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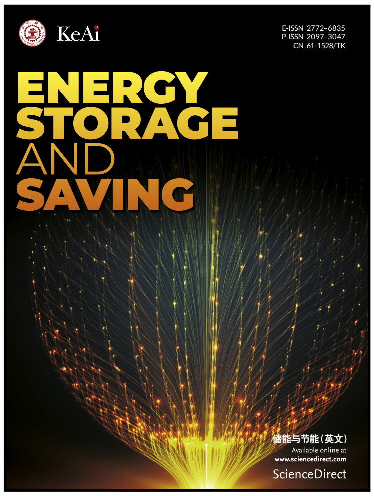

An Electric Vehicle Battery and Management Techniques: Comprehensive Review of Important Obstacles, New Advancements, and Recommendations

Mohammad Waseem , G. Sree Lakshmi , E. Sreeshobha , Shahbaz Khan

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Electric vehicle battery and management techniques: comprehensive review of important obstacles, new advancements, and recommendations

Mohammad Waseem[1*], G. Sree Lakshmi[2], E. Sreeshobha[3], Shahbaz Khan[4]

1. **Corresponding author**
   Dr. Mohammad Waseem
   Faculty and Researcher
   University Polytechnic
   Faculty of Engineering and Technology
   Jamia Millia Islamia (A Central University)
   Jamia Nagar, New Delhi 110025, India
   Phone No.: +91-9935061275
   Email-waseem159088@st.jmi.ac.in
   Orchid Id: 0000-0001-8929-7047

2. **Co-Author II**
   Dr. G. Sree Lakshmi
   Designation: Assistant Professor
   Department of Electrical & Electronics Engineering,
   CVR College of Engg., Hyderabad, India
   E-mail: g.sreelakshmi@cvr.ac.in
   Orchid Id: 0000-0001-5049-5011

3. **Co-Author II**
   Dr. E. Sreeshobha
   Designation**:** Assistant Professor
   Department of Electrical Engineering,
   University College of Engineering, Osmania University, Hyderabad, India
   E-mail: sreeshobha.e@uceou.edu
   Orchid Id: 0000-0002-5379-8904

4. **Co-Author III**
   Dr. Shahbaz Khan
   Designation: Assistant Professor
   Department of Industrial Engineering
   University of Tabuk, KSA
   E-mail: shahbaz.me12@gmail.com
   Orchid Id: 0000-0003-3543-9729

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DECLARATIONS

I. Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

II. Competing interests

The authors declare that they have no competing interests.

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Abstract

The challenges that electric vehicles (EVs) must overcome today include the high cost of batteries, poor specific energy, and ineffectiveness in estimating the state of batteries using traditional methods. This article reviews (i) current research trends in EV technology according to the Web of Science database, (ii) current states of battery technology in EVs, (iii) advancements in battery technology, (iv) safety concerns with high-energy batteries and their environmental impacts, (v) modern algorithms to evaluate battery state, (vi) wireless charging technology and its practical limitations, (vii) key barriers to battery technology, and (viii) conclusions and recommendations are also provided. This paper examines energy-storage technologies for EVs, including lithium-ion, solid-state, and lithium-air batteries, fuel cells, and ultracapacitors. The core characteristics, advantages, disadvantages, and safety concerns associated with these batteries are discussed. Internet-of-Things (IoT)-based approaches are described to assess the battery state in real-time. Furthermore, for enhanced electric mobility, wireless power transfer charging techniques are discussed. Finally, recent advancements and potential outcomes for future EV technologies are outlined.

Keywords: EVs, Li-ion battery, solid-state battery, Li-air battery, artificial intelligence, wireless charging.

Acronyms

AC	Alternative current
AEV	All-electric vehicle
Ah	Ampere-hour
AI	Artificial intelligence
ANN	Artificial neural network
BAT	Battery
BEV	Battery electric vehicle
BMS	Battery management system
BTMS	Battery thermal management system
CC	Cloud computing
DC	Direct current
DoD	Depth of discharge
DT	Digital twin
EDLC	Electric double-layer capacitor
ESS	Energy-storage system
EV	Electric vehicle
FCEV	Fuel-cell electric vehicle
FCHEV	Fuel-cell hybrid electric vehicle
FCV	Fuel cell vehicle
HEV	Hybrid electric vehicle
HFC	Hydrogen fuel cell
ICE	Internal combustion engine
IEA	International Energy Agency
IoT	Internet of Things

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ISC	Ion-solvent-coordinated
LAB	Lithium air battery
LCA	Life cycle assessment
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
LIC	Lithium-ion capacitor
Li-ion	Lithium-ion
Li-Si	Li-ion silicon
LMB	Lithium-metal battery
MC-WPT	Magnetic-coupling wireless power transfer
Ni-Cd	Nickel-cadmium
Ni-MH	Nickel-metal hydride
NMC	Nickel-manganese-cobalt
NN	Neural network
OER	Oxygen evolution reaction
ORR	Oxygen reduction reaction
PCM	Phase-change material
PEMFC	Polymer electrolyte membrane fuel cell
PEO	Polyethylene oxide
PHEV	Plug-in hybrid electric vehicle
PP	Payload period
RL	Reinforcement learning
SMEV	Society of Manufacturers of Electric Vehicles
SoC	State of charge
SoF	State of function
SoH	State of health
SoL	State of life
SoP	State of power
SoT	State of temperature
SSB	Solid-state battery
SVM	Support vector machine
SWPDT	Simultaneous wireless power and data transfer
UC	Ultracapacitor
UCEV	Ultracapacitor-based electric vehicle
VCC	Vehicular cloud computing
WHO	Wild horse optimizer
WPT	Wireless power transfer
Zn-ion	Zinc-ion

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1.Introduction

The imminent exhaustion of fossil fuels, poor air quality, and environmental degradation have recently raised the awareness of ecologically acceptable alternatives worldwide [1,2]. Most transport vehicles use internal combustion engines (ICEs), which are a major cause of environmental problems and global warming [3,4]. Additionally, 18% of India's total energy consumption, primarily derived from the importation of crude oil, is directed toward the country's transportation sector [5]. Approximately 142 million tons of CO_2 is emitted annually by India's transport sector [5]. By 2030, India would be required to reduce its emissions concentration by 33%–35% from 2005 levels, as discussed at the COP21 Summit in Paris [5]. Owing to India's rapid economic extension and urbanization, alternate forms of transportation must be implemented. Worldwide, researchers and the automobile sector are particularly attentive to the advancement in electric vehicles (EVs) in the hope of preventing environmental destruction [6−8]. Several other factors contribute to the concept that EVs represent the future of transportation: (i) aspiration for long-term sustainability, (ii) lowering the dependence on gasoline, (iii) reducing carbon emissions, (iv) radically transforming justifiable transportation, (v) mitigating the consequences of climatic change, and (vi) greater emphasis on computers in self-propelled vehicles.

Fig. 1 shows the global sales of EVs, including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), as reported by the International Energy Agency (IEA) [9,10]. Sales of BEVs increased to 9.5 million in FY 2023 from 7.3 million in 2002, whereas the number of PHEVs sold in FY 2023 were 4.3 million compared with 2.9 million in 2022. Overall, 13.8 million EVs were sold in FY 2023. Hence, the sales of EVs increased by a factor of 26% in FY 2023 compared with 2022. The inability of EVs to preserve the power of their battery cells is the most significant obstacle to user satisfaction and dependability [11].

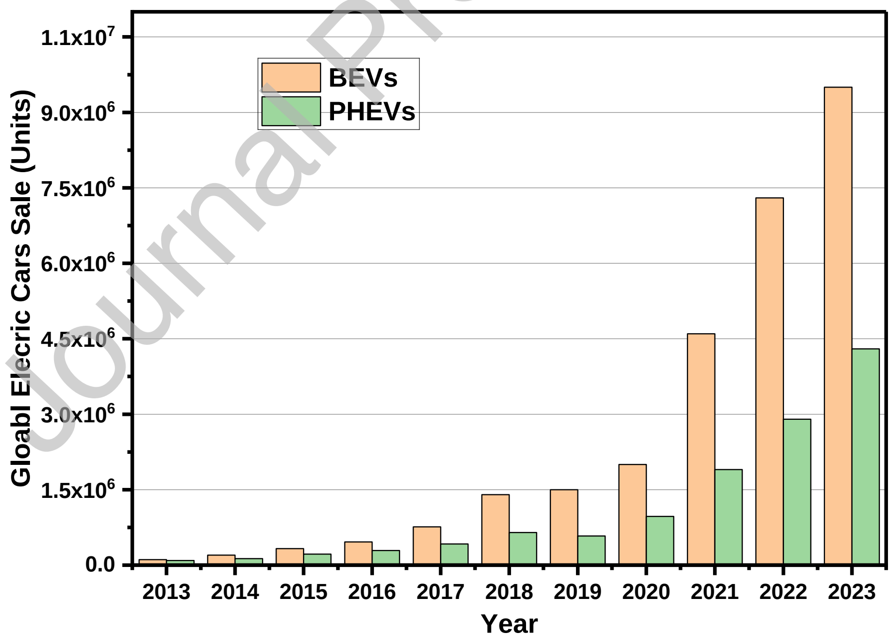

Fig. 1.Global electric vehicle sales according to EIA report

Electrochemical (batteries and fuel cells), chemical (hydrogen), electrical (ultracapacitors (UCs)), mechanical (flywheels), and hybrid systems are some examples of many types of energy-storage systems (ESSs) that can be utilized in EVs [12,13]. The ideal attributes of an ESS are high specific power, significant storage capacity, high specific energy, quick response, prolonged life cycle, high operational proficiency, and low maintenance expenses [11,14]. Rechargeable lithium-ion batteries (LIBs) are currently emerging as the dominant technology among various batteries owing to their low cost, small size, and ability to recharge. [15,16]. These batteries have higher potential and energy densities than other batteries [17]. Additionally, future LIBs are expected to have an energy density of approximately 500 Wh·kg^{-1}, which is comparable to that of fossil fuel vehicles [18,19]. Lithium-metal batteries (LMBs) are solid-state batteries with high energy densities that have attracted significant interest for potential applications in EVs. However, this technological field still requires further study and advancements [20].

This article compares and contrasts several new types of storage batteries as alternatives to the more conventional methods of storing energy for EVs; these include Li-ion silicon (Li-Si), solid-state batteries (SSBs), zinc-ion (Zn-ion), lithium-air, and flow batteries. The advantages of Li-air battery storage for EVs are compared with those of LIBs, including better energy efficiency, fewer blockage problems, and longer driving range. Next, different safety concerns associated with batteries, such as thermal runaway, undesired chemical reactions, and mechanical, electrical, and thermal abuse, are covered. Furthermore, alternative storage techniques such as fuel cells and UCs are being explored and compared with traditional battery storage in terms of their operational features and sustainability for EVs.

Another electrochemical device, the fuel cell, is attracting considerable interest because it can produce electricity from oxygen and water when used in conjunction with batteries for transportation in EVs [21,22]. Owing to their enhanced power density, UCs and supercapacitors are also used in EVs during their first power supply in conjunction with batteries [23]. Mechanical flywheels are attracting particular interest as energy-storage devices owing to the rapid spin caused by torque [24].

A battery management system (BMS) tracks any cell in the battery module that degrades or deteriorates during charging or discharging [25]. It also monitors the battery health while ensuring the durability and security of the battery pack [26]. For the safe and effective functioning of battery systems, an effective BMS is required for both failure diagnostics and prediction. The calculation of battery constraints such as state of charge (SoC), state of health (SoH), state of temperature (SoT), state of life (SoL), and state of power (SoP) is done a combination of hardware and computerized BMS tools [27].

The BMS in EVs monitors, manages, optimizes, and offers safety insurance against substantial hazards to the battery performance [28]. Various rules, logic, and algorithms regulate many BMS components in EVs, including sensors, actuators, and controllers. Internet of Things (IoT)-based computerized techniques have attracted considerable interest for estimating the SoC, SoH, and SoT owing to their flexibility and benefits of being standard-free [29]. They do not employ model estimation approaches;

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hence, they are unaffected by concerns regarding modeling and constraint detection. When new batteries are paired with IoT technology to analyze and oversee energy management, the performance of a BMS improves [30]. The sensing block of the BMS evaluates various battery restrictions, including the current, voltage, and temperature, and provides numerical signals (SoC, SoH, SoT, etc.) [11]. Next, a suitable IoT-based algorithm is employed to regulate the excessive charge–discharge current in real time while monitoring the battery condition [31].

Equivalent electric models and model-based methods are used in LIBs to forecast various states, including SoH, SoC, SoT, and SoP [32]. These methods produce unsuitable values because they depend on models. Hence, optimal algorithms are required to address complicated systems [33]. Numerous cutting-edge methods, such as cloud computing (CC), big data, the IoT, digital twins, and blockchain, have received considerable interest for diagnosing problems and abnormalities related to batteries in EVs. CC technology creates a digital representation of battery patterns by participating in assets and exchanging data [34]. The blockchain strategy is more precise and robust than conventional approaches for obtaining charge data from multiple stakeholders by reducing the estimation errors in the SoH [35]. Setting up big data via IoT in real time is one of the most strategic techniques for forecasting battery states in practical applications [36]. Furthermore, using capacitive-charging techniques when driving on lanes of a road might lessen the reliance of an EV on its battery [37]. Finally, significant challenges and restrictions are addressed in terms of energy-storage technology, BMSs, and charging infrastructure in EVs.

1.1. Motivation and research gap

Selection, performance, safety, and reliability are the prime factors associated with the ESS in EVs. Different ESSs, such as LIBs, lithium-metal batteries, metal-air batteries, solid-state batteries, fuel cells, UCs, and hybrid systems are employed in EVs. Rechargeable LIBs are considered the dominant technology for electric mobility. Their high energy densities can extend the driving range of EVs. However, their safety concerns, cost benefits, and environmental impacts must be investigated and analyzed. Reliable techniques for gauging the internal cell states are essential for maximizing the lifetime and efficiency of battery systems. Robust real-time monitoring technology for BMSs is another critical component of battery optimization. Customer interest in electric mobility is directly correlated with the availability of charging stations and the speed at which EVs may be refueled.

Although a large literature exists on the subject, the aforementioned reviews are now somewhat out of date owing to advancements in energy-storage technology, such as batteries, fuel cells, UCs, BMSs, charging infrastructure, and methods for estimating the SoC in real time. This article discusses a range of topics related to EV technology, including different types of energy storage, methods for evaluating

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the SoC using the IoT, and the effect of a vehicle's wireless charging topology on its driving distance. Furthermore, this paper explores the function of advanced diagnostic techniques used by BMSs, which has not been thoroughly explored before. It aims to elucidate the precise estimation of battery conditions in real-time applications for safe and dependable operation of EVs by examining comparisons based on the results. Table 1 [38−44] provides a summary of the literature review in terms of key findings, techniques, applications, and research gaps in various storage technologies relevant to battery-state estimation and BMSs.

A systematic analysis of current energy-storage technologies for EVs was conducted by the in [38]. The results show that despite being the most popular technology, LIBs have many problems such as heat management, degradation, and lack of resources, even if they are very efficient and have a high energy density. Supercapacitors, despite offering rapid charge–discharge cycles and long lifespans, have lower energy densities, making them less suitable for standalone use in EVs but highly effective in hybrid configurations. Flywheels present a robust alternative with excellent power densities and longevity but are hindered by high costs and complexity. The findings highlight important unsatisfied needs such as improved heat management systems, scalable manufacturing processes to lower prices and increase accessibility, and new materials to boost battery performance. This review emphasizes the need for ongoing innovation and multidisciplinary research to overcome these obstacles and promote the long-term use.

An innovative approach integrating battery and supercapacitor technologies to enhance the performance and efficiency of EVs was presented [39]. The main results show that compared with conventional battery-only systems, this approach has considerable improvements in the charge–discharge rates, total system longevity, and energy density. Improving the efficiency and longevity of EVs, which could result in a decrease in the expense and hassle of replacing batteries, was the main objective of this research. Nevertheless, additional investigation is required to completely utilize the capabilities of the hybrid system, as the study noted knowledge gaps in areas such as the optimization of energy management algorithms and the integration difficulties exhibited by various ESSs.

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Table 1. Review of the literature on different energy-storage system (ESS) and battery management system (BMS) techniques in electric vehicle (EV)

Method	Key findings	Applications	Research gaps	Ref.
Comparative analysis of ESSs: batteries, supercapacitors, flywheels	Lithium-ion batteries (LIBs): High energy density, efficiency, but challenges in thermal management, degradation, and resource availability. Supercapacitors: Rapid charge–discharge cycles, long lifespan, low energy density, effective in hybrid systems Flywheels: Excellent power density, longevity, but high costs and complexity	Combining batteries and supercapacitors to optimize performance and lifespan in EV applications	Need for advanced materials to enhance battery performance. Need for better thermal management solutions. Scalable manufacturing processes to reduce costs and improve accessibility	[38]
Advanced simulation techniques, real-world testing, efficiency evaluation, lifespan assessment, cost-effectiveness analysis	Improved energy density, enhanced charge–discharge rates, increased system longevity, superior performance compared with traditional battery-only system s	Development of more efficient and durable EVs	Need for optimized energy management algorithms, integration challenges of different energy-storage technologies, further exploration required for full potential	[39]
Literature review, meta-analysis	Fuel-cell hybrid electric vehicles (FCHEVs) can significantly reduce greenhouse gas emissions and improve energy efficiency compared with ICE vehicles	Passenger and commercial transportation	High cost of fuel cell systems, limited hydrogen refueling infrastructure, challenges in fuel cell durability and performance	[40]
Combination of batteries and supercapacitors or fuel cells	Extended battery life, improved power density, and increased overall system efficiency.	Hybrid ESSs for EVs	Need for integrated testing and validation in diverse real-world scenarios to ensure robustness.	[41]
Genetic algorithm optimization	Improved efficiency and lifespan of HESSs, balanced load between battery and supercapacitor, reduced thermal stress.	Enhanced EV performance by ensuring stable power output and prolonging battery life	Need for real-time implementation and validation of the proposed strategy under various driving conditions; development of adaptive algorithms for real-time applications.	[42]
Improved wild horse optimizer (WHO), deep learning techniques, BMS integration	Enhanced battery lifespan and efficiency, reduced maintenance costs	IoT-based Hybrid electric vehicles (HEVs)	Scalability for different vehicle models, need for further investigation into long-term real-world applications	[43]
Model predictive control (MPC) for managing battery/supercapacitor hybrid ESSs (HESSs) in EVs	MPC enhances HESS performance and lifespan Efficient power distribution Reduced battery stress Optimized supercapacitor usage during high power transients	Enhancing reliability and energy management of EVs	Need for real-world validation of the MPC strategy Exploration of scalability integration with other advanced EV systems	[44]

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A comprehensive literature review and meta-analysis to examine the current status of fuel-cell hybrid electric vehicles (FCHEVs) was employed in [40]. According to key research, compared with traditional cars powered by ICEs, FCHEVs have the potential to significantly lower greenhouse gas emissions and increase energy efficiency. As fuel-cell technology improves and governments provide incentives, an increasing number of industries are using FCHEVs in their transportation networks, whether for passengers or commodities. Numerous gaps were filled in this study. These include problems with fuel-cell performance and durability, the lack of hydrogen refueling infrastructure, and the high cost of fuel-cell systems.

Various control strategies used in hybrid ESSs (HESSs) for EVs are investigated in [41]. The key findings highlight that combining batteries with supercapacitors or fuel cells enhances overall performance, including extending battery life and improving power density. Despite these advancements, this research identified gaps, such as the need for more comprehensive real-world testing and the development of adaptive control systems that can dynamically respond to varying driving conditions and user demands.

Researchers have utilized a genetic algorithm to optimize the energy management strategy of a HESS in EVs, considering the effects of temperature on battery performance [42]. Significant improvements in efficiency and longevity have been observed as a result of the ability of the revised strategy to balance the load between the battery and supercapacitor, thereby decreasing thermal stress. This strategy can enhance EV performance by ensuring stable power output and prolonging battery life. However, this study identified a gap in the real-time implementation and validation of the proposed strategy under various driving conditions, suggesting that future studies should focus on developing adaptive algorithms for real-time applications.

A novel strategy for hybrid electric vehicles (HEVs) powered by the IoT that combines a deep-learning-enabled BMS with an upgraded wild horse optimizer (WHO) is introduced in [43]. The methods employed include the enhancement of the WHO algorithm to optimize battery performance and the incorporation of deep learning techniques for predictive maintenance and energy management. The key findings indicate a significant improvement in battery lifespan and efficiency with reduced maintenance costs. This approach in HEVs that rely on the IoT can improve the overall performance and dependability of a vehicle. Nevertheless, additional studies on its practical and long-term use are required, and information on the scalability of the system for other vehicle models is lacking.

1.2. Originality and contributions

The following are the key points of this paper in terms of originality and contributions:

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- We uncover and examine recent movements in EV advancement by searching the Web of Science (WoS) database for articles published between 2013 and 2023. The current trends include different EV technologies such as BEVs, fuel-cell electric vehicles (FCEVs), LIBs, fuel cells, UCs, BMSs, and wireless charging.
- This paper compiles a critical analysis of 305 publications from various sources, including Science Direct, Springer, ACS, RCS, Wiley, IEEE, and MDPI.
- We provide an in-depth analysis of emerging battery technologies, including Li-ion, solid-state, metal-air, and sodium-ion batteries, in addition to recent advancements in their safety, including reliable and risk-free electrolytes, stabilization of electrode–electrolyte interfaces, and phase-change materials. This article also offers a cost-benefit analysis of different battery technologies and their environmental impacts.
- This article explores the application of IoT-based BMS techniques, such as artificial intelligence (AI) and CC, in EVs. Real-world practical applications and case studies of these innovative techniques make significant contributions to this field.
- This review covers various aspects of battery-charging infrastructure, including AC charging, DC charging, and wireless charging. Furthermore, the practical challenges and limitations of wireless power transfer (WPT) technology are explored.

1.3. Review approach

A search technique was employed to identify relevant studies for the planned evaluation. Different key words were used to access the Scopus, IEEE, and Web of Science databases: “electric mobility”, “energy storage (ES) medium”, “Li-ion battery”, “solid-state battery”, “Li-air batteries technology”, “battery management system”, “IoT-based BMS”, “wireless charging” and “key barriers with battery”. A flowchart of the planned current research study is shown in Fig. 2.

The main objective of this article is to review (i) current research trends in EV technology according to the WoS database, (ii) current states of battery technology in EVs, (iii) advancements in battery technology, (iv) safety concerns with high-energy batteries and their environmental impacts, (v) modern algorithms to evaluate battery state, (vi) wireless charging technology and its practical limitations, (vii) and key barriers to battery technology. Conclusions and recommendations are provided.

A comparative study of EV technological requirements, power sources, and standards is conducted. Subsequently, the technology for Li-based batteries in EVs is described. International battery standards and comparisons of various technological battery elements to promote EV use are analyzed. Innovative battery technologies, including solid-state, metal-air, and flow batteries, are investigated and analyzed in terms of their benefits, limitations, and safety concerns. Many operating aspects of fuel-cell and UC storage techniques are reviewed and compared with batteries in EVs. We explore

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new IoT-based diagnostic approaches, such as digital twins, CC, block chains, big data, and AI, to assess a BMS SoC, SoT, and depth of discharge (DoD). The core characteristics, advantages, and disadvantages of battery and BMS diagnosis technologies for EVs are discussed, along with current technical advancements, upcoming difficulties, and potential future applications. The advancement of EVs through wireless charging is highlighted, along with improvements in driving range and reliability.

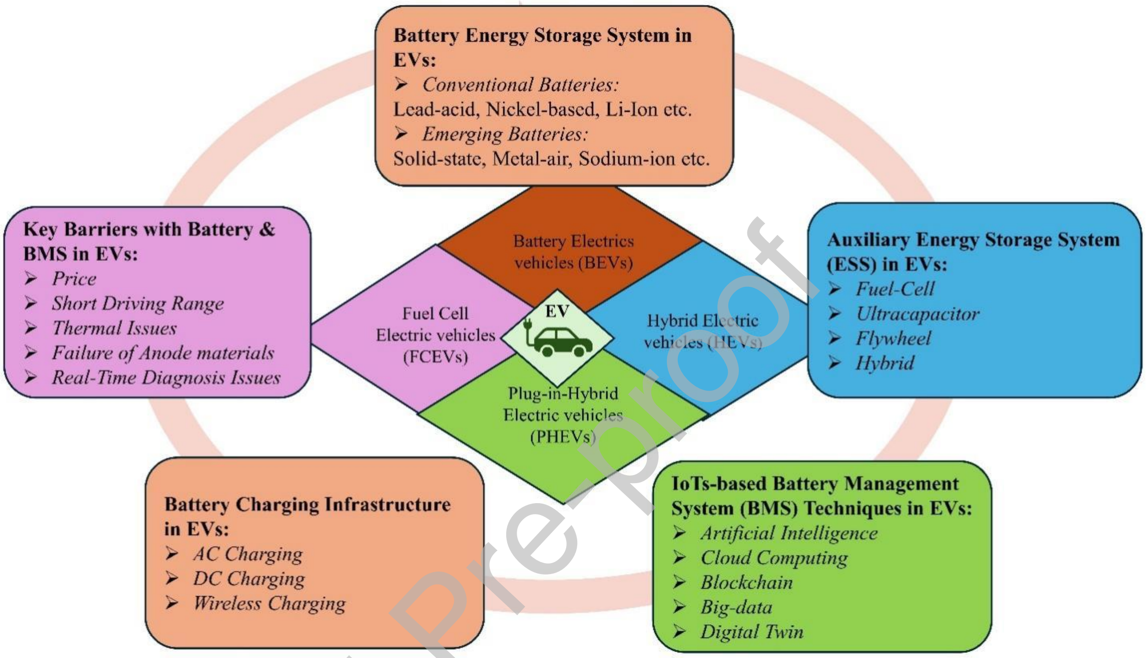

Fig. 2. Flowchart for this study

The remainder of this article is structured as follows. Section 2 summarizes the current research trends in battery technology according to the WoS database. Various EV classes and their power sources are summarized in Section 3. In Section 4, several energy-storage technologies such as lithium-based batteries, fuel cells, supercapacitors, and solid-state, metal-air, and flow batteries are discussed. Section 5 examines BMS capabilities in monitoring battery conditions. The wireless charging infrastructure used in EVs is discussed in Section 6. The main impediments to battery technology and BMS techniques for EVs are discussed in Section 7. The overall evaluation and recommendations for future improvements in EVs are presented in Section 8.

2.Current research trends in EV technology

Fig. 3 depicts the recent developments in EVs advancement, consisting of articles published in the WoS database between 2013 and 2023. The current trends include different EV technologies such as BEVs, FCEVs, LIBs, fuel cells, UCs, BMSs, and wireless charging. Fig. 3 summarizes, the general trends in research that align with EV initiatives; LIBs and fuel cells have been the dominant research subjects. Approximately 54,969 fuel-cell-related papers were published from 2013 to 2023. The second most popular topic was LIBs, with 46,083 relevant articles published by 2023. BEVs are ranked third, with approximately 15,354 research articles published up to 2023. Fig. 3 shows that BMS technology has been attracting much interest, with 10,041 research articles published by 2023. Furthermore, in 2023, research topics such as UCs were more prominent than FCEVs and wireless technology. However, because of recent advancements in EV technologies, LIBs have undergone more significant developments than any other technologies since 2013.

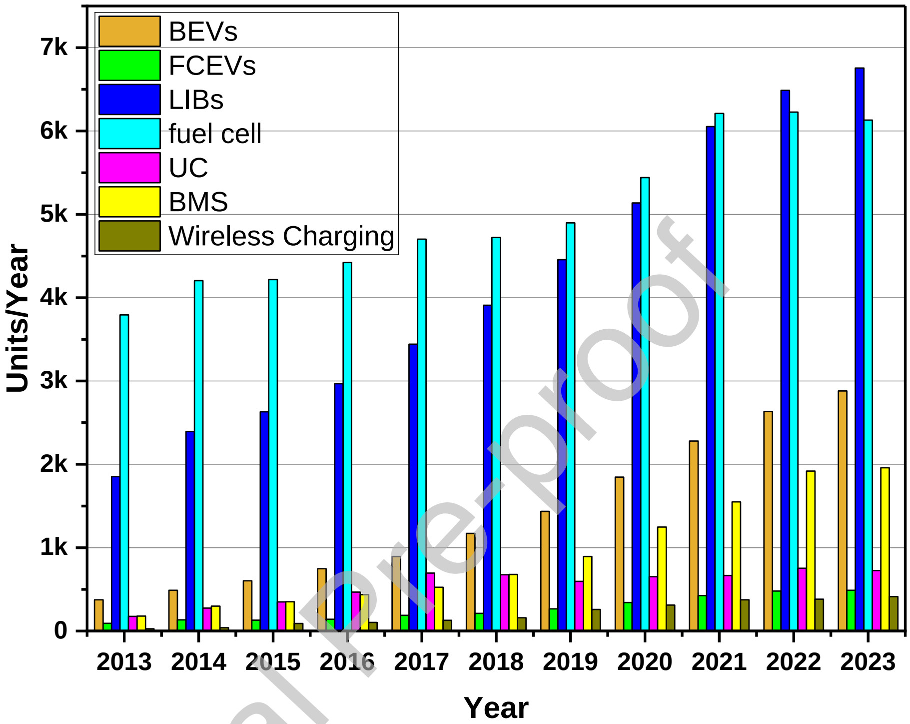

Fig. 3. Research articles linked to BEVs, FCEVs, LIBs, fuel cells, UC, BMS, and wireless charging according to the WoS database from 2013 to 2023. BEV: Battery electric vehicle; FCEV: Fuel-cell electric vehicle; LIB: Lithium-ion battery; UC: Ultracapacitor; BMS: Battery management system.

3.Advancements in EV technology

EVs comprise various subsystems that interact with each other to perform specific functions. Different types of machinery are employed to operate these subsystems. EVs have the option of operating completely on electricity and along with an ICE [45,46]. However, several variants may use various power sources in addition to batteries, resulting in fundamental and adaptable types of EVs. Automobiles that require double or supplementary alternative energy sources, storage mechanisms, or combinations are referred to as hybrid vehicle technologies, as long as at least one of them generates electricity [47]. Automobiles powered by internal combustion and electric motors are HEVs, vehicles with batteries and capacitors are UCEVs, and vehicles with fuel cells are FCEVs [48]. According to this established standard, as shown in Table 2 [49−52], EVs can be categorized into subsequent groups, as shown in Fig. 4.

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Table 2. Worldwide accepted standards and codes for EVs, HEVs, and fuel-cell vehicles

Standards	Nation	Vehicle categories
SAE-J1715, SAE-J2344, and SAE-J2758	N. America	EV and HEV terminology with power instructions [49]
Specified in SAC-GB/T 19751-2005 and SAC-GB/T 18384.2-2015	China	Motor vehicles that are propelled electrically and how they are protected in HEVs [49,50]
AIS-102 and AISC-049 (Part 1)	India	EV and HEV type authorization through CMVR
Series: ISO 15118	International	Interface for V2G communication, encompassing Parts 1, 2, and 3 [51]
ANCE-2013/C22.2 No. 280-13/UL 2594, NMX-J-677	USA, Canada, and Mexico	Auxiliary equipment for EVs [49]
IEC 61982	International	Performance and endurance testing for secondary batteries (apart from lithium) used in EVs [49]
2009, 2010, and 2011 versions of GB/T 23645	Japan	Fuel-cell car system development and testing [52]
ISO 23828:2013	International	Part 1 of the energy consumption measurement for fuel-cell road vehicles: Vehicles powered by compressed hydrogen [52]
NFPA 52, SAE-J2579, and HGV3.1	America	Hydrogen-powered vehicle fuel system components and their codes [52]

Note: EV: electric vehicle; HEV: hybrid electric vehicle; CMVR: Central Motor Vehicles Rules.

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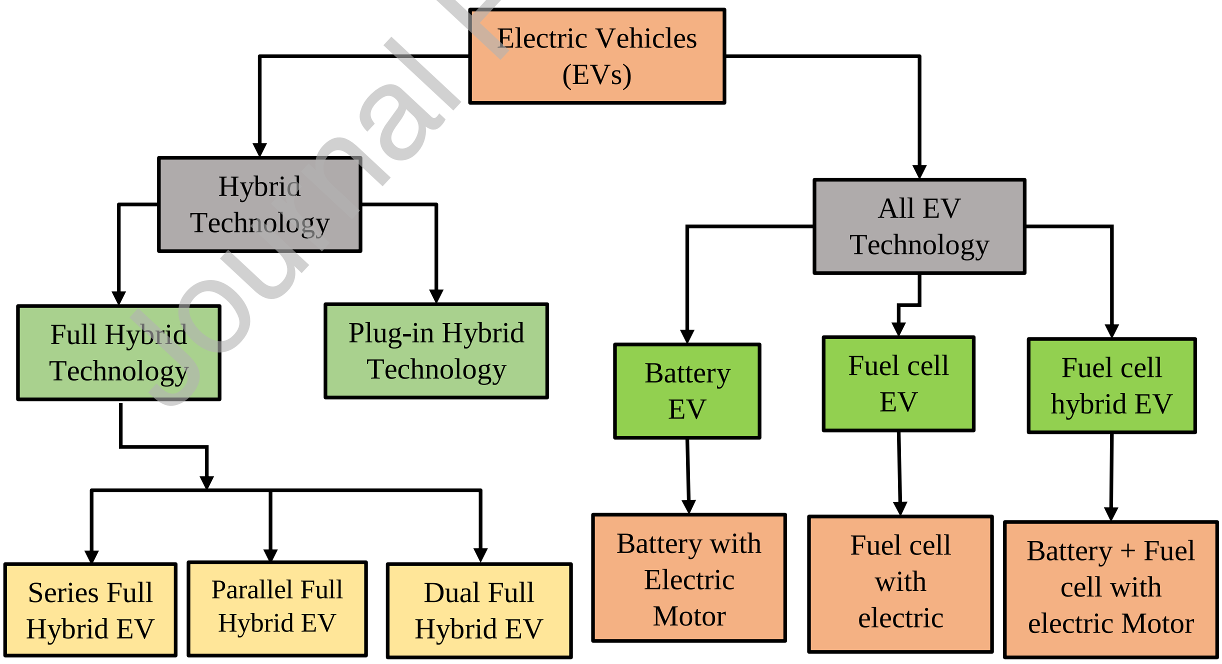

Fig. 4. Various categories of electric vehicles (EVs)

3.1. Categories of EVs

Alternative fuel vehicles can be categorized into hybrid and all-electric vehicles. The principal propulsion system of an EV is an electric motor. Automobiles that rely solely on electricity for propulsion are referred to as electric automobiles. Six distinct power transmission topologies for completely electric vehicles have been examined in the literature [53]. Based on the preferred energy source, there are three main types of fully electric automobiles: BEVs, FCEVs, and FCHEVs. Although BEVs and FCEVs have similar powertrains, the powertrain of FCHEVs is a combination of batteries and fuel cells. Fuel-cell-based HEVs are classified as zero-emission vehicles because they produce their own power through the electrolysis of hydrogen and produce water as a byproduct at the tail end of the chemical process. BEVs and fuel cell-based HEV are presented in the following subsections:

3.1.1. Battery EVs (BEVs)

Owing to utilization of rechargeable batteries to supply power, BEVs are referred to as "pure EVs." These batteries are less harmful to the environment than conventional energy-conversion techniques. Concerns regarding battery production and its deterioration over time have significantly increased in recent years [54]. These batteries can be recharged with power from the grid or any other source through a charging port [55−58]. BEVs require slightly longer charging times than traditional ICE-based vehicles. Fig. 5 shows the drivetrain of a battery-operated front-wheel-drive vehicle. BEVs can power a vehicle for 100 to 400 km, depending on the battery size of the powertrain. The BMW i3, Nissan Leaf, Tesla, and several Chinese cars are examples of BEVs currently in demand. Many research organizations have recommended using hybrid electric cars to increase travel distance [59,60].

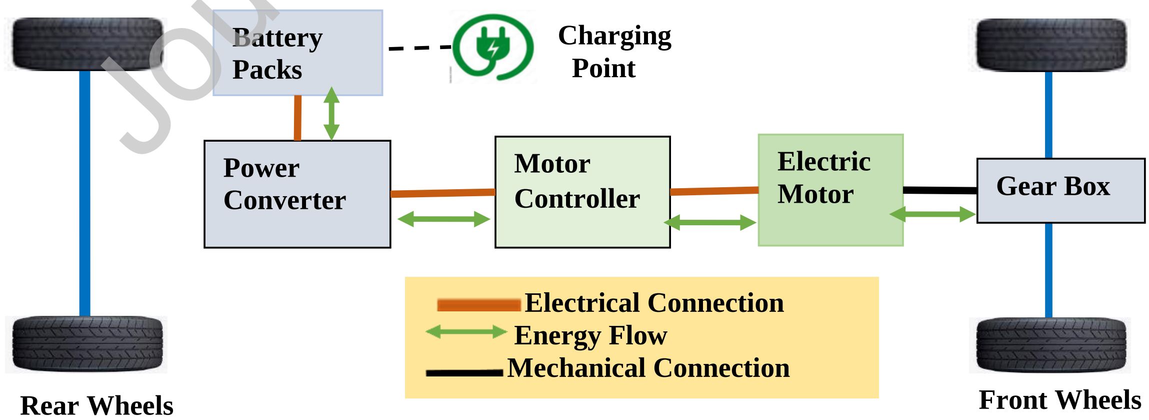

Fig. 5. Architecture of electric vehicles (EVs) powered by batteries

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3.1.2. Fuel-cell based EVs (FCEVs)

Unlike BEVs, FCEVs use fuel cells instead of batteries to power electric motors. The name "fuel cell" derives from it being a fundamental component of fuel-cell vehicles (FCVs), which use electricity generated through organic processes [61]. Because hydrogen is the ideal fuel for FCVs, they are repeatedly referred to as "hydrogen power vehicles." When compared with other types of fuel cells, the polymer electrolyte membrane fuel cell (PEMFC) has significant power, low operational warmth (60–80 °C), and reduced destruction, making it suitable for application in automobiles [41,62]. The arrangement of the FCEV drivetrain is shown in Fig. 6, in which a fuel cell generates electric power for the traction system.

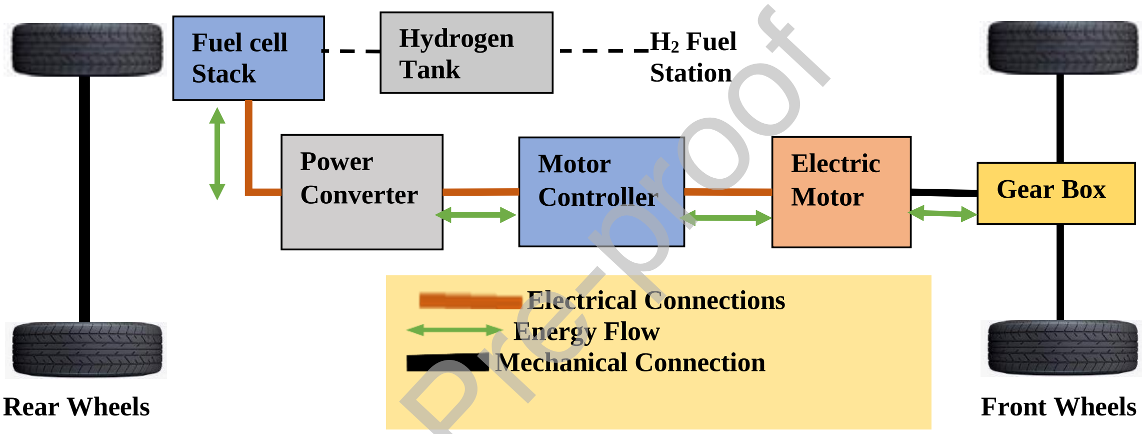

Fig. 6. Drivetrain configuration for a fuel-cell electric vehicle (FCEV)

3.1.3. Fuel-cell based hybrid EVs (FCHEVs)

By altering the powertrain of FCEVs, a completely new car design called the FCHEVs is created. This type of vehicle design uses various supplemental energy systems to support fuel cells, as shown in Fig. 7. Fuel cells are the main power source in FCHEVs, and other storage systems consist of UCs or batteries. Compared with EVs, these vehicles can significantly reduce their carbon footprints [63]. One of the greatest advantages is the refueling time, which is approximately the same as refueling a regular car at a petrol station.

4.Storage systems in EVs

EVs typically employ electrochemical, chemical, electrical, mechanical, and hybrid ESSs for primary and secondary power storage, either singly or in conjunction with one another one. The main categories of sources used in EVs are shown in Fig. 8. Fuel-cell, UC, and flywheel technologies are employed to supply and store auxiliary power requirements in EVs, along with batteries, in scenarios in which batteries are not adequate to achieve a long driving range or have a low energy density, or recharging infrastructure is lacking. Fuel cells are a key source of power in fuel-cell or hydrogen-based EV technology. UCs or supercapacitors are employed in EVs as the initial power supply owing to their high power densities. Flywheels are becoming popular as energy-storage media through the fluctuation in speed due to a variation in torque. Batter, fuel-cell, UC, and flywheel energy-storage technologies for EVs are discussed in the following subsections:

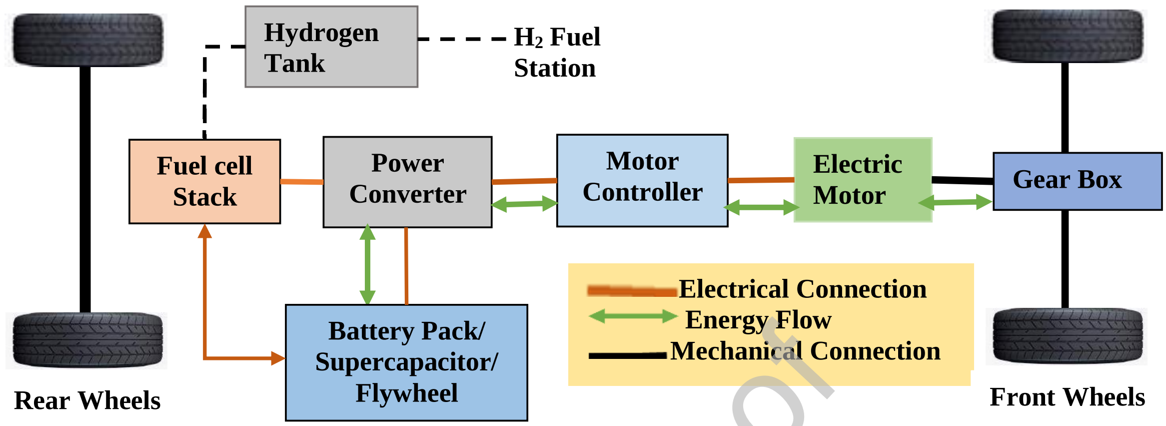

Fig. 7.Framework for the powertrain of fuel-cell hybrid electric vehicles (FCHEVs)

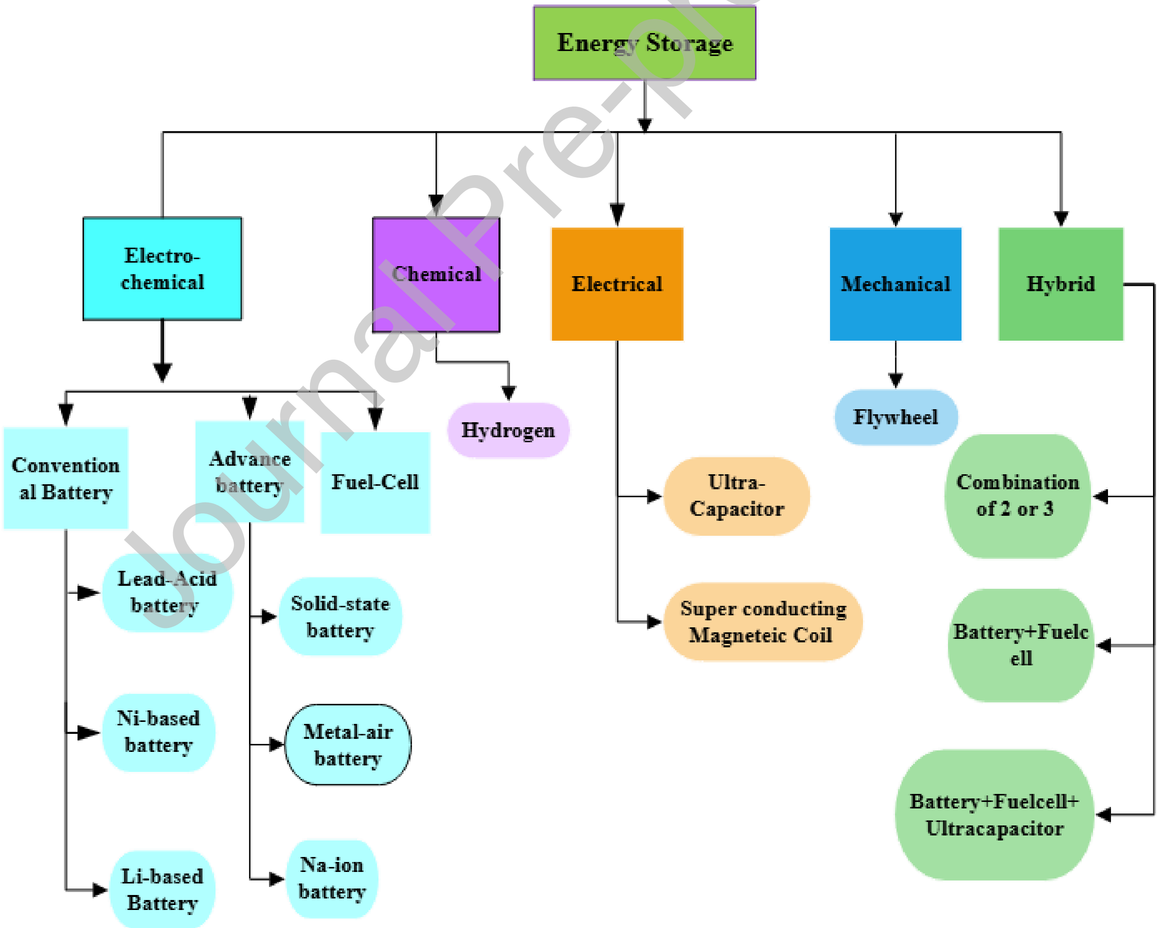

Fig. 8. Classification of different energy-storage media for electric vehicles (EVs)

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4.1. Battery technology in EVs

When discharged, a battery produces electrical energy by converting chemical energy, and when charged, it converts electrical energy back into chemical energy. Batteries are composed of electrochemical cells placed in a parallel–series configuration. The four leading battery types employed in EVs are lead-acid, nickel-metal hydride (Ni-MH), nickel-cadmium (Ni-Cd), and Li-ion [64]. Batteries created from lead acid were first developed in 1859 by French inventor Gaston Plante [65,66,67]. Ni-Cd batteries were developed more than 40 years after lead-acid batteries and are mostly employed in low-power applications [68]. The "memory effect," which occurs immediately a battery is partially charged and discharged, degrading its capacity, is the fundamental problem with Ni-Cd batteries. Furthermore, the cadmium in the battery makes it environmentally unfriendly. Li-ion and Ni-MH batteries were invented in 1990. The impact and power concentration of these batteries are superior to those of lead-acid and Ni-Cd batteries [69], [70]. Unlike other electric car batteries, LIBs have notable advantages and energy intensities [71], [72]. Li-ion-based batteries are utilized as the main energy source in BEVs, such as the Nissan Leaf, and Ni-MH batteries are frequently employed as backup energy sources in HEVs, such as the Toyota Prius.

Table 3. International guidelines for EV battery testing [73]

Standards	**UN 38.3 Sections 38.3.4.3 & 38.3.4.4**	**ISO 12405-1 Sections 8.3 & 8.4**	**SAE J2380 Section 4.4**	**GMW 16390 Sections 7.3, 8.3, & 9.3**
Frequency limit (Hz)	7–200	5–200	10–190	8–1000
Test time (h)	Z: 3 Y: 3 X: 3	Z: 21/15/12 Y: 21/15/12 Z: 21/15/12	Z: 16.2/10.95 Y: 38.18/13.58 Z: 38.18/13.58	Z: 24 Y: 24 X: 24
Sine or random G level	Small batteries: 0.5-12 kg, 8G Large batteries: >12 kg, 2G	X: 0.96 Grms Y1: 1.23 Grms Y2: 0.95 Gram (below passengers compartment) Z: 1.44 Grms	Z: 1.9 & 0.75(N)/ 0.95(A)Grms Y: 1.5 & 0.4(N)/ 0.75(A)Grms X: 1.5 & 0.4(N)/ 0.75(A)Grms	Z: 1.4 Grms Y & X: 1.1 Grms
Mechanical shock	Small batteries: 150G @6ms Large batteries: 150G @11ms	51G @6ms	NA	Pothole:10G@16ms Minor collision: 100G@11ms, 40G@11ms
Shock quantity	±X/±Y/±Z: 3	X/Y/Z: 10	NA	Pothole: ±X/±Y/±Z: 3 Minor collision: ±X/±Y: 3

As a crucial module of EV, the battery has undergone a lengthy development process to fulfill the requirements of EV manufacturers. Additionally, the testing protocols and criteria are continually reviewed. Vibration and shock tests must be performed on batteries to guarantee their reliability and protection. Currently, three international test standards, namely, UN 38.3, ISO 12405-1, and SA J2380, are frequently used for battery vibration and shock testing. The test standards for battery security and safety are listed in table 3 [73]. However, some automobile manufacturers have their own testing requirements.

4.1.1. Li-ion based battery

EVs use various LIBs. The negative electrodes (anodes) in most power battery cells are created from carbon, whereas the positive electrodes (cathodes) are created from $LiCoO_2$ (LCO), $LiMn_2O_4$ (LMO), $LiNi_xCo_yMn_zO_2$ (NCM), $LiFePO_4$ (LFP), $LiNi_xCo_yAl_zO$ (NCA), or other metal oxides [74,75]. The operating range of LIBs is typically 1.5 to 4.2 V [55]. LIBs have reliable operating temperatures: -20 to 55 °C when discharging and 0 to -45 °C when charging [55]. The chemistry of the LIB technology is shown in Fig. 9.

The anode, cathode, electrolyte, and separator are the fundamental building blocks of a LIB, as shown in Fig. 9. The anode (negative electrode) in the LIB stores lithium ions during charging and releases them during discharging [76]. The cathode has opposite function to the anode: it releases lithium ions during charging and stores them during discharging. The electrolyte consists of a lithium salt (lithium hexafluorophosphate) dissolved in a solvent (ethylene carbonate or diethyl carbonate) to facilitate the movement of lithium ions between the anode and cathode. The separator is a porous membrane that prevents direct contact between the anode and cathode while allowing lithium ions to pass through [77]. LCO, LMO, NMC, and LFP are used as cathode materials. The majority of anodes are carbon-based, whereas a small percentage are alloy-based (e.g., silicon and germanium) or formed through the conversion of transition metal compounds (e.g., oxides, phosphides, sulfides, and nitrides)[78].

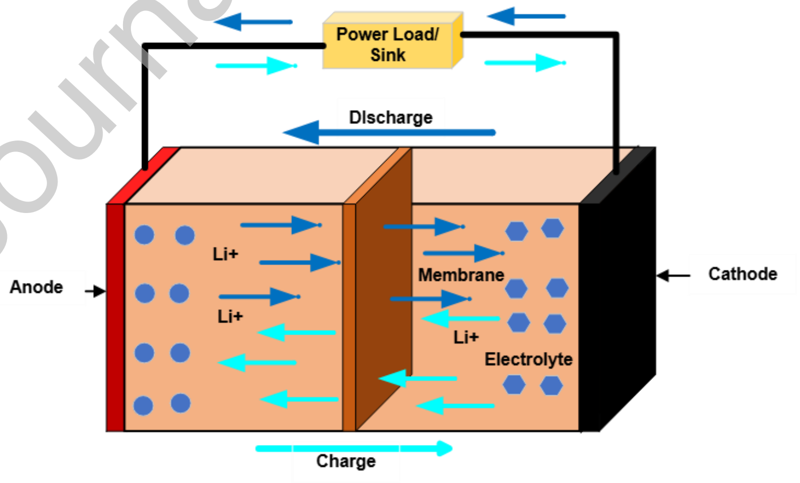

Fig. 9. Chemistry of Li-ion battery technology

Working principle of a LIB: When charging, an external voltage is applied across the battery, releasing Li ions and electrons from the cathode. Li ions dissolve in the electrolyte solution and move towards the anode through the nanoporous membrane, as shown in Fig. 9 [79]. Li ions are intercalated (inserted) into the layered structure of the graphite anode, whereas electrons travel through the external circuit to balance the charge movement (Fig. 9) [80]. During discharging, the Li ions and electrons released from the anode move in opposite directions to counterbalance each other, as shown in Fig. 9.

Table 4. Comparative analysis of different Li ion batteries for EVs

Li-based Battery	Cell-voltage (V)	Specific energy (Wh/kg)	C-rate (Charge)	C-rate (Discharge)	Cycle span	Thermal runaway	EV model	Driving range	Reference
Lithium cobalt oxide ($LiCoO_2$)	3–4.2	150–200	0.7–1 C	1 C	500–1,000	150 ℃	-	-	[81,82]
$LiMn_2O_4$	3–4.2	100–150	0.7–1 C	1 C	300–700	250 ℃	Nissan Leaf Nissan Leaf S	172 364	[81,83]
lithium nickel manganese cobalt oxide	3–4.2	130–240	0.7–1 C	1 C	1,000–2,000	210 ℃	Renault Zoe 50 VW ID.3 Pro S	390 550	[84,85]
lithium iron phosphate	2.5–3.6	90–120	1 C	1 C	1,000–2,000	270 ℃	Chevrolet spark BAIC E220	132 206	[86,87]
lithium nickel cobalt aluminum oxide	3–4.2	200–300	0.7–1 C	1 C	500–700	150 ℃	Tesla 3 Tesla Y	500 550	[88,89]
Lithium Nickel Dioxide	3–4.2	150–200	0.7–1 C	1 C	>300	150 ℃	-	-	[29,89]

Li-ion-based batteries have been produced by several companies including SAFT, GS Hitachi, Panasonic, SONY, and VARTA. The advantages of LIBs include low weight, extended lifespan, quick and secure charging, high useful capacity, and increased temperature tolerance. However, the main concerns are the monitoring of battery cell voltage, computation of battery states of charge, consistency, and defect detection [90]. 130 °C is the melting point for the separator, which will cause the cell to shut off [90]. Immediately the temperature increases to a range of 150–300 °C, the positive substance begins to decompose [91]. The comparative data for several LIBs are listed in Table 4 [29, 81–89]. Mobile devices such as smartphones, laptops, tablets, cameras, e-bikes, electric power trains, uninterruptible power supplies (UPSs), and laptops require LIBs.

4.1.2. Solid-state battery

In SSBs, the liquid electrolyte and separator are swapped using solid-state electrolytes. During operation, LIBs with liquid electrolytes exceed the threshold limit of maximum energy density, which causes significant safety problems. Solid-state batteries are anticipated to be the future generation of vehicle power batteries owing to the increased safety provided by switching from liquid to solid electrolytes and the potential to use Li-metal anodes to considerably boost the energy density. Removing the separator reduces the required thickness of the electrolyte, thereby boosting the energy density of the battery[92]. Theoretically, the capacity of a normal battery can be increased by more than twice by swapping it with an SSB of the same volume [92]. Fig. 10 shows the chemistry of LIB

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and SSB technologies. Because of its high energy concentration (900 W·L^{-1}), stability, and safety, lithium is considered a promising anodic metal for SSBs. However, owing to its poor Columbic proficiency and short life cycle (1,000 cycles), lithium is a real-world challenge for EVs. Table 5 [93] shows a comparison between SSBs and LIBs. SSBs are considered promising alternatives for EVs because of their increased power density, longer lifetime, and more operable temperature stability. The operation of the SSB is similar to that of the LIB with the modification of the solid electrolyte, which also functions as a separator, as shown in Fig. 10. Solid electrolytes include ceramics (oxides, sulfides, and phosphates (e.g., $Li_7La_3Zr_2O_{12}$–LLZO)) and polymers (polyethylene oxide (PEO) mixed with lithium salts) or glasses (lithium-phosphate-based glasses) to conduct lithium ions between the anode and cathode while being electronically insulating.

Table 5. Comparison of technical parameters between an SSB and LIB [93]

Constraints	SSB	LIB
Electrolyte	Solid	Liquid
Protection	Decreased possibility of leaks, thermal runaway, and fires	Deflagration, thermal runaway, and leakage dangers
Power Density	Superior	Inferior
Life of a Cycle	Extended	Quicker
Durability	More durable against bodily harm	Unstable against physical harm
Fabrication	expensive and difficult	Arduous and expensive
Available in the marketplace	Development is still in its infancy.	Broadly accessible

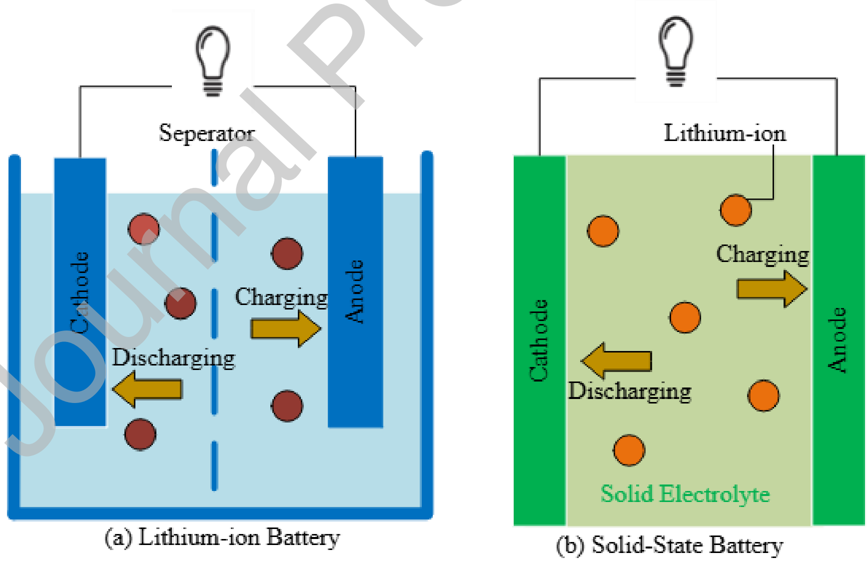

Fig. 10. Chemistry and structure of a lithium-ion battery (LIB) and solid-state battery (SSB)

4.1.3. LAB

LABs offer up to four times the energy density of LIBs and can store one kilowatt-hour or more per kilogram of energy. The energy density of these batteries, which is 3,621 Wh·kg^{-1} (during charging) or 5,210 Wh·kg^{-1} (during discharging), is a key advantage [12]. The primary purpose of a non-aqueous LAB is to enhance the pore volume to minimize costs and boost conductivity. Solid pore carbon materials with an optimal size of 10–200 nm are employed in non-aqueous Li-air batteries to reduce the blockage problems associated with LIBs [94]. A range of 1,500 km on a single charge can be attained using a LAB; this has the potential to eliminate a key barrier to mainstream EV adoption. A single charge allows most all-EVs to cover 100–400 miles, according to the DOE's Office of Energy Efficiency [95]. Compared with their Li-ion competitors, LABs pose fewer safety problems and supply chain disruptions because they use oxygen from the surrounding air [96]. The structural layout of the LAB is shown in Fig. 11.

The key components of the LAB are the anode, cathode, electrolyte, and catalyst, as depicted in Fig. 11. Lithium metal, which is both lightweight and has a high electrochemical potential, provides a high capacity for LAB anodes. A typical cathode features a carbon structure with pores that allow airborne oxygen to diffuse. This process occurs during the oxygen reduction process. Both aqueous and non-aqueous electrolytes are acceptable. Because of their stability and compatibility with lithium metal, non-aqueous electrolytes are used more frequently. A LAB catalyst may accelerate the oxygen evolution reaction (OER) during charging and the oxygen reduction reaction (ORR) during discharging. Conductive materials include metals and oxides.

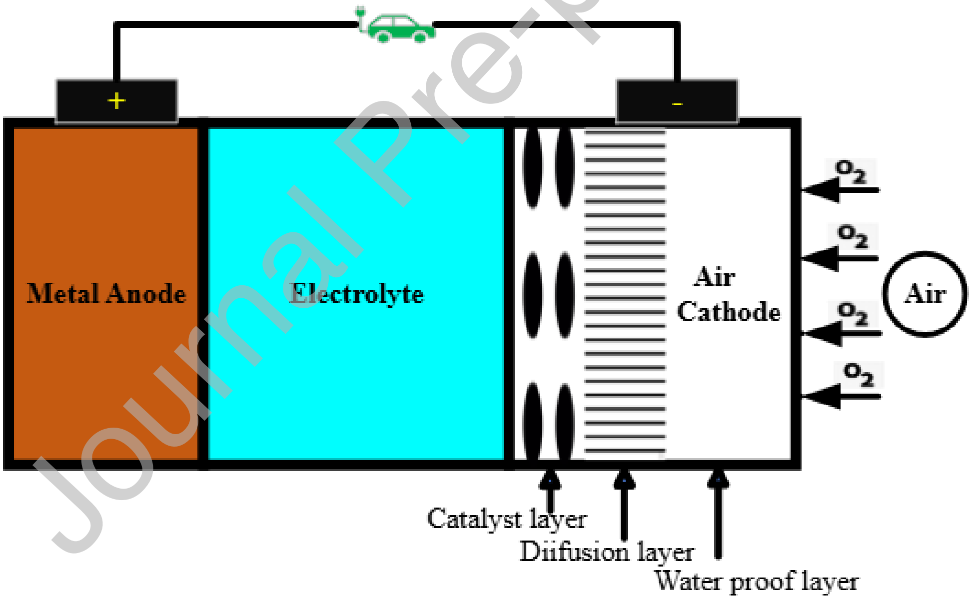

Figure 11.Structure layout and components of lithium-air battery technology

Working chemistry of a LAB: During discharging, Li metal at the anode is oxidized, releasing electrons and forming Li-ions (Li^+) at anode chemical reaction as follows:

$$Li \rightarrow Li^{+} + e^{-}$$

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At the cathode during discharging, the external circuit's electrons (e^-) and Li^+ ions combine with atmospheric oxygen (O_2) to produce lithium peroxide (Li_2O_2) or lithium oxide (Li_2O) according to the following reactions:

$$O_2 + 2Li^+ + 2e^- \rightarrow Li_2O_2$$

or

$$O_2 + 4Li^+ + 4e^- \rightarrow 2Li_2O$$

When the battery is charged, the reactions are opposite, breaking down the Li_2O or Li_2O_2 to release Li ions and oxygen according to the following processes:

$$\mathrm{Li_2O_2} \rightarrow \mathrm{O_2} + 2\mathrm{Li}^+ + 2e^-$$
$$2Li_2O \rightarrow O_2 + 4Li^+ + 4e^-$$

4.1.4. Advancements in battery technology

The term "advanced batteries" refers to cutting-edge battery technologies that are currently being researched and tested in an effort to become foreseeable future large-scale commercial batteries for EVs. Examples of these technologies include Li-ion silicon (Li-Si), solid-state , zinc-ion (Zn-ion), metal-air, and flow batteries. Because Li-ion salts such as $LiPF_6$ are hazardous and unstable during heat waves, and non-aqueous electrolytes are extremely combustible, aqueous electrolytes exhibit enhanced efficiency when measured against safety [97]. The superior durability and safety properties of aqueous-based LIBs make them appealing for use in aircraft and submarines, and they have also attracted the interest of engineers developing EVs for industrial use [98]. The LIB with the Li_2SO_4 electrolyte has a capacity of 100 $Ah\cdot kg^{-1}$, power density of 30 $W\cdot kg^{-1}$, and cyclic longevity of 10^3 sets [99,100]. However, there is an urgent need to enhance its incriminating and emitting efficiencies by two orders of magnitude greater than for required to create it; the current value is more acceptable for EV applications [101].

Another effective rechargeable metal-air battery, the Zn-air battery, was developed by Meng et al. [102]. It offers an extraordinary ultimate power intensity (210 $MW\cdot cm^{-2}$), in addition to exceptional riding stability. A strong contender in support of the upcoming energy-storage technology is the Li-S battery, which has a specific energy greater than 2,500 $Wh\cdot kg^{-1}$ [103]. In SSBs, the liquid electrolyte and separator are swapped using solid-state electrolytes [104]. SSBs can produce excellent levels of energy and safety compared with conventional Li-ion systems [105]. Table 6 [11, 106−110] lists the uses of different battery technologies and the advantages and disadvantages of each.

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Table 6. Applications for various battery technologies and their advantages and disadvantages

Battery category	Advantages	Disadvantages	Applications	Ref.
Pb-acid	•Low price and excellent durability. •Low maintenance. •Accessible in bulk, with a wide range of sizes and styles to choose from.	•Ineffective in both cold and heat climate condition •Constraints on lifespan •Charge rates is slow •Discharge rate that is quite high •Restrictive density of energy	Chrysler Voyager and the Ford Ranger	[11,106]
Nickel-based	•Low price and high specific power •Exceptionally rapid charging with little strain •Reliable operation at low temperatures and under strain	•Inefficient and low specific energy •Discharge rate that is quite high •The element cadmium is extremely poisonous during disposal on land.	Toyota and Honda EV Plus	[11,107]
Li-ion	•Extraordinary specific ability, •Extreme energy efficacy •Lengthy cycle. •Excellent effectiveness •Easy to carry	•Reasonable price and blaze risk •Needs a dedicated charging system •Extremely heat-sensitive •Damage to the battery occurs with complete drain.	Nissan Leaf, BMW i3, and Tesla 3	[11,108]
Metal-air	Cost-effective, highly precise energy, and easy recharging	Costly, inefficient, and with a small running temperature window	GM-Opel, MB410, and Mercedes-Benz	[11,106]
Solid-State battery	•High energy density •Long life cycles •Wide working temperature range (−40–150 °C) •Diminishing rates of self-discharge •Persist over a greater number of cycles.	•Cost-prohibitive factor •Electrochemical instability problem, •Developing technology •No interphase layer development of solid electrolytes	Vehicles, ships, aircraft, cellphones, etc.	[11,109,110]
Na-sulfur battery	•Significant power •Excellent effectiveness •Lack of responsiveness to external factors •Extreme density of energy	•High production cost •Stringent operation and maintenance requirements •Safety concerns •Need to be operated above 300 °C	Tokyo EV	[106]
Flow battery	•Cheap and liquid refueling •Quickly charge and drain •Instant response eras •Long life	•Low energy •Bigger in size •Low power •Expensive for regularity repairs	Toyota EV-30 and the Fiat Panda.	[11,106]

4.1.5. Safety concerns with high-energy batteries

The study of battery safety involves an interdisciplinary approach that requires solving problems at multiple scales, including those involving individual components, cells, and systems. Consideration of these factors in relation to electric car applications with high-energy battery systems has made them more significant [111]. The importance of safety features such as enhanced quality control and operating stability is increasing in response to the ever-increasing demand for storage batteries [112]. Many modern commercial devices still use organic electrolytes in batteries, which are combustible and nonaqueous, although intrinsically safe energy-storage technologies now exist [113]. For this

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application of organic electrolytes, heat management strategies that reduce the pack-level energy density are required, which motivates the development of new, nontoxic electrolytes [112]. In addition, when considering new cathode and anode chemistries, a basic understanding of how electrodes function and degrade is crucial to enhancing the stability of the electrode–electrolyte interfaces [114]. Li-ion, solid-state, and metal-air batteries have a higher density of energy and power when used in EVs. The crucial problems and protection associated with batteries in EVs are described below:

(i) Thermal runaway

Overheating is a major risk in EV batteries. High temperatures can produce thermal runaway, which can spark flames. To avoid thermal runaway, the cooling systems of EVs must function efficiently. Overheating and short circuits are recognized as the primary indicators of thermal runaway in LIBs [76]. Short circuiting caused by separator damage, electrical misuse, and mechanical wear are also major contributors to thermal runaway [115]. Thermal runaway is a perpetual concern for stored energy. It occurs when the rate of energy release from a battery exceeds its dissipation capacity [111]. This may occur when the battery is subjected to internal or external conditions that cause its temperature to increase uncontrollably, leading to potentially explosive venting, combustion, and smoke [111]. Thermal runaway can be prevented if the battery can be cooled sufficiently, either naturally or using external cooling mechanisms [116].

The thermal runaway process occurs in three distinct stages. During stage I, the battery begins to function abnormally and overheats because of the problems mentioned earlier. The end of stage I and beginning of stage II is marked by an increase in the internal temperature. In the second stage, the temperature increases, and oxygen builds up within the batteries. The accumulation of sufficient oxygen and heat for combustion in the battery triggers a transition from stage II to stage III , which involves combustion and explosion. Combustible electrolytes cause explosions and fires.

(ii) Undesirable chemical reactions

Electrochemical activities become more complicated at high temperatures and voltages, including the disintegration of the solid electrolyte interface layer. This layer disintegration and interfacial interactions initially exacerbate the increase in temperature, consequently increasing the risk of oxygen leakage from the active cathode materials [117].

(iii) Mechanical wear

Car batteries must be sufficiently strong to withstand impacts and remain safe during accidents or collisions. The shell casing of an LIB must endure mechanical stress without breaking and ensure that the interior structure is not harmed under particular deformation conditions [76]. Air enters the battery system instantly after it has been damaged and interacts with the active components and

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electrolyte [118]. Manufacturers provide batteries with protective shields or materials that can resist mechanical stress and bending.

(iv) Electrical problems

When a battery is overcharged, overdischarged, or subjected to an external short circuit, it suffers from electrical wear and undergoes a sequence of unfavorable electrochemical processes [76]. If the terminals of a car battery come into physical contact during charging, a short circuit may occur, resulting in a fire. Low voltages and temperatures at the positive and negative terminals result in internal short circuits in LIBs. Overcharging is one of the most harmful causes of electrical misuse [119].

(v) Thermal wear

Thermal abuse occurs when a battery receives a thermal shock or has a very high local temperature [117]. A battery can catch fire during charging or when surrounding automobiles catch fire. If the generated heat accumulates instead of being dispersed, exothermic side reactions begin, increasing the concentration of thermal stress [76]. The explosion is triggered by the accumulation of thermal stress and pressure. Table 7 [76,115,120−125] lists various international safety test standards for LIBs that can be used in EVs.

Table 7. Different international safety test standard and protocols for lithium-ion batteries (LIBs) in electric vehicles (EVs)

Routine procedure	**Standard code**	**Published year**	**Official full name**	**Ref.**
Freedom CAR	SAND 2005– 3123	2006	Harming test for an electrical energy-storage device Operating instructions for EVs and plug-in hybrid electric vehicles (PHEVs)	[120]
Society of Automotive Engineers (SAE)	SAE J2464-2009	2009	Recharging for electric and hybrid vehicles. Safety and misuse tests for ESSs	[121]
International Standardization Organization (ISO)	ISO 16750–2	2010	Automobiles: test settings for electrical and electronic equipment, section 2: electrical loads	[122]
International Electrotechnical Commission (IEC)	IEC 62660–2-2010	2010	Part 2: Assessing the dependability and abuse of secondary LIBs for usage in electric road vehicles	[123]
Underwriters Laboratories (UL)	UL 2580–2010	2013	Battery safety standards for EVs	[76]
Chinese standard GB/T	GB/T 31485–2015	2015	Safety criteria and test techniques for traction batteries in EVs	[124]
United Nations (UN)	UN38.3	2015	Section 38.3 of the United Nations manual on hazardous materials, transportation testing, and standards	[125]
Volkswagen (VW)	VW PV8450	2016	Volkswagen battery test standards for EVs	[76]
SMTC	SMTC 9 N20 011–2018	2018	Electrochemical performance and testing Plan of EVs for LIBs	[115]

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(vi) Recent advancements in battery safety technologies

Numerous studies have investigated possible methods of enhancing battery safety by simplifying the component design in response to battery thermal runaway. The following sections provide an overview of different approaches for enhancing battery safety.

(a) Reliable and risk-free electrolytes

It is essential to determine electrolyte chemistries that are compatible with Li metal anodes for use in Li-metal batteries. An electrolyte that is both electrochemically stable against Li metal and facilitates smooth Li plating should be selected. An effective method to avoid solvent degradation on the electrode surfaces during electrochemical cycling is to regulate the solvent molecular coordination geometry. A study conducted by Xiao et al. [126] demonstrated that electrolytes known as "ion-solvent-coordinated" (ISC) can efficiently inhibit parasitic processes on Li metal surfaces. Another method for stabilizing electrolytes was suggested by Zhang et al [127]   It comprises an ingredient for bipolar electrolytes with a perfluorinated nonpolar tail and polar head that dissociates Li^+ ions. Polymer electrolytes for LMBs can be effectively developed through the in-situ copolymerization of molecular and ionic monomers, as demonstrated by Shan et al. [128]. Using cone calorimetry to characterize the thermal behavior of organic electrolytes, Yang et al. [129] conducted a comparative assessment of their safety. Buyuker et al. [130] studied the thermal stability of various ether-based electrolytes in relation to an NMC811 cathode, a Li-metal anode, and abusive circumstances. In contrast to conventional carbonate-based electrolytes, ether-based electrolytes exhibited superior thermal resilience.

(b) Stabilizing interfaces

Battery devices undergo material alterations at buried interfaces, which can only be understood using better characterization and diagnostic techniques. The mysterious phenomenon of Li dendrites is an example of a material transition that affects various battery chemistries. Song et al. [131] suggested Li-metal imaging in LIBs using an operando neutron technique. Battery interfaces, component contact changes, and gas development in large batteries can be studied easily using ultrasonic technology [132]. In their latest demonstration, Xiong et al. [133] demonstrated a novel composite electrolyte setup that prevents the formation of Li filaments and ensures consistent electrode–electrolyte contact by impregnating a solid electrolyte with electrically insulating polyphosphoric acid. Contact with low-potential Li metal causes the degradation of several solid electrolyte materials. Liu et al. [134] demonstrated that new Janus-polymer interfaces can be used with solid electrolytes, leading to longer cycle lifetimes when combined with Li metal.

(c) Phase-change materials in the battery

Batteries pose fire and explosion hazards in extremely hot environments; therefore, efficient emergency management and safety technologies are required. Chen et. al. [135] presented a potential solution for a battery thermal management system (BTMS) as a phase-change material (PCM), which has many benefits such as being inexpensive, consuming little energy, and providing consistent temperatures. Based on their composition, PCMs are categorized as organometallic, inorganic, and eutectic PCMs [136]. The effective heat transmission of the battery is significantly affected by the thermal conductivity of the PCM. Power batteries can be made safer by the addition of high-thermal-conductivity elements such as carbon and metal-based compounds, which increase the thermal conductivity of PCM [137,138]. Zhao et al. [139] discovered that air cooling is the primary mechanism responsible for the thermal-management effect of PCMsClick or tap here to enter text. They observed that embedding heat pipes inside the PCM and adding the PCM to the module reduced the temperature differential by approximately 30%. Pakrouh et al. [140] investigated a novel PCM–thermoelectric cooler–based liquid cooling system. When these three cooling methods operate together, the battery system can dissipate heat more effectively. By integrating flame-resistant SiC with flame-resistant PCMs, Chen et al. [141] improved the thermal management of batteries by effectively dissipating heat. Because organic PCMs are inherently fragile, they cannot withstand the constant charge–discharge cycles used in battery modules. Since then, efforts to make PCM more flame-resistant and structurally stable have increased. The mechanical characteristics and structural stability of PCMs can be enhanced using polymers and nanoparticles [135].

4.1.6. Cost-benefit analysis of different battery technologies and their economic feasibility

(a) Cost analysis: Currently, the best energy-storage solutions for powering PHEVs and BEVs are LIBs. Market rivalry and technological advancements are likely to reduce the prices of new and used EV batteries. Price tags can be associated with individual cells or entire battery packs. The components of a battery pack consist of individual cells and electrical connections that link them to the packaging and system that controls the battery. The prices of packs are frequently approximately 20% higher than those of cells [142,143]. The term “battery pack cost” can mean either the original production cost or the consumer's actual out-of-pocket expense [144]. The literature costs for new and retired vehicle battery are summarized in Table 8 [145–152].

The costs of LIB packs decreased by almost 14% annually, reaching an average of $445 USD/kWh in 2014, according to an analysis by Nykvist and Nilsson [145] of 85 cost estimates published between 2007 and 2014. Manufacturing costs for battery packs were projected to fall from $290·kWh^{–1}$ in 2015 to $97–130·kWh^{–1}$ in 2030 according to projections by the Boston Consulting Group, who assumed a 6%–8% yearly decline in costs beyond 2020 [146]. To predict the cost of batteries through 2050, Mauler et al. [147] analyzed 22 papers that relied on technical knowledge, literature, and expert commentary. During the years 2030, 2040, and 2050, the predicted LIB pack costs would be \$184·kWh^{-1}, \$75·kWh^{-1}, and \$43·kWh^{-1}, respectively. The LIB pack price index decreased from \$792·kWh^{-1} in 2013 to \$163·kWh^{-1} in 2022, a 79% decline, and by 2026, it will decrease to below \$109·kWh^{-1}, as reported by the BNEF 2022 [148].

Table 8. Cost analysis of different LIBs according to the literature

Class	Cost (USD) per kWh	Contributor	Ref.
New battery	>\$1,082 in 2007 \$445 (270–725) in 2014 \$325 (150–670) in 2014	Battery production cost	[145]
	\$290 USD in 2015 \$97–130 Euros in 2030		[146]
	\$184 in 2020 \$75–110 in 2030 \$43–54 in 2050		[147]
New battery Cell	\$545 in 2013 \$130 in 2022 \$143 in 2030 \$100 in 2040 \$76 in 2050	Cost to EV manufacturer	[149]
New battery Pack	\$792 in 2013 \$163 in 2022 <\$109 by 2026	Global volume weighted average LIB prices for various end users including both $LiFePO_4$ and $LiNi_xMn_yCo_zO_2$ batteries	[148]
Retired battery selling price	\$251 (new EVBs) in 2017 \$78 (second-life battery) in 2017	Battery selling price	[150]
	\$25–35 (retired EVBs) in 2020 \$67–76 (second-life battery) in 2020	Battery selling price	[151], [152]

(b) Economic feasibility: Static and dynamic approaches are the two main categories of economic studies on investment projects. The payback period, total cost, and yearly cost-benefit analyses are the three most common static approaches for evaluating investments. Power levelization, net present value, and discounted payback time are the three most common dynamic methodologies used to evaluate investments. Financial assessments of EV battery lifetimes are presented in Table 9 [153−159].

Omrani and Jannesari [153] calculated the payback times for various uses of recycled EV batteries, including those in homes, businesses, and photovoltaic power plants in Ahvaz, Iran. While the EV batteries used were not cost-effective for homes, they operated well in factories and photovoltaic power plants. Steckel et al. [154] used a power-levelized cost (PL) approach to determine the cost of implementing an ESS with EV batteries. The reusable battery PL was calculated at \$234–278·MWh^{-1}, whereas new battery power cost \$211·MWh^{-1}. They concluded that reusable batteries are not cost-effective although their initial costs are much lower. The new battery cost estimates from Steckel et al. were \$151·kWh^{-1} , and the one from Kamath et al. were \$209·kWh^{-1} .

Table 9. Economic analysis of new and old batteries technology according to the literature

Approach	Economic Constraints and Factors	Remarks	Applications	Ref.
Payload period (PP)	Expenses associated with batteries, O&M, government electricity, battery quantity, and lifespan	Used EV batteries are too expensive for domestic use in Ahvaz, Iran., i.e., PP has a duration greater than 10 years. The PP for industrial uses ranged from 2.9 to 9.1 years, whereas for PV plant applications it was 3.6 to 4.9 years.	Uses in homes, businesses, and photovoltaic power plants	Mirzaei Omrani & Jannesari [153]
	Initial investment, power expenses, cutoff point, maximum hourly discharge, and overnight charge level	Since the PP for peak shaving is 30 years and the PP for even discharge is 25 years—both exceeding the battery lifetime of 16 years—using second-life batteries is not cost-effective.	Battery storage for home use during peak loads, even discharge, and photovoltaics	Gladwin et al. [155]
Power levelization (PL)	Costs of battery, PV, and inverter; electricity prices; discount rate and inflation; project lifetime; efficiency and lifetime of battery	Reusing LIBs instead of buying new ones for energy storage can save PL by 12%–41%.	Power-renewing infrastructure	Kamath et al. [156]
	Operational days, construction time, total capital cost, battery capacity, energy to power ratio, and cost of charging	There is a \$211 MWh^{-1} difference between PL for new and second-life batteries over a 15-year time horizon. Compared with brand-new BESS, the total capital cost for used BESS ranges from 64% to 79%.	longevity of ESSs that use batteries	Steckel et al. [154]
Net Present Value (NPV)	Electricity rates, testing and restructuring expenses, income from EV charging, cost of photovoltaic, battery systems, operations and maintenance cost	The PV charging station's annual cumulative NPV is greater when using a second-life LFP battery rather than a traditional energy-storage device.	Charge station for combining energy storage and photovoltaics	Han et al. [157]
	Operating and maintenance costs; installation; home circuits; advantages of application; discount rate; power conditioning, controllers, interfaces; accessories, facilities, shipping, catch all	Energy storage with a mix of uses and a lifespan of 10 years: net present residual value battery prices range from \$397 for the Prius PHEV to \$1,510 for the Volt and \$3,010 for the Leaf. Reductions in leasing price for the battery throughout its initial 8 years in use: 11% for Pride PHEV, 22% for Volt, and 24% for Leaf	Dispersed electrical storage units for residential energy storage	Williams [158]
Discounted payback time (DPT)	Capital expenditure, operating costs, and replacement costs; power load balancing, and the residual value of batteries, improved grid reliability, and decreased carbon emissions	The difference between the DPT of new and old battery is 20 years, with the latter having a lifespan of 15 years. The price of batteries, governmental subsidies, and power rates are crucial variables.	Battery ESS	Zhang et al. [159]

4.1.7. Environmental impact for the different battery technologies

Life cycle assessment (LCA) is an established approach for measuring the environmental consequences of a battery over its entire life cycle. It considers energy use, resource consumption,

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and pollution levels [160]. Greenhouse gas (GHG) emissions are impact indicators in vehicle LCA [161]. According to Bieker, EVs reduce greenhouse gas emissions by 19%–34% in India, 37%–45% in China, 60%–68% in the United States, and 66%–69% in Europe [162]. The battery-centered LCA method examines the entire battery life cycle, including the initial use and subsequent recycling in EVs. The production of batteries, their usage in EVs, their remanufacturing, their second life, and their end of life are often considered to belong to the system border [163]. Table 10 presents an environmental assessment of different batteries employed in EVs.

Ahmadi et al. [164] conducted a comprehensive LCA of LFP batteries and examined their power consumption and ecological consequences from production to disposalClick or tap here to enter text.. GHG emissions over the battery pack's lifetime were estimated to be approximately 0.25 kg CO_2 for every kilowatt-hour of power input. The production phase of battery packs was responsible for 40% of the GHG emissions, followed by the use phase (31%), remanufacturing phase (3%), and first application phase (26%). Similarly, Quan et al. [165] analyzed the LCA of LFP and NMC batteries, considering their initial usage in EVs, subsequent use in energy-storage devices, and recycling. When used in an ESS, a second-life LFP battery produces 441 kg CO_2, whereas an NMC battery produces only 181 kg CO_2. Richa et al. [166] determined the lifetime GHG emissions of LIB and lead-acid battery system. Their research showed that LIBs have fewer negative impacts and contribute 15% less to carbon dioxide and GHG emissions than lead-acid batteries. After examining the effects of LFP batteries across their entire lifespan, Wang et al. [167] discovered that in the ten-year scenario, emissions decreased by 178–197 kg CO_2 based on the subsequent recycling procedure.

Table 10. Economic impact assessment of different battery technologies

Objective or unit	Method and constrains	Environmental impact	Ref.
LFP battery delivering 35,040 kWh in EV and 29,004 kWh in ESS	Examination of ICEs by EVs in Canada	The GWP of an echelon electric car combined with an ESS is less than that of a traditional gasoline vehicle combined with natural gas.	Ahmadi et al. [164]
LFP and NMC battery with 1 kWh capacity	Evaluate the different effects of LFP and NMC on the environment over their lifetimes. Data on Chinese LFP and NMC batteries' capacity degradation	Since LFP batteries last longer and experience higher energy losses when used in ESS for secondary purposes, their total impacts are higher compared with NCM batteries.	Quan et al. [165]
Second life with 24 kWh $LiMn_2O_4$ EV battery pack	Make a comparison between a battery that is used once and a battery that is used twice	The life cycle energy and carbon footprint are reduced by 15% when battery is used.	Richa et al. [166]
LFP battery with 1 kWh battery capacity	Assess LFP batteries in China. Total effect calculated using primary and secondary service lifetimes of 1 and 10 years, respectively.	Reducing net emissions by 178–197 kg CO_2 is possible under this 10-year scenario.	Wang et al. [167]
Stationary energy storage delivering 150 kWh per day for 20 years	Examine the lead-acid battery utilized in ESS compared with second life battery (SLB).	Compared with lead acid batteries, SLB scenarios provide 12%–46% reductions in life cycle energy and 13%–46% reductions in carbon emissions.	Richa et al. [166]

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Used LMO/NMC battery	Evaluate the new LIB scenario's environmental implications compared with SLB scenario, in Netherlands.	An SLB reduces emissions by 58% and energy consumption by 62% compared with a new LIB. Over a diesel generator, SLB reduces greenhouse gas emissions by 49%.	Bobba et al. [168]
Backup energy source: SLB Storage capacity: 1 kWh	Evaluate an SLB's eco-friendly performance against that of lead-acid batteries	SLB use reduces GHGs by 20% compared with lead-acid battery.	Yang et al. [169]

Note: LFP: lithium iron phosphate; ICEs: internal combustion engines; NMC: nickel-manganese-cobalt; ESS: energy-storage system; NCM: $LiNi_xCo_yMn_zO_2$; EV: electric vehicle; LFP: $LiFePO_4$; LMO: $LiMn_2O_4$; LIB: lithium-ion battery; GHG: Greenhouse gas.

4.2. Fuel cell

Electrochemical devices are called fuel cells and use the chemical energy in fuel to create electricity. They use fuel and O_2 as inputs, and atomic exchange produces electrical energy and H_2O. Fig. 12 shows the construction of the inner fuel cell. The fuel cells can continue to operate indefinitely as long as fuel is supplied. Fuel cells operate similarly to batteries in terms of their performance under load. The first fuel cell was constructed by Sir William Robert Grove in 1839 [170]. However, the fundamental concept was first proposed in 1838 by the Swiss academic Christian Friedrich Schönbein [171]. The first 5-kW alkaline fuel cell was developed by Sir Francis Bacon in 1950 [20]. An improved fuel cell from the International Fuel Cell company with a 12 KW capacity was used in NASA spacecraft [52]. Fuel cells are promising energy solutions for transportation, mobile, and stationary applications [172,173]**.** A fuel cell may operate at temperatures as high as 1,000 °C [174,175].

In fuel cells, fluid or gassy petroleum functions as the positive terminal, and O_2, air, and Cl function as oxidants in the negative terminal. Hydrogen fuel cells (HFCs) based on hydrolysis technology are widely available [176,177]. The H_2 and O_2 in the HFCs together generate electrical power. This grouping may be regenerative and adaptable because of the utilization of water and air [178]. The fueling process distinguishes between two main forms of HFCs: direct and indirect fuel cell systems [179]. Fuel cells are further divided into six types, as shown in Table 11 [53,180−186], depending on the gasoline and oxidizing agent classes [187].

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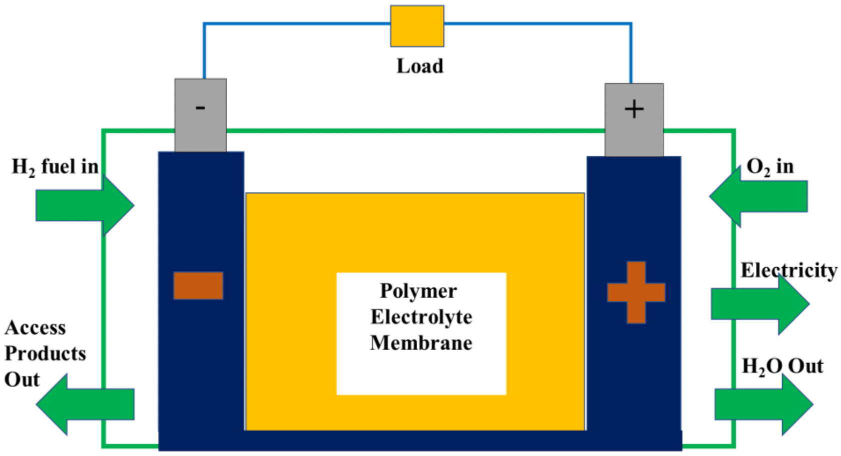

Figure 12.Electricity chemistry in fuel cells

Table 11. Various fuel cell technology and operating features

Fuel-cell class	Fuel employed	Operating temp. (°C)	Cell voltage (V)	Electrical proficiency	Power bound (kW)	Applications	Ref.
Alkaline fuel-cell	Hydrogen	88–100	1.0	60–66	10–100	Space and military	[53]
Phosphoric acid fuel-cell	Hydrogen	145–200	1.1	40–43	50–1,000	Production supply systems	[180-182]
Solid oxide fuel-cell	Hydrogen, CH_4, CO	655–1,000	0.8–1.0	36–45	5–3,000	Backup energy, utility	[183]
Molten carbonate fuel-cell	hydrogen, CO, CH_4	600–700	0.7–1.0	44–60	1–1,000	energy supply	[184]
Proton exchange membrane fuel cell	Hydrogen	55–100	1.1	45–65	1–250	Accessible power, mobility	[185]
Direct methanol fuel-cell	Methanol	65–200	0.2–0.4	35–40	0.001–100	Mobile devices and computers	[186]

4.3. Ultracapacitor

A UC is a storage device with high energy density. The highest longevity among the different storage media was observed for a UC (approximately 40 years) [38]. UCs are employed in EV applications owing to their high power storage, low maintenance requirements, and insensitivity to temperature variations [188]. Honda, Toyota, Nissan, and Hyundai are examples of EV producers that support the adoption of UCs in HEVs, BEVs, and FCEVs to quickly inject or absorb power. UCs are effectively used in power systems, UPSs, and green transportation. Table 12 [189–193] lists various UCs and their respective features.

Table 12. Comparing several UC features and parameters

Parameters	Electric dual coating	Advanced carbon	Advanced carbon	Pseudo-capacitive	Hybrid capacitor	Hybrid capacitor

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Electrode materials	Stimulated carbon	Black lead	Nanotubes forest	Metal oxide	C/metal oxide	C/PbO_2
Energy-storage mechanism	Charge parting	Charge transmission	Charge parting	Redox charge transport	Twin coating/charge transport	Dual film/faradaic
Cell voltage (V)	2–3.0	3–3.5	2.5–3.0	2–3.5	2–3.3	1.5–2.2
Energy density (Wh·**kg−1**)	4.5–7.5	7.5–12.5		9.5–15.5	9.5–15.5	9.5–12.5
Power density (W·**kg−1**)	1×10^6–3×10^6	1×10^6–2×10^6	-	1×10^6–2×10^6	1×10^6–2×10^6	1×10^6–2×10^6
Efficiency (%)	99	95		95	90	90
Life span (Years)	35–40	30–35	30–35	20–30	15–20	10–20
Applications	UPS, vehicle power, GSM	Elevators, cranes etc.	Pulse lesser and welding	UPS	Satellites phone, digital wireless communication devices, etc.	Aircraft electronics, space shuttle
Ref.	[189]	[190]	[191]	[192]	[189], [193]	[190]

There are three distinct types of UCs: hybrid capacitors, pseudo-capacitors, and electric double-layer capacitors (EDLCs). Despite having a higher work intensity than conventional capacitors, EDLCs are more expensive and have a lower specific energy (5–7 W h/kg) and fast self-discharge rate [194,195]. The fundamental components of an EDLC are a diaphragm, electrolytes, and electrodes. Double-dormant carbon-permeable electrode plates are submerged in an electrolyte, and a voltage is applied to the surface of one of the plates. This attracts negative ions to the positive electrode plate. The positive ion-attracting surface of the negative electrode plate creates an electrical twin-coated capacitor on both electrodes [196]. Li-ion capacitors (LICs), which are advanced capacitor technologies developed by researchers, have higher terminal voltages, denser power densities, and higher energy densities than other UCs. LICs for EVs are already commercially available and have a power density of 80 Wh·kg^{-1} [197].

A comparative study of the fuel-cell, UC, and traditional battery storage techniques used in EVs is presented in table 13. According to their analysis, LIBs exhibit better performance based on their lifespan, power density, and operating temperature [198]. According to observations, fuel cells have a low efficiency, high energy density, and long life cycle compared with other storage methods.

Table 13. Comparison of fuel-cell, UC, and traditional battery storage systems

Operating parameters	Pb-acid battery	Ni-Cd Battery	Li-ion battery	Ultracapacitor	Fuel cell	Ref.
Power density (W·kg−1)	150–200	150–350	200–450	900–19,500	1,000–2,500	[199,200]
Energy density (Wh·kg−1)	30–50	40–70	120–140	2–20	10,000–15,000	[30,38]
Cycle span	225–1,490	490–3,125	750–5,000	5,000–10,000	4,000–13,000	[201]
Price (USD·kW^{-1})	130–145	145–390	115–1,325	30–2,000	175–1,250	[202,203]
Efficiency (%)	75–90	55–90	70–95	>90	40–70	[204,205]

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Temperature (℃)	−20–55	−20–60	−20–65	−40–70	25–1,000	[206,207]
Environmental impact	Critical	Coherent	Practical	Controlled	Worthwhile	[208]

5.Functions of the battery management system

A BMS is a specialized technology designed to ensure the safety, performance, balance, and control of rechargeable battery packs or modules in EVs. Internal operating constraints such as temperature, voltage, and current are monitored and controlled by the BMS when the battery is being charged and drained. To achieve a better performance, the BMS technically determines the SoC and SoH of the battery. The battery module is protected from overcharging and overdischarging by the BMS. The charge level is maintained between the maximum and minimum permissible levels to prevent unforeseen occurrences (explosions). Therefore, a BMS is a crucial technology for guaranteeing the security of both the battery and user. After identifying a problem with the functioning constraints (voltage, temperature, etc.), the BMS generates an alarm signal and disconnects the battery pack from power. The BMS in an EV monitors, controls, optimizes, and provides safety insurance against significant risks to battery performance [28]. The various BMS components (sensors, actuators, controllers, etc.) in EVs are manipulated using several rules, patterns, and indicators. Fig. 13 shows a typical operating arrangement of the BMS module.

The BMS performs several tasks, including checking the SoC of the battery and discovering battery-cell or structural block faults [209,210]. Modern technology has been combined with IoT-based technologies to evaluate and supervise battery states [30]. The modeling and estimation of battery conditions are complex activities performed by the BMS [211]. Numerous battery constraints, such as current, voltage, and temperature, are evaluated by the sensing block in the BMS, which also yields numerical indications. These acquisition restrictions are used to determine the performances of the batteries (SoC, SoH, and SoT). An appropriate algorithm is used by a block that manages the battery to control excessive charge–discharge current. The results of this block are transmitted to the cell equalizer to prevent anomalies from occurring through excessive charging and discharging of the battery. To guarantee that the battery functioned in a reliable and secure manner, temperature monitoring is performed through a thermal management block. This block controls the heater and fan to ensure that the battery is maintained at the ideal operating temperature. Another ground fault diagnosis block is added to the system to increase the security. Finally, an efficient transmitter that complies with the rules is required to convey and capture a large number of records [212].

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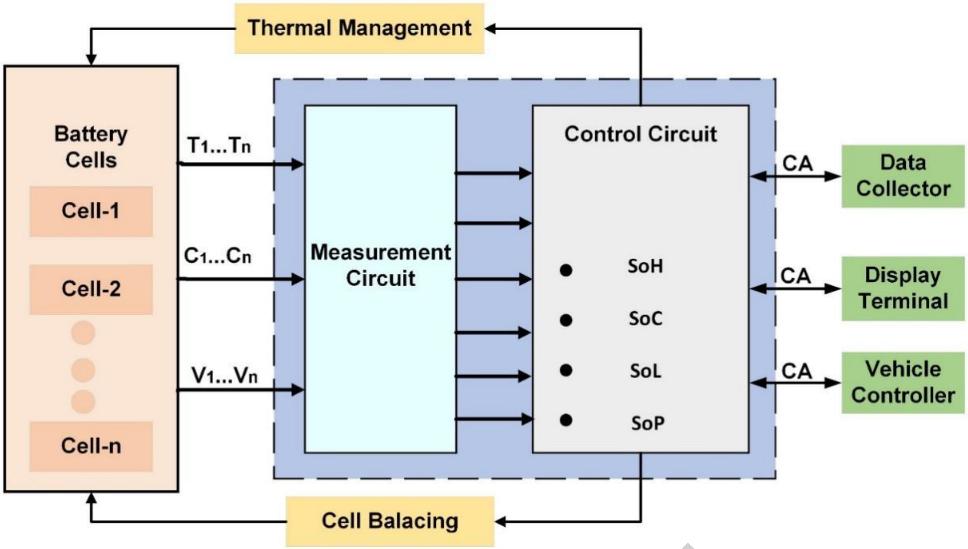

Figure 13.Basic battery management system design

5.1.IoT-based BMS techniques

For enhanced battery functionality, the states of the battery/cell, such as SoC, SoH, SoT, SoP, DoD, and SoF, when an EV is in operating mode should be monitored. The display screen shows the degree of responsibility (SoC) of the cells based on the amount of battery power that is still stored. The operating performance of EVs is significantly affected by the reliability and security of the battery systems. Internal short-circuiting, external short-circuiting, overcharging, sensor faults, actuator faults, connections, and insulation faults are the different categories of faults associated with batteries. A dedicated BMS is required to diagnose and predict these failures so that the battery can operate safely and efficiently [213,214]. The cell capacity diminishes as cell breakdown progresses, whereas the internal cell endurance increases rapidly. This results in poor battery cell performance, rendering them unsuitable for use in EVs. Consequently, it is essential to check the SoH of the battery cells.

A trio of techniques are used to assess the battery status: data-driven, direct, and model-based [215]. Because they are unable to function online and require sufficient time to check the SoC, direct approaches cannot be employed while the vehicle is moving. Therefore, a battery model must be developed to evaluate the SoC online. Computerized approaches to estimate SoC, SoH, and SoT have attracted much interest because of their elasticity and the benefits of being standard-free. They do not use model estimation methodologies; therefore, they are unaffected by concerns regarding modeling and constraint detection.

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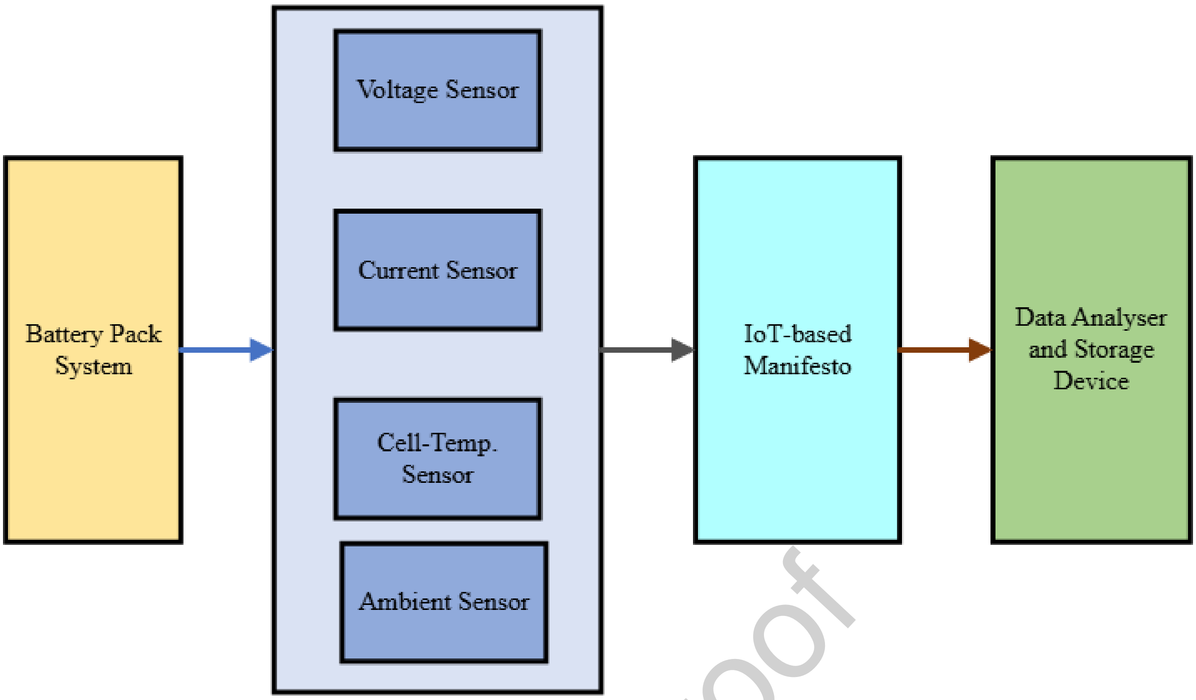

Fig. 14. Block diagram of an IoT-based battery monitoring system

Innovative techniques have attracted considerable interest for diagnosing problems and irregularities associated with batteries in EVs, including CC, AI, digital twins, machine learning, big data, and the IoT. Robust approaches have been developed to determine the premature responsibility prior to updraft blockbusting in battery booths [216,217]. The IoT functions as a mediator for consultations between various sensors (hardware) and applications (software). The primary purposes of IoT techniques are data collection from diverse hardware, the utilization of a range of protocols, remote device configurations, and device management [218]. The power flow, SoC, SoH, DoD, and other parameters are estimated using local communication between the vehicle master controller and the observed parameters [214]. An IoT system wirelessly transmits the calculated and approximate values to a remote location [219]. Fig. 14 shows a block schematic of the battery monitoring system based on IoT. Different innovative methods for estimating the battery state are discussed in the following subsections.

5.1.1. Artificial Intelligence

Numerous AI techniques, such as support vectors, neural networks (NNs), radial basis functions, and machine learning, have the unique potential to diagnose the state of battery *i.e.*, SoC, and SoH [220−222]. A battery-state twin can be created by fusing AI and BMSs. This provides a wise, truthful, and practical framework for a more precise assessment of various battery circumstances. Numerous studies have demonstrated positive results using AI algorithms. Using synthetic NN simulations, many battery defects, including temperature and charge levels, are successfully anticipated [223]. Additionally, a sophisticated evolving set of principles are used to successfully control the charge level of the battery [224]. Fig. 15 shows how an expertly constructed artificial NN (ANN) was used to predict various battery defects [225]. In the future, these AI-based technologies will improve the performance of BMSs for battery health monitoring in real-time applications.

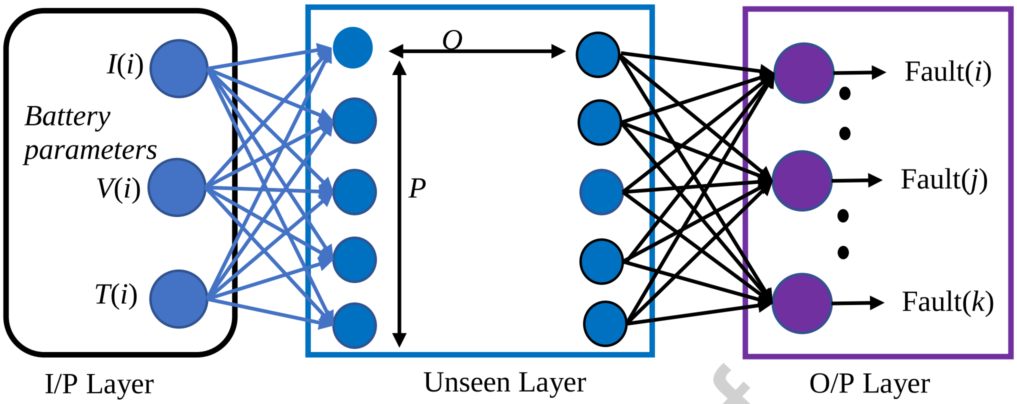

Fig. 15.Artificial neural network-based model for battery faults diagnosis

5.1.2. Cloud computing

The CC approach offers a pool of programmable computer resources that are instantaneously accessible over an easy, on-demand network and released with little oversight or interaction with service providers [226]. With CC technology, information regarding the current condition of the battery can be processed and sent to a CC center [227]. The high processing power of the cloud enables the application of complex calculations [228]. Vehicular cloud computing (VCC) tools can be employed to utilize the features of participating cars because the parked cars can serve as parts of a link for CC [229]. The cloud, connectivity, and EV architectures comprise three components at the edge of VCC [230]. A local server acquires a large amount of actual spell data to use a CC facility to perform complex algorithms [231]. These systems require excessive time to maintain local or onboard batteries to handle large datasets. The fault diagnosis system for future EVs is depicted in Fig. 16, based on CC and AI strategies. Through asset participation and data exchange, the CC battery system creates a digital representation of battery patterns [34]. Technology from the IoT for cars and CC enables the creation of a dual-layer dispersed throughout the Internet planning for concurrent time worldwide optimization [232]. The research progress on big data for onboard power management in EVs is presented in Table 14 [231,233–237].

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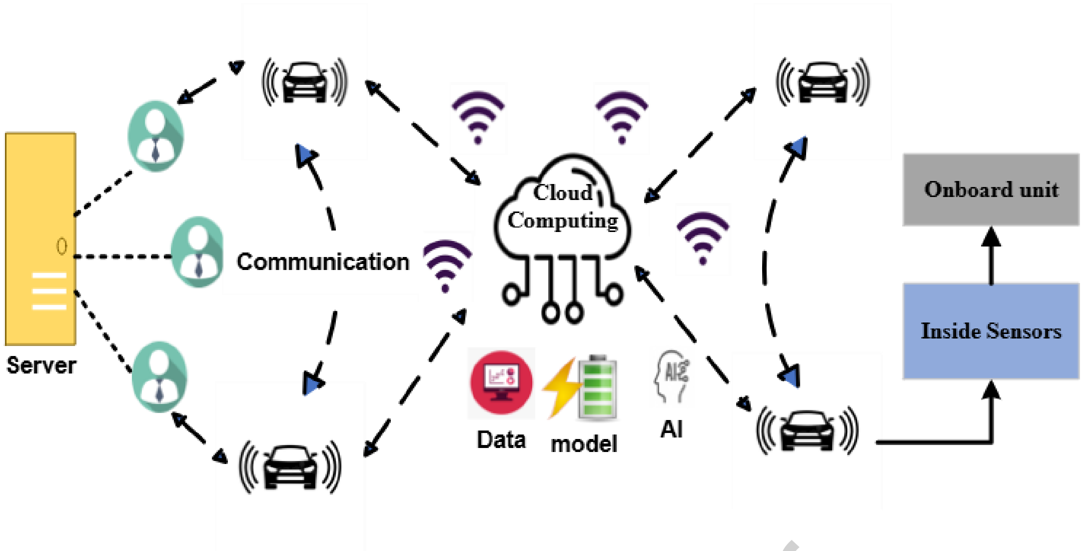

Figure 16.CC and AI-based fault diagnosis system in electric car

Table 14. Research progress on big data for on-board power management in electric vehicles (EVs)

Methods	Implemented year	Applications	Functions/objective	Ref.
Big-data analytical platform	2016	Battery management of EVs	•To assess the battery management systems (BMSs) degree of dependability for EVs •To provide integrated prognoses, error detection, error diagnostics, and error forecasts	[233]
Big-data platform and cyber-physical system	2021	Battery modeling of electric buses	•To provide an adaptive data cleansing technique to address the problem of cloud battery management •To lessen the under-fitting problem and increase the accuracy of the cloud-based battery model	[231]
Cloud computation and big-data platform	2022	Online state estimation of battery in EVs	•Using data from various EVs, we can make educated guesses about the battery's voltage and energy level. •To achieve localized, real-time scenario prediction by the cloud platform	[234]
Big-data framework	2022	Assessments of EV performance degradation	•To examine the partial correlations between EV performance and temperature via real-world EV data	[235]
Big-data platform	2022	Vehicle battery monitoring and management in EV	•To improve the reliability of data used for tracking vehicle batteries in the cloud. and management data cleaning framework •To verify the efficacy of the created data cleansing using the Internet of vehicles and big data platforms	[236]
Big-data platform	2023	State of charge estimation of battery in real time in EV	•To achieve data management, energy interaction, and vehicle functioning •To monitor, gather, upload, and keep track of real-time battery operating data	[237]

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5.1.3. Innovative technology in EV: case studies and real-world applications

Table 15 [238−241] lists some real-world applications and case studies for estimating the SoC, SoH, and related parameters using IoT, machine learning, and AI-based approaches. Giazitzis et al. [238] implemented an ANN-based tiny machine learning algorithm to estimate the SoC of a 2.5 Ah NMC battery model for integration into IoT devices. Both the selected models operated satisfactorily in the tests, demonstrating high levels of accuracy, particularly during the early phases of the battery lifecycle. Compared with the more complicated NN model, the ANN performed better in terms of computing load. The ANN successfully achieved a mean absolute error (MAE) in the initial cycles with an error rate of 2.81%. Obuli et al. [239] used machine learning algorithms consisting of SVM, NN, and Gaussian process regression to enhance the SoC estimation of LIBs for real-time data. The implemented technique offers a trustworthy data-driven system that improves battery management through accurate real-time state-of-charge monitoring, enabled by advanced analytics. It performed best on the test dataset, achieving a root mean square error (RMSE) of 0.8% and a mean square error (MSE) of 0.6.

Table 15. Case studies and practical applications of innovative technologies in EVs

Case study/ practical	Innovative Techniques	Remarks	Applications	Ref.
Case study	ANN-based machine learning	Before deployment on the PSoC 6 target device, two distinct deep learning models are learned and then quantized using PTQ. ANN succeeded in achieving an MAE in the initial cycles with an error rate of 2.81%.	LG 2.5 Ah 18,650 batteries of NMC type	[238]
Case study	Machine learning algorithms: SVM, NN, and Gaussian Regression Process	Offers a trustworthy data-driven system that improves battery management through accurate real-time state-of-charge monitoring made possible by advanced analytics. It performed the best on the test dataset, achieving an RMSE of 0.8% and an MSE of 0.6.	LIB	[239]
Case study	RL-based EMS	Gives an account of the findings from a study that examined RL-based EMS in PHEVs and FCEVs.	LIB of multi-power source EV models	[240]
Practical	Analysis of Five methods: Modified Coulomb counting method, extended Kalman filter, NN, support vector machines, and KNN	The KNN method outperformed the EKF approach, which had a maximum error value of about 0.26%.	LIB with PV 750 W	[241]

Note: ANN: artificial neural network; PTQ: post-training quantization; MAE: mean absolute error; NMC: nickel-manganese-cobalt; SVM: support vector machine; NN: neural network; RMSE: root mean square error; MSE: mean square error; RL: reinforcement learning; EMS: energy management strategy; PHEVs: plug-in hybrid electric vehicles; FCEVs: fuel-cell electric vehicles; LIB: lithium-ion battery; EV: electric vehicle; KNN: K-nearest neighbor; EKF: extended Kalman filter; PV: photovoltaic.

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5.1.4. Performance matrix and comparison of different algorithms

Different direct, model, and data-driven conventional methods have been employed to estimate the battery state, such as SoC, SoH, SoT, and SoP. Additionally, the integration of machine learning- and IoT-based algorithms with data-driven methods enhances the performance matrix of the system and results in a precise estimation of the battery state. Different key battery performance parameters, such as the SoC, remaining useful life (RUL), and SoH, are efficiently evaluated using machine learning algorithms. Algorithms based on machine learning improve processing speed and extend battery life. Machine learning methods include NN, RL, NNs with radial basis functions, and NNs with recurrent neural networks. Table 16 [29,242−256] presents the performance matrix and a comparison of the traditional and new estimation approaches.

Table 16. Performance matrix and comparison of different SoC estimation algorithms

Technique's name		Battery	Capacity	Accuracy	Merits	Demerits	Ref.
Direct conventional methods	OCV CC IR	$LiFePO_4$ LIB	1.1 Ah 2.3 Ah	MAE≤±1.2% MAE≤±1.1% MAE≤±1.3%	Easy and straightforward strategies Less expensive Need low power	Useful when a vehicle is not moving An extended period of rest Inaccurate and exhibit ageing problems	[242−244]
Model-based conventional methods (Filter-based) (Observer-based)	UKF RLS NLO SMO PIO	LiNMC $LiFePO_4$ LIB LIP LI cell	24 Ah 90 Ah 10 Ah 5 Ah 90 Ah	ME≤±0.12% MAE≤±2.26% MAE≤±0.88% ME≤±2.0% ME≤±2.5%	Online estimation precise estimate Rapid convergence Non-linear in dynamic state Strong and effective performance	Subject to model accuracy complex calculations are required The model's accuracy may be affected by ageing, hysteresis, and temperature effects	[245−249]
Data driven methods (Data training & learning algorithms)	NN FL GA SVM ANFIS Machine learning	- - - - 36 LIC	- - - - 40 Ah	MAE≤±3.8% ME≤±5.0% MAE≤±2.98% MAE≤±6.0%	Precision in the estimation An independent model Precision in a nonlinear environment	The need for sample training The cost of computation is likewise substantial Data storage is required for training data.	[250−254]
Cloud computing Blockchain technology Hybrid methods		LIB	-	MAE<1.2% MAE<1.1% MAE<1.0%	Execute intricate algorithms Cloud hub High accuracy Effective and ensure the privacy	Privacy concerns and complex computing Fusion of multiple models Complex design Undeveloped technology	[29,255,256]

Note: ME: maximum error; MAE: maximum absolute error.

6.Charging infrastructure for EVs

EVs are charged using AC or DC. The "levels", or the required charging current and voltage, are used to characterize various charging connector type. Additionally, EVs are charged via "wireless" charging, an advanced technology. Type 1, Type 2, and US Tesla connectors are further divided into AC charging, whereas CHAdeMO, CCS, Tesla Super chargers, and GBIT China connectors are used for DC charging. While maintaining the same voltage level, DC charging is faster and more effective [257]. Using the most recent DC fast charging (DCFC) technology, an EV can be fully charged in 20 min [258,259].

As of March 2021, India had 16,200 EVs and 1,800 charging outlets, according to SMEV [260]. The Indian government has been researching several charging strategies to accelerate EV proliferation of EVs. In terms of the EV standards for India, the BIS suggests CCS Type-2 and CHAdeMO. The specifications of the charging infrastructure for India are listed in Table 17 [261], [262]. India has two main categories of chargers that differ in terms of charging speed: Slow chargers: Single-phase 5–15 A, plugs are used with these chargers, which range in power from 1.2–3 kW. These chargers are compatible with both residential and community charging locations. The battery of an EV must be fully charged within 5–6 h. They provide an onboard charger in the car with alternating electricity, which is transformed into direct current before charging the battery. Fast chargers: To be accessed at municipal charging locations, these chargers may produce 15–50 KW of power. By providing the EV battery with DC, the battery can be fully charged in 30–90 min [260,262].

Table 17. Specifications for India's charging infrastructure

Charger type	Connector type	Voltage level	Total connector guns	Application in electric vehicles (EVs)
DC (Direct current) Slow/moderate	Bharat DC-001, 15 kW	48 V	1CG	2,3,4-W vehicles
	Bharat DC-001, 15 kW	72–200 V	1CG	2,3,4-W vehicles
	Bharat DC 001, 15 kW	230 V	3CG	2,3,4-W vehicles
DC Fast	CCS (Min. 50 kW)	200–1,000 V	1CG	4-W vehicles
	CHAdeMO (Min. 50 kW)	200–1,000 V	1CG	4-W vehicles
	Type 2 AC (Min. 22 kW)	380–480 V	1CG	2,3,4-W vehicles

6.1. Wireless charging

Inductive and capacitive charging are two different forms of wireless charging. In contrast to inductive WPT, which connects conducting coils with an electromagnetic field, conducting plates are connected to an electric field in capacitive WPT [43]. Fig. 17 shows the power transfer via wireless technology.

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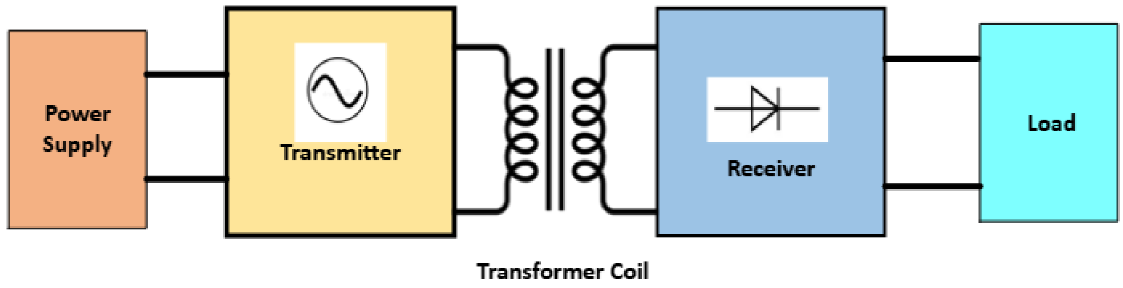

Fig. 17. Power transfer via wireless technology

(a) Inductive wireless charging: A two-coil arrangement is used in the electromagnetic induction-based approach. The charging coil is placed on the ground during installation, and the receiving coil is positioned inside the car [97]. Charging can be performed while driving and does not require a traditional connector; however, it requires universal pairing technology [263]. Inductive wireless charging is not economically viable because of its high cost, low power-transfer density, large coils, and complex design [264]. The power transmission efficiency is boosted by static wireless charging owing to the improved alignment [265]. Dynamic wireless charging eliminates EV concerns regarding range, battery size, and cost [266].

(b) Capacitive wireless charging: Capacitive WPT is significantly more advantageous than inductive WPT because it eliminates the need for electromagnetic shielding owing to the directionality of the electric field [267,268]. Because a high-frequency device can be employed without ferrite, a smaller and less expensive device can be constructed. The primary problem with capacitive WPT is the preservation of high power while ensuring electromagnetic safety, relocating the intensity, and appropriate productivity [269].

6.2. Practical challenges and limitations of wireless charging technologies

Wireless charging has become popular over the past few years because it enables EVs to be charged without the inconvenience of cords [29]. WPT technology has matured considerably after almost 20 years of rapid advancement and is now somewhat practicable. Because of its well-rounded performance, magnetically coupled WPT technology has attracted interest from researchers [270]. Nevertheless, several problems require further investigation and solutions. These include security problems, vast-scale free-space WPT technologies, simultaneous wireless power and data transfer (SWPDT), and other similar technologies.

6.2.1. Security in an electromagnetic environment

The implementation of WPT technology must prioritize the protection of electromagnetic environments by adhering to electromagnetic protection regulations, managing electromagnetic fields (EMFs), and suppressing electromagnetic interference (EMI). For magnetic coupling WPT

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systems to be EMF-safe, they must follow worldwide standards, such as ICNIRP2020, as well as rules set out by the FCC and IEEE [271,272]. The safety design criteria for high-power WPT applications, such as EV charging, are specified by standards such as SAE J2954. Designs for smart homes and medical equipment that expose users for long periods of time need to reduce EMF impacts without compromising efficiency [273].

6.2.2. Vast-scale free-space WPT technologies

The MC-WPT technology is essential for charging consumer electronics. However, although this is effective for stationary applications, it is not as successful for charging mobile devices in larger spaces. New developments have increased capacity of WPTs to cover 18 and 25 m^3, demonstrating the possibility of easy charging in large regions [274]. Problems with improving electricity transmission and efficiency, as well as ensuring that people are safe, prevent its wider implementation [275]. Extending transmission distances and improving efficiency without sacrificing safety or economic sustainability are important challenges.

6.2.3. Simultaneous wireless power and data transfer (SWPDT)

Recent developments in SWPDT have resulted in various systems that provide distinct advantages in specific contexts. Problems such as inefficient energy conversion, signal interference, and complicated systems persist despite advancements [276]. Owing to signal interference concerns, high-frequency transmissions are currently supported only by point-to-point technologies [277]. Future research should focus on finding better methods to modulate signals, create more efficient energy converters, and increase the rate at which signals are transmitted.

6.2.4. Maximizing efficiency in long-range WPT

Devices in distant places, IoT nodes, and consumer gadgets without a direct line of sight could benefit significantly from the ability of far-field technology to enable WPT over long distances. However, this technology must overcome several obstacles [278]. These include problems with power efficiency over greater distances, concerns about safety and regulation when transmitting high-power beams, and precise beam aiming. Alignment is required to ensure effective energy transmission. One major problem is that L-WPT systems achieve an efficiency of only approximately 20%, which is too low to be considered commercially viable.

Table 18 [11,20,22,30,38,202−207,222−224,264,269,279−285] summarizes the limitations of this study in terms of batteries, fuel cells, UCs, BMSs, IoT-based BMS techniques, and EV charging methods.

Table 18. Comprehensive assessment of potential utilization and limitations of various technologies

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Technology/technique	Potential utilization	Limitations	Ref.
Lead-acid battery	Chrysler Voyager and the Ford Ranger EVs	Low specific energy, heavy and less efficient	[11,279]
Nickel-based battery	Toyota and Honda EV Plus	Recycling issue and poor specific energy	[11,280]
Li-ion battery	Nissan Leaf, BMW i3, and Tesla 3	Explosion and recycling problems	[11,281]
ZEBRA battery	BMW and Vito Mercedes EVs	Safety concerns and significant costs	[11,282]
Metal-air battery	GM-Opel, MB410, and Mercedes-Benz EVs	Costly, inefficient, and with a small running temperature window	[11,283]
Flow battery	Toyota EV-30 and the Fiat Panda EVS	Low energy, low power, high expense for regularity repairs, and bulky	[202,203]
Solid-state battery	Vehicles, ships, aircraft, cellphones, etc.	High cost, high internal resistance at solid electrodes, and instable at extreme temperature	[206,207]
Fuel cell	Honda Clarity, Toyota Mirai-II, Hyundai Nexo, Mercedese-Benz GLF	Low efficiency and high cost compared with batteries	[204,205]
Ultracapacitor	Tesla future plan, hybrid form in Audi SQ7, Bentley Bentayga, Porsche Taycan EVs	Poor specific energy, low power density and ineffective to provide power for long duration of time	[30,38]
Neural network	State of charge estimation and energy transfer among internet of vehicles	The necessity of practice training, high price of computing, and large space needed for storage of training data	[223,224]
Cloud Computing and artificial intelligence	EV charging and discharging scheduling and online state estimation of battery in EV	The potential risk of data leaks and privacy problems	[220,222]
Inductive wireless charging	EV charging	High cost, low power transfer density, large coils, and complex design	[264,284]
Capacitive wireless charging	EV charging	Low efficiency around 60%–70%, for small airgap only, safety concerns	[269,285]

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7.Key barriers to battery technology

Electric mobility technology implies more than indicating in the future that batteries can satisfy all the demands for energy while being affordable, harmless, and dependable. Furthermore, the accurate estimation, identification, and isolation of faults or failures are linked to the battery system, as well as their monitoring. This enhances public awareness and boosts consumer satisfaction with EVs. The different problems associated with batteries and battery health monitoring techniques are discussed below.

7.1. Price of batteries

EVs do not have ICEs; instead, they employ electric traction systems, batteries, and electronics. The battery, which is the primary means of energy production and one of the most difficult commercialization problems of all these components, also has one of the largest initial capital prices. Batteries are among the most significant components of EVs, and because they consume 30% of the total budget of an EV, the use of inexpensive materials for battery expertise is a serious concern[286]. According to polls, several prospective buyers worldwide are dissatisfied with the high initial costs of EVs [286].

7.2. Short driving range and lengthy recharge process

Over time, battery life (such as that of LIBs) deteriorates in terms of strength and capacity density, which shortens the time it takes to recharge and decreases its efficiency [287]. The replacement of these stable batteries with new ones adds to the despair of EV users. New batteries can be added to increase the range of EVs; however, this increases the weight of the vehicle and necessitates the use of a more powerful electric motor [288]. Long periods are required to recharge batteries, even when they are removed from consumer time, which may be used for employment [286]. All these factors add to the cost for EV purchasers.

7.3. Cathode and anode material losses

The major influences on the longevity of LIBs include failures such as the destruction of functional materials for anodes and cathodes, also referred to as a decrease in the graphite anode of these battery components [289]. The degradation of LIBs, which is connected to significant power loss when the cell resistance increases, is believed to significantly affect the lifespan and evolution of Li axons for a positive terminal probe material [290]. The different methods of anode material degradation include excess voltage, excess current, excessive SoC, impending temperatures, and under-charge scenarios. Graphite anode deterioration is reportedly responsible for a 33 percent reduction in the dimensions of LIBs used to store energy and electricity. However, the damage caused by the conduction within the cell was responsible for approximately 20% of the decrease in power [289].

7.4. Security concerns

Organizations in charge of regulating the global transportation industry have created safety standards[291]. The United States-defined SAE standard is the most extensively utilized standard in the automotive industry. These specifications include guidelines for the EV system strategy and examination, insurance concerns, automobile recital skills, exuding, persevering, using car links, and fuel routines [292]. Every ESS requires maintenance and security for correct operation. For use in EVs, LIBs must be safeguarded against fleecing, Zn-air batteries must be protected against short circuits, and Na-S batteries must be protected from extreme temperatures [293]. Modern EVs have developed successful facilities and safe attributes for ESSs by utilizing the capacity of microelectronic approaches [294,295].

7.5. Battery heat management problem

Real-time temperature regulation of battery systems remains extremely challenging [296]. The battery should perform at its optimum efficiency without putting itself at unnecessary risk in the low- and high-temperature range limits [297]. A component that enables the battery structure to successfully control the temperature is the heating of each individual cell, which fluctuates depending on modifications to the battery's self-heating and heat degeneration situations throughout the course of usage [298]. Consequently, an appropriate and stable heat-degeneracy regulation should be designed to cool battery systems. Another theory is that low-temperature settings cause LIBs to operate noticeably poorly and permanently destroy batteries [299]. Only a few studies have been conducted on the balanced heating method that is applicable to actual onboard battery systems [300]. However, this is necessary for the EVs to function under all weather conditions.

7.6. Real-time vehicle battery failure detection system

The approach to problem identification in a laboratory setting is unavailable for direct use with the battery system itself [301]. The ultimate objective of problem diagnosis is to establish the SoH of an onboard battery system precisely. Few investigations have been conducted on the true diagnosis of automotive battery systems, as mainstream current research is focused on single cells and battery modules in a laboratory context [302]. Most current research relies on battery data gathered in an environment with few cells, such as a laboratory, and accurate data can be obtained for each cell [303]. A full simulation of the actual working situation of a car is not possible, and it has not yet been proven that the system can detect problems in a genuine battery system [304]. Additionally, there are some discrepancies between the properties of big data and those collected in laboratories. For example, solutions for diagnosing and recreating models with scant data and large sampling intervals are critical [305].

8.Conclusions

To support extensive and in-depth research, we incorporated energy-storage technologies such as LIBs, SSBs, flow batteries, LABs, fuel cells, and UCs for electric mobility in this assessment. To estimate the SoC, SoH, and SoT, IoT-based computerized algorithms are used to manage excessive charge–discharge current in real time to monitor the battery status. Furthermore, to enhance electric mobility, WPT charging techniques have been extensively investigated. The significant contributions of this study are as follows.

- Energy storage for EVs are available in various forms, including LIBs, LABs, SSBs, fuel cells, and UCs. The safety considerations and environmental impacts of high-energy batteries in EVs have been extensively covered.

- The advantages, disadvantages, and technical information regarding Li-based batteries in relation to EVs are covered with nickel–metal hydride batteries and flow batteries. Fuel-cell and UC storage solutions have been compared with traditional battery storage in terms of efficiency, power density, cost, life cycle, and sustainability of EVs.

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• The capabilities of the BMS for monitoring battery conditions, including SoC, DoD, and SoT, are highlighted using IoT-based diagnostic methodologies through real-world applications and case studies.

• Inductive and capacitive wireless charging methods for EVs are investigated, along with the specifications of the charging infrastructure in India. Practical challenges and limitations of wireless charging in EVs have also been reported. Several infrastructural impediments, safety concerns regarding batteries, and problems with BMSs have been identified for electric mobility.

8.1. Future possibilities and suggestions

After evaluating the available information on the states of batteries, fuel cells, UCs, BMSs, and charging infrastructure, we attempted to provide and compile databases that might be effective in overcoming the obstacles to EV progress. High energy density (230 Wh/kg) and high power density are required to extend the driving range of an EV beyond 500 km. ; However, safety, fast charging, economic feasibility, environmental impact, and cycle life should not be compromised.

- The energy density of LIBs can be improved by increasing the Ni concentration in cathodes. However, sustainability problems may result from the increased demand for crucial metals (Li, Co, and Ni), which are becoming scarcer with time.
- Research should focus on reliable and nonflammable solid electrolytes instead of volatile and flammable liquid electrolytes to enhance the energy density and safety of lithium-based batteries. However, SSB commercialization is in its early stages, and overcoming many obstacles related to solid-state electrolytes, interfaces, and scale-up production requires considerable time.
- Batteries made of sodium ions, lithium air, or zinc ions have more energy and power than LIBs and may be a cheaper and more reliable option because of their large crustal storage capacities. The performance of these batteries has greatly improved in the laboratory; however, the magnitude of these improvements is still significantly lower than that of batteries used in real-world applications.
- To prevent the formation of Li dendrites and degradation of the electrolyte in LIBs, it is necessary to concentrate techniques such as Li metal plating to ensure consistency at the electrode–electrolyte interface.
- To increase electric mobility dependability, research should focus on robust and secure AI- and IoT-based algorithms for estimating, monitoring, and diagnosing LIB conditions (SoC, SoH, SoP, DoD, etc.) in real time, with practical validation.

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- Further, to enhance future e-mobility in terms of rapid charging of LIBs via magnetic coupling WPT technology, studies should concentrate on WPT-related problems, such as extension of transmission distances and improving efficiency, without sacrificing safety or economic sustainability.

CRediT author statement

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Declaration of competing interests

The authors declare that there are no conflicts of interest.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. **"An Electric Vehicle Battery and Management Techniques: Comprehensive Review of Important Obstacles, New Advancements, and Recommendations".**

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