also looking into alternative battery chemistries. With this strategy, EVs can function as energy storage devices that actively communicate with the electrical grid in addition to being energy consumers. EVs can feed stored energy back into the grid, supporting grid stability and helping to balance supply and demand during times of low electricity consumption or high renewable energy generation. The worldwide battery market is anticipated to

Li-ion batteries' increased efficiency, power density, energy density, and dependability are the main reasons for their appeal. Li-ion batteries' expanding commercial use has also been made possible by their falling production costs, which have allowed its adoption in a variety of industries. To guarantee safe operation, increase driving range, improve power management, prolong battery life, and cut expenses, effective battery management is crucial. When used in electric vehicles, batteries require careful handling. Overcharging or overdischarging are examples of improper behavior that can seriously jeopardize battery safety, hasten aging, and potentially result in fire or explosion situations. Battery systems in electric cars support a number of different electrical components in addition to powering the motor. These cars usually operate under difficult circumstances, such as rapid acceleration and deceleration, and user charging patterns can frequently be

The study explores different battery modeling approaches and looks at the kinds of batteries often used in EVs. It covers a variety of approaches for determining the State of Health (SOH) and estimating the State of Charge (SOC) for individual cells and battery packs. The paper also discusses current developments in cell balancing topologies and examines both traditional and sophisticated battery charging methodologies, as well as pertinent optimization techniques. The development of thermal management in lithium-ion batteries (LIBs) to manage high cycles of charge and discharge is summarized. Problems with BMS are discussed, as well as possible fixes and future lines of inquiry. The study's conclusion provides a summary of the state of the field and recommendations for further BMS development.

Electric cars, or EVs, are now at the forefront of contemporary mobility due to the quick shift to sustainable energy alternatives. Since the beginning of electric mobility, battery technology has advanced significantly, and it is essential to the performance, affordability, and feasibility of EVs. This study traces the technological turning points that have influenced the development of EV batteries and provides a thorough analysis of their evolution. From the earliest lead-acid and nickel-metal hydride (NiMH) batteries to the most advanced lithium-ion (Li-ion) batteries today, it covers a variety of battery chemistries. Additionally, it investigates developments meant to enhance energy density, longevity, charge times, and environmental impact. This overview offers insights into the difficulties and innovations that have shaped the development of EV batteries by looking at past developments and upcoming trends, laying the groundwork for a future of sustainable transportation.

Types of Batteries in Ev

Electric vehicles (EVs) rely on various types of batteries, which can be broadly categorized into primary (non-rechargeable) and secondary (rechargeable) types. Primary batteries are limited to single use, while secondary batteries are rechargeable, making them suitable for EVs and hybrid electric vehicles (HEVs). Among these, secondary batteries with high cycle life, low energy loss, and reliable safety are essential for modern EV applications. Commonly used options include lithium-ion (Li-ion), lead-acid, nickel-cadmium (NiCd), and nickel-metal hydride (NiMH) batteries.

EV batteries are classified as primary (non-rechargeable) and secondary (rechargeable). Secondary batteries, such as Li-ion, lead-acid, NiCd, and NiMH, are essential for EVs due to their rechargeability, long cycle life, and safety.

Importance of Lithium-ion Batteries

Li-ion batteries are preferred for EVs due to their long life (6-10 years), high energy density (200-250 Wh/kg), and efficiency. They are lightweight, safe, environmentally friendly, and free from memory effect, making them ideal for EVs and other applications.

Advances in Lithium-ion Technology : Efforts to improve Li-ion batteries focus on enhancing energy density, safety, and performance. Their compact, efficient design makes them a critical component of EV development.

Emerging Alternatives

Lithium-sulfur (Li-S) batteries offer higher energy density, improved safety, and cost advantages. However, challenges like durability and scalability need resolution before widespread use.

Electric vehicles use a variety of battery types, including **lithium-ion (Li-ion)**, **lead-acid**, **nickel-cadmium (NiCd)**, and **nickel-metal hydride (NiMH)**.

Fig-1: Types of Batteris in Ev

1) Metal/Air Batteries

Metal/air batteries utilize metal anodes and air cathodes. The energy capacity of these batteries is primarily influenced by the anode capacity and the management process. Despite this limitation, metal/air batteries offer very high energy densities and specific energies, with maximum values reaching 400 Wh/L and 600 Wh/L, respectively. Various types include zinc/air, aluminum/air, iron/air, magnesium/air, calcium/air, and lithium/air batteries. These batteries can be classified into primary (non-rechargeable), electrically rechargeable, or mechanically rechargeable types, with mechanically rechargeable batteries offering the benefit of refueling and recycling.

2) Sodium-Beta Batteries

Sodium-beta batteries are known for their high energy density, though only two main technologies have been developed in this field: sodium/sulfur (Na/S) batteries and sodium/metal chloride (Na/MCl2) batteries. These batteries require high operating temperatures, typically between 270°C and 350°C, to maintain the necessary ionic conductivity.

3) Sodium/Metal Chloride (Na/MCl2) Batteries

Na/MCl2 batteries use transition metal chlorides, such as iron chloride (Na/FeCl2) and nickel chloride (Na/NiCl2), as cathode materials. Among these, the Na/FeCl2 battery has seen more significant development, while the Na/NiCl2 battery offers advantages such as higher power density, a broader operating temperature range, and reduced corrosion of metallic elements.

4) Sodium/Sulfur Batteries

Na/S batteries feature a beta-alumina ceramic electrolyte, a sodium anode, and a sulfur cathode. However, the performance of these batteries tends to degrade as internal resistance increases, especially with deeper discharges. Recent research has focused on developing room-temperature Na/S batteries, which have shown promising results in terms of consistent cycling performance.

Battery Modeling Techniques

Since it is crucial for determining the health of the battery, developing an accurate battery model forms the basis of Battery Management System (BMS) design. The three main types of battery models are connected, thermal, and electrical models. The accuracy and complexity of these models differ.

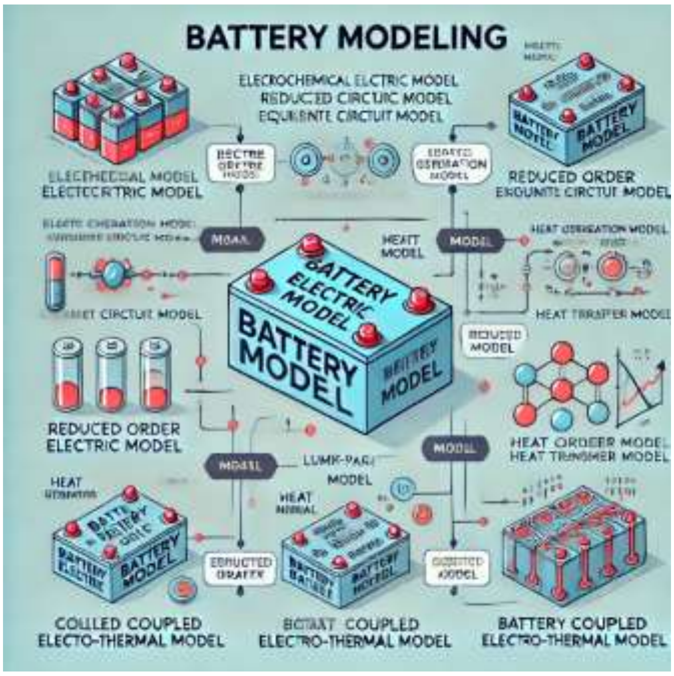

Fig-2: Battery Modelling Techniques

1) Electrochemistry Model (EM)

Electrochemical models use partial differential equations to explain battery behavior, taking into account electrolyte concentration, electrode size, and battery electrochemical processes. Despite the fact that these models offer accurate battery properties, it requires a substantial amount of processing power and time to solve complex equations including battery current, temperature, electrolyte content, and other variables. This makes real-time implementation challenging. Numerous approaches have been proposed by researchers to address these issues.

2) Equivalent Circuit Model (ECM)

Capacitors, resistors, and voltage sources are some of the components that the ECM uses to mimic the battery's electrical behavior. For example, a high-value capacitor or controlled voltage source can be used to represent the Open Circuit Voltage (OCV), which is essential for state estimation. These elements are utilized to account for OCV changes in models like the Rint and Thevenin. The PNGV model includes OCV, polarization resistance, and capacitors, although it may not work well at high states of charge (SOC). Various ECMs, such as one, two, and three RC network models, are commonly used for online applications. In particular, the two RC network model is well known for its accuracy in predicting input-output correlations and battery charging/discharging schedules.

3) The Data-Driven Model, or DDM

ECM and EM models can be effectively replaced by data-driven models (DDMs), which can simulate complex battery behaviors without necessitating a thorough understanding of fundamental structures. Techniques like Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) are commonly used for battery modelling. DDMs are particularly useful when a global mathematical model is uncertain or not feasible. They can handle complex systems with many parameters. These models employ data and computational intelligence to capture battery behavior and offer advantages such as high computation speeds, fault tolerance, and adaptability. While rule-based systems can grow computationally complex, the T-S fuzzy model is one example of a DDM that can manage nonlinear battery dynamics.

B. Battery Thermal Model

Temperature, in particular, is a crucial aspect of EV BMS since it significantly affects battery performance and lifespan. Several models, such as data-driven models, reduced-order thermal models, heat transfer models, and heat generation models, have been developed to represent battery thermal behavior. The amount of heat generated in batteries is influenced by activation, concentration, and ohmic losses. For instance, Abada et al. provided a thermal model for Li-ion battery packs to balance heat generation and dissipation. This model considers ion mobility, chemical interactions, and other temperature-influencing factors. Although the electrochemical-thermal model offers a comprehensive knowledge of battery activity, it is computationally demanding.

C. Electro-thermal Model Coupled with Batteries

Batteries in conjunction with an electro-thermal model

Coupled electro-thermal models combine electrical and thermal phenomena to simulate battery performance. These models enable the simultaneous consideration of electrical parameters such as voltage, current, and SOC, as well as thermal parameters such as interior temperature. One such is a threedimensional electro-thermal model created by Goutam et al. that effectively computes the temperature distribution and battery state of charge at various current levels. Other studies have confirmed simplified electro-thermal models at low temperatures and investigated how discharge current and coolant flow rate affect battery temperature. These coupled models illustrate the critical role that contact resistance plays in thermal dynamics.

Charging and Discharging of a Battery

When a battery's energy is depleted, discharging should stop when the voltage falls below the cut-off value or the SOC drops to 20% or less. The battery then requires recharging. Proper charging is essential to prevent issues like over-discharging, over-charging, or improper charging, all of which can accelerate battery degradation. For Li-ion batteries, temperature management is critical, and charging below freezing should be avoided. By accurately estimating SOC and SOH, optimal charging strategies can be developed to extend battery life, prevent overheating, and maximize capacity use.

A. Traditional Battery Charging Methods

Various charging methods have been used, such as Constant Current (CC), Constant Voltage (CV), Constant Current Constant Voltage (CCCV), and others. Each has its pros and cons. For example, Trickle Charging is simple but slow, taking over 10 hours for a full charge. Constant Current Charging (CC) reduces charging time by increasing current but risks reducing battery life. Constant Voltage (CV) charging ensures stability but can lead to temperature issues and incomplete charging if not set correctly. CCCV, combining CC and CV, is commonly used for fast charging, though CV mode extends the charging time.

To optimize charging, methods like Multi-Step Constant Current Charging (MCC) have been developed, though finding the right current for each step can be challenging. Soft computing algorithms such as genetic algorithms and particle swarm optimization are used to optimize MCC for faster, more efficient charging. For rapid charging, Boost Charging (BC) involves applying high voltage for a brief period, followed by CCCV charging. However, BC is not ideal for real-time applications, as it requires the battery to be fully discharged first. Pulse Charging (PC) is another fast method, but selecting the right charge pulse and frequency can be difficult. These methods aim to improve charging efficiency and minimize capacity loss.

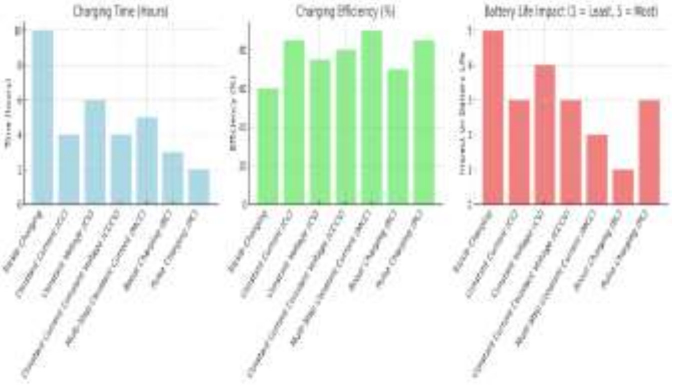

Fig-3: Comparison of Charging Techniques

State of charge

Battery charging requires efficient and careful management to ensure smooth operation, and the State of Charge (SOC) is a key measure representing the battery's remaining energy relative to its total capacity. SOC, akin to a fuel gauge in conventional vehicles, is critical for estimating the range and performance of electric vehicles (EVs). SOC is typically calculated using the formula:

$SOC(\%)=100\times((Q0+Q) / Qmax)$

where $Q0$ is the initial charge, Q is the charge added or depleted, and $Qmax$ is the maximum capacity. Multiple estimation methods improve SOC accuracy by combining data from voltage, current, and other sources, utilizing techniques like Extended Kalman Filters, Particle Filters, adaptive filters, neural networks, and hybrid models. Each model addresses nonlinearity, uncertainty, and dynamic changes in battery behavior, offering various levels of precision and computational demand.

SOC estimation for EV battery packs, consisting of interconnected cells, is more complex due to variations in individual cells. Approaches like "Big cell" modeling, "short board effect," and per-cell calculations each offer trade-offs between safety, energy efficiency, and computational costs. Screening processes help standardize cell characteristics to improve SOC consistency in battery packs, enhancing safety and reliability in applications.

State of health

It is crucial to distinguish between remaining useful life (RUL) prediction and battery health state (SOH). Battery cycle life reflects the maximum cycles a battery can sustain based on its type, design, and usage recommendations. SOH assesses a battery's current health and performance relative to a new one, typically through the ratio of actual to nominal capacity, influenced by factors like current, resistance, and voltage. Temperature is critical, with optimal battery performance between 15°C and 45°C; exceeding this range risks thermal runaway and reduced lifespan.

SOH, defined uniquely by manufacturers, can be evaluated by monitoring capacity, resistance, and power fade, as well as by examining electrode performance and electrolyte state. Battery aging manifests as irreversible changes in these components and is classified into cycle aging (from use) and calendar aging (from storage). Battery aging and degradation can be observed through key indicators such as internal resistance and impedance, which generally rise over time, indicating declining SOH.

Estimation methods for SOH vary. Experimental methods use internal resistance, impedance, and capacity measurements. For example, resistance can be measured via current pulse methods, while impedance often utilizes Electrochemical Impedance Spectroscopy (EIS) for non-destructive analysis. In terms of capacity, tracking changes over time during cycling allows for SOH assessment, though it is typically conducted offline.

Model-based methods include data fitting and Coulomb counting, which respectively track resistance and charge transfer over cycles. Adaptive models employ Kalman filters and observers for real-time SOH estimation, while least square-based filters and data-driven approaches like neural networks offer accuracy by analyzing historical and real-time data.

Key Issues in Battery Management Systems (BMS) and Suggested Solutions:

1.Data Challenges: Large, diverse datasets increase complexity and overfitting risks; real-world testing enhances reliability.

2.Algorithm Optimization: Parameter tuning is time-consuming, risking underfitting or overfitting.

3.Charger Issues: Lack of universal chargers leads to waste; safe discharge systems are critical.

4.**Cell Imbalance**: Uneven cell capacities cause safety risks, requiring advanced BMS designs.

5.Aging Effects: Capacity and performance degrade over time; models must account for aging.

6.Safety Risks: External factors like temperature and overcharging increase fire and explosion risks.

7.Operational Challenges: Maintaining stable conditions and avoiding overcharging or undercharging are essential.

8.Recycling & Reuse: Ensuring safety and sustainability in reused batteries is vital.

9.Disposal: Proper waste management is critical to minimize environmental harm.

10.Miscellaneous: Data logging, circuit complexity, and SOC imbalances challenge efficiency.

Recommendations for Improving BMS:

1. Leverage Big Data & Cloud: Improve algorithm accuracy & real-time data management.

2. Promote Reuse & Recycling: Reduce waste & extend resource lifespans.

3. Enhance Capacity & Quick Charging: Develop new tech for efficient LIB use.

4. Analyze Aging Impact & Life Cycle: Research non-toxic materials & understand aging effects.

5. Follow Installation Best Practices: Ensure safety & compatibility during equipment replacement.

6. Advance Sensor-on-Chip Tech: Improve health diagnostics & defect forecasting with compact BMS design.

Methodology

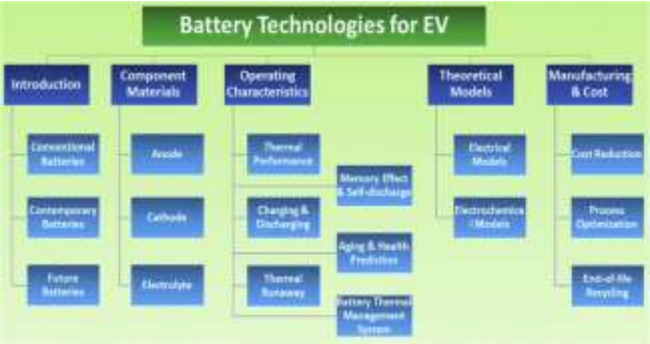

Fig-4: Battery Technologies for Ev

1. Introduction

This section outlines the historical progression of battery technologies:

Conventional Batteries:

Includes early technologies such as lead-acid and nickel-metal hydride (NiMH) batteries, which were bulky, had low energy density, and limited performance, making them less suitable for modern EVs.

Contemporary Batteries:

Primarily lithium-ion batteries, which dominate today's EVs due to their higher energy density, lighter weight, and better performance.

Future Batteries:

Emerging technologies like solid-state, lithium-sulfur, and sodium-ion batteries, focusing on improved safety, cost reduction, and higher performance. These represent the direction of battery evolution for the next generation of EVs.

2. Component Materials

This section highlights the materials critical to battery performance and evolution:

Anode: Historically made from carbon-based materials like graphite, but advancements are moving toward silicon-based anodes for higher energy storage.

Cathode:

Transition from cobalt-rich chemistries to nickel-rich ones (e.g., NMC or NCA cathodes) has improved energy density and reduced costs. Research is now focusing on cobalt-free alternatives for sustainability.

Electrolyte:

Liquid electrolytes dominate today but face safety concerns like flammability. Solid-state electrolytes are being explored to address these issues, marking a significant leap in battery safety and performance.

3. Operating Characteristics

This section explains how batteries perform and the challenges they face:

Thermal Performance:

Managing heat generated during operation is crucial to prevent degradation or failure. Thermal management systems have evolved to handle this.

Charging & Discharging:

Improvements in charging speeds and efficiency have been key to EV adoption. Faster charging methods are being developed to reduce wait times without compromising battery life.

Thermal Runaway:

This refers to uncontrolled heat generation that can lead to battery fires. New chemistries and cooling systems aim to mitigate this risk.

Battery Thermal Management System:

Advanced systems ensure optimal temperature control, enhancing lifespan and safety while improving overall performance.

4. Theoretical Models

This section focuses on the simulation and prediction of battery behavior:

Electrical Models:

Used to analyze voltage, current, and charge-discharge behavior for optimizing battery design and performance.

Electrochemical Models:

Help understand the internal chemical processes, aiding in the development of next-generation batteries by predicting capacity, aging, and efficiency.

5. Manufacturing & Cost

This section highlights challenges in scaling battery production and reducing costs:

Cost Reduction:

The cost per kWh of lithium-ion batteries has significantly decreased over the years, driving EV affordability. Future breakthroughs will focus on cheaper materials and simplified production techniques.

Process Optimization:

Automation and innovative manufacturing techniques aim to increase production speed while maintaining quality, especially for complex chemistries like solid-state batteries.

End-of-life Recycling:

Recycling processes are being developed to recover valuable materials (e.g., lithium, cobalt, and nickel), reducing environmental impact and material scarcity. This is critical for the sustainability of EVs.

Research gaps

A. Joint Estimation Technique

Traditionally, battery states like SOC (state of charge), SOH (state of health), SOP (state of power), and SOE (state of energy) are estimated separately. However, in joint estimation, multiple states are evaluated simultaneously. While this can be effective in some cases, challenges arise when interdependencies between three or more states need to be managed in real-time. Developing a Battery Management System (BMS) that can estimate these states accurately is essential.

B. Battery Pack Equalization, Uniformity, and Reuse

Battery pack design considers uniformity at the manufacturing stage, but this doesn’t guarantee consistent performance in operation due to cell imbalances. Recycling and reusing battery packs can minimize waste, while identifying cells with remaining capacity for repurposing can help address disposal issues.

C. Redesign of Battery Packs for Safety and Efficiency

Optimizing battery packs for better spatial use, crash resistance, and ease of disassembly can improve safety and recycling. Emerging technology integrating photovoltaics and supercapacitors can further extend EV range and storage, supporting EVs in cases where additional energy is available from hybrid sources.

D. Redesign and Optimization of Battery Packs

Research focuses on redesigning battery packs to maximize space, improve crash safety, and simplify recycling through easy disassembly and replacement. Optimizing battery topology and integrating photovoltaic systems, supercapacitors, and hybrid energy sources can enhance EV efficiency and range. For instance, microgrid EV stations with solar, wind, and battery storage can supply surplus energy to the grid and offer backup during outages.

Current challenge: While lithium-ion batteries have dominated EVs, their energy density (amount of energy stored per unit of mass or volume) is still relatively limited. This affects the driving range of EVs, as consumers often seek longer ranges between charges.

There’s a need to identify new materials or chemistries that can provide higher energy densities without compromising safety, cost, or charging time. Solid-state batteries, for example, have the potential to significantly increase energy density, but they still face challenges in scalability and stability.

Current challenge: Most EVs rely on lithium-ion batteries, which, despite their success, have limitations such as limited lifespan, high cost, and reliance on scarce materials like cobalt.

A critical research area is the development of alternative chemistries, such as solid-state batteries, sodium-ion, and lithium-sulfur batteries. These could offer better performance, lower costs, and more sustainable materials. For instance, solid-state batteries promise to be safer and more energy-dense, but challenges remain in their manufacturing processes and long-term stability.

Example:Sodium-ion batteries are considered a potential replacement because sodium is more abundant and cheaper than lithium. However, they typically suffer from lower energy density and cycle life.

Current challenge: EV batteries are the most expensive component of electric vehicles, making up a large portion of the overall cost. Even though battery costs have decreased significantly in the past decade, they remain a barrier to widespread adoption of EVs, especially in lower-price segments.

There is a need for breakthroughs in manufacturing processes that can reduce the cost of battery production while maintaining or improving performance. Additionally, scaling up advanced battery technologies (e.g., solid-state) for mass production requires developing cost-effective, scalable manufacturing methods. This includes addressing supply chain constraints and ensuring that the materials needed are widely available and affordable.

Current challenge: The environmental impact of batteries, both in terms of resource extraction and disposal, is a significant concern. The production of lithium-ion batteries requires mining of materials like lithium, cobalt, and nickel, which have environmental and ethical implications.

There’s a critical need for sustainable practices, including better recycling methods that allow for the recovery of valuable materials from used batteries. While recycling rates have increased, much of the material in used batteries is still not reused effectively. Moreover, new battery chemistries should be designed with end-of-life recycling in mind to minimize environmental impact.

Improving the efficiency of lithium-ion battery recycling could help reduce the reliance on newly mined materials, which would reduce both environmental damage and geopolitical risks associated with material scarcity.

Current challenge: The charging infrastructure for EVs is still insufficient in many regions, and charging times are still a major concern for consumers. While the introduction of fast-charging stations has helped, there’s still a need for more widespread infrastructure.

In addition to expanding the charging network, there is a need for faster charging technology that doesn't degrade battery life. Fast charging often leads to higher temperatures, which can cause accelerated degradation in current batteries. Research on advanced cooling systems and new charging protocols that allow for ultra-fast charging while preserving battery health is vital. Additionally, development of universal standards for fast-charging systems will help create a seamless charging experience for EV owners, regardless of manufacturer.

These research gaps address fundamental challenges in the evolution of EV batteries. Progress in these areas will not only improve the performance, cost, and sustainability of batteries but also accelerate the global adoption of electric vehicles. Tackling these issues is crucial for the continued growth of the EV market and the transition to cleaner, more efficient transportation systems.

Comparison of Energy Density and Cycle Life of Batteries Used in Electric Vehicles

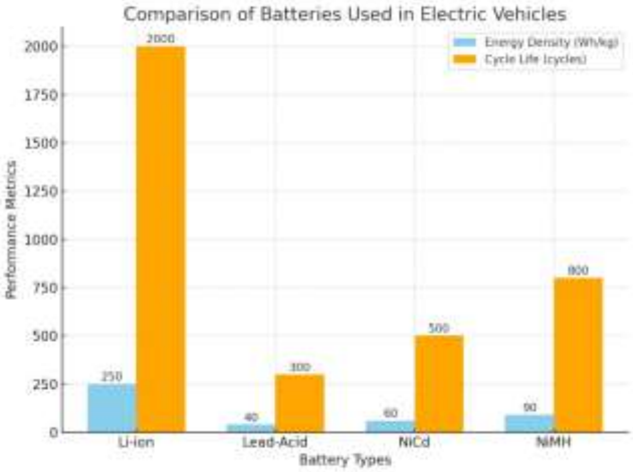

Fig-5: Comparison of Batteries used in Electric Vehicles

The bar graph provides a comparative analysis of four commonly used battery types in electric vehicles (EVs): **Li-ion**, **Lead-Acid**, **NiCd**, and **NiMH**. The comparison focuses on two key performance metrics: **Energy Density (Wh/kg)** and **Cycle Life (number of charge-discharge cycles)**.

1.Energy Density:

Li-ion batteries have the highest energy density (250 Wh/kg), making them ideal for EVs due to their ability to store more energy in a smaller and lighter package.

Lead-Acid batteries have the lowest energy density (40 Wh/kg), making them less efficient for EVs but still suitable for applications where cost is a priority.

NiCd and NiMH batteries fall in the mid-range, with 60 Wh/kg and 90 Wh/kg respectively, making them moderately efficient but bulkier compared to Li-ion.

2.Cycle Life:

Li-ion batteries again outperform others with a cycle life of approximately 2000 cycles, ensuring a longer lifespan in EVs.

Lead-Acid batteries have a significantly lower cycle life (300 cycles), limiting their durability.

NiCd and NiMH batteries offer moderate cycle lives of 500 and 800 cycles, respectively, making them more durable than Lead-Acid but less efficient than Li-ion.

3.Key Insights

Li-ion batteries are the most advanced option, excelling in both energy density and cycle life, which explains their dominance in the EV market.

Lead-Acid batteries are cost-effective but lag behind in efficiency and durability, making them less suitable for modern EVs.

NiCd and NiMH batteries provide balanced performance but are increasingly replaced by Li-ion technology due to its superior characteristics.

This comparison highlights the importance of Li-ion batteries in driving the evolution of EVs while emphasizing the need for continued advancements in battery technology.

Results

Aspect	**Current Status**	**Challenges**	**Future Prospects**
Energy Density	Lithium-ion batteries offer high energy density (150 Wh/kg).	Energy density still needs improvement for long-range EVs.	Solid-state and next-gen chemistries could improve it.
Thermal Management	Active cooling systems are common.	Overheating risks and efficiency loss during extreme conditions.	Enhanced cooling technologies, like phase change materials.
Charging Speed	Fast-charging (30-60 minutes for 80% charge).	Still slower compared to refueling of traditional vehicles.	Ultra-fast charging (15-20 minutes).
Material Sustainability	Reliance on lithium, cobalt, and nickel.	Limited supply of raw materials and environmental impact.	Alternative materials like sodium-ion, solid-state, and recycling advancements.
Battery Lifespan	Lithium-ion batteries last 8-10 years.	Gradual performance degradation over time.	Advanced materials to reduce degradation and improve longevity

Table-1: Challenges and Advancements in EV Battery Evolution

Battery Energy Density Over Time

The evolution of batteries in electric vehicles (EVs) has been pivotal in shaping their adoption and performance. Initially, lead-acid and nickel-metal hydride (NiMH) batteries dominated, but their low energy density and high weight severely limited EV range. The emergence of lithium-ion batteries marked a breakthrough, offering significantly higher energy density (~150 Wh/kg), longer lifespan, and lighter weight, making modern EVs practical. However, challenges persist, including the need for further improvements in energy density to support longer ranges and the development of advanced materials to overcome resource scarcity and environmental impact.

Thermal management has also been a critical focus. While current systems use active cooling mechanisms to maintain safety and efficiency, overheating and temperature fluctuations remain concerns, especially under high-load conditions. Future technologies, like phase-change materials, aim to enhance safety and battery longevity. Additionally, charging speed, although improved with fast-charging systems, is still slower than traditional fuel refueling, creating a barrier for widespread EV adoption. Innovations targeting ultra-fast charging could revolutionize convenience by reducing charging times to under 20 minutes.

Sustainability is another pressing issue, as the heavy reliance on lithium, cobalt, and nickel impacts both cost and the environment. Research into sodium-ion batteries, solid-state alternatives, and advanced recycling methods offers hope for more eco-friendly solutions. Lastly, battery lifespan, currently limited to 8-10 years due to gradual degradation, is being addressed through new chemistries designed to retain capacity over extended cycles.

In summary, while significant advancements have been made in EV battery technology, addressing challenges like energy density, thermal management, charging speed, sustainability, and lifespan will be essential for the continued growth and adoption of EVs.

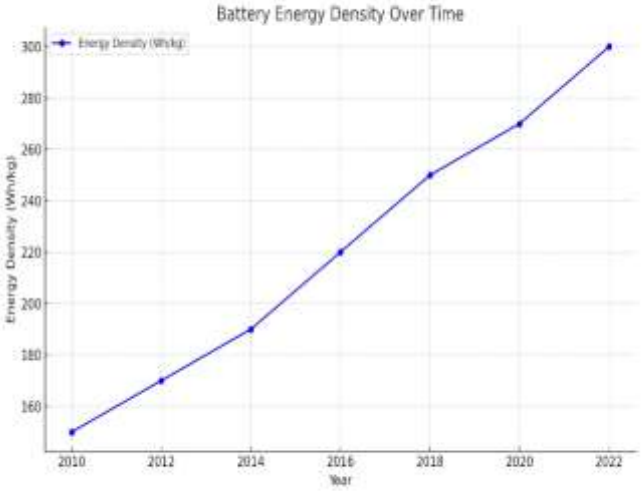

Fig-6: Battery Energy Density Over Time

Cost Reduction Of batteries Over Time

The evolution of batteries in electric vehicles (EVs) has been pivotal in transforming the industry, as illustrated by the presented diagrams. **Battery energy density** has significantly increased over the years, enabling modern EVs to travel greater distances on a single charge without increasing battery size or weight. This improvement, driven by advancements in lithium-ion technology and ongoing research into next-generation chemistries such as solid-state batteries, has addressed one of the key barriers to EV adoption: range anxiety.

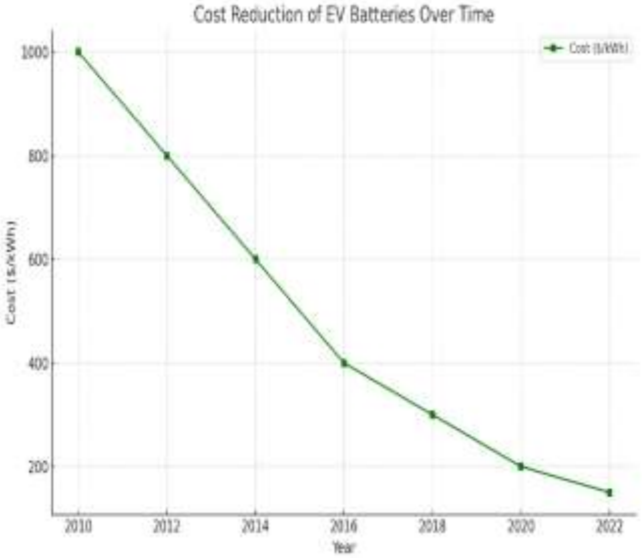

Fig-7: Cost Reductionof Ev Batteries Over Time

Battery Lifespan vs Battery Chemistry

The **cost of EV batteries** has also witnessed a remarkable decline, dropping from approximately $1,000/kWh in 2010 to under $150/kWh in recent years. This cost reduction, facilitated by innovations in manufacturing, economies of scale, and material efficiency, has made EVs more affordable and competitive with traditional vehicles. Continued cost improvements are expected to further accelerate EV adoption by reducing the overall cost of ownership.

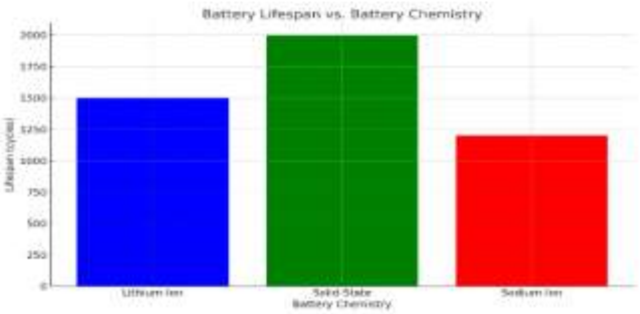

Fig-8: Battery Lifespan vs Battery Chemistry

The **comparison of battery lifespan by chemistry** highlights the progress in battery durability. While lithium-ion batteries dominate the market with lifespans of around 1,500 charge-discharge cycles, emerging technologies like solid-state batteries promise extended lifespans of over 2,000 cycles while enhancing safety and energy density. However, cost-effective alternatives like sodium-ion batteries still lag behind in cycle life, indicating room for further research and development.

Conclusion

The Battery Management System (BMS) is crucial for the efficient operation of Battery Energy Storage Systems (BESS) in electric vehicles (EVs). This paper provides an in-depth review of essential BMS elements, focusing on battery modeling, state estimation, and charging. Accurate battery modeling and precise state estimation are critical, as they offer key insights into operating conditions and support optimized charging strategies. However, fully realizing the potential of BMS technology faces notable challenges, especially in terms of validating these systems in real-world environments. This study highlights these challenges and emphasizes the need to address them to enable smooth BMS integration into EVs.

Promising future directions include developing a universal BMS to standardize technology across different platforms and manufacturers. Enhanced predictive methods and hybrid intelligent algorithms could further improve BMS accuracy. The study also calls for effective prototype designs, essential to converting theoretical advancements into dependable solutions. An interesting area of innovation is BMS virtualization, allowing engineers to simulate various conditions, accelerating testing, and refining BMS technology for faster industry adoption. Overcoming these challenges is vital for mainstream EV integration.

The recommendations in this paper provide valuable guidance to engineers and EV manufacturers in creating safer, more efficient, and reliable BMS solutions. Looking ahead, the paper advocates for a dynamic, data-driven electro-thermal model,

which would enable real-time status monitoring, health diagnostics, and optimized charging. Such a model could enhance EV operational efficiency, extend battery life, and support broader EV adoption. This research not only captures the current BMS landscape but also outlines a path forward by identifying challenges, proposing innovative strategies, and highlighting the potential of new approaches, serving as a foundation for future BMS advancements in EVs.

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